A STAGE-SPECIFIC ACCOUNT OF DESIRABLE DIFFICULTY

MEMORY EFFECTS FROM COGNITIVE CONTROL: A STAGE-SPECIFIC ACCOUNT OF DESIRABLE DIFFICULTY

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Lay Abstract

There is an intuitive notion that making a learning experience hard will hinder memory of that information later on. Contrary to this belief, in *certain* circumstances, making learning difficult can actually enhance the memory of that information – this has been termed *desirable difficulty*. The issue with these desirable difficulties is that they are only sometimes effective. Originally it was proposed that general task-wide difficulty would lead to an enhancement in memory. This thesis, however, provides evidence suggesting that task difficulty is stage-specific in nature, meaning that for the difficulty to enhance memory, the difficulty needs to be at a specific stage of cognitive processing. For difficulty to have a beneficial effect on memory, the particular difficulty needs to focus an individual's attention on the core meaning of what they are trying to remember, or else the difficulty will direct attention away from this important information causing a possible decrease in memory. These findings provide a framework for how and when to use difficulty as a means to enhance learning.

Abstract

This thesis investigates predictions from prominent conflict theories of cognitive control that information experienced under high conflict conditions should be better encoded. More specifically, recent research suggests that selectively attending to relevant stimuli while ignoring conflicting stimuli can lead to better memory. These ideas have been broadly discussed in the desirable difficulty literature – described by instances where increasing difficulty during initial task performance leads to better later memory. As a growing number of studies have attempted to produce these effects with mixed success, calls for more focused investigations into the underlying mechanisms have been made. This encoding benefit for high-control-demand or high-difficulty situations has been broadly conceptualized as a task-general property, where all activated representations should be better encoded. The goal of this thesis was to investigate whether memory-enhancing effects of difficulty manipulations depend on inducing additional cognitive control at particular information processing stages. This thesis documents some of the first work showing that the within-task locus of conflict and attentional control is critical to whether later memory benefits are seen – conflict/control focused on semantic item representation produces better memory, but conflict/control focused away from item representations at response selection gives no memory benefit. These findings and theory are then extended to physiological measures of pupil dilation and sequential (Grattron-like) conflict/control situations. This thesis proposes a stage-specific conflict-encoding

model which complements and extends current leading theories of conflict-driven cognitive control.

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Table of Contents

Preface

This is a “sandwich thesis”, meaning that the empirical chapters are all stand-alone publications that have either been published or submitted for publication. Chapter 2 is published in a peer-reviewed journal, and Chapters 3 and 4 are both submitted for publication in peer-reviewed journals. In Chapter 2, my collaborators Dr. Sandra Thomson and Dr. Karin Humphreys are second and third authors, respectively, and my supervisor, Dr. Scott Watter, is the final author. My collaborator for Chapter 3 is Kara Hannah who is the second author, while Dr. Scott Watter is the final author. Dr. Scott Watter is the second author for Chapter 4. My contributions to each of these manuscripts are outlined below.

The first empirical chapter (Chapter 2) is a reprint of Ptok, M. J., Thompson, S. J., Humphreys, K. R., & Watter, S. (2019). Congruency encoding effects on recognition memory: A stage-specific account of desirable difficulty. *Frontiers in Psychology*, 10:858. doi: 10.3389/fpsyg.2019.00858. My role in this manuscript included experimental design, programming, data collection from human participants, data analysis, and I was also the primary writer.

The second empirical chapter (Chapter 3) is the following manuscript: Ptok, M. J., Hannah, K., & Watter, S. (Submitted). Memory effects of conflict and cognitive control are processing stage specific: Evidence from pupillometry. *Psychological Research*. Manuscript ID: PRPF-D-19-0018. My role in this manuscript included experimental design, programming, data collection from human participants, data analysis, and I was also the primary writer. The third empirical chapter (Chapter 4) is the following manuscript: Ptok, M. J., & Watter, S. (Submitted). Memory consequences of congruency sequence effects: Stage specific conflict encoding. *Cognitive Psychology.* Manuscript ID: COGPSY-D-19-00018. My role in this manuscript included experimental design, some programming, data collection from human participants, data analysis, and writing.

Please note that since these manuscripts are intended to be standalone publications, there will be some redundancy within the introductions and discussions of these chapters. There will also be some redundancy in the methodology across the chapters as we used similar methods across all experiments in each chapter. Despite this overlap, the goal of each chapter was to answer different theoretical questions, all of which are related to the common issues presented in this thesis.

List of Figures

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 1: Introduction

Understanding conditions under which optimal learning takes place has become a focus in recent years for both researchers and practitioners who want to apply cognitive principles to educational settings. Notable work by Bjork (1994) has pointed to various human learning and memory effects suggesting that difficulties during encoding or retrieval can lead to benefits in long-term memory. From a pure research perspective, this question is important, in that it sits at the intersection of several large and fundamental fields in cognitive psychology (selective attention, long term memory, and cognitive control/divided attention). A solution to why most kinds of difficulty lead to interference and poorer later memory (typical costs of interference or divided attention), but in some circumstances lead to enhanced encoding and later memory for in-the-moment difficult events (so called ‘desirable difficulty’), would be valuable to many areas of research.

The New Theory of Disuse (Bjork & Bjork, 1992; 2011) has become a prominent model in explaining the general desirable difficulty account. This theory distinguishes between the storage strength and the retrieval strength of information stored in memory. Storage strength reflects how entrenched a memory representation is, whereas retrieval strength reflects the current accessibility of that representation. Retrieval strength in this case is heavily influenced by situational cues, exposure to the representation and recency of study (e.g., retrieval becomes more difficult when the information has not been recently activated). From this, it is assumed that current performance is a reflection of the current retrieval strength, and storage strength acts to delay the loss (forgetting) and elevate the gain (relearning) of retrieval strength. The key takeaway is that conditions that increase retrieval strength differ from those that increase storage strength. Therefore, when learners interpret their current retrieval strength as their storage strength, they will prefer conditions of poorer learning compared to conditions of better learning.

These findings of so-called ‘desirable difficulties’ are at odds with the more intuitive idea that if a task is easier, there should be more resources available to encode the information presented. Examples of these ‘desirable difficulties’ include the spacing effect, where increasing temporal spacing between encoding events increases difficulty at study but improves long-term memory (Bjork & Allen, 1970; Cuddy & Jacoby, 1982). Additionally, generation effects (Landauer & Bjork, 1978; Carrier & Pashler, 1992; Roediger & Karpicke, 2006; Kornell, Hayes, & Bjork, 2009) as well as varying conditions of practice, such as varying the environmental setting learning takes place, or interleaving versus blocking study (Shea & Morgan, 1979; Simon & Bjork, 2001; Rohrer & Taylor, 2007; Kornell & Bjork, 2008), have all been shown to enhance long-term memory.

In addition to this more memory-focused literature, other researchers have investigated processing difficulties during initial encoding, in the form of perceptual interference (Hirshman & Mulligan, 1991; Nairne, 1988), hard to read fonts (Diemand-Yauman, Oppenheimer, & Vaughan, 2011), and inverted words

(Sungkhasettee, Friedman, & Castel, 2011). These have been shown to enhance retention. Processing difficulties such as these therefore appear to be 'desirable' for learning.

In general, the traditional ideas of 'desirable difficulty' (e.g., spacing and interleaving) in addition to the perceptual effects have one thing in common: The positive effect these task manipulations have on incidental memory encoding. Currently, the term represents a broad description of outcomes and no explanation for them (Dunlosky & Mueller, 2016). For this reason, more groups of researchers have recently been interested in exploring the potential mechanisms involved as the common underlying causes of 'desirable difficulty' need to be better operationalized. An example of this effort comes from Dunlosky and Mueller (2016) who reviewed evidence suggesting that processing disfluency may elicit additional attentional processing leading to better encoding and later memory. We wanted to investigate these ideas further. The goal of this thesis is to better understand the processing difficulties at encoding that leads to these later memory benefits and to apply these findings to help explain the broader desirable difficulty literature.

Attentional mechanisms of desirable difficulty

The desirable difficulty framework established by Bjork and Bjork (1992, 2011) has been influential in steering researchers to consider situations where general cognitive conflict costs can be avoided, or even reversed. This paradox is a twist on the distinction between performance and learning. Performance is what we measure during training, whereas learning is a more permanent change in knowledge which is the target of instruction (Bjork & Bjork, 2011). You can have instances where learning occurs with no apparent change in performance, and you can also have changes in performance where no change in learning has occurred. This can be dangerous, because people may interpret their current performance as a valid indicator that learning has occurred, which leads to them relying on conditions that hinder their learning.

Based on these ideas, Bjork and Bjork (1992, 2011) discovered better conditions of learning that, while more difficult at encoding (as indicated by poorer performance), actually lead to more durable learning. Over the years, there have been many examples of these desirable difficulty effects, however these results are not only observed in the typical spacing effect, generation effect, and perceptual difficulty literatures. Across many experiments which are in line with this ‘increased attentional processing’ research, recent investigations using congruency priming (when the ability to categorize a target stimulus is facilitated/interfered with by a prime stimulus that either matches or does not match the target stimulus information) have shown that an increase in selective attention by cognitive control mechanisms benefits subsequent memory for difficult (incongruent) items relative to easier (congruent) items, where the demands on selective attention during encoding are lower (Krebs, Boehler, De Belder, & Egner, 2015; Rosner, D’Angelo, MacLellan, & Milliken, 2015)

Within this literature, 'difficulty' has been broadly conceptualized as a task-general property, with no strong prediction of what particular task elements should produce a desirable difficulty benefit. Unfortunately, there has been no strong prediction of what particular task elements should produce these effects. One theory suggests that these effects occur due to disfluent information leading to enhanced item-specific processing, which produces superior item recognition performance. This then supports the idea that difficult-to-process information initiates encoding mechanisms that direct the learner to understand the information better. This is in comparison to fluent items which encourage broader relational encoding, encoding that is less focused on the to-be-remembered information (McDaniel & Bugg, 2008). But what about situations where these processing difficulties are not desirable for learning?

Challenges to the desirable difficulty principle

Not all processing difficulties are desirable for learning. The broader history of experimental psychology has largely agreed that additional task difficulty tends to lead to worse, not better, memory for task content. The divided attention literature is a good example of this, where divided attention on a task is difficult, and also typically impairs memory for task information (Baddeley, Lewis, Eldridge, & Thomson, 1984; Craik, Govini, Naveh-Benjamin, & Anderson, 1996; Dudukovic, DuBrow, & Wagner, 2009; Fernandes & Moscovitch, 2000; Gaspelin, Ruthruff, & Pashler, 2013; Mulligan, 1998; but for an exception see Kessler, Vandermorris, Gopie, Darros, Winocur, & Moscovitch, 2014). Even though the desirable difficulty framework has shown situations where these general costs of divided attention can be avoided, there have been other examples of when desirable difficulty situations are not so desirable. In fact, there are examples which should in theory produce stronger memory traces leading to an increase in later memory, yet they fail to do so.

Recent work on disfluency in the form of perceptual difficulty has been an area of interest for this reason. According to the disfluency theory (Alter, Oppenheimer, Epley, & Eyre, 2007) disfluency will trigger a monitoring process whereby learners evaluate the difficulty of the learning material. When the difficulty is high, it will activate more effortful processing which is more evaluative. However, there have been many examples over recent years where perceptual difficulty manipulations have failed to increase performance (Eitel & Kühl, 2015; Lehmann, Goussios, & Seufert, 2015; Margreeehan, Serra, Schwartz, & Narciss, 2015; Rummer, Schweppe, & Schwede, 2015; Sidi, Ophir, & Ackerman, 2015; Strukelj, Scheiter, Nyström, & Holmqvist, 2015), suggesting that any positive effects are either marginal or bound to specific conditions (Kühl & Eitel, 2016).

One example of these problematic results is work by Hirshman et al. (1994), who examined whether manipulating stimulus contrast at the time of encoding would have any effect on memory performance. During the study phase, participants identified words with perceptually high contrast (i.e. white words on a black background) or low contrast (i.e. dark grey words on a black background).

Reaction time (RT) was 30 ms faster for high contrast works compared to low contrast words. However, there was no difference in memory performance between the high contrast and low contrast items.

In line with this problematic result was work reported by Yue, Castel, and Bjork (2013). The researchers demonstrated results from five experiments where they manipulated perception of words (i.e., perceptually clear, perceptually blurred) at the time of encoding. These researchers were interested in the relation between judgments of learning (JOLs) at encoding and memory performance at test. JOLs were measured for each word presented at encoding by asking participants to indicate (on a scale of 1-100) how likely they would remember the word later on. According to the desirable difficult framework, it would be predicted that participants would judge that they would better remember the words that were easier to process at study (i.e., perceptually clear) when in fact they would have better memory for words that were more difficult to process at study (i.e., perceptually blurred). Across the five experiments, Yue et al. found that participants' JOLs were indeed higher for clear compared to blurry words, but there was no benefit for blurry words over clear words either for recall or for recognition. Additionally, there was a consistent trend across the experiments where there was better memory for clear compared to blurry words.

More recently, Kühl and Eitel (2016) edited a special issue reviewing the effects of disfluency on learning outcomes. Their review article assessed 13 studies across 6 papers which all failed to show better performance due to disfluency (Eitel & Kühl, 2015; Lehmann, Goussios, & Seufert, 2015; Margreeehan, Serra, Schwartz, & Narciss, 2015; Rummer, Schweppe, & Schwede, 2015; Sidi, Ophir & Ackerman, 2015; Strukelj, Scheiter, Nyström, & Holmqvist, 2015). It was hypothesized that the majority of the disfluency manipulations did not trigger effective control processes such as more effortful control which leads to an increase in performance. Although disfluent study information increased study times (e.g., Eitel & Kühl, 2015; Rummer et al., 2015), the overall mental effort for encoding the study material was not higher (e.g., Eitel & Kühl, 2015).

For the desirable difficulty principle to be useful to researchers and educators, it is important to look at both the successes and failures so that we can have a better understanding of its effective components. By understanding where these difficulties do not lead to learning benefits, we can come closer to understanding when and where these situations do benefit learning. Situations in which difficulties are desirable include when they require more generative processing at encoding, which produces stronger memory traces and in turn fosters later recall (Bjork, 1994). When it comes to disfluency, however, these situations might exercise useful processes that are not supported by characteristics of the to-be-learned information. In other words, reading a disfluent font might not activate the processes needed to remember the to-be-remembered information (Bjork, 2016). Next, I turn toward some of the recent incongruency conflict literature. These attentional manipulations have been a recent focus for investigating task processing demands (focusing attention on the relevant information while ignoring irrelevant information) on encoding difficulty effects.

Incongruency effects on memory

Focusing one's attention while actively ignoring irrelevant information – congruency priming – has been a common way to investigate cognitive control and selective attention (e.g., Stroop, 1935; Simon & Small, 1969; Eriksen & Eriksen, 1974). These effects are well-described by the conflict-monitoring model of cognitive control, where the conflict detected between response representations from the font colour and word name of an incongruent Stroop trial triggers a top-down increase in attention toward task-relevant information (in this case the colour), reducing interference from task-irrelevant information (the word name; Botvinick, Braver, Barch, Carter, & Cohen, 2001). Recently, this type of selective attention processing has been shown to produce improvements in learning for high-conflict (incongruently primed) situations (e.g., Botvinick, 2007; Krebs et al., 2015; Rosner et al., 2015; Verguts & Notebaert, 2008).

Krebs et al. (2015) examined the effect of conflict-induced cognitive control on memory using a face-word Stroop task. Participants were asked to judge the gender of a face while ignoring a superimposed gender label (i.e., male or female). This task produced a congruency effect where participants had the fastest responses to congruent face-word pairs and slowest to incongruent pairs. Memory for the faces was later assessed as a function of whether the irrelevant distractor word was incongruent, congruent, or neutral (e.g., the word "house").

They found that faces from incongruent trials were better recognized than faces from congruent or neutral trials. Therefore, even though there was interference with processing during initial encoding, there was enhanced attention toward target information leading to better incidental encoding of the faces.

Similar results were obtained in a series of experiments conducted by Rosner, D'Angelo, MacLellan, and Milliken (2015). They asked participants to read aloud a red word that was interleaved with either a second presentation of the same word presented in green (congruent trial) or a different word presented in green (incongruent trial). Consistent with Krebs and colleagues (2015), they demonstrated a congruency effect where reading incongruent trials was slower than congruent trials. A later surprise recognition memory test again revealed better memory for the incongruent trials despite the conflict at encoding. Follow up studies demonstrated that the recognition memory effect was not driven by additional time-on-task for incongruent trials. The authors speculated that the effect was driven by increased selective attention demands for incongruent items (Rosner et al., 2015).

Furthermore, Chiu and Egner (2015) demonstrated new evidence on control processes of response inhibition. In a series of experiments, participants categorized faces by gender during go/no-go, stop-signal, and yes/no tasks. Following a short delay, participants performed a surprise recognition memory test which revealed that the control demands of response inhibition divert attention away from stimulus encoding. This resulted in poorer memory for trials with response inhibition responses. These negative effects of response inhibition on memory are opposite to the memory enhancement when resolving conflict found in related research (Krebs et al, 2015; Rosner et al, 2015). The authors suggest that this effect is due to response inhibition directing attentional allocation away from stimulus encoding.

The attentional boost literature shows evidence for a similar and converging set of ideas. Swallow and Jiang (2010) devised a study to show that increased attention on specific trials can overcome the typical negative effects of divided attention on memory. Participants studied a series of pictures that were each overlaid with a small square. In addition to remembering the pictures, participants in the dual-task condition were told to detect and respond to infrequent white squares. In this condition, memory for pictures presented with distractor items (black squares) was impaired relative to the full attention condition where the squares were ignored (replicating the typical divided attention cost), but memory for pictures paired with target squares received a relative 'boost', effectively eliminating the divided attention deficit. This attentional boost effect has also been reproduced using words (Mulligan, Spataro, & Picklesimer, 2014; Spataro, Mulligan, & Rossi-Arnaud, 2013). Swallow and Jiang (2010) proposed that the detection of a target triggers the opening of an attentional gate that causes a transient increase in attention (Olivers & Meeter, 2008). This increase in attention enhances not only the processing of the target, but also of concurrently presented information, producing the attentional boost effect. The increase in attention to the pictures on target-present trials is thus able to overcome the negative effect of divided attention on memory.

Similar research examined the effects of stimulus repetition on recognition memory (Collins et al., 2018; Rosner et al, 2018). In these experiments, participants read aloud a red target word that was preceded by a briefly presented green prime word. On half of the trials the target and prime words were the same (repeated trials), and on the other half the prime and target words were different (not-repeated trials). Repeated target words had faster RTs at study than non-repeated words. In a later recognition memory test, participants made old/new judgments on presented words to indicate whether they had seen that word during the first phase of the experiment. Results indicated better memory for not-repeated target words compared to repeated target words – these authors refer to this as the repetition decrement (RD) effect. Follow-up studies show that this effect remained even when repetitions at study were separated by unrelated words. However, the RD effect only occurs when the primes are ignored. When the primes in these experiments were attended to, this effect was eliminated. In other words, repetitions where the prime is unattended created fluency, resulting in relatively poorer engagement with the repeated target words, leading to poorer memory for repetition trials. These various findings all provide evidence that attentional allocation at study may have an important influence on incidental memory encoding.

Using congruency priming, the present thesis aimed to determine whether memory benefits from incongruent priming are indeed produced by this kind of task-general elicitation of greater cognitive control, or whether this incongruency memory benefit may depend on a more processing stage-specific mechanism.

Overview of Empirical Chapters

With the growing interest in how processing difficulty influences learning and memory, researchers have also become interested in understanding the mechanisms involved. As recently stated by Sidi et al. (2016), "the types of difficulties that are indeed desirable, and the appropriate conditions under which they enhance performance, are still unclear". We agree: Not all processing difficulties are desirable for learning and it remains an open question as to why processing difficulty leads to memory benefits in some cases and not others.

Therefore, the goal of this thesis is to investigate why some kinds of difficulty enhance later memory and why others do not. Understanding whether this effect operates under task-general mechanisms or whether this effect operates under mechanisms that are more stage-specific in nature will give us a better understanding of why and when these memory effects are produced.

In Chapter 2 of this thesis, I examine the particular task elements that produce these encoding memory effects. In particular, from stage processing models of single-and dual-task performance, I propose that memory-enhancing difficulty manipulations should strongly depend on inducing additional cognitive control at particular processing stages (e.g., semantic versus response selection stages of processing). When processing difficulty does not enhance attentional allocation toward the to-be-remembered information, we should not see these memory benefits. In Chapter 3, I use physiological pupil dilation measures to directly assess this stage-specific model of conflict encoding effects. In particular, I propose that greater cognitive control during a task will lead to greater pupil dilation but only the cognitive control directed at the to-be-remembered information will lead to a later memory benefit. Finally, in Chapter 4, through the use of congruency sequence effects, I investigate whether the upregulation of cognitive control from the previous trial has an influence on these memory effects, as a direct prediction of a general conflict-control model, and contrast this with memory effects from within-trial sources of semantic and response stage conflict. All of this work points to a stage-specific account of these desirable difficulty effects, where I argue that later memory benefits will be elicited only with an increase in cognitive control directed at the core meaning of the to-be-remembered information.

CHAPTER 2: Congruency encoding effects on recognition memory: A stage-specific account of desirable difficulty

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Preface

Chapter 2 presents the results of six experiments examining a stage-specific account of congruency encoding effects on recognition, and how this framework could contribute to a mechanistic account of the desirable difficulty effect. The method for Experiment 1 used backward compatibility effect (BCE) response priming in the psychological refractory period paradigm (PRP) to produce a response priming manipulation on a primary task. The other five experiments used incongruency priming to increase cognitive control at either the categorization or response selection stage of processing. Participants were asked to categorize words (e.g., an object as big or small, or a name as male or female) while ignoring irrelevant but related distractor words (e.g., “big” or “small”, “male” or “female”) during study. Afterward, participants performed an old/new recognition memory test for the classification task words.

Experiment 1 revealed a congruency priming effect where participants took longer to respond to incongruent trials compared to congruent trials.

However, when attentional allocation was directed toward response selection, there was a typical divided attention effect where lower conflict congruent trials led to better memory. Experiment 2 aimed to replicate the basic response incongruency priming findings from Experiment 1 using a single-task priming design akin to those used for the semantic priming experiments in the rest of the paper. Experiment 2 showed a conceptual replication of Experiment 1, finding a congruency priming effect at study, but no memory difference for congruent compared to incongruent primes.

Experiment 3 aimed to use the same single-task priming design as Experiment 2, but with semantic primes (i.e., classifying words as big or small in comparison with the computer screen and “BIG” or “small” word primes). Results demonstrated a congruency priming effect; surprisingly, however, memory was not better for incongruent versus congruent words – memory performance was again equivalent. These results were explored further in Experiment 6.

Experiment 4 used the same stimuli and design as Experiment 3, but had participants classify words based on animacy (i.e., alive or not alive with “animal” or “thing” as word primes). Results demonstrated a congruency priming effect and a substantial incongruency encoding benefit on later memory. To generalize and extend this effect, we conducted a conceptual replication of this semantic congruency priming experiment as Experiment 5, using the name stimuli and gender classification task from Experiment 2, with semantic category primes (i.e., "male" or "female") instead of response primes. Again, we found a congruency effect at study and a significant later memory benefit for incongruent stimuli.

The aim of Experiment 6 was to understand why Experiment 3 did not show our predicted incongruency memory benefit, even though the same stimuli were used. It was hypothesized that the size task used in Experiment 3 required more effortful evaluative judgments of relative stimulus size, that elicited increased processing and attentional focus on all trials, eliminating a differential memory effect of high-conflict incongruent primes. In Experiment 6, the additional evaluative work was taken out of the task and only canonically big or small stimuli (e.g., "elephant" or "flea") were used along with the same "BIG" or "small" word primes, generally allowing more automatic responding, and (in theory) allowing the conflict from incongruent priming to elicit relatively greater control and focus for those trials, leading to better later memory. We observed a congruency effect at study and a convincing incongruency encoding benefit when using canonically big or small stimulus items. The results of these experiments demonstrate a highly stage-specific mechanism for producing conflict/control related incidental encoding effects. These results constitute a first demonstration of the idea that "difficulty" being viewed simply as task-or stimulus-directed is not sufficient for eliciting memory benefits.

Abstract

Recent research suggests that selectively attending to relevant stimuli while having to ignore or resist conflicting stimuli can lead to improvements in learning. While mostly discussed within a broader "desirable difficulty" framework in the memory and education literatures, some recent work has focused on more mechanistic questions of how processing conflict (e.g., from incongruent primes) might elicit increased attention and control, producing enhanced incidental encoding of high-conflict stimuli. This encoding benefit for high-control-demand or high-difficulty situations has been broadly conceptualized as a task-general property, with no strong prediction of what particular task elements should produce this effect. From stage processing models of single and dual-task performance, we propose that memory-enhancing difficulty manipulations should strongly depend on inducing additional cognitive control at particular processing stages. Over six experiments, we show that a memory benefit is produced when increased cognitive control (via incongruency priming) focuses additional processing on the core meaning of to-be-tested stimuli at the semantic categorization stage. In contrast, incongruency priming targeted at response selection within the same task produces similar effects on initial task performance, but yields no memory benefit for high-conflict trials. We suggest that a simple model of limited-capacity and stage-specific cognitive control allocation can account for where and when conflict/difficulty encoding benefits will occur, and may serve as a model for desirable difficulty effects more broadly.

Introduction

The ability to deliberately focus one's attention while ignoring irrelevant distractions has become a foundational way of defining selective attention and cognitive control (e.g., Eriksen & Eriksen, 1974; Simon, 1969; Stroop, 1935). More recently, evidence suggests that selectively attending to relevant stimuli while having to ignore or resist conflicting stimuli can lead to improvements in learning (e.g., Botvinick, 2007; Krebs, Boehler, De Belder, & Egner, 2015; Rosner, D'Angelo, MacLellan & Milliken, 2015a; Verguts & Notebaert, 2008). This apparent stimulus encoding benefit under high-conflict incongruent priming conditions has been typically interpreted as a task-general effect of increased cognitive control under high-conflict conditions, following the influential conflict monitoring and cognitive control model of Botvinick, Braver, Barch, Carter, and Cohen (2001).

The preset study sought to test whether these memory benefits from incongruent stimulus priming are indeed produced by this kind of task-general elicitation of greater cognitive control, or whether this incongruency memory benefit may depend on a more processing stage-specific mechanism. To anticipate our results, we show that priming with incongruent semantic information in a range of semantic categorization tasks leads to later benefits in recognition memory, but that incongruent response priming or incongruent semantic priming in more evaluative or demanding tasks does not. We argue that the locus of selective attention and cognitive control demands relative to the stage-specific processing conflict within particular task settings is a critical aspect of these differential memory effects, and show how this kind of model makes straightforward predictions about when different kinds of incongruency conflict should help or hinder later memory. We suggest that these ideas might also serve as a valuable general model for more mechanistically predicting and accounting for so-called desirable difficulty effects.

Incongruency Effects On Memory

Congruency priming manipulations are commonly used to investigate selective attention and cognitive control. The conflict-monitoring model of cognitive control (Botvinick et al., 2001) has been an influential framework in understanding how cognitive control processes modulate selective attention so as to protect intended performance from varying degrees of interference from irrelevant stimulus information. For example, in a typical Stroop task, the conflict detected between font colour and word name on an incongruent Stroop trial triggers a top-down increase in attention toward task-relevant information (in this case, the colour), reducing interference from task-irrelevant information (the word name). The effects of this kind of increased cognitive control or divided attention demand on later memory have typically been seen to be negative (e.g., Craik, Govoni, Naveh-Benjamin & Anderson, 1996; Gaspelin, Ruthruff & Pashler, 2013). However, several recent studies have shown that in similar kinds of congruency priming tasks, subsequent memory for incongruent (higher conflict) items can be better relative to congruent (lower conflict) items (e.g, Krebs et al., 2015; Rosner et al., 2015a). These authors have argued that the increase in selective attention due to increased cognitive control elicitation from incongruent stimuli likely provides a memory encoding benefit for incongruent items in these cases.

Krebs et al. (2015) examined the effect of "conflict"-induced cognitive control on memory using a face-word Stroop task. Participants were shown male and female faces superimposed with the word "male", "female", or a neutral word, and their task was to identify the gender of the face as quickly as possible. This task produced a congruency effect, where responses were fastest to congruent face-word pairs and slowest to incongruent pairs. Later, participants completed a recognition memory test for the faces, where Krebs et al. found that faces from incongruent trials were better recognized than faces from congruent or neutral trials (which did not differ). Although incongruent words interfered with the processing of face targets during the face-word Stroop task, Krebs et al. argued that top-down attentional enhancement for target information led to better incidental encoding of face stimuli in this more demanding incongruent condition.

Similar evidence for increased selective attention demands producing a recognition memory benefit comes from a series of experiments conducted by Rosner et al. (2015a). The stimuli were two interleaved words, one in red and one in green, with participants instructed to read the red word aloud. On half of the trials, the green distractor word was identical to the to-be-named red word (congruent trials) and on the other half of the trials it was a different word (incongruent trials). Consistent with Krebs et al. (2015), they demonstrated a congruency effect in word reading, where word reading was slower on incongruent trials than on congruent trials. Yet incongruent words subsequently showed better recognition memory. Follow-up studies showed that this recognition memory benefit for incongruent words was not simply driven by the additional time-on-task for incongruent trials in the word naming phase (Rosner & Milliken, 2015), but appeared to be a consequence of the increased selective attention demands for incongruent items.

Additionally, Chiu and Egner (2015) shed new light on control processes of response inhibition. In a series of experiments, participants performed go/no-go, stop-signal, and yes/no tasks on male and female faces. Subsequent memory tests revealed that the control demands of response inhibition divert attention away from stimulus encoding, resulting in lower memory for trials with response inhibition. The negative effects of response inhibition on memory are opposite to the enhancement in memory performance when detecting and resolving conflict found in related research (Krebs et al., 2015; Rosner et al., 2015a). They suggest that the conflict resolution leading to better incidental encoding in these tasks involves top-down attention toward target stimuli (Botvinick et al., 2001; Egner & Hirsch, 2005), whereas the response inhibition in their tasks directs attention away from concurrent stimulus encoding.

Similar recent research has also examined the effect of stimulus repetition on recognition memory (Rosner, Lopez-Benitez, D'Angelo, Thomson, &

Milliken, 2018; Collins, Rosner & Milliken, 2018). In these experiments, participants underwent a study phase where they had to read a word aloud that was preceded by the same word (repeated trials) or a different word (not-repeated trials). Across experiments, these authors found not surprisingly that repeated words had faster reaction times at study than non-repeated words. In a subsequent test phase, participants were presented with words and were asked to indicate whether they had seen them in the first phase of the experiment, using old/new judgments. They found that non-repeated words were better remembered than repeated words. This effect remained even when repetitions at study were separated by an unrelated word and was eliminated if attention was directed toward primes rather than toward the targeted word. These findings provide additional evidence that attentional allocation at study may have an important impact on incidental memory encoding.

The Present Study

In the present study, we investigated cognitive control demands induced selectively at different processing stages, and whether this stage-specific focus of control demands would influence later memory performance for high versus low conflict trials – that is, whether these incidental encoding effects are task-general or could be predictably stage-dependent. In a typical divided attention task, cognitive control demands limit attention to information in a primary task by requiring participants to also monitor and perform a secondary task. As Chiu and Egner (2015) suggest from their recent cognitive control manipulations that direct attention away from stimulus encoding (inhibitory control tasks) rather than toward it, we suggest that in order for some difficulty manipulation (e.g., incongruent versus congruent stimulus priming) to induce a memory benefit, the difficulty must elicit increased selective attention to the information that will be later tested for a potential memory effect.

In these high versus low conflict/congruency situations, we suggest that the particular stage of processing that is the recipient of facilitation or conflict is a critical consideration for predicting whether a beneficial effect will occur on later memory. This is in contrast to simply thinking of incongruency or conflict as eliciting greater cognitive control or attentional focus for the whole task in general. Therefore, we predict that memory enhancement effects from various encoding difficulty manipulations are not task-general effects of attention, but instead should reflect enhancement of encoding via cognitive control demands that do not divert the focus of this control away from the core semantic representation of task stimuli. If task difficulty in general improves incidental encoding, then we should observe a memory benefit for items encountered in more difficult task conditions, independent of which particular processing stage is involved with this conflict. Alternatively, a stage-specific account would predict that memory facilitation should only occur when an encoding difficulty manipulation enhances selective attention toward important and relevant features or the meaning of to-be-tested target stimuli.

Figure 1 shows examples of several theoretical situations and predictions for different kinds of congruency priming, where participants are asked to classify typical female or male names as Female or Male, responding with left or right key presses respectively (e.g., "Kate" is a female name, press the left key). The left half of the figure shows examples of semantic priming where (1.a) incongruent ("male") and (1.b) congruent ("female") distractor stimuli with task-relevant semantic feature information are shown along with the primary stimulus. Greater conflict and interference with an incongruent prime in (1.a) elicits greater high-level attentional focus and cognitive control work (gray ovals) to resolve the classification outcome, leading to slower task RT but also more substantial attentional focus and processing of the core semantic and associative information for the stimulus name compared to the congruent condition in (1.b), predicting better memory for incongruently primed stimuli

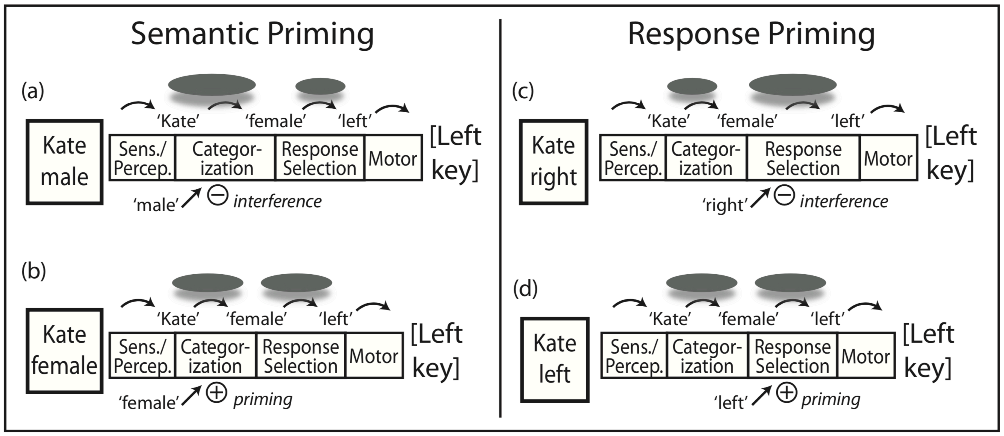

Figure 1. Information processing model of stage-specific incongruency encoding effects. A male/female name classification task is shown with different kinds of (a) incongruent versus (b) congruent priming of semantic categorization information, and (c) incongruent versus (d) congruent priming of response selection information. Grey ovals represent central focus of selective attention and cognitive control processes, with greater size representing proportionately greater focus and investment of processing at a given stage. Incongruent prime information induces additional cognitive control focus to the relevant information processing stage. Increased control and processing focus on semantic representations in (a) versus (b) predicts better subsequent memory for incongruently primed stimuli. Increased control and processing focus on response selection in (c) versus (d) diverts cognitive control focus away from central representation of to-be-tested stimulus information, predicting no benefit of increased conflict/control demand on later memory with incongruent response priming, despite greater attentional control and focus on the task in general. See text for more detail. Sens. = Sensation; Percep. = Perception.

In contrast, the right half of Figure 1 shows examples of response priming where (1.c) incongruent (“right”) and (1.d) congruent (“left”) distractor stimuli carry task-relevant response feature information (and not semantic category information) along with the primary task stimulus. Greater conflict and interference with an incongruent response prime in (1.c) elicits greater high-level attentional focus and cognitive control work to resolve the response selection outcome, leading to slower task RT. However, because this difference in cognitive control focus is directed away from processing and representation of the stimulus information that will later be the focus of a memory test, we predict that this situation should not lead to any memory benefit for stimuli in high response conflict/incongruent trials.

Within this framework, we might predict that with a sufficiently strong conflict control demand at response selection, semantic or associative processing of stimulus information could in a sense be cut short, disrupting incidental encoding of stimulus information compared to the congruent condition in (1.d). This could lead to worse memory for incongruently primed stimuli, typical of the usual costs of divided attention and distraction, despite the overall increased attentional and cognitive control investment for the incongruent trial. In a less severe or less disruptive case, incidental encoding of stimulus information might simply be unaffected by cognitive control demands at response selection; in that case we would predict no congruency/difficulty differences on a later memory test despite processing conflict costs on initial RT performance. Importantly, in both cases, there is a strong prediction that there should not be a later memory benefit of task incongruency/conflict difficulty when that difficulty diverts the focus of cognitive control away from the representation of stimulus information. In this sense, we propose that so-called "desirable" difficulty for future memory benefit is not a task-general property, but needs to be considered as a processing stage-specific effect where the stimulus information that will be the focus of a later memory test needs to be the focus of conflict-elicited cognitive control focus.

We conducted six experiments, where we used these kinds of congruency/interference priming manipulations to selectively influence different stages of task processing, and then assessed the influence of these stage-specific manipulations on later recognition memory for initial task stimuli. Experiments 1 and 2 used response congruency/priming to target response selection, independent of semantic information for to-be-tested stimuli. Experiments 3 through 6 used a range of different tasks with semantic congruency/priming to assess the generalizability of a semantic focus explanation for these effects, and to assess potential boundary conditions related to the relative difficulty or task demands of semantic classification itself.

In developing a general paradigm to test this stage-specificity of incongruency encoding effects, we attempted to define a general set of inclusion/exclusion criteria for participant data, that 1) were well-motivated theoretically, 2) served to exclude likely unreliable data while including as much data as possible, and 3) were independent of our primary memory measures of encoding difficulty. Considering that we are interested in the memory differences produced by difficulty manipulations at study, we excluded participants a) with overall poor task performance at study (less than 75% correct in any condition), suggesting they were not performing the task adequately; and b) who showed substantially reversed difficulty/priming effects at study (more than a 50 ms priming benefit for incongruent versus congruent primes), where we cannot be sure that our difficulty manipulation is actually making the task more difficult for those participants. Thus, our data reported here represent study congruency effects on later memory for participants a) with reasonable study performance, and b) who were influenced as expected by difficulty manipulations at study.

Experiment 1

For our first experiment, we used backward compatibility effect (BCE) response priming in the psychological refractory period (PRP) paradigm, to produce a response priming manipulation on a primary task (Task 1 of the dual task PRP pair). In a typical PRP paradigm, participants are presented with two stimuli separated by a variable stimulus onset asynchrony (SOA), and respond to each stimulus in turn according to its own task set rules. We did not use this design to implement a typical dual task difficulty manipulation where the degree of difficulty depends on single versus dual task performance, which has been generally shown not to produce difficulty benefits for memory (e.g., Craik at al., 1996; Gaspelin et al., 2013). Instead, here participants always performed a dual task. Our difficulty manipulation was within Task 1, where response congruency with automatically activated Task 2 response information provides the relative difficulty for Task 1 performance.

The backward compatibility effect is well-studied, and is thought to reflect automatic stimulus-response translation and activation of Task 2 response representations, prior to any deliberate performance of Task 2 on a given trial, in parallel with attended Task 1 performance (Ellenbogen & Meiran, 2008; Giammarco, Thomson & Watter, 2016; Hommel, 1998; Hommel & Eglau, 2002; Watter & Logan, 2006). This automatically generated Task 2 response information is observed to prime Task 1 RT, with converging evidence suggesting direct priming of the concurrent Task 1 response selection stage (Thomson, Danis, & Watter, 2015). Using a PRP paradigm with two semantically unrelated tasks (here, a size categorization task on words for Task 1, and a shape classification task for Task 2) that both used the same pair of response keys, enabled us to manipulate response congruency priming on the Task 1 response selection stage, without any priming of Task 1 semantic information.

Recent findings by Krebs et al. (2015) and Rosner et al. (2015a) suggest that enhanced demand for cognitive control (elicited through incongruent prime stimuli) should lead to better later memory. Chiu and Egner’s (2015) findings suggest that this should be the case if the control demand draws selective attention to the task and stimulus processing at hand, rather than diverting this processing away to a secondary task (or in their case, a focus on withholding a response). In our experiment here, the BCE priming of Task 1 response selection occurs while participants are selectively and deliberately focused on performing Task 1 (via automaticity of directly activating Task 2 response information in the presence of the Task 2 stimulus, before participants change their focus of attention to deliberately perform Task 2). Importantly, our difficulty manipulation here maintains focus on the primary task, much like the congruency manipulations of Krebs et al. (2015) and Rosner et al. (2015a), though our manipulations are selectively targeting response selection.

In addition to potential incongruency priming effects, presenting Task 1 and Task 2 stimuli at varying SOAs allowed us to independently assess a more general effect of divided attention on later memory. Dual task interference is typically observed as a general divided attention or distraction effect on primary task performance when a distractor stimulus or task is present. As such, we might predict a similar general distraction effect on memory for stimuli presented at short versus long SOAs, separate to our primary congruency manipulations – that is, a distraction effect when a prime appears close in time with the primary stimulus, overlapping with much of attended Task 1 processing, versus when the prime appears toward the end of (or even after) Task 1 performance.

With respect to our principal focus on congruency/conflict effects, we predict that despite enhanced cognitive control demands with incongruent response priming, we should not observe incidental memory encoding benefits under higher conflict conditions here, as findings from Krebs et al. (2015) and Rosner et al. (2015a) might predict. We predict that priming conflict at response selection should focus selective attention and cognitive control on resolving response conflict, and as such there should be no enhanced processing of central stimulus representations under high conflict conditions, and hence no incongruency memory benefit. Only in our later experiments, where difficulty/congruency manipulations draw selective attention and cognitive control to increase focus on central stimulus representations, should we observe incidental memory benefits with incongruent priming conditions.

Method

Participants

Twenty first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity, and spoke English fluently. Data from one participant were excluded due to low study task accuracy (< 75 % correct), and data from an additional two participants were eliminated due to substantially reversed (> 50 ms) response priming effects on Task 1 RT during study task performance. Data from one other participant were lost due to unrelated technical issues, leaving 16 participants for reported data analysis. Our data collection employed a stopping rule of 20 or more participants, assessed at the end of each week of data collection. We based this n on typical numbers used in many PRP experiments to reliably study the backward compatibility effect (e.g., Hommel, 1998; Hommel & Eglau, 2002; Miller & Alderton, 2006).

Apparatus and Stimuli

All stimuli were presented on a standard Windows 7 PC and experiments were programmed in Presentation (v. 14, neurobs.com). Primary study and test stimuli were drawn from a list of 240 concrete nouns, all unambiguously classifiable along dimensions of animacy and size, with equal numbers of animate-small, animate-big, inanimate-small, and inanimate-big items. For the study/encoding phase, 160 of these words were presented once each as stimuli for Task 1 (S1) in a PRP paradigm. The other 80 words were used as foils (new items) in the subsequent memory test phase. To create counterbalanced study-test stimulus sets, we initially split the 240 words into three lists (A, B, C), balanced across lists for item category and the first letter of stimulus words. Participants saw stimuli from two of these three lists at study (e.g., A, B), and then were tested on stimuli from one of these two study lists plus the unseen third list (A, C). The six possible combinations of list arrangements were counterbalanced across participants in the experiment.

In the study/encoding phase, words were presented in white Arial font, sized to be 1.5 cm vertically on screen. Task 2 stimuli (S2) were one of four shape stimuli (star, diamond, circle, pentagon), presented in filled white, also 1.5 cm vertically. A pre-stimulus cue consisted of two rows of single dashes separated by spaces (“-   -”), indicating a central position where stimuli would appear. Task 1 and 2 stimuli were presented in consistent positions centered on the screen, with S1 (word) always above S2 (shape), separated by approximately a 0.75cm gap. Participants sat at a viewing distance of approximately 60 cm from the screen. In the memory phase, single words were presented centrally in the same Arial font, at a larger size (approx. 2.5 cm vertically).

Procedure

The basic study design for this and subsequent experiments is shown in Figure 2. In the study/encoding phase, a single trial began with the cue presented for 500ms. This was immediately replaced with S1 (word). After a variable SOA (150 or 700 ms, randomly varied), S2 (shape) was presented below S1 on the screen. Each stimulus was removed from the screen 1000 ms after presentation, giving a consistent exposure time for both stimuli across SOAs. Participants were instructed to prioritize Task 1, and not to move on to considering Task 2 until they had responded to Task 1. Response alternatives for both Task 1 and Task 2 were mapped to index and middle fingers of the right hand, using the "1" and "2" keys of the computer keyboard numeric keypad. Participants classified the referents of Task 1 word stimuli as bigger or smaller than the computer monitor, and classified shapes into [star or diamond] versus [circle or pentagon] sets. Response mapping for both tasks was counterbalanced across participants. An inter-trial interval of 2000 ms (blank screen) separated the offset of S2 and presentation of the cue beginning a subsequent trial.

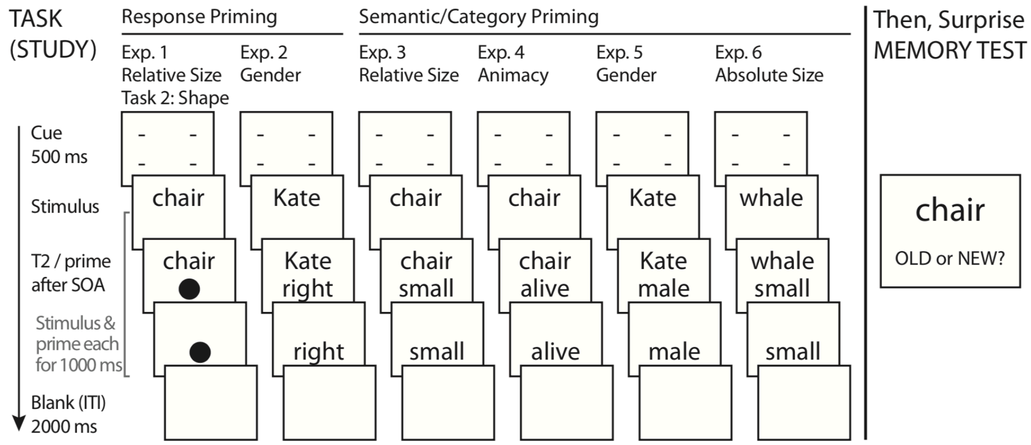

Figure 2. Task design and procedure for Experiments 1 to 6. Across experiments, participants classified stimuli along single dimensions of size, name gender, or animacy. An old/new recognition memory test followed each categorization task. T2 = Task 2 stimulus; ITI = Inter-Trial Interval.

The study/encoding phase consisted of five experimental blocks, each with 32 trials, for a total of 160 trials. Trial information was pre-generated, with SOA and Task 2 shape iterated over Task 1 stimulus categories (with individual items pre-randomized within condition for every new participant), to ensure equal number of trials across conditions and randomize S1-S2-SOA groupings across participants. These condition-balanced and item-randomized trials were then presented to participants in random order. Using a separate 64-word stimulus set, an additional two blocks (32 practice stimuli each with randomized SOA and S2), were presented initially as practice, and not considered for memory test or analysis. Prior to data analysis, trials with Task 1 RT faster than 300 ms or slower than 2000 ms were excluded from analysis (less than 0.5% of all trials).

After the completion of the study/encoding phase, participants were given 2 minutes rest before proceeding to the surprise memory test. Stimuli consisted of 160 words; 80 old items shown during the encoding phase, and 80 new items, as outlined above. Participants were instructed to classify the words as “old” or “new” in relation to the encoding phase – whether they had seen that word during the encoding phase task. Stimuli were presented in randomized order, and remained on the screen until a response was made by pressing “Z” for old words or “/” for new words on the computer keyboard. A blank screen of 1000 ms separated response and the next memory stimulus. Trials were presented in blocks of 32 items, with short self-paced breaks in between.

Results

Encoding phase

Mean data for encoding phase Task 1 reaction time for correct trials, and Task 1 accuracy, are shown in the left half of Figure 3. A 2x2 repeated measures ANOVA on RT data that treated response congruency (congruent, incongruent) and SOA (150 ms, 700 ms) as factors revealed a main effect of response congruency, $F(1, 15) = 6.18$, $p = .025$, $\eta_p^2 = .29$, with faster reaction times for congruent (M = 991.33 , SD = 207.41) versus incongruent (M = 1020.23, SD = 229.64) stimuli. There was no significant effect of SOA, $F(1, 15) = 1.93$, $p = .185$, $\eta_p^2 = .11$, and no interaction, $F < 1$. These data suggest that response incongruency presents a relative difficulty on Task 1 performance, replicating typical prior findings for the backward compatibility effect.

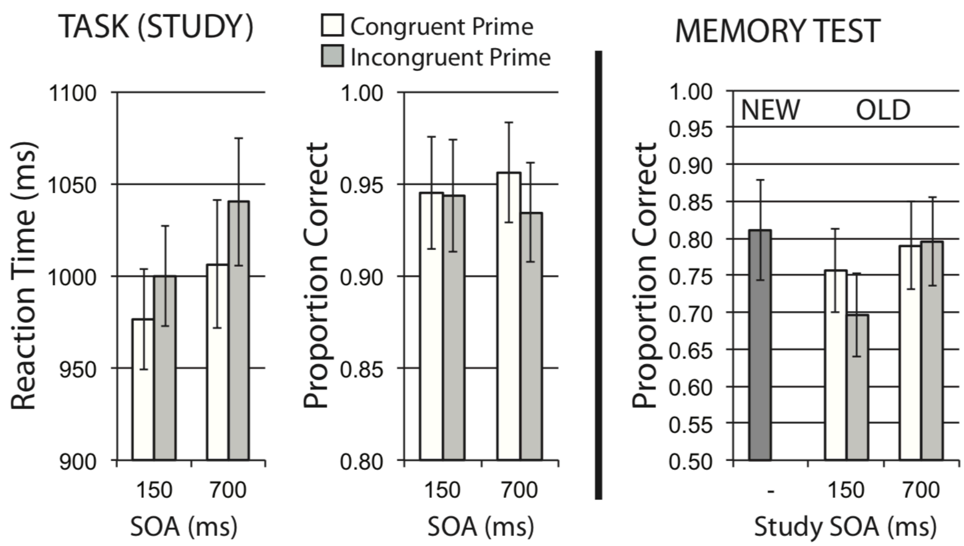

Figure 3. Size categorization task with response priming (Experiment 1). Response incongruency priming produced costs on categorization performance (left panel), but showed no evidence of an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Task 1 mean accuracy at study was relatively high. Using the same ANOVA structure, no main effects were observed for response congruency or SOA, *F*s < 1. While the interaction was not significant, $F(1,15) = 2.29$, p = .151, $\eta_p^2 = .13$, the direction of response congruency difference observed at 700 ms SOA is toward reduced accuracy for incongruent trials, in accordance with a general difficulty manipulation.

Task 2 performance data are not directly relevant to our incongruency priming hypotheses or later memory data, but are presented here for completeness, and to confirm that our dual task PRP design did indeed impose considerable dual task costs on Task 1 performance. Mean data for Task 2 RT for correct Task 2 responses, and mean Task 2 accuracy, were analyzed for trials on which a correct Task 1 response was made (94.5% of all trials). Task 2 data were consistent with a typical dual-task PRP effect, with a substantial delay of Task 2 responding at short versus long SOA. Task 2 mean RT for correct trials was substantially slower at short SOA trials for both response-congruent (1219 ms) and response-incongruent (1235 ms) trials, compared to long SOA trials (834 ms, 836 ms). This was reflected by a strong main effect of SOA, $F(1, 15) = 1238.98$, $p < .001$, $\eta_p^2 = .99$, with no main effect of congruency and no interaction, *F*s < 1. Task 2 accuracy was numerically lower for response-congruent versus response-incongruent trials for both short SOA (90.2%, 94.4%) and long SOA trials (90.7%, 94.3%), but this effect of response congruency was not significant, $F(1,15) = 2.43$, p = .140, $\eta_p^2 = .14$. There was no effect of SOA, and no interaction, *F*s < 1. This numerical pattern of lower Task 2 accuracy for response-compatible trials is observed in other PRP studies exploring congruency effects between Task 1 and Task 2 (e.g., Watter & Logan, 2006), and is interpreted as a later "partial match" interference effect (Hommel, 2004, 2007) on Task 2 (e.g., a change in semantic information focus but with response information repeated), rather than any index of task difficulty during Task 1 performance.

Memory phase

Figure 3 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding the small number of items (per participant) incorrectly responded to at study. In this and subsequent experiments, old items were divided by the SOA and congruency priming conditions in which they were experienced in the prior study/encoding phase (the classification task). As the set of new items was not related to any of the particular study conditions, the calculated False Alarm (FA) rate for a given participant (incorrectly responding "old" to new items) was a single value – e.g., it is not possible in this design to calculate independent FA rates for congruent and incongruent conditions. As such, subtracting the same FA rate from congruent and incongruent Hit rates (correctly responding "old" to old items) for each participant would not alter statistical comparisons of our congruency effects for old items. For this and subsequent experiments we reported and analyzed Hit rates for congruent and incongruent old items at respective study SOAs, and present proportion correct responses for the set of new items (Correct Reject responses) as a comparison.

Hit rates for old items served as the dependent variable in a 2x2 repeated measures ANOVA that treated stimulus study conditions of response congruency and SOA as factors. The analysis revealed a significant main effect of SOA, $F(1, 15) = 7.20$, $p = .017$, $\eta_p^2 = .32$, but no significant main effect of congruency $F(1, 15) = 2.71$, $p = .121$, $\eta_p^2 = .15$, with a non-significant interaction, $F(1, 15) = 2.34$, $p = .147$, $\eta_p^2 = .14$. Given that the BCE response congruency manipulation at study is typically observed to influence performance maximally at short SOAs, we examined memory performance separately based on study SOA. A significant congruency effect on memory was observed for stimuli presented at the 150 ms SOA, $t(15) = 2.27$, $p = .038$, where congruent stimuli were better remembered than incongruent stimuli. Memory performance at the 700 ms SOA was similar for congruency conditions, $t(15) = -.18$, $p = .856$. The memory benefit observed here for congruently primed stimuli at a short SOA is the opposite of an incongruency/conflict benefit on memory.

Discussion

Experiment 1 imposed a response congruency priming manipulation on a size classification task, using the backward response compatibility effect from a semantically unrelated shape classification task within a PRP paradigm. Study task performance was in keeping with a relative difficulty effect on Task 1 PRP performance for response incongruent trials. We observed a subsequent memory benefit for congruently primed trials, compared to incongruently primed trials at short SOA – memory was better for relatively lower-conflict (response congruent) trials, with relatively worse memory for stimuli presented with a response-incongruent Task 2 stimulus. These results are consistent with the typical pattern of divided attention costs on memory (e.g., Craik et al., 1996). These results do not support a general account of task-focused cognitive control demand, where increased selective attention on incongruent trials improves incidental encoding (e.g., Krebs et al., 2015; Rosner et al., 2015a). This does not at all suggest that findings from Krebs et al. and Rosner et al. are incorrect, but suggests that a more processing stage-specific view of cognitive control demand may be required.

We note that in this first experiment, we also observed a more general dual task or divided attention influence of study task conditions on memory, independent of congruency condition. The significant main effect of study SOA on "old" recognition performance showed a 6.7% benefit for stimuli presented at 700 ms SOA compared to stimuli at 150 ms SOA. This effect is straightforwardly interpretable as a general divided attention or distraction effect, where having any prime presented close in time to the primary stimulus has a negative effect on incidental encoding, compared to primes presented half a second later, allowing more of the time course of Task 1 processing (most critically we presume, central representation of stimulus information) to be completed before potential distraction from the prime. In the present experiment, the size of this distraction difference on memory, due to simple overlap in time course (the effect of study

SOA on memory), was comparable to the effect of congruency prime information at the short SOA (in fact, numerically larger). The observation of this kind of general divided attention/distraction effect with study SOA, independent of prime congruency relations, is a useful manipulation check, and increases our confidence in our finding of no incongruency benefit to memory, given that we can show our manipulation to be sensitive to other kinds of similar attentional/control encoding effects on later memory. We anticipate this general divided attention influence of study SOA on memory in subsequent experiments, where it should also serve as a useful manipulation check for potential incongruency memory effects.

Experiment 2

Experiment 2 aimed to replicate the basic response incongruency priming findings from Experiment 1 – an incongruency cost on initial study task performance suggesting greater difficulty, but no benefit of this difficulty on a later memory test – using a single-task priming design akin to those used for the semantic priming experiments in the rest of the current paper. Krebs et al. (2015) observed an incongruency encoding benefit with memory for face stimuli using a gender classification task, with congruent versus incongruent word primes ("male" versus "female"). We adapted this idea to use typical male and female names as primary task stimuli in a name gender classification task, to push an interpretation of a potential encoding effect more strongly toward enhancement of central semantic representations rather than visual perceptual features.

We presented individual male and female names along with congruent and incongruent response primes (words “left” and “right”), and asked participants to identify the gender of the name, with responses assigned to left and right keys, while ignoring the prime words. We again presented primes at short and long SOAs, but reduced the SOA durations in this experiment considering the generally faster time course of single-task versus dual-task performance.

Method

Participants

Twenty-eight first-year McMaster university students participated in this experiment for course credit. Informed written consent was obtained and McMaster’s Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke English fluently. Data from one participant were excluded due to low accuracy (< 75%), and data from three participants were excluded due to substantially reversed RT priming effects during the encoding/study phase (> 50 ms incongruency benefit). A total of 24 participants were included for reported data analysis.

Apparatus, Stimuli and Procedure

Methods were identical to Experiment 1 with the following exceptions. We presented name stimuli as for Task 1 in the dual task PRP paradigm from Experiment 1, with response prime stimuli (words “right” or “left”) presented below the Task 1 stimulus in place of the original Task 2 shape stimuli. Prime words were in the same white Arial font as primary task stimuli, at 1.5 cm vertically on screen. Primes appeared following Task 1 word stimuli at SOAs of 17 ms (one video frame at 60Hz) or 600 ms.

The single task was a name gender classification task (i.e., "Is this a male or a female name?"). Participants responded using the "Z" and "/" keys on the computer keyboard with left and right index fingers, with male/female category alternatives mapped to left and right keys, counterbalanced across participants. A final set of 240 typical Western/Anglophone names (120 female, 120 male) that we thought our participant pool would be familiar with, and that were not gender ambiguous (e.g., "Alex"), was compiled and reviewed by several independent raters (from an originally larger list). Three 80-item lists, each with 40 male and 40 female names, balanced across lists for first letter of names, were used to create six counterbalanced sets of study-test materials, following the same procedures as described in Experiment 1. This gave stimulus sets with 160 experimental trials at test, half of which were used at memory test with the remaining 80 items as new items. Sets of study trial conditions counterbalanced for prime congruency and SOA were created as described previously, and again presented in randomized order for each participant. Stimuli were presented in four blocks of 40 trials each. An additional 12 trials with separate name stimuli were initially presented as a practice block, and not considered for analysis or memory test. Prior to data analysis, trials with RT faster than 300 ms or slower than 1500 ms were excluded from analysis (less than 0.5% of all trials); in this and subsequent experiments, this lower threshold for too-slow RT performance was adopted considering expected performance for single task versus dual task demands. The memory task followed the same format as in Experiment 1, now with 160 total trials using name stimuli.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 4. A 2x2 repeated measures ANOVA revealed a main effect of congruency, $F(1, 23) = 5.63$, $p = .026$, $\eta_p^2 = .20$, with relatively slower RTs for incongruently primed trials reflecting the expected difficulty/congruency influence on initial task performance. The main effect of SOA was not significant, $F(1, 23) = 1.20$, $p = .284$, $\eta_p^2 = .05$, with no interaction $F < 1$. Accuracy in the priming task was numerically worse for incongruent versus congruent trials at the short SOA, consistent with the difficulty manipulation, but the interaction of SOA and congruency was not significant, $F(1,23) = 2.23$, $p = .149$, $\eta_p^2 = .09$, with no significant main effects, $Fs < 1$.

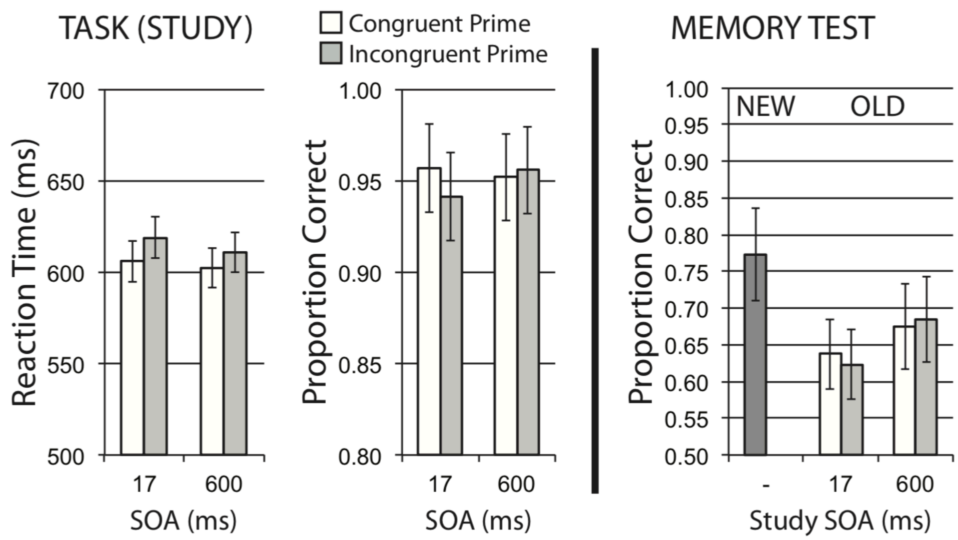

Figure 4. Name gender categorization task with response priming (Experiment 2). Response incongruency priming produced costs on categorization performance (left panel), but showed no evidence of an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Memory phase

Figure 4 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding items (per participant) incorrectly responded to at study. A 2x2 repeated measures ANOVA for old items revealed a main effect of SOA, showing a general influence of divided attention with better subsequent memory performance from long versus short SOA trials, F (1, 23) = 5.91, p = .023, $\eta_p{}^2$ = .204. There was no significant effect of congruency, and no interaction, Fs < 1.

Discussion

Experiment 2 used a single task response priming design, with a gender name categorization task. As in Experiment 1, there was an influence of study SOA on later memory, reflecting a general divided attention/distraction effect for primes presented close in time to the primary task at short SOA, independent of prime congruency relations. While there was clear evidence that response incongruency priming influencing classification task performance, there was no evidence of this encoding incongruency effect on later memory. These findings provide a conceptual replication of Experiment 1 with a single task design, again showing that incongruency/difficulty manipulations targeting response selection do not produce a related benefit in later memory. We again observed this lack of incongruency effect on memory while we were able to directly measure a separate encoding effect of divided attention/distraction (SOA) effect on memory, increasing confidence in our interpretation of this lack of an observable incongruency memory benefit.

Experiment 3

Experiments 1 and 2 showed that when a targeted congruency/difficulty manipulation at the response selection stage produced increased cognitive control demand with incongruent primes, there was no benefit to later memory. For the rest of the present paper, we aimed to directly demonstrate how semantic incongruency priming in these same situations would produce encoding difficulty memory benefits where response priming had not. In this situation, we predict that semantic processing conflict will draw selective attention and cognitive control processes to focus on central semantic and associative representations of the to-be-tested task stimuli, producing better memory encoding compared to congruently primed stimuli.

The aim of Experiment 3 was to begin to use the same primary tasks in our response priming experiments, now instead with a semantic congruency prime. For this experiment, we used the same size classification task as in Experiment 1, now as a single task with no Task 2. We presented semantic category primes (the words “BIG” and “small”) at short and long SOAs, in place of the Task 2 stimuli for Experiment 1, producing a semantic category congruency priming task, and we again assessed later recognition memory. We reverted to the slightly longer SOAs used in Experiment 1, to allow a more direct comparison between response and semantic priming outcomes with the same primary size classification task. In addition, we aimed to double our sample size for this and subsequent experiments, adopting a stopping rule of 40 or more participants, assessed at the end of each week's data collection.

Method

Participants

Forty-six first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke English fluently. Data from one participant were excluded due to low encoding phase accuracy (< 75%). Data from four more participants were eliminated due to large reversed RT priming effects during the encoding/study phase (> 50 ms incongruency benefit). A total of 41 participants were included for reported data analysis.

Apparatus, Stimuli and Procedure

Methods were identical to Experiment 1 with the following exceptions. We adapted Task 1 from the dual task PRP paradigm from Experiment 1 to a single task, with category prime stimuli (words "BIG" or "small") presented below the Task 1 stimulus in place of the original S2 shape stimuli. Prime words were in the same white Arial font as primary task stimuli, at 1.5 cm vertically on screen. Participants responded to the size categorization task with left and right index fingers using the "Z" and "/" keys on the computer keyboard, with big/small response mappings counterbalanced across participants. We presented the same number of study/encoding trials, followed by the same memory test as in Experiment 1.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 5. A 2x2 repeated measures ANOVA revealed a strong main effect of congruency, $F(1, 40) = 19.60$, $p <.001$, $\eta_p{}^2 = .33$, with relatively slower RTs for incongruently primed trials reflecting the expected difficulty/congruency influence on initial task performance. The main effect of SOA was not significant, $F(1, 40) = 2.01$, $p =.156$, $\eta_p{}^2 = .05$, with no interaction $F < 1$.

Accuracy in the priming task appeared to be relatively worse for incongruent versus congruent trials at the short SOA, with a significant interaction of congruency and SOA, $F(1, 40) = 5.38$, $p = .026$, $\eta_p{}^2 = .12$, but no significant main effects of Congruency, $F(1, 40) = 2.04$, $p = .161$, $\eta_p{}^2 = .5$, or SOA, $F < 1$. Individual assessment of congruency effects at separate SOAs showed a significant accuracy benefit for congruent trials at the short SOA, $t(40) = 2.57$, $p = .014$, with no apparent difference at the long SOA, t(40) = -.70, p = .491. These accuracy results align with RT results suggesting that incongruent primes create additional processing difficulty in task performance, as expected.

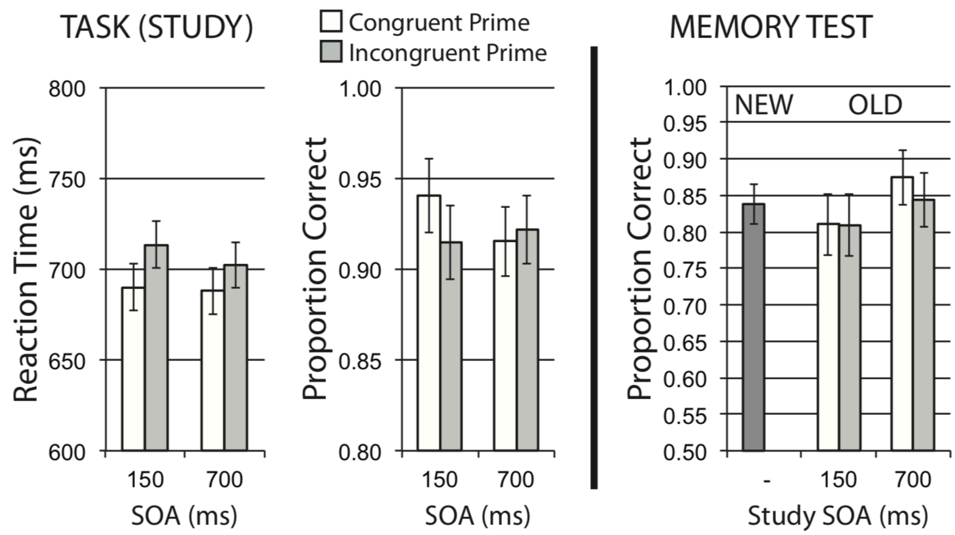

Figure 5. Size categorization task with semantic priming (Experiment 3). Semantic incongruency priming produced costs on categorization performance (left panel), but unexpectedly showed no evidence of an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Memory phase

Figure 5 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding items (per participant) incorrectly responded to at study. A 2x2 repeated measures ANOVA for old items revealed a main effect of SOA, showing a general influence of divided attention/distraction with better subsequent memory performance from long SOA trials versus short SOA trials, $F(1, 40) = 13.44$, $p < .001$, $\eta_p^2 = .25$, as observed in previous experiments. Contrary to our predictions of an incongruency memory benefit with semantic priming, the main effect of congruency was not significant, $F(1, 40) = 1.29$, $p = .263$, with no significant interaction, $F(1, 40) = 1.14$, $p = .292$.

Discussion

Contrary to our predictions, these data again suggest no evidence that increased attentional and cognitive control demands on incongruent trials improve incidental memory encoding, despite a clear and expected difficulty effect on initial task performance. We observed this lack of incongruency benefit on later memory despite using a semantic priming task, and again inconsistent with studies where increased selective attention on incongruent trials improves incidental encoding (e.g., Krebs et al., 2015; Rosner et al., 2015a). We note that we again observed a general effect of study SOA on later memory, consistent with a general effect of greater distraction by primes at the short SOA (independent of congruency condition), when primes overlap with a greater proportion of the time course of primary task processing, again encouraging our belief that we should be able to measure some degree of incongruency priming benefit were one to be present.

While we predicted that our response priming difficulty manipulations in Experiments 1 and 2 would not produce such memory effects, we were initially quite surprised by the present result, given our strong prediction that we should find an increase in incidental encoding here with semantic incongruency priming. Despite these results from Experiment 3, we still predict that a semantic congruency manipulation that elicits cognitive control and selective attention via incongruency conflict should enhance later memory, if those control processes enhance representations of the meaning of the to-be-tested stimuli. We address the particular issue of these unexpected semantic priming results with an additional clarifying test in Experiment 6. In the meantime, to further explore these stage-specific predictions for congruency encoding effects, we employed several other semantic classification tasks with the same study design.

Experiment 4

The aim of Experiment 4 was to try to observe incongruency memory benefits with the same stimuli but a different categorization task from Experiment 3. The stimulus set used for the size classification task in Experiments 1 and 3 was composed of items counterbalanced on a second semantic dimension, animacy. It would be a powerful demonstration if we could show incongruency encoding effects using the same stimuli that had previously not shown such an effect, when classifying them along a different semantic dimension. Finding an incongruency encoding benefit with the same stimuli using an animacy classification task would suggest that something about our size task may have prevented us from producing an incongruency encoding effect in Experiment 3, and more importantly, might give us some insight into the nature of what kinds of priming that are able to produce such effects.

We also reconsidered the timing of the SOAs that we were using for these tasks. We had chosen our original SOAs of 150 and 700 ms for producing an optimal backward response compatibility effect with a dual task PRP procedure in Experiment 1. We had persisted with these SOAs in Experiment 3 for consistency, but were concerned that they may be relatively slow for producing strong semantic category priming. As such, we returned to our shorter SOAs of 17 and 600 ms as in Experiment 2, to preserve the separate onsets of task stimulus and prime, but to introduce greater temporal overlap between prime and stimulus, and hopefully to produce more effective semantic priming.

Method

Participants

Forty-one first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke English fluently. Data from one participant were excluded due to low accuracy (<

75%) in the study/encoding phase, leaving 40 participants for reported data analysis.

Apparatus, Stimuli and Procedure

Methods were identical to Experiment 3, aside from the following changes. We used the same stimulus sets as in Experiment 3, which were originally counterbalanced on both size (big, small) and animacy (alive, not alive) dimensions. We presented study/encoding trials in four blocks of 40 trials (rather than five blocks of 32 trials as previously), given the reduced trial length with shortened SOAs. Inter-trial intervals were maintained at 2000 ms as before. Participants classified the referents of single word stimuli as either animate (alive) or inanimate (not alive). Primes were the words “animal” or “thing,” and were presented with counterbalancing and randomization procedures as previously described, at SOAs of 17 or 600 ms. A single practice block of 48 trials using a separate stimulus set (a subset of the prior 64 practice items) was presented at the beginning of the experiment, and was not considered for analysis or memory test. The memory test was the same as in Experiment 3.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 6. A 2x2 repeated measures ANOVA of RT revealed a significant main effect of congruency, $F(1, 39) = 4.53$, $p = .040$, $\eta_p^2 = .10$, with no significant effect of SOA, $F < 1$, and a marginal interaction, $F(1, 39)$

= 2.86, p = .098, η_p^2 = .07. These RT data suggest that the congruency manipulation was producing an expected difficulty effect on task performance.

Accuracy data showed no significant main effect for congruency, $F(1, 39)$ = 1.71, p = .199, no main effect of SOA, F < 1, and no interaction, $F(1, 39)$ = 1.26, p = .269. The direction of observed numerical differences in congruency conditions at the short SOA is consistent with the RT data and the expected difficulty manipulation.

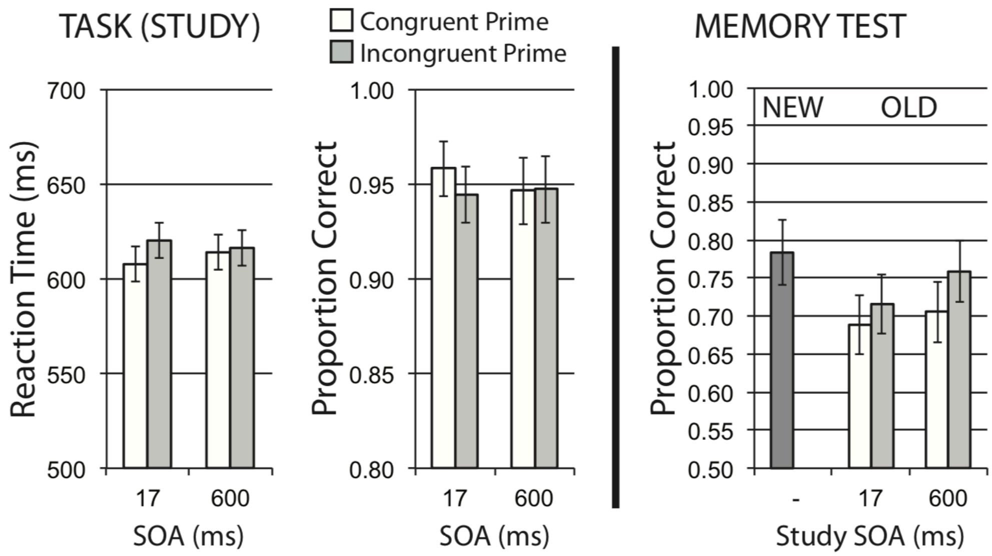

Figure 6. Animacy categorization task with semantic priming (Experiment 4). Semantic incongruency priming produced costs on categorization performance (left panel), and also produced an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Memory phase

Figure 6 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding items (per participant) incorrectly responded to at study. A 2x2 repeated measures ANOVA for old item data revealed a strong main effect of congruency, $F(1, 39) = 8.32$, $p = .006$, $\eta_p^2 = .18$, with incongruently primed stimuli at study showing relatively better memory performance. This finding represents a substantial incongruency encoding benefit. There was no significant effect of SOA, $F(1, 39) = 2.74$, $p = .106$, $\eta_p^2 = .07$, and no significant interaction, $F < 1$.

Discussion

Using the same concrete noun stimuli as in Experiment 3, but having participants classify items on the basis of animacy instead of size, we observed a substantial incongruency encoding benefit on later memory using semantic category primes for animacy information. These findings are consistent with the results from Krebs et al. (2015) and Rosner et al. (2015a), where greater incongruency or conflict for study items produced better later memory. While we did not observe a significant general divided attention/distraction effect of SOA as in previous experiments, data here were numerically consistent with this pattern. This is the first experiment in this paper where we observe our predicted incongruency encoding benefit for semantic incongruency priming. To generalize and extend this effect, we conducted a conceptual replication of this semantic congruency priming experiment, using the name stimuli and gender classification task from Experiment 2, with semantic category primes instead of response primes.

Experiment 5

The aim of Experiment 5 was to again investigate the influence of task difficulty targeted at the semantic stage of processing, using a different categorization task. We used the same name gender classification task from Experiment 2, now presenting the individual male and female name stimuli along with congruent and incongruent semantic category primes (words "male" and "female") in place of previous response primes (words "left" and "right"). Continuing our attempt to find optimal SOA conditions for single task semantic priming to observe reliable difficulty encoding effects on memory, we used a single 100 ms SOA for this experiment. This was an attempt to maintain a similar subjective perceptual separation of stimulus and prime as in our prior experiments, but with a more optimal time course to better produce temporal overlap and maximize semantic priming. We again predicted that we should observe a congruency encoding effect on a later memory test, with better memory for stimuli originally presented with incongruent semantic category primes.

Method

Participants

Fifty-two first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke English fluently. Data from two participants were excluded due to low accuracy at study (< 75%), leaving a total of 50 participants for reported data analysis.

Apparatus, Stimuli and Procedure

Methods were identical to Experiment 2, aside from the following changes. The primary task was the same name gender classification task (i.e., "Is this a male or a female name?"). Primes were the words "male" and "female". Stimulus lists were constructed and counterbalanced as described previously, but now with all trials presented with a constant 100 ms SOA.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 7. A significant congruency priming effect was observed in RT, $t(49) = 2.86$, $p = .006$, suggesting that incongruent trials imposed additional difficulty on task performance. Accuracy was numerically worse for incongruent trials, in line with this difficulty expectation, though this effect was only marginal, $t(49) = 1.75$, $p = .086$.

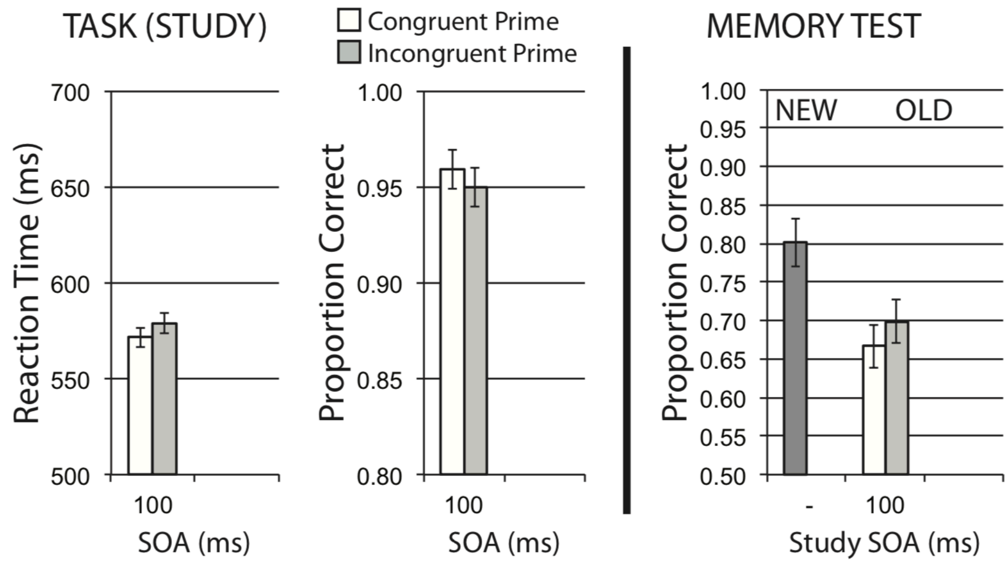

Figure 7. Name gender categorization task with semantic priming (Experiment 5). Semantic incongruency priming produced costs on categorization performance (left panel), and also produced an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Memory phase

Figure 7 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding items (per participant) incorrectly responded to at study. A significant memory benefit for old stimuli with incongruent priming at study was observed, $t(49) = 2.28$, $p = .027$. This finding represent a clear memory benefit for items with semantic incongruency priming at study.

Discussion

Experiment 5 showed a significant later memory benefit for stimuli initially experienced under more difficult incongruent semantic priming conditions. These data provide a conceptual replication of Experiment 4, and fit directly with our mechanistic prediction of increased cognitive control at semantic categorization to compensate for interference from an incongruent prime. These results are consistent with recent work (Krebs et al., 2015; Rosner et al., 2015a), where increased selective attention on incongruent trials leads to better later memory. Enhancing difficulty at the categorization stage of processing induces greater attentional control toward central semantic information of to-be-tested task stimuli, leading to better encoding and better later memory performance.

Experiment 6

In Experiment 4 (animacy) and Experiment 5 (gender), stimuli in these different semantic classification tasks were better remembered when they were presented with incongruent versus congruent semantic primes. While Experiment

1 (size task) and Experiment 2 (gender task) showed no evidence of an incongruency benefit to memory with response priming, as predicted under our stage-specific encoding benefit model, there is still a question as to why Experiment 3 (size classification with semantic priming) did not show our predicted incongruency memory benefit, even though the very same stimuli did show an incongruency memory benefit when categorized on another semantic feature (animacy, in Experiment 4). One intriguing possibility that would fit this pattern of data may be the relative degree of automaticity involved with the classification task itself, or put another way, how essential or central the decision-relevant features for a given classification task are for the stimuli being classified.

If stimuli have strong associates or semantic features that are rapidly and automatically activated or retrieved under relevant classification task set rules, participants should typically have categorization-relevant information directly activated from semantic memory with little deliberation. In this situation, additional attentional control elicited through incongruent priming would focus selective attention on essential semantic information from the task stimulus.

On the other hand, if a category decision relies on additional comparative or evaluative work with the retrieved semantic contents from a stimulus in order to resolve a categorization decision, participants may end up performing a more controlled or algorithmic decision process no matter what the prime stimulus is. In this situation, the demands of the categorization task itself may act to elicit some greater degree of control in processing, or to simply involve a greater or richer extent of representation of stimulus information, for all trials.

A recent example that we suggest illustrates this kind of influence is studies of perceptual desirable difficulty using blurry versus clear word stimuli, by two different research groups (Rosner, Davis, & Milliken, 2015b; Yue, Castel, & Bjork, 2013). Both groups aimed to study essentially the same question – whether reading words that were presented under blurry or clear conditions would lead to subsequent better memory for the more difficult to read blurry items. Over many experiments, Yue et al. (2013) found a convincing absence of any encoding difficulty benefit on memory due to blurring of words, despite clear performance costs at study. Also over many experiments, Rosner et al. (2015b) found a consistent memory benefit for blurry versus clear words. Both studies were well-conducted, and independently are quite convincing in their findings.

A critical difference determining these two robust and opposite outcomes was explored and verified in the final experiments of Rosner et al. (2015b) – the task performed at encoding. For experiments in Rosner et al. (2015b) showing a memory benefit of encoding difficulty, participants simply had to say the words – a relatively minimal task, and one where participants could rely substantially on automaticity in low-conflict (non-blurry) trials. In this task, the elicitation of more effortful and controlled processing in the presence of conflict/difficulty with blurry items leads to a memory benefit for those items, relative to the minimal-control conditions experienced for clear words.

In contrast, for Yue et al. (2013), the primary task required participants to make "judgments of learning" (JOL) for each clear or blurry word stimulus – that is, to explicitly evaluate how likely they thought it was that they would be able to remember that they had seen that word at study, on a later memory test. Rosner et al. (2015b) replicated this lack of memory effect when adding JOL responding to their procedures which had otherwise shown a difficulty memory benefit; they also discuss other studies in related memory literature that have similarly shown JOL procedures to disrupt other kinds of differential memory effects.

We suggest that the degree of engagement and effort required for this kind of more evaluative JOL task is substantially greater than simply reading or saying a word. With the JOL task, any potential differences in cognitive control elicitation due to processing difficulty or conflict from blurry words is unlikely to lead to substantial differences in central stimulus representations at study, as all stimuli are much more effortfully and completely represented because of the more demanding and evaluative task requirements themselves.

We propose that this kind of higher-demand task situation was likely happening in our Experiment 3, where we did not find an incongruency memory benefit with semantic primes. In retrospect, our size classification task there is really a relative size comparison task, rather than a classification of essentially big and small items. Most items in this stimulus set were not canonically big or small (e.g., "elephant" or "flea"), and our explicit instructions were to compare many smaller or larger (but not canonically so) items relative to the size of the computer monitor. This is in contrast to the animacy task (Experiment 4), where with the exact same stimuli, we did find an incongruency memory benefit – here animacy is an essential property of living but not non-living things, which we suggest participants have strong and relatively automatic memory access to within the task context of preparing to categorize items on the basis of animacy (we note that our animate items were all animals, not plants, and that our inanimate objects were either human-made items, e.g., "toaster", or geologic features, e.g., "mountain").

We predicted that we should be able to find an incongruency memory benefit for a size judgment task with semantic congruency primes (words "BIG" and "small"), if we used canonically big and small stimulus items that would allow participants to approach the task as a more direct semantic categorization task, rather than a more effortful evaluative task comparing each item to a reference object. We repeated the size classification task with semantic primes from Experiment 3, with a subset of canonically big and small items drawn from the larger stimulus set used in previous experiments, with instructions to simply judge items as typically big or small things.

Method

Participants

Forty-four first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke

English fluently. Data from three participants were excluded due to low accuracy (< 75%), and data from another three participants were eliminated due to substantially reversed priming effects (> 50 ms incongruency benefit), during the study/encoding phase. Another two participants were excluded due to an unrelated interruption of the experimental session and loss of data. A total of 36 participants were included for reported data analysis.

Apparatus, Stimuli and Procedure

Methods were identical to Experiment 3, with the following exceptions. From our original set of 240 concrete nouns, we selected a subset of 96 words (half big, half small) that were canonically big and small items, excluding items where size was not a central semantic feature. These words were divided into three 32-item lists, with stimulus-test sets generated as described in previous experiments. For a given participant, this gave 64 items at study, with half of these items presented at test as “old” items, with the remaining 32 items as “new” items. Prime words were again “BIG” and “small.” We continued with the single SOA at 100 ms for this experiment. An initial practice block of 8 trials presented a separate set of absolute big or small stimuli, which were not assessed or considered for the memory test. The memory test was the same as in previous experiments, with two blocks of 32 items each, in random order.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 8. A significant congruency priming effect was observed in RT, $t(35) = 3.39$, $p = .002$, suggesting that incongruent trials imposed additional difficulty on task performance. Accuracy was numerically worse for incongruent trials, in line with this difficulty expectation, though this effect was not significant, $t(35) = .90$, $p = .372$.

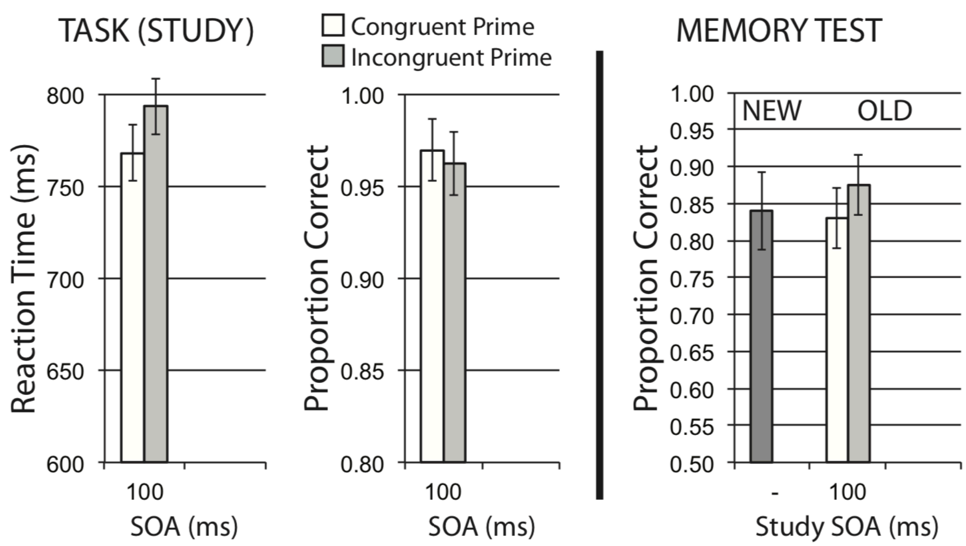

*Figure 8***.** Size categorization task with semantic priming (Experiment 6), using canonical big/small stimuli. Semantic incongruency priming produced costs on categorization performance (left panel), and also produced an incongruency benefit for later memory (right panel). Error bars represent 95% CIs for congruent/incongruent mean paired differences, as a direct assessment of congruency effects.

Memory phase

Figure 8 (right half) shows mean recognition memory performance (proportion correct) for old and new items at test, excluding items (per participant) incorrectly responded to at study. A significant memory benefit for old stimuli with incongruent priming at study was observed, $t(35) = 2.23$, $p = .032$. These findings represent another clear memory benefit from semantic incongruency priming.

Discussion

In Experiment 6, we observed a convincing incongruency encoding benefit with semantic congruency priming in a size classification task, when we used canonically big or small stimulus items. This is in direct contrast to the lack of any incongruency memory benefit with the same big/small size classification task in Experiment 3, where most stimuli required a more relational comparison of size relative to a common middle-sized reference object.

While it is possible that in Experiment 3 we may have a subset of these canonical big/small stimuli that have a hidden encoding effect, we suspect that the more evaluative or relational processing required for the majority of stimuli likely induces this kind of processing as a general approach to the task for most trials. We conducted a small number of follow-up analyses on a subset of Experiment 3 canonical big/small stimuli, but did not find a comparable incongruency encoding benefit for memory there. For participants to take advantage of automaticity in categorization, they may require the more general task situation to support this.

We suggest that this difference in primary task demands moderating incongruency memory effects, and the similar task dependency of difficulty-related memory effects with blurry versus clear perceptual desirable difficulty described by Rosner et al. (2015b), are both examples of a broader limitation of task processing demands on encoding difficulty effects.

General Discussion

Several recent papers have suggested that the demand for increased selective attention and cognitive control on incongruent trials leads to better incidental encoding of task stimuli (e.g., Krebs et al., 2015; Rosner et al., 2015a). Similarly, if inhibitory control demands redirect the focus of selective attention away from stimulus processing, a relative memory difference can again be observed (Chiu & Egner, 2015). Our present findings are directly in line with all of these recent results, and present substantial additional detail about the stage-by-stage processing dependencies involved in producing such encoding effects on later memory.

We demonstrated that these incidental encoding effects on memory can be produced by semantic incongruency priming, when primes induce additional attention and control at a processing stage that is focused on the core meaning of to-be-tested task stimuli. We demonstrated these effects with animacy classification using concrete nouns (Experiment 4), with male/female name gender classification (Experiment 5), and with size classification using concrete nouns (Experiment 6). In all of these situations, categorization tasks targeted core semantic features and/or strong associate information of these classes of stimuli, i.e., gender for typical/traditional names, animacy for animals versus inanimate objects, and size for a set of canonically big or small items (e.g., "elephant" versus "flea"). We suggest that in all of these cases, the categorization task required minimal evaluative processing to determine the category decision. In the presence of an incongruent semantic prime, increased conflict/control would increase focus on the rapidly and automatically activated semantic and strong associate content of the item itself, resolving categorization conflict and also leading to relatively better encoding of item information.

In contrast, using size (Experiment 1) and name gender (Experiment 2) classification tasks, we showed an absence of these incongruency encoding effects on memory when we prime response representations. In these cases, we suggest that additional attention and control is focused on central response selection processing, to resolve the conflict and competition induced by priming with incongruent response information. This diversion of cognitive control focus away from central representation of stimulus information with response priming predicts that later memory should not benefit from an increase in elicited cognitive control on incongruent/high-conflict trials, as we demonstrated. Our dissociation of conflict-related costs on task performance in general, versus the selectivity with which particular kinds of processing conflict at study will produce later memory benefits, is an important new finding for this broader literature.

An additional possibility is that with sufficiently strong control demands at response selection from incongruent response priming, attentional focus on semantic representations of stimulus information could be reduced or cut short, leading to relatively poorer encoding of stimulus semantic information and a relative cost on later memory. A strict interpretation of this mechanism would predict that this should occur only at shorter SOA, where response primes would generate conflicting response information relatively early in the time course of Task 1 to strongly influence response selection; in contrast, this effect should be much reduced at long SOAs where substantial amounts of semantic encoding could occur for both congruency types prior to the onset and influence of the response prime. Data from Experiment 1 (see Figure 3) show this precise pattern, with incongruency costs on memory selectively at the short 150 ms SOA, and no congruency effect at long SOA, even though initial task RT performance is similarly affected by incongruent response priming at both SOAs. It is possible that the backward compatibility response priming in the dual task PRP design in Experiment 1 was a particularly potent method of Task 1 response selection priming, compared to the "left"/"right" word primes in the single task Experiment 2.

In addition, and most strikingly, in Experiment 3 we showed that semantic congruency priming failed to produce an incongruency encoding memory benefit, despite using the same size categorization task and prime stimuli that did produce an incongruency encoding benefit in Experiment 6, and the same word stimuli that produced an incongruency encoding benefit with animacy classification in Experiment 4. We suggest that the critical difference between Experiments 3 and 6 with the same size categorization task is the nature of the word stimuli we used, and subsequently the kind of categorization performance participants were required to perform because of this. Experiment 3 required a more effortful relational or comparative assessment of size information from stimuli that mostly did not have big or small size as a central semantic feature or strong associate, so this increased evaluative processing demand of the primary task itself leading to better central representation of stimulus information for all trials, and minimizing any potential semantic incongruency memory effect.

This finding, along with similar findings of encoding difficulty effects being dependent on primary task demand (e.g., saying versus making judgments of learning on blurry versus clear words, and more general disruption of memory effects with judgment of learning tasks within the broader literature) as discussed by Rosner et al. (2015b), leads us to a second important consideration about likely mechanisms of incidental encoding difficulty effects on memory in general. Within general task designs that can be shown to elicit difficulty-related memory benefits, we have seen that added processing or evaluative demand in and of the primary task itself can abolish the memory benefit of greater task difficulty, despite this difficulty manipulation still imposing considerable costs in initial performance in all cases. The evaluative assessment in these tasks requires attentional control that benefits encoding of all items, independent of congruency or general task difficulty. This strongly suggests that in situations where we do observe conflict encoding benefits, the difference represents a relative cost to encoding in low-conflict conditions (involving relatively fluent performance with considerable support from automaticity), rather than a special enhancement to encoding under high-conflict conditions eliciting more controlled attentional processing.

Critically, we suggest that difficulty encoding effects represent a contrast between lesser-versus-normal control and attentional engagement, rather than a normal-versus-enhanced difference, where "normal" means the kind of engagement and processing that might be achieved if participants fully attended to and considered the stimulus with good focused endogenous top-down control. Put another way, difficulty encoding effects may be showing us that participants have relatively minimal semantic engagement with familiar stimuli and simple tasks under low-conflict conditions – interpreting difficulty memory benefits against this low-control baseline condition is valid and indeed revealing, but we suggest that the "benefit" to memory here is only a benefit with respect to an inherently encoding-poor situation. Inducing participants to focus more on the content or meaning of stimuli with different task demands (e.g., comparative size judgments, or judgments of learning) quickly equates memory for all stimuli, despite other differential difficulty manipulations. We agree with the idea that increased trial conflict or difficulty is likely to elicit increased cognitive control (e.g., Krebs et al., 2015; Verguts & Notebaert, 2008), but suggest that this may not additionally enhance encoding where stimulus information is already strongly attended and represented by demands of the task itself. This interpretation is a pessimistic one with regard to the broader desirable difficulty and related cognition and education literatures – it suggests that making a task more engaging in itself is a better path to retention of content, and that these kinds of conflict encoding benefits, arguably a major focus of a wide array of perceptual desirable difficulty benefits, may only be beneficial against a backdrop of minimal engagement with the meaning of any task material.

A more stage- and process-specific approach to considering conflict effects on memory may also help us align other recent findings in this emerging literature. Several recent studies (Ortiz-Tudela, Martin-Arevalo, Chica, & Lupiáñez, 2018; Ortiz-Tudela, Milliken, Botta, LaPointe, & Lupiáñez, 2017) have shown what on the surface appears to be an opposite memory effect of incongruency for objects displayed in congruent versus incongruent background scene contexts – incongruent items were quicker to be identified and localized (though with more error) in a change detection task, but showed worse later memory compared to congruent items. The authors discuss their findings as being at odds with theories of conflict-elicited learning (Verguts & Notebaert, 2008, 2009), but compatible with more general principles such as desirable difficulty or depth of processing. We suggest that a task analysis of what processes elicit more or less cognitive control, and where that control is subsequently focused, is both consistent with presumed mechanisms and data from change detection, and also predicts the observed memory results.

In our own incongruency priming tasks here (and for Rosner et al., 2015a, and others), incongruent priming adds noise to the classification process (more information for the alternative incorrect category for a given stimulus), and participants are forced to employ a greater degree of top-down cognitive control to elicit adequate semantic feature/category information from the stimulus. More simply, our conflict condition makes participants do more high-level attentional work, and in our semantic priming conditions, this work is directly focused on the meaning or essential category information of the stimulus itself. In contrast, in the change blindness studies (Ortiz-Tudela et al., 2017, 2018), the incongruent condition provides a strong automatic (and presumably rapid, pre-volitional) cue, both that something does not match, and also possibly a spatial cue to where the contextually inappropriate object is in the scene. In this case, it is the congruent condition that requires more deliberate attentional work and controlled processing to find the changing object. The authors themselves describe essentially this in terms of "desirable difficulty" (Ortiz-Tudela et al., 2017). We would agree, and suggest that beyond a concept of general difficulty, elicitation of greater cognitive control that focuses processing on to-be-tested information should lead to better memory performance – the particular circumstances of the change detection task allows participants to do less deliberate effortful controlled search (hence giving worse memory) due to the automaticity benefits of detection of contextual mismatch in visual scenes.

Finally, one potential limitation within our results is that while Experiment 1 used a response priming manipulation to show no incongruency memory effects, the primary task was the same relative size categorization task used in Experiment 3, where we similarly found no semantic incongruency memory effects. While this is a possible limitation in Experiment 1, our direct dissociation of memory effects between Experiments 2 and 5 (name gender classification with response priming versus semantic priming) provides an additional independent demonstration of our basic stage-specific findings on incongruency encoding benefits.

Implications For 'Desirable Difficulty' Effects

These selective attention-related encoding benefits may be highly relevant to the broader literature of desirable difficulty effects (Bjork, 1994; Bjork & Bjork, 1992, 2011), where difficulty experienced while processing an item (most commonly during retrieval) promotes better long-term memory. Well-documented examples of desirable difficulties include spaced practice (for a review, see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006), interleaving study materials (Kornell & Bjork, 2008; Rohrer & Taylor, 2006), and test-enhanced learning (e.g., Roediger & Karpicke, 2006). In addition to these, processing difficulties during initial encoding, in the form of perceptual interference (Hirshman & Mulligan, 1991; Nairne, 1988), hard to read fonts (Diemand-Yauman, Oppenheimer, &

Vaughan, 2011), and inverted words (Sungkhasettee, Friedman, & Castel, 2011), have been shown to enhance retention. Processing difficulties such as these therefore appear to be "desirable" for learning.

However, not all processing difficulties are desirable for learning. Indeed, the broader history of experimental psychology has largely converged on a view that additional task difficulty tends to lead to worse performance, both in the moment and for later memory. For example, divided attention tasks are difficult, but typically impair memory for learned material (Baddeley, Lewis, Eldridge, & Thomson, 1984; Craik, Govini, Naveh-Benjamin, & Anderson, 1996; Dudukovic, DuBrow, & Wagner, 2009; Fernandes & Moscovitch, 2000; Gaspelin, Ruthruff, & Pashler, 2013; Mulligan, 1998; but for an exception see Kessler, Vandermorris, Gopie, Darros, Winocur, & Moscovitch, 2014). The desirable difficulty framework established by Bjork and Bjork (1992; 2011) has been influential in steering researchers to consider situations where these apparently general costs might be avoided, or even reversed.

As Chiu and Egner (2015) suggest from their recent cognitive control manipulations that direct attention away from stimulus encoding (inhibitory control tasks) rather than toward it, it is reasonable to assume that for a difficulty manipulation to induce a memory benefit, the difficulty must increase selective attention to the to-be-remembered information. However, more than an attentional or control focus toward or away from a primary task, our present experiments show that this is an even more specific requirement. We suggest that the particular stage of processing that is the recipient of facilitation or conflict is likely to be a critical consideration for predicting whether a “desirable difficulty” effect on later memory will occur. Put another way, our results show that task difficulty in general does not improve memory, but instead will occur only in cases where the information to be encoded (to be assessed at later memory test) was the beneficial recipient of the enhanced attention and cognitive control required by the task.

The results of the current study suggest a stage-specific model of desirable difficulty in several ways, and may help to clarify other issues in this literature. First, our study may contribute to continuing interpretation of relevant classic prior work, showing that more difficult encoding conditions produce memory benefits (e.g., Jacoby, Craik, & Begg, 1976). Additionally, it might be argued that difficulty benefits on later memory may arise simply due to available time on task – that the additional time required to process and respond to high-conflict compared to low-conflict items directly produces additional encoding through longer exposure, leading to a memory benefit. Our experiments can address both of these issues. As can be seen in Experiments 1, 2, and 3, although conflict and extra time on task was present for incongruent versus congruent trials during primary task performance, no memory benefits were found. Enhanced memory is not apparent for all difficult selective attention-encoding conditions, but rather depends on the particular stage of processing at which this additional difficulty occurs.

Conclusion

Taken together, our results suggest a highly stage-specific mechanism for producing conflict/control-related incidental encoding effects. We generally agree with accounts in the literature suggesting that conflict resolution involving top-down attention toward task-relevant information should facilitate memory for that information (e.g., Botvinick, 2007; Egner & Hirsch, 2005). Furthermore, our results are similar to those in recent studies showing memory effects from congruency priming tasks, where incongruent (higher conflict) items are better remembered relative to congruent (lower conflict) items (e.g., Krebs et al., 2015; Rosner et al., 2015a). We agree with these authors that an increase in selective attention due to increased cognitive control elicitation from incongruent stimuli likely provides a memory encoding benefit for incongruent versus congruent items in these cases.

What we have shown here is an important constraint on this kind of effect – that this encoding benefit is stage-specific, and only occurs when additional control is directed at a processing stage focused on the representation of to-be-tested information. In some cases, task demands will serve to focus this difference in processing conflict at a semantic representation stage, and we observe memory benefits in high-conflict situations. On the other hand, the variability of results in the broader desirable difficulty literature, not to mention that conflict-related desirable difficulty itself, is still a somewhat novel and surprising effect within psychology's long history of divided attention costs, suggesting that "difficulty" simply being task- or stimulus-directed might not be sufficient for eliciting memory benefits.

Further, we suggest that difficulty/conflict encoding benefits are likely to be observed when demands of the task itself are relatively lower and allow a degree of automaticity in responding – if the task itself requires substantial evaluative work, additional attentional and cognitive control focus on stimulus information from stimulus-focused difficulty manipulations does not seem to further enhance memory encoding, even though it imposes a cost on initial task performance. In this sense, conflict/difficulty encoding benefits as a general class of effects might be limited both (1) to situations where cognitive control demand focuses processing on to-be-tested information, and also (2) to situations where typical task engagement is relatively fluent, automatic, and encoding-poor, rather than cognitive control elicitation having some additional encoding benefit in all situations. It is important to note that this need not be a deliberate experimental manipulation of semantic congruency – the critical consideration is what information ends up as the focus of central attention, rather than the particular task manipulation used to achieve this. We suggest that many desirable difficulty effects where interference manipulations are purely perceptual will often still focus central attention on to-be-tested stimulus information. So long as those perceptual manipulations and related task requirements do not require too much effortful or evaluative work to access or represent relevant stimulus meaning, we would expect memory benefits from differential attentional encoding effects for more demanding perceptual conditions, against a background of relatively fluent and automatic performance in low-conflict conditions.

The present results should be investigated further from a desirable difficulty perspective. Further research should make it possible to make better predictions about how and where these kinds of processing conflict or desirable difficulty effects should occur, and that fundamental ideas and knowledge we already have within cognitive psychology might provide more guidance than we may have suspected. For now, these results provide evidence toward a stage-specific model that predicts when incongruency conflict in task performance should and should not lead to better incidental encoding of task stimuli.

CHAPTER 3: Memory effects of conflict and cognitive control are processing stage specific: Evidence from pupillometry

Ptok, M. J., Hannah, K., & Watter, S. (Submitted)

Preface

Chapter 3 presents the results of three experiments using pupil dilation measures to assess the proposed stage-specific conflict-encoding model. The general method for all experiments involved the presentation of prime-target pairs at study followed by a surprise recognition memory test where participants were told to classify a sequence of words as old or new. In Experiment 1, we replicated the semantic (i.e., “male” or “female” word primes) gender name classification task from the previous paper while also measuring event-related pupil dilation. We found a congruency effect where incongruent words took longer to classify than congruent words, indicating a difficulty at encoding. Results also demonstrated a conflict-encoding benefit with semantic priming. The pupillometry data provided converging evidence for these effects. Event-related pupil dilation was observed for the name classification task, with greater pupil dilation for incongruent trials, suggesting greater elicited cognitive control for higher-conflict situations.

Experiment 2 used the same name gender task as Experiment 1, but with response primes (left or right arrows). As expected, results showed a congruency effect at encoding but an absence of the conflict-encoding memory effects due to attentional allocation being directed toward response selection, and replicating the response priming results from Chapter 2. Notably, these data dissociate event-related pupil dilation evidence of greater conflict for incongruent trials and the absence of this influence on later stimulus recognition memory predicted by our stage-specific conflict-encoding model.

Experiment 3 helped to demonstrate that the degree of effort in a task could modulate expected conflict-encoding effects. Methods were identical to Experiment 1 with one exception: Instead of sitting back in their chair, participants sat forward with their chin on a chin rest. This was done to induce participants to focus more effortfully on the encoding task. Results showed a congruency effect at study, no memory differences between incongruent and congruent stimuli at encoding, and much larger and equal pupil dilation responses for both congruent and incongruent stimuli. These results parallel the high-evaluation (relative size judgment) semantic priming task data from Experiment 3 in Chapter 2. Again, these results are directly in line with our prediction of reduced conflict-encoding benefits with increased overall endogenous effort in categorization task performance.

Taken together, these results show clear dissociation of greater elicited control as indexed by greater pupil dilation on incongruent trials (Experiments 1 and 2), and conflict-related encoding benefits only seen with semantic priming. Additionally, we also show the dependence of potential conflict-encoding effects on the degree of overall endogenous task engagement (Experiment 3). The present study provides substantial support and converging physiological evidence for a more selective and stage-specific mechanism of conflict-elicited encoding effects, and the dependence of these effects on relatively less engaged or more automatic performance.

Abstract

An increasing number of studies in the conflict/control and perceptual desirable difficulty literatures show memory benefits for information in high-conflict task situations. Recent work suggests that increased conflict does not produce a task-wide encoding benefit; rather, to produce an encoding benefit, conflict must focus high-level attention on to-be-tested information. We used pupil dilation measures to directly assess this stage-specific model of conflict-encoding effects. The experiment showed clear evidence of incongruency (slower RT and larger pupil dilation) with both semantic and response priming, but a memory benefit only with semantic conflict. Further, when participants were encouraged to focus more (eliciting greater endogenous effort and control for all trials, not just incongruent trials), we observed larger and more similar pupil responses and reduced memory differences between high and low semantic conflict conditions. These data confirm and extend a stage-specific model of conflict-encoding effects, with converging behavioural and physiological data.

Introduction

Congruency priming manipulations (e.g., Eriksen & Eriksen, 1974; Simon & Small, 1969; Stroop, 1935) are commonly used to investigate selective attention and cognitive control. The conflict-monitoring model of Botvinick et al. (2001) has been highly influential in understanding how cognitive control protects performance from interference in these kinds of tasks. Subsequent extensions of this model have described how elicitation of increased cognitive control should lead to stronger encoding and better subsequent memory for task information in high-conflict situations (Botvinick, 2007; Verguts & Notebaert, 2008, 2009).

In recent years, several studies have reported evidence supporting this view, demonstrating better memory for target stimuli in the presence of incongruent versus congruent distractors. For example, Krebs, Boehler, De Belder, and Egner (2015) observed better memory for faces presented in a gender classification task along with an incongruent versus congruent gender label. They argued that better encoding resulted from participants having to resist incongruent information. Similarly, Rosner, D'Angelo, MacLellan, and Milliken (2015a) showed better subsequent memory for target words presented interleaved with a second different word, versus interleaved with the same repeated target word. These authors suggested that the additional attentional selection of the target word from a distracting different second word led to better target word encoding. Although framed somewhat differently, the expanding literature on perceptual desirable difficulty has produced a number of similar findings suggesting encoding benefits with enhanced central attentional demands – for example, better memory for text in unusual fonts (Diemand-Yauman, Oppenheimer, & Vaughan, 2011), and better memory for blurry versus clear words (Rosner, Davis, & Milliken, 2015b).

All these findings converge on the general idea that increased task conflict leads to better stimulus encoding, via elicitation of increased cognitive control and related high-level attentional processes. All these studies discuss the influence of conflict and control on memory in a task-general way, where conflict from a range of sources is assumed to elicit some overall greater degree of cognitive control and result in better encoding of information from the entire task (for an accessible discussion, see Verguts & Notebaert, 2009). However, there is recent evidence that conflict/control effects on memory may in fact be more selective and specific than this. As one constraint on this general idea, Chiu and Egner (2015) found that high-conflict trials in stop-signal and go/no-go paradigms (i.e., stop and no-go trials requiring response inhibition) were associated with worse memory for trial information, not better memory as a general conflict-encoding relation would predict. They suggested that the control demands of a task need to draw selective attention toward the processing of target information rather than divert it away in order to receive an encoding benefit of high task conflict.

Most recently, Ptok, Thomson, Humphreys, and Watter (2019) proposed a processing stage-specific model of how and when task conflict should (and should not) lead to enhanced memory for task information that also explains similar memory effects (and lack thereof) in the perceptual desirable difficulty literature. Over a series of six experiments with various semantic word classification tasks (size and animacy of concrete nouns, and gender of common names), Ptok et al. (2019) showed better recognition memory for target words when shown with incongruent versus congruent semantic prime words (i.e., category labels of size, animacy, or gender), but no memory benefit with incongruent versus congruent response priming (left/right prime words, or response congruency priming from a secondary task). For example, classifying “Lisa” as female (via LEFT keypress) with an incongruent (“male”) versus congruent (“female”) prime word gave slower reaction time (RT) for classification, but better subsequent recognition memory of the name “Lisa.” In contrast, incongruent response priming with “Lisa–right” versus “Lisa–left” again lead to slower RT for a correct left keypress, but gave no benefit to later memory for the name “Lisa.”

Where Chiu and Egner (2015) argued that, to give an encoding benefit central attention needed to be directed toward task information rather than to inhibitory processes. Ptok et al. (2019) argued for an even more selective and specific within-task dependency of where selective attention would be focused by different kinds of processing conflict. Figure 1 (adapted from Ptok et al., 2019) demonstrates how the stage-specific locus of central interference predicts and dissociates the independent effects of RT slowing and potential encoding benefits. Most simply, selective interference at either semantic/categorization or response selection stages (here, selectively implemented using either incongruent category or response primes) will lead to relative slowing of RT performance, compared to equivalent congruent prime conditions. However, memory effects should depend solely on whether to-be-tested information is better represented or encoded – here, semantic incongruency priming (interference) elicits greater control and attentional focus on to-be-tested target word information, predicting better memory for semantic incongruent versus congruent trials. In contrast, response incongruency priming elicits greater focus on response selection representations, and not to-be-tested target word information, and so should give no memory benefit despite greater conflict and control at study. Critically, we argue that the relation between increased conflict/control and better encoding is not task-general, but is considerably more processing stage-specific.

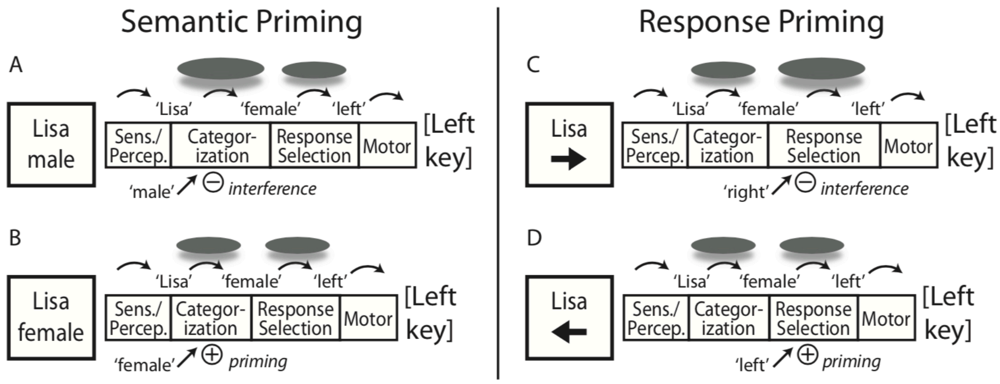

Figure 1. Information processing model of stage-specific conflict-encoding effects, following Ptok et al. (2019). A male/female name classification task is shown with incongruent versus congruent semantic priming (panel A vs B), and incongruent versus congruent response priming (panel C vs D). Gray ovals represent central focus of selective attention and cognitive control processes, with greater size representing proportionately greater focus and control. Incongruent priming produces interference and elicits greater control relative to equivalent congruent conditions. Eliciting greater control and central processing at semantic/classification representation predicts better encoding of stimulus information and better subsequent recognition memory performance. However, increased control and central processing at response selection diverts cognitive control focus away from central representations of to-be-tested stimulus information, predicting no benefit of increased conflict/control on later memory, despite increased control and focus for the task more generally. Sens. = Sensation, Percep. = Perception.

In addition, Ptok et al. (2019) established a second constraint that may limit the ability to obtain incongruency/conflict memory benefits, even when conflict focuses central control processes on to-be-tested stimulus information. From their own data and related perceptual desirably difficulty studies, Ptok et al. (2019) argued that the incongruency memory benefit represents a difference between elicited high-focus processing on incongruent trials versus relatively automatic, low-control or low-focus processing on congruent trials, rather than an additional enhancement of encoding over and above nominal attended performance. When tasks require substantial evaluative processing (e.g., making relative size judgments in comparison to a reference object), no incongruency priming benefits are seen in memory; these memory benefits for incongruent/conflict trials return in highly similar tasks (e.g, making absolute size judgments on canonically big or small items) when the task demands are reduced to be less evaluative and can rely more on well-learned and rapidly accessible semantic knowledge, supported by automaticity. Ptok et al. (2019) demonstrate this dissociation of memory effects, and point to similar differences in the perceptual desirable difficulty literature – e.g., with blurry versus clear words, making judgments of learning gives no memory benefit with difficulty (Yue, Castel, & Bjork, 2013; Rosner et al., 2015b), but simply reading the words gives a memory advantage for higher-demand blurry items (Rosner et al., 2015b).

The present study sought to explicitly and directly test these two dissociations of conflict/control and memory encoding – that the locus of conflict is critically important for producing memory benefits, and that observing conflict-encoding benefits also depends on relatively less-focused versus more-focused task performance – and to do so with a direct physiological measure of the degree of elicited central control, event-related pupil dilation. Pupil dilation has a long history in cognitive psychology (for reviews, see Beatty & Lucero-Wagoner, 2000; Sirois & Brisson, 2014) and is considered to be a reliable general index of cognitive work and attentional focus or effort. More specifically for the current study, cognitive event-related pupil dilation is an observable physiological response indexing cognitively-relevant transient sympathetic nervous system activation, driven primarily by activity in the locus coeruleus. Verguts and Notebaert (2008, 2009) propose that locus coeruleus activity is the mechanism by which increased trial-specific learning is driven across cortical areas, secondary to the locus coeruleus being activated by conflict detection and control elicitation by medial frontal cortex/anterior cingulate structures. As such, event-related pupil dilation responses are an excellent index by which we can directly assess degree of elicited conflict/control.

We conducted three experiments, using the gender name classification task from Ptok et al. (2019). In Experiment 1, we sought to replicate the semantic incongruency memory benefit, where we predict incongruency effects on RT and pupil dilation, and also benefits to memory. Experiment 2 used the same gender name task with response (left/right arrow) primes, where we again expect RT and pupil dilation effects of incongruency, but no encoding benefits. Finally, Experiment 3 repeated the semantic priming of Experiment 1 but increased performance demands – in this case, we would predict larger and more similar pupil responses due to greater and more similar engagement between congruency conditions, and subsequent reduced congruency effects on memory, despite the semantic locus of interference.

Experiment 1

Experiment 1 sought to directly replicate the incongruency encoding benefit observed by Ptok et al. (2019) using the same name gender classification task, and additionally to gather event-related pupil dilation data. Participants classified typical female or male names as female/male, while trying to ignore a congruent or incongruent semantic prime (words "male" or "female") shown underneath each target word. An old/new recognition memory test on name stimuli followed the classification task. This replication was expected to show costs to classification performance for incongruently primed trials (slower RT and higher error rate), and also a benefit to later recognition memory for these higher-conflict incongruently primed items. We predicted that pupil dilation data from the classification task should show a larger event-related pupil dilation effect for the incongruent condition, as a measure of increased cognitive control demand.

Method

Participants

Twenty-nine first-year McMaster University students participated in this experiment for course credit. Our data collection plan for this and subsequent experiments followed the rule that we would schedule participants week by week, and terminate data collection at the end of a week once we had a minimum of 24 participants. McMaster's Research Ethics Board approved the study, and informed written consent was obtained from each participant. All participants reported normal or corrected-to-normal visual acuity, normal color vision, and spoke English fluently.

For this and subsequent experiments, we established two thresholds for study task performance, to ensure that pupil dilation and memory performance data were being generated from participants adequately performing the classification task and being influenced as expected by our priming difficulty manipulations. Adapting methods from Ptok et al. (2019), we excluded participants with less than 75% accuracy on the name gender classification task, or with a substantially reversed congruency priming effect (> 30 ms faster performance for incongruent trials) suggesting that performance was not made more difficult by congruency priming. In addition, we excluded participants with less than 25% of good pupil dilation trials (more than 75% of trials flagged for excessive missing or extreme outlier values), given the degree of noise these low-n mean traces would be likely to add with repeated measures analysis.

For this experiment, data from one participant were excluded due to a substantially reversed incongruency RT effect; no participants were excluded for poor accuracy or bad pupil data. Partial data were lost for an additional four participants due to recording equipment errors, leaving 24 participants for data analysis.

Apparatus and Stimuli

Stimulus presentation and behavioural response collection used a standard Windows 7 computer with Presentation experiment software (v.20, neurobs.com), and a 22-inch flat panel LCD monitor running at 60 Hz. Stimuli and task procedures closely followed the name gender classification task described by Ptok et al. (2019). Stimuli were a set of 240 typical non-gender-ambiguous Western/Anglophone names (120 female, 120 male). Three 80-item lists were created, balanced for gender and first letter of the name. For the study/encoding phase of the experiment, words from two lists were presented once each as stimuli, randomly assigned to equal numbers of congruent and incongruent trials, and presented in random order. Primes were the words “male” and “female.” In the subsequent memory phase of the experiment, words from one of the two initial study lists were presented (as old items) along with words from the third unseen list (as new items). The six possible combinations of these list arrangements were counterbalanced across participants.

In the study/encoding phase, words were presented in dark green Arial font (RGB value 0, 163, 0), sized to be 1.5 cm vertically on a grey screen (RGB value 96, 96, 96). These colours were selected to approximate isoluminant stimulus conditions (versus background), to minimize the contribution of the simple pupillary light reflex to potential pupil dilation effects. The prime words were presented directly underneath, separated by an approximately 0.75 cm gap, in the same color, size, and font. A pre-stimulus cue consisting of two rows of single dashed separated spaces (“- -”) was presented as an indication of the central position where stimuli would appear. Participants sat at a viewing distance of approximately 50 cm from the computer screen. In the memory phase of the experiment, single words were presented centrally in the same Arial font, in a larger size (approximately 2.5 cm vertically).

Pupil dilation data were collected using an EyeTribe remote desk-mounted eye tracker, sampling at 30 Hz. The eye tracker was positioned on the desk, aligned centrally and just below the stimulus presentation computer monitor. The eye tracker was connected to a second computer, which was used to run an initial 9-point calibration, and then to record gaze position and pupil dilation data throughout the study/categorization task (not during the memory test). Lab Streaming Layer (LSL) software (github.com/sccn/labstreaminglayer; LabRecorder and EyeTribe LSL acquisition driver) was used on the eye tracker computer to record eye tracker data along with time-synchronized stimulus event markers from Presentation across a local wired network connection.

Procedure

The experimental design for this and subsequent experiments is outlined in Figure 2. During the study/encoding phase, a trial began with the cue presented for 500 ms and was immediately replaced with the stimulus word. After 100 ms, the prime word was presented below the stimulus on the screen. Each stimulus lasted on the screen for 1000 ms. Participants were instructed to focus on the name stimuli while ignoring the prime word throughout the experiment, and to categorize the stimulus word as 'male' or 'female' and respond as quickly and accurately as they could. Response alternatives were mapped to index fingers of left and right hands, using the 'Z' and '/' keys of a standard computer keyboard. Response mapping was counterbalanced across participants. An inter-trial interval of 2000 ms (blank screen) separated the end of the presentation of the prime word and the cue beginning a subsequent trial. The study/encoding phase consisted of four blocks of 40 trials, for a total of 160 trials. An additional 12 trials with separate name stimuli was initially presented as a practice block, and not considered for analysis or the later memory test.

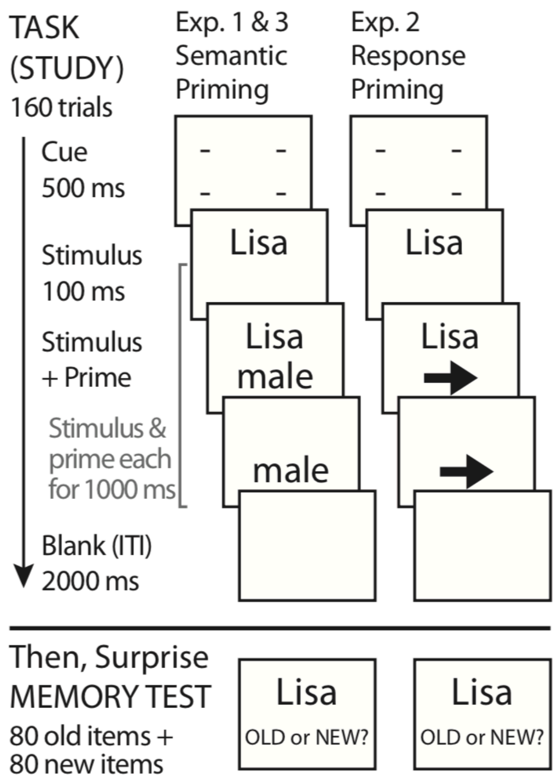

Figure 2. Task design and procedure for Experiments 1-3. Participants first performed a name gender classification task, with semantic or response primes. An old/new recognition memory task followed each categorization task. ITI = Inter-trial Interval.

After the study/encoding phase, participants were given 2 minutes rest, and this was followed by the memory test. Participants were instructed to classify the words as old or new depending on whether they had seen that word during the study/encoding phase. Stimuli were presented in randomized order, and remained on screen until a response was executed. Responses were made by pressing the "Z" key for old words or the "/" key for new words on the computer keyboard. A blank screen lasting 1000 ms separated the response from the next stimulus. Trials were presented in four blocks of 40 trials, for a total of 160 trials, with self-paced breaks in between.

Data Analysis

Mean classification trial accuracy was computed on the basic of correct classification responses from all trials. Mean classification RT was computed for correct trials, and excluded trials faster than 300 ms or slower than 1500 ms. RT cutoffs excluded approximately 1% of RT data in each experiment. Memory test data were computed as proportion of trials correctly classified as old and new respectively, after excluding the small number of old trials (per participant) incorrectly classified at study.

In addition to general cognitive findings on the relation between mental workload and increased pupil dilation (e.g., Beatty & Lucero-Wagoner, 2000; Sirois & Brisson, 2014), pupil dilation effects have been directly associated with incongruency priming in common conflict/control tasks, including Stroop (e.g., Laeng, Ørbo, Holmlund, & Miozza, 2011), flanker (e.g., Wendt, Kiesel, Geringswald, Purmann & Fischer, 2014), and Simon (e.g., Van Steenbergen & Band, 2013) tasks. Given all these converging findings, we interpret pupil dilation as an index of elicited conflict and cognitive control from semantic and response incongruency priming.

Continuous pupil diameter data for left and right eyes were recorded at 30 Hz sampling rate for the entire study/classification phase. Missing data segments (typically due to blinking) were linearly interpolated after removing one sample before and after each missing segment, to avoid potential measurement artifacts from half-occluded pupils due to blinking. Data were then smoothed by a 7-point moving average filter, and then left and right eye data traces were averaged to give a single dataset. Analysis epochs were defined as 3-second windows beginning at stimulus word onset. Data were assessed as proportion change from baseline – the mean pupil diameter value from the 500 ms segment prior to the stimulus word onset was first subtracted from the epoch pupil data, and then the epoch data value was divided by this value. Epochs with greater than 25% missing values in original unprocessed data were marked as bad and excluded from the dataset. Condition averages within an experiment were computed by-participants for repeated measures analyses, and also by-trials (ignoring participant) for grand mean waveforms. Continuous data for individual participants and conditions were then averaged into 100-ms time bins for easier statistical analysis.

Results

Encoding phase

Mean correct RT and mean accuracy for the gender classification task are shown in the top row of Figure 3. Classification performance was overall highly accurate. A significant congruency priming effect was observed in RT, $t(23) = 3.18$, $p = .004$, indicating that incongruent trials imposed a difficulty on task performance. Accuracy was also significantly worse for incongruent trials, providing further evidence for this difficulty manipulation, $t(23) = 2.44$, $p = .023$.

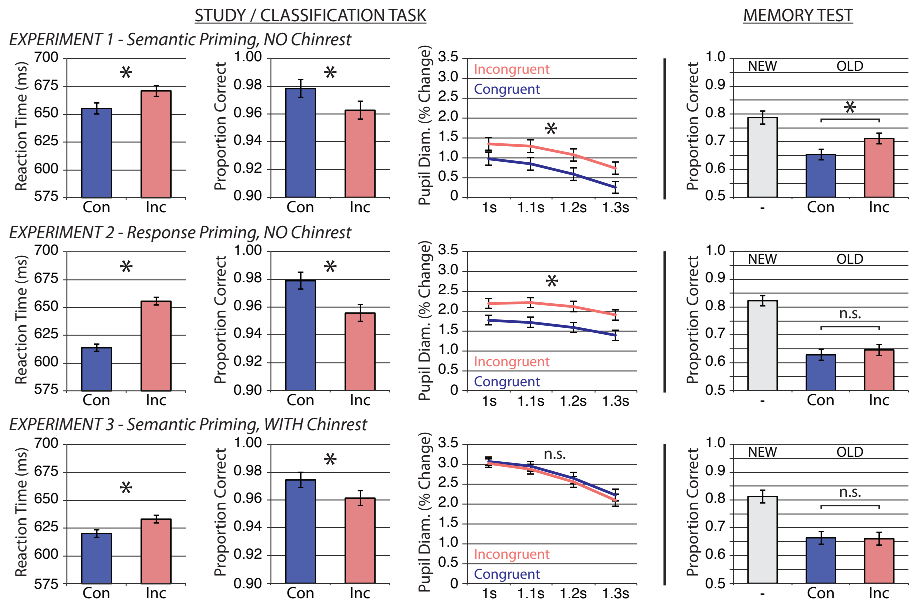

Figure 3. Results for Experiments 1-3. Asterisks denote statistically significant differences between congruency conditions. Semantic versus response priming (Exp. 1 versus 2) shows conflict effects on behaviour and pupil dilation, but this only produced a memory benefit with semantic priming, not with response priming (control directed toward versus away from to-be-tested stimulus information). Exp. 3 elicited greater endogenous focus with participants sitting forward with a chinrest for the classification task; with the same semantic priming as Exp.1, greater endogenous effort produced more similar control/focus in both congruency conditions as indexed by equivalent pupil responses, leading to no memory differences. Error bars represent within-subject SEM for each condition. Con = Congruent, Inc = Incongruent, Diam. = Diameter.

Grand mean pupil dilation responses to the name gender classification task are shown in Figure 4 (weighted averages by number of trials per participant). A general peak dilation response was observed for both congruent and incongruent conditions here in Experiment 1 (and in all experiments), with a maximum amplitude approximately 1.1 seconds after stimulus onset. Pupil data from individual participants were averaged within condition, giving a single average pupil trace over time for each condition for each subject (akin to typical Event Related Potential EEG analyses). To analyze these and subsequent pupil data, we computed mean amplitude in 100-ms bins, comparing congruent versus incongruent conditions over three time points at the start of the trial (0, 0.1, 0.2 second bins), and three time points where dilation amplitude was maximal (1.1, 1.2, 1.3 second bins). These mean by-subjects pupil data are shown in Figure 3. These data were subjected to a 2 (congruency) x 6 (time) repeated measures ANOVA, with Greenhouse-Geisser correction (given sphericity violations with within-subject time series data), to assess whether congruency differences resulted in differences in peak pupil dilation compared to baseline-adjacent data.

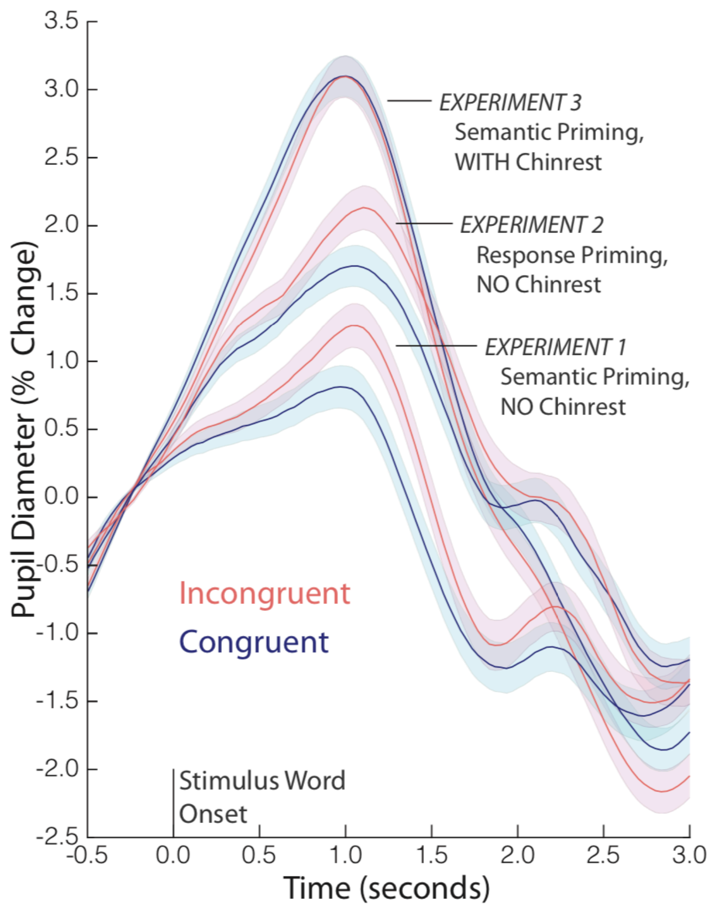

Figure 4. Grand average mean pupil dilation data for Experiment 1-3. Data represent proportional change of pupil diameter, after baseline adjustment to the mean diameter in the 500 ms prior to stimulus onset. Data represent averages of all valid single trials (ignoring subjects) following linear interpolation of missing data (equivalent to weighted averages by n trials per subject). Shaded areas indicate +/- 1 SEM.

Pupil dilation data showed a peak dilation response that was larger for incongruent than congruent trials. This congruency difference at later peak amplitudes compared with earlier time points was supported by a significant interaction of congruency and time, $F(5, 115) = 6.11$, $\varepsilon = 0.26$, $p = 0.014$, $\eta_p^2 = 0.21$. There were no significant main effects of time, $F(5, 115) = 1.14$, $\varepsilon = 0.22$, $p = 0.301$, or congruency, $F(1, 23)$, $p = 0.101$. Direct assessment of the mean maximal amplitude difference over the 1.1 to 1.3 second bins showed significantly larger event-related pupil dilation for incongruent versus congruent trials, $t(23) = 2.17$, $p = 0.040$. This event-related pupil dilation difference suggests that greater high-level attentional work was elicited for incongruent versus congruent trials, in accord with the predicted influence of our congruency manipulation.

Memory phase

Figure 3 (top row, last panel) shows mean recognition memory accuracy for old and new items at test, for Experiment 1. A significant memory benefit was observed for old items originally presented with incongruent primes, compared to old congruent items, $t(23) = 2.99$, $p = 0.006$. This incongruency memory benefit is in line with both the pupillometry and behavioural encoding results, suggesting that increased conflict-elicited control and processing for incongruent items led to a later recognition memory benefit for those items.

Discussion

Experiment 1 replicated the name gender classification results from Ptok et al. (2019), showing a conflict-encoding benefit with semantic priming. Incongruent semantic priming during the initial categorization task led to better subsequent recognition memory of target names compared to items categorized with congruent primes. Our pupillometry data provide converging evidence for these effects. Event-related pupil dilation was observed for the name classification task, with greater pupil dilation for incongruent trials suggesting a greater degree of elicited cognitive control for this higher-conflict situation.

While these findings are compatible with a general conflict-encoding account (e.g., Verguts & Notebaert, 2008, 2009), we argue that these memory benefits should be limited to task situations where processing conflict directs in-the-moment processing and central attention to focus on to-be-tested stimulus information. Experiments 2 and 3 aimed to demonstrate some of these limitations, with the additional contribution of pupil dilation measures as a direct index of conflict and elicited control.

Experiment 2

In Experiment 2, we used the same name gender task as Experiment 1, but with response (left/right arrow) primes. We predicted typical effects of incongruency/conflict on behavioral and pupil dilation data at study – slower RT, increased error, and larger pupil dilation for incongruently primed items. However, following Ptok et al. (2019), we predicted that increased cognitive control from incongruency conflict should not produce a memory benefit here, given the focus of conflict and control away from stimulus information and toward response selection.

Method

Participants

Thirty-three first-year McMaster University students participated in this experiment for course credit. All participants reported normal colour vision, normal or corrected-to-normal visual acuity, and spoke English fluently. No participants were excluded on the basis of classification task accuracy or reversed RT priming effects. Two participants were excluded for having fewer than 25% good pupil data trials. Partial data were lost for one additional participant due to recording equipment errors, leaving 30 participants for analysis.

Apparatus, Stimuli and Procedure

This experiment directly repeated methods for Experiment 1, except using response congruency primes in place of semantic primes in the study phase. Instead of semantic primes “female” and “male,” this experiment used left and right arrow stimuli, presented in the same position below the target stimulus name on each trial, illustrated in Figure 2. Single arrow stimuli were congruent or incongruent with the correct left or right button response for the gender classification task on each trial, generated with the same counterbalancing and randomization as for semantic primes in Experiment 1. The memory test phase was identical to Experiment 1.

Results

Encoding phase

Mean correct RT and mean accuracy data for Experiment 2 are shown in the middle row of Figure 3. A significant congruency priming effect was observed for RT, $t(29) = 12.38$, $p < .001$, in line with expectations of a more demanding incongruent priming condition. Accuracy was also significantly worse for incongruent trials, providing further evidence for the effectiveness of this difficulty manipulation, $t(29) = 3.88$, $p < 0.001$.

Pupil dilation data were assessed as in Experiment 1. As seen in Figures 3 and 4, by-subjects and grand mean pupil dilation data for Experiment 2 again showed a larger peak pupil dilation for incongruent versus congruent trials. This congruency difference at peak dilation versus earlier baseline-adjacent data was supported by a significant interaction between congruency and time, $F(5, 145) = 6.00$, $\varepsilon = 0.27$, $p = 0.012$, $\eta_p^2 = 0.17$. This interaction modified a significant main effect of congruency, $F(1, 29) = 5.88$, $p = 0.022$, $\eta_p^2 = 0.17$. A main effect of time was also observed, $F(5, 145) = 4.24$, $\varepsilon = 0.21$, $p = 0.046$, $\eta_p^2 = 0.13$, reflecting a general pronounced pupil dilation response over time in both conditions. Direct assessment of the mean maximal amplitude difference over the 1.1 to 1.3 second bins again showed a significantly larger event-related pupil dilation for incongruent versus congruent trials, $t(29) = 2.86$, $p = 0.008$. This pupil dilation effect is again consistent with our expectation of greater elicited high-level attentional work for incongruent versus congruent trials.

Memory phase

Figure 3 (middle row, last panel) shows mean proportion correct recognition memory performance for old and new items for Experiment 2. In contrast to the semantic priming incongruency effect in Experiment 1, here with response priming there was no memory benefit for incongruent items, $t(29) = 0.88$, $p = 0.388$.

Discussion

These results replicate the absence of conflict-encoding memory effects with response priming, as similarly shown by Ptok et al. (2019). Despite using the exact same name gender classification task as in Experiment 1 (with evident conflict-encoding effects), and despite showing clear evidence of higher conflict for incongruent items at study, there were negligible benefits of encoding conflict here with response priming. Notably, these data dissociate event-related pupil dilation evidence of greater conflict and greater locus coeruleus activation for incongruent trials, and the absence of this influence on later stimulus recognition memory, as predicted from the stage-specific conflict-encoding model proposed by Ptok et al. (2019).

The combination of Experiments 1 and 2 show strong converging evidence that the representational focus of processing conflict is an important predictor of conflict-related encoding and subsequent memory benefits. In addition to this processing stage specificity of conflict-encoding effects, we argue (again, following Ptok et al., 2019) that the degree of automaticity and required or elicited engagement with a task is also likely to modulate potential conflict-encoding effects on later memory. We explore this issue further, again using pupillometry methods, in Experiment 3.

Experiment 3

Experiment 3 sought to demonstrate that the degree of effort or engagement in a task could modulate expected conflict-encoding effects – specifically, that increased endogenous engagement with the task in general should reduce memory benefits of incongruency priming. If memory benefits reflect conflict-elicited engagement with better encoding for incongruent trials, versus more disengaged and automatic performance with reduced encoding for congruent trials, then a generally increased task focus with both congruent and incongruent trials should predict larger and more similar pupil responses and reduced memory differences due to trial conflict.

In conducting initial pilots of our gender name task with isoluminant stimuli in preparation for these pupillometry studies, we originally ran a pilot study with semantic priming using a chinrest (but not collecting pupil data), and were initially surprised not to find any memory effects. In light of our predictions about degree of focus and engagement modulating conflict-encoding effects, we were encouraged that this simple change to our semantic priming method from Experiment 1 might be sufficient (without changing any other element of our task) to elicit more effortful and focused performance from our participants. To match our tasks as closely as possible, we decided to try this implicit postural manipulation with the chinrest as a potential way to induce participants to focus more effortfully on the study/encoding task. Experiment 3 here was a separate new experiment (not including any original pilot data), as an exact replication of Experiment 1, with the simple addition that participants sat with their chin in a chinrest to perform the initial study/categorization task.

Method

Participants

Thirty-one first-year McMaster University students participated in the experiment for course credit. Participants reported normal or corrected-to-normal visual acuity, were fluent in English, and reported normal colour vision. No participants were excluded on the basis of classification task accuracy or reversed RT priming effects. Two participants were excluded for having fewer than 25% good pupil data trials. Data from two additional participants were lost due to technical data recording errors, leaving 27 participants for reported data analysis.

Apparatus, Stimuli and Procedure

This experiment directly repeated the methods of Experiment 1, returning to the same semantic congruency manipulation with "female" and "male" prime words. Instead of participants sitting back against their chair for both phases of the experiment, however, for the study phase participants sat forward with their elbows on the table and their chin in a chin rest at the edge of the table, now with a stimulus viewing distance of approximately 40 cm (versus 50 cm in Experiments 1 and 2). The chinrest was removed after the study/classification task, and participants sat back in their chairs to perform the recognition memory test as for previous experiments.

Both the stimulus viewing distance and the eye tracker camera-to-participant distance were smaller (closer) in this experiment compared to Experiments 1 and 2. While this may raise some concern about biasing pupil dilation measures, these effects were minimized by our approach to data collection and analysis. These experiments used isoluminant mid-brightness green on grey stimuli in a bright room environment – the difference in brightness from the closer viewing distance was negligible as a proportional change of total ambient light. Raw pupil data are calculated by the eyetracker simply as the number of camera pixels representing the pupil diameter in each frame/sample, and so a closer seating position gives larger raw pupil diameter values. Our analysis of pupil data as proportional change from pre-stimulus baseline for individual trials removes this systematic bias of closer seating position in Experiment 3, and more generally controls for any potential seating or postural changes over a single session for individual participants in all experiments.

Results

Encoding phase

Mean correct RT and mean accuracy data for Experiment 3 are shown in the bottom row of Figure 3. A significant congruency priming effect was observed in RT, $t(26) = 3.68$, $p = 0.001$, indicating that task performance suffers on incongruent trials due to increased difficulty. Accuracy was significantly worse for incongruent trials compared to congruent trials, which is also in line with this prediction, $t(26) = 2.41$, $p = 0.023$.

Pupil data were assessed as in Experiments 1 and 2. From the grand mean pupil dilation waveforms in Figure 4, the peak amplitude of the pupil dilation response in this experiment appeared to occur slightly earlier than in Experiments 1 and 2; as such, we assessed maximum amplitude pupil differences over slightly earlier time bins (1.0, 1.1, 1.2 seconds) to better match conditions from prior experiments. (We note that analysis with the same time bins as for Experiments 1 and 2 gives very similar results here.) As seen in both Figures 3 and 4, a large peak pupil dilation effect was observed, with a strong main effect of time, $F(5, 130) = 12.38$, $\varepsilon = 0.22$, $p = 0.001$, $\eta_p^2 = 0.32$. However, in contrast to the same semantic priming conditions in Experiment 1, there was no apparent effect of congruency on peak pupil dilation, with no interaction of congruency and time, $F(5, 130) = 0.50$, $\varepsilon = 0.25$, $p = 0.523$. The main effect of congruency was not significant, $F(1, 26) = 1.65$, $p = 0.290$, with numerically larger dilation values for congruent trials, numerically reversed from the incongruency effects in previous experiments. Direct assessment of the mean maximal amplitude difference over the 1.0 to 1.2 second bins showed no event-related pupil dilation difference between incongruent versus congruent trials, $t(26) = 0.41$, $p = 0.683$.

The difference between overall pupil dilation responses in this experiment and Experiment 1 was substantial, and confirms that our manipulation of greater engagement or effort here was successful. Here in Experiment 3, sitting forward using a chinrest, average peak pupil dilation increased approximately 3% from baseline. This was three times the size of the approximately 1% dilation response in Experiment 1, performing the identical experiment but with participants sitting back in their chairs. As seen in Figures 3 and 4, this between-experiments pupil dilation difference was significant, $F(1,49) = 4.23$, $p = 0.045$, $\eta_p^2 = 0.08$, assessing mean data between experiments from 1.0 to 1.3 second bins. Similarly, mean RT was 36 ms faster overall in this experiment versus Experiment 1, consistent with increased endogenous focus or effort. This between-experiment difference was approximately two to three times the size of the within-subject semantic priming effect observed in both experiments. While suggestive and numerically in the right direction, this between-experiments RT difference did not reach significance, $t(49) = 1.52$, $p = 0.134$.

Memory phase

Figure 3 (bottom row, last panel) shows memory performance for Experiment 3. In contrast to the same semantic priming conditions in Experiment 1, no memory benefit was observed for incongruent versus congruent stimuli here, $t(26) = 0.16$, $p = 0.875$.

Discussion

The combination of no memory differences between congruent and incongruent items, along with larger and now equal degrees of pupil dilation response, are directly in line with our prediction of reduced conflict-encoding benefits with increased overall endogenous effort in categorization task performance. Ptok et al. (2019) describe aspects of their own data and comparable results from the perceptual desirable difficulty literature where more evaluative or demanding task requirements (e.g., relative size comparisons for objects, or judgments of learning for stimulus words) led to equivalent memory performance for high and low conflict trials; when the same tasks were performed with reduced evaluation or engagement demands (e.g., big/small classification for typically big or small objects, or just reading words), conflict-encoding effects were observed with better memory for high-conflict trials. Ptok et al. (2019) argued that the conflict-encoding effect does not represent a special enhancement of encoding over and above full engaged attentional focus; rather, they argued that conflict-driven memory enhancement represents trial-specific elicitation of better control in high-conflict situations in the context of relatively less engaged and more automatic overall task performance.

We suggest that our data in Experiments 1 and 3 here show a direct manipulation of this degree-of-engagement dependency of conflict-encoding benefits, using an implicit method (sitting forward with a chin rest versus sitting back in the chair) to encourage better engagement from participants while controlling for other variables by using the exact same task. This provides both additional evidence and also better task constraint compared to prior demonstrations of this effect (e.g, high versus low demand versions of related semantic size judgment tasks as in Ptok et al., 2019, or judgment of learning versus simple word reading of the same items as in Rosner et al., 2015b). Further, we suggest that our pupil dilation data, considered as a relatively direct index of cognitive control engagement and related locus coeruleus activation, are a particularly relevant piece of evidence here. These data provide direct physiological support for our claim of both greater and more similar endogenous engagement for congruent and incongruent priming conditions, while showing abolition of memory effects typically observed in this paradigm (semantic priming for name gender classification). We suggest that this lends considerable support to the idea of automaticity/engagement dependency of conflict-encoding effects proposed by Ptok et al. (2019).

General Discussion

The present study shows a clear dissociation of greater conflict-elicited control as directly indexed by greater pupil dilation in incongruent trials, observed in both Experiments 1 and 2, and conflict-related encoding benefits only seen with semantic priming. Memory benefits are produced only when conflict draws additional processing to focus on stimulus information (Experiment 1 with semantic priming), and not direct it away from stimulus information to response selection (Experiment 2 with response priming; see Figure 1).

We also show the dependence of potential conflict-encoding effects on the degree of overall endogenous task engagement, again directly indexed by pupil dilation measures. Using the exact same semantic priming task, having participants sit leaning forward using a chinrest (Experiment 3) elicited substantially more focus or effort, as indexed by much larger event-related pupil dilation responses compared to sitting back (Experiment 1). Equivalent larger pupil responses for congruent and incongruent conditions suggests stronger endogenous attention and control on all trials, and directly predicts the lack of memory difference under higher-demand endogenous control, despite the potential for a semantic conflict-encoding effect in a less demanding task situation.

The present study provides substantial support and converging physiological evidence for a more selective and stage-specific mechanism of conflict-elicited encoding effects, and the dependence of these effects on relatively less-engaged or more automatic performance. These findings extend recent data and theory from Ptok et al. (2019), whose model predicts when particular kinds of task conflict should and should not lead to encoding benefits in a range of congruency/control and desirable difficulty paradigms. These findings fit well with recent work on memory effects of inhibitory control paradigms (Chiu & Egner, 2015), and provide a more detailed framework to consider underlying mechanisms of conflict-encoding effects.

Along with Chiu and Egner (2015) and Ptok et al. (2019), the current study is a challenge to the generality of the conflict-encoding model of Verguts and Notebaert (2008, 2009). We want to emphasize that we do not criticize this model in general. We suggest that this model itself makes good predictions – this model mostly talks about better learning of stimulus-response bindings under high versus low conflict conditions. Our current paradigm deliberately uses priming/conflict for many single instances of unique to-be-tested semantic items to isolate sources of semantic/category versus response conflict; by doing so, we can observe that the within-task locus of elicited cognitive control on a specific trial is an important determinant of what gets better encoded on that trial.

However, we are critical of how conflict-encoding ideas are being approached in the literature. We believe that an increasing number of congruency/conflict-encoding and perceptual desirable difficulty studies are interpreting Verguts and Notebaert (2008, 2009) much too broadly, and are making erroneous predictions based on a too-general assumption that any kind of greater task conflict should lead to better encoding for task information. Our data here, along with other recent work (Chiu & Egner, 2015; Ptok et al., 2019), argues strongly for a much more specific set of within-task dependencies for conflict-encoding benefits.

In their recent introduction to a special issue of the journal Metacognition and Learning focusing on disfluency effects on later memory, Kühl and Eitel (2016) discuss the disconnect between the growing enthusiasm for trying to find disfluency-encoding effects across a wide range of paradigms, and both the relative lack of trying to understand common underlying mechanisms and a more obvious difficulty of finding convincing disfluency-encoding effects in the first place. We agree with this description, and would advocate for a much more mechanistic approach to these and related questions. While often framed in different language, we suggest that there is likely a much stronger overlap of important issues and underlying mechanisms between perceptual desirable difficulty, issues of conflict and cognitive control, and relations between these and influences on memory encoding. We suggest that our stage specific conflict-encoding model (Ptok et al., 2019) may be able to account for and predict where and when a wide range of conflict/difficulty manipulations should (and should not) lead to enhanced later memory, and may serve as a useful model and roadmap for helping to understand and further explore these fundamental control-encoding issues.

CHAPTER 4: Memory consequences of congruency sequence effects: Stage-specific desirable difficulty

Ptok, M. J., & Watter, S. (Submitted)

Preface

Chapter 4 presents the results of three experiments to assess the trial-to-trial modulation of attentional control processes (congruency sequence effects; CSEs) that occurs in a congruency task focused on inducing conflict at the semantic and response selection stages of processing. It was predicted that because CSEs are considered to be driven by response conflict (Jentzsch & Leuthold, 2005), and memory benefits are produced by conflict at the semantic stage but not at the response selection stage of processing (Ptok et al., 2019), it was predicted that conflict from CSEs would not produce later memory benefits. The general method for all experiments involved the presentation of prime-target pairs at study followed by a surprise recognition memory test, using the same gender name classification task and stimuli from previous chapters.

In Experiment 1, we investigated the CSEs of Experiment 5 from Chapter 2 of this thesis (Ptok et al., 2019), re-analyzing these data to examine sequential trial conflict influences. Study results showed that semantic priming conflict and the response selection-focused conflict from sequence effects influenced RTs additively, confirming the processing stage separation of these two effects. Additionally, there was no benefit of sequence effect conflict on memory, which is in line if CSE operates on response selection. These results fit with Ptok et al. (2019) where memory effects will only be evident when the incongruent trials of the semantic priming task direct attention to the core representations of the to-be-remembered information. Experiment 2 directly replicated Experiment 1 using a larger sample size with new data. Results once again showed evidence of additive RT at study, and no benefit of sequence conflict on later memory.

Experiment 3 aimed to show contrasting effects using response priming. We did a re-analysis of CSE effects in Experiment 2 data from Chapter 3 (Ptok, Hannah & Watter, submitted), where the same gender classification task was used with congruent and incongruent response primes (left and right arrows). Results showed typical interactive RT Gratton effects (Gratton, Coles, & Donchin, 1992) at study, where the incongruency effect is reduced following incongruent trials. These results are consistent with the response priming task and CSE conflict both having their effects at the response selection stage. In keeping with this, we observed no evidence of conflict-encoding benefits from either within-task response priming or CSE conflict. These results once again provide evidence that memory encoding effects are only produced when congruency priming induces additional attention and control at a processing stage that is focused on the to-be-remembered representations of the stimulus. Additionally, these findings provide evidence that our congruency task is very selectively priming the semantic or response stages of processing, providing additional support for the findings in Ptok et al. (2019).

Abstract

This paper considers predictions from prominent conflict theories of cognitive control that information under high conflict conditions should be better encoded. In addition to immediate effects on conflict-control associative learning, several authors have shown better later recognition memory for task stimuli from high-conflict trials. However, these conflict-encoding benefits appear not to extend to all task-relevant information. Recent work by Ptok, Thomson, Humphreys, and Watter (2019) showed that the within-task locus of conflict and elicited attentional control is critical to whether later memory benefits are seen: Conflict/control at semantic item representation (via semantic incongruency priming) produces better memory, but conflict/control focus away from item representations at response selection (with response feature priming) gives no memory benefit. This paper extends these findings and theory to sequential (Gratton-like) conflict/control. Typical conflict/control models (e.g., Verguts & Notebaert, 2009) predict better memory for high-control sequence trials (trials following prior high-conflict trials). Instead, we present model predictions and confirmatory data that sequence conflict effects hurt rather than enhance memory for trial stimuli. We show how our stage-specific conflict-encoding model predicts both RT and later memory effects for the various combinations of sequential control modulation and within-task semantic and response congruency effects, and discuss how these findings integrate with and extend existing cognitive control models.

Introduction

This paper considers recent developments in data and theory concerning the longer-term memory consequences of congruency/conflict task manipulations and the related cognitive control processes involved with them. A series of recent experiments by Ptok, Thomson, Humphreys, and Watter (2019) have suggested that conflict-related encoding benefits are substantially more limited to particular information processing stages than previously thought. Here we consider the case of Gratton-style sequence effects (Gratton, Coles, & Donchin, 1992) on congruency priming tasks – now often referred to in the literature as Congruency Sequence Effects (CSEs) – and the potential memory consequences of this kind of sequential task conflict and control.

CSEs are often discussed as a quintessential demonstration of conflict-elicited cognitive control mechanisms – greater automaticity and influence of distractor/prime information (both facilitation and interference) is observed following a trial with low conflict/control demands, while relative protection from or reduction of the effects of distractor/prime information is observed following trials with high conflict/control demands. General conflict-encoding models (e.g., Botvinick, 2007; Verguts & Notebaert, 2009) predict greater encoding of task information under higher control conditions, and should directly predict similar CSE-related conflict-encoding benefits, namely better memory for information for trials that followed high conflict/control trials. The present paper tests this general prediction for congruency-encoding benefits from CSEs, and demonstrates a more selective alternative set of predictions based on the stage-specific conflict-encoding model of Ptok et al. (2019).

Conflict-Encoding Effects

Cognitive control is often studied using congruency priming manipulations, such as Stroop (Stroop, 1935) and flanker tasks (Eriksen & Eriksen, 1974). The influential conflict-monitoring model of Botvinick, Braver, Barch, Carter, and Cohen (2001) provides a mechanistic account of how increased cognitive control is elicited via response conflict, and accounts for data from other similar congruency/conflict situations. This model also gives a plausible mechanistic explanation for the Gratton effect (Gratton, Coles, & Donchin, 1992), where the sequence of high and low conflict trials in a congruency priming task modulates subsequent task performance. From a conflict-control viewpoint, increased control elicited from a high-conflict trial persists to influence the subsequent trial, temporarily reducing the influence of irrelevant/priming task information (Botvinick et al., 2001).

Refinements of the Botvinick et al. (2001) model have extended to the potential memory encoding influences of increased cognitive control and related selective attentional processes. In general, it has been argued that increased central attention and control under high-conflict conditions should lead to better encoding of task information compared to low-conflict situations (Botvinick, 2007; Verguts & Notebaert, 2008, 2009). Verguts and Notebaert (2009) suggest that trials with increased conflict will elicit greater cognitive control, which in turn leads to greater arousal, producing enhanced associative binding of active stimulus and response feature representations. The assumption of this "adaptation by binding" model that active feature representations are more likely to be related to task-relevant processing provides a simple and elegant mechanism by which current task information is likely to be captured, and predicts that all activated stimulus and response features should be the recipient of this enhanced binding/encoding process.

A number of authors have begun to investigate whether these conflict-encoding predictions from cognitive control models might extend to longer-term memory consequences, namely better subsequent memory for stimuli encountered in high conflict/control situations. Krebs, Boehler, De Belder, and Egner (2015) used a face-word Stroop task, and examined recognition memory for face stimuli. Participants were asked to judge the gender of male and female faces, while ignoring a superimposed prime word (Dutch words for "man", "woman", or the unrelated word "house"). Consistent with expectations of difficulty with conflict, classification reaction time was slower for faces presented with an incongruent prime (e.g., "man" presented with a female face). Critically, memory for these incongruently primed face stimuli was better on a later recognition test than for faces initially categorized with congruent or neutral primes. Similarly, Rosner, D'Angelo, MacLellan and Milliken (2015) presented a task with two interleaved words, one in red and one in green, where participants had to read aloud the red word while ignoring the green word. On half of the trials, the green distractor word was identical to the red target word (congruent trials) and on the other half it was a different word (incongruent trials). Rosner et al. (2015) demonstrated conceptually similar congruency effects to Krebs et al. (2015), where target words in incongruent trials exhibited slower immediate naming time performance but were better remembered on a later recognition memory test. Subsequent studies indicated that these effects were due not simply to additional time-on-task but rather to the increased selective attention elicited for incongruent trials (Rosner & Milliken, 2015).

While these conflict-encoding effects for later memory support the general idea from Verguts and Notebaert (2009) that activated task-relevant information in high conflict trials should be better encoded, several studies have begun to demonstrate substantial limits on this conflict-encoding benefit. Chiu and Egner (2015a, 2015b) used face stimuli in a range of inhibitory control tasks (e.g., go/no-go and stop signal paradigms), and tested later recognition memory for task face stimuli. They showed that high-conflict no-go and stop signal trials with enhanced control demands led to worse memory for face stimuli on a later memory test, contrary to the general prediction that greater control should produce better memory for relevant task information. The authors argued that in cases like Krebs et al. (2015) and Rosner et al. (2015), attention is directed to task-relevant stimulus information to resolve conflict, leading to better stimulus encoding for high-conflict trials; with inhibitory control tasks, the same attentional processes are directed toward response inhibition, reducing the focus on task-relevant stimulus information in high conflict no-go and stop signal trials, and leading to poorer stimulus encoding.

Stage-Specific Conflict-Encoding Effects

Most recently, these within-task cognitive control demands and their relation to memory encoding effects have been shown to be even more selective. Ptok, Thomson, Humphreys, and Watter (2019) showed that the particular stage at which processing conflict is imposed is a critical determinant of whether participants show better later memory due to increased task conflict and control. Over six experiments, Ptok et al. (2019) demonstrated that when conflict is elicited at the level of semantic or category representation (via semantic incongruency priming), better memory is observed. In contrast, when conflict is elicited at response selection (via response incongruency priming), no memory benefit is seen. The authors argued that within-task demands of conflict and control must direct high-level selective attention to the to-be-tested item information for memory benefits to ensue. Directing controlled processing away from item information representation to resolve response conflict still produces a conflict-related performance cost, but produces no later memory benefits for item information. Ptok et al. (2019) argue that this stage-specific conflict-encoding model makes direct predictions of when and where task conflict manipulations should (and should not) produce memory benefits.

Figure 1 (adapted from Ptok et al., 2019) shows examples of the theoretical predictions for the congruency priming tasks presented in this study.

Participants were asked to categorize typical male and female names as male or female, responding with left or right key presses respectively (e.g., "Anne" is a female name, press the left key). The left half of the figure shows examples of semantic priming where congruent ("female" relative to the current stimulus "Anne") and incongruent ("male") distractor stimuli are shown along with the stimulus name. Conflict from an incongruent prime (noted by an asterisk in the Figure 1 model) elicits greater high-level cognitive control and attentional focus to help resolve the category representation. This leads to slower RT for the categorization task, but also to more attentional focus on the core semantic and associative information of the task stimulus compared to the congruent priming condition. This higher level of attentional allocation to stimulus-related information leads to better memory for those incongruently primed stimuli. Ptok et al. (2019) argued that a range of perceptual conflict or difficulty manipulations should also lead to memory enhancement, if high-demand task requirements elicit greater attentional focus on stimulus-related information.

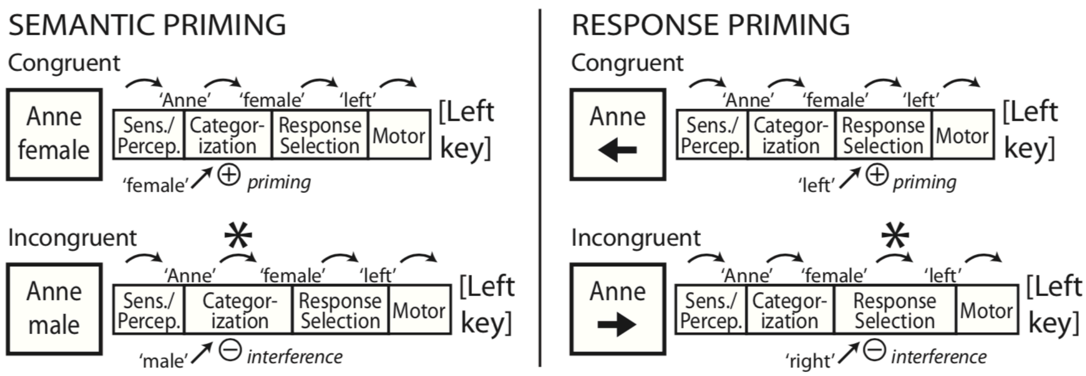

Figure 1. An information processing model and stage-specific conflict-encoding effects, following Ptok, Thomson, Humphreys, & Watter (2019). A female/male name classification task is presented with congruent and incongruent primes relating to semantic ("female" or "male") or response (left or right arrows) features. Incongruent semantic priming focuses additional control and selective attention (asterisk) on to-be-tested stimulus information – this predicts a conflict-encoding benefit for later item memory as well as slower categorization task performance. Incongruent response priming focuses additional control and selective attention (asterisk) on response selection representations, diverting focused attention away from to-be-tested stimulus information – this predicts *no* conflict-encoding benefit for later item memory, despite slower categorization task performance and enhanced cognitive control. Sens. = Sensation; Percep. = Perception.

In contrast, the right half of Figure 1 shows a response priming version of this experiment where congruent (left arrow) and incongruent (right arrow) distractor stimuli are shown along with the stimulus name. It is important to note here that the primes in this case do not carry semantic category information, but do have response feature information. Greater conflict with an incongruent response prime elicits greater high-level cognitive control and attentional focus to resolve the central response selection representation. This again leads to slower RT for the categorization task, but since central attention is directed away from the stimulus-related semantic and associative information, this increased focus and control does not lead to better encoding of stimulus information.

Ptok et al. (2019) argue that if response conflict was sufficiently strong, the diversion of central attention could be large enough to disrupt or cut short stimulus-focused central processing, leading to a relative cost to later memory with high-conflict response-focused control; lesser degrees of response-focused conflict may simply have no effect on memory, simply by focusing differences in conflict-elicited control and attention away from stimulus-related processing. These findings are consistent with the focus-of-attention conflict-encoding view proposed by Chiu and Egner (2015), and provide considerably more constraint. Ptok et al. (2019) argued that this model not only can help to explain not only the effects of congruency priming manipulations on later memory, but also may account for the heterogeneous set of findings in the perceptual desirable difficulty literature.

Congruency Sequence Effects (CSEs)

Considering the general conflict-encoding predictions of Botvinick (2007) and Verguts and Notebaert (2009), which are echoed across much of the congruency-encoding and perceptual desirable difficulty literature, congruency sequence effects (i.e., Gratton effects) would seem to be a prime target for testing the generality versus specificity of conflict-elicited memory effects. CSEs have been directly studied with respect to associative learning accounts of cognitive control, where the dependency of CSEs on the presence of consistent stimulus and response features across tasks has been taken as evidence for conflict-related associative binding models of cognitive control (e.g., Braem, Verguts, & Notebaert, 2011). This kind of conflict-encoding mechanism has been a direct motivation for studying the potential longer-term memory effects of cognitive control, i.e. later recognition memory for task stimuli (e.g, Krebs et al., 2015).

Davis, Rosner, D'Angelo, MacLellan, and Milliken (2019) recently investigated the potential long-term memory outcomes from CSE-related conflict, using the same interleaved words task as Rosner et al (2015). Davis et al. (2019) found that the recognition memory benefit for incongruent versus congruent priming within a single trial was robust, replicating Rosner et al. (2015). Davis et al. (2019) also included analyses of their conflict-encoding experiments to assess potential memory effects of CSE-related conflict, expecting (as we believe most authors in the field would predict) that the greater control in trials following incongruent/high-conflict trials would lead to better encoding.

They observed a typical pattern of sequential RT effects (i.e., typical Gratton effects) for trials following prior congruent versus incongruent trials, suggesting that control processes were modulating task performance relative to sequential conflict as expected. However, in contrast to expectation, Davis et al. (2019) did not find a memory benefit for high-conflict sequence trials (i.e., trials preceded by an incongruent trial), and more generally reported that they found no evidence for either proactive or reactive sequential control effects on later recognition memory.

The Present Study

The present paper seeks to examine the potential memory consequences of congruency sequence effects more closely. We consider whether this kind of elicited cognitive control should be expected to produce encoding benefits for task stimuli, as recently demonstrated in other conflict-encoding situations. We extend the stage-specific conflict-encoding model from Ptok et al. (2019) to consider the influence of high or low conflict from a previous trial (trial n-1) onto a present trial (trial n), and how this sequentially elicited control would be expected to influence current task (trial n) processing.

This sequential conflict-encoding model is presented in Figure 2. Our model makes the same two basic assumptions as Ptok to al. (2019): (i) that the locus of conflict in the present task will elicit additional controlled processing to resolve that conflict, and (ii) that for this additional conflict/control to have a beneficial effect on memory for task information, it needs to focus task processing on the representation of relevant stimulus information for that trial. This basic model predicts that conflict (e.g., congruency priming) manipulations on semantic or category information will direct the focus of additional control to produce better representations of relevant stimulus information and better subsequent memory. Similar manipulations on response information will focus additional control away from item information toward response representations, predicting no memory effects with less severe control demands, and possibly a cost to memory for high-conflict items requiring a large enough demand for response-focused control.

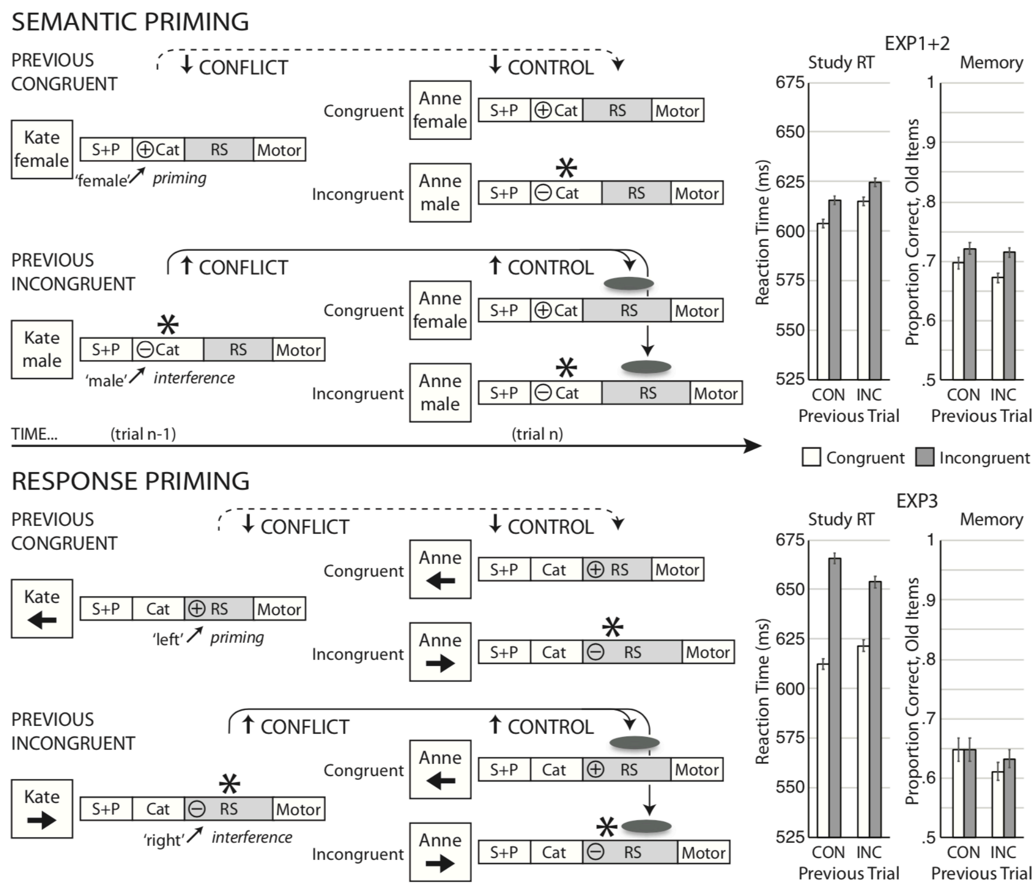

Figure 2. An information processing model of stage-specific conflict-encoding effects extended to include sequential conflict-control effects. Possible combinations of within-task and across-task sequential effects are shown for current trials (trial n, centre of figure), following previous congruent or previous incongruent trials (trial n-1, left of figure). Summary data from semantic priming from Experiments 1 and 2, and response priming from Experiment 3, are shown along with corresponding model conditions (right of figure). Processing conflict elicits greater control and focused selective attention at the source/stage of conflict within a task (asterisks); increased conflict/control at any processing stage on a previous (n-1) trial elicits greater sequential control on a subsequent trial (n), implemented at response selection (grey ovals). Semantic congruency priming (top half) produces additive RT effects with separate stage influences of semantic incongruency and sequential control at response selection. Response congruency priming (lower half) produces interactive Gratton-like RT effects with common stage influences of response incongruency and sequential control at response

selection. Later memory for task stimuli is only enhanced when semantic incongruency elicits greater attention to to-be-tested item information, and not when response incongruency diverts central focus away from this item information. S+P = Sensation and Perception, Cat = Categorization, RS = Response Selection, CON = Congruent, INC = Incongruent. Error bars for data represent within-subjects SEM for the difference of condition means for associated congruent/incongruent condition pairs.

We consider the influence of sequential control effects from a prior task in a similar stage-specific way. From established theory and data, we assume that this conflict-elicited cognitive control is implemented at response selection. Botvinick et al. (2001) and subsequent versions of that model (e.g., Verguts & Notebaert, 2009; Shenhav, Botvinick, & Cohen, 2013) very explicitly discuss conflict detection and implementation of control with respect to response conflict at a later relatively common and central response selection stage. We note that these models typically describe the response representation layer/nodes in these models in terms of their category representations (e.g., responses “red” and “green” for the Stroop example); our model and experiments here explicitly separate out selective semantic-only and response-only priming effects, and so we discuss response selection processes with respect to central representations of response alternatives (e.g., left and right response keys).

Our sequence conflict-encoding model (Figure 2) demonstrates how stage-specific conflict and elicited compensatory control (here via congruency priming) at either semantic/category representation or subsequent response selection is predicted to combine with sequential modulation of cognitive control driven by conflict on the previous trial. We suggest that the *source* of a conflict signal on a previous trial to elicit enhanced cognitive control on a subsequent trial may arise from conflict in a number of different representational stages, not only response competition. However, the *implementation* of the persistent, task-wide sequential control adjustment on the subsequent trial is always at response selection.

Thus, with a purely semantic congruency manipulation, we should predict additive RT effects of semantic incongruency (central semantic/category stage conflict) separate from the sequential conflict-elicited control modulation of RT at the response selection stage. We would further predict memory effects only for semantic incongruency, and not for sequence conflict, given that sequence congruency effects focus central attention onto response selection processing, and away from item information in the task.

With a response congruency manipulation, both the immediate congruency priming effect and the sequential conflict-control modulation effect are both focused at response selection. Here we would predict an interactive pattern of RTs, typical of those usually seen with Gratton-style sequence effects with Stroop and flanker tasks. In this case, we predict no benefits of either response incongruency or sequence conflict on memory encoding, as both of these effects focus central attention away from to-be-tested stimulus information.

In both semantic and response priming situations, if sequential conflict elicits sufficient control and focus away from central representation of stimulus information, we might predict a relative cost to memory for trials preceded by a high-conflict/incongruent trial, opposite to more general conflict-encoding predictions, and independent from potential within-trial conflict-encoding effects with stimulus/semantic-focused versus response-focused processing.

This coherent set of predictions follows directly from the basic ideas laid out in the stage-specific conflict-encoding model of Ptok et al. (2019). We directly examine those predictions for both immediate within-task congruency and CSEs, for their effects on immediate task performance and later memory, with both semantic and response congruency priming. We begin by reanalyzing data from a previous semantic congruency experiment for potential CSEs on RT and memory performance (Experiment 1), where we predict and observe additive RT effects, and memory effects of within-task semantic priming but not of sequential conflict. Next, in Experiment 2, we conduct a new larger experiment to reproduce and replicate these semantic priming effects from Experiment 1 data, to confirm and extend these findings. Finally, as Experiment 3, we reanalyze data from another previous experiment with response priming to demonstrate and confirm our predictions of more typical Gratton-like RT effects but no memory effects from response-focused within-trial priming or sequential conflict.

Experiment 1

Experiment 1 aimed to investigate the CSEs of Experiment 5 by Ptok et al. (2019) through a reanalysis of their data. This experiment investigated the influence of task difficulty targeted at the semantic stage of processing using a name gender classification task. Male and female name stimuli were presented along with congruent and incongruent semantic category primes (words "male" and "female") at a stimulus onset asynchrony (SOA) of 100ms. Looking at the influence of previous trial congruency, we predict the CSEs will not produce sequential conflict-encoding effects for later memory as they drive attentional allocation to response selection processing. If the influence of sequential control is implemented at central response selection as we predict (and as is generally assumed by most conflict-control models), we should observe additive RT effects of sequential control and within-task semantic congruency priming, distinct from the typical Gratton-like interactive modulation of RT incongruency effects.

Method

Participants

Fifty McMaster University students participated in this experiment for course credit. McMaster's Research Ethics Board approved the study and informed written consent was obtained. All participants spoke English and reported normal or corrected-to-normal visual acuity. Participant enrolment followed a stopping rule where data collection would continue until data from 40 or more participants had been collected, assessed at the end of each week of data collection.

Apparatus and Stimuli

Apparatus, stimuli, and procedures for our subsequent Experiment 2 closely followed methods here from Ptok et al. (2019) Experiment 5, and so we re-describe those methods fully here. Stimuli were presented on a standard Windows 7 PC using Presentation experiment software (v. 14, neurobs.com). Stimuli were 240 typical Western/Anglophone names (120 male, 120 female) and did not include any gender ambiguous names (e.g., 'Alex'). These were divided into three 80-item lists, balanced for gender and first letter of names. Stimuli from two lists (160 names) were presented for the study/classification task; stimuli from one of these lists plus the remaining unseen list were presented in the subsequent recognition memory test phase as old and new items, respectively. Stimulus lists were used as above in fully counterbalanced fashion across participants. For the study/categorization phase, name stimuli were first randomly ordered (separately for male and female names), then assigned to equal numbers of congruent/incongruent conditions, and then order was randomized across all stimuli for task presentation. Prime stimuli were the words “female” and “male.” For the memory test, name stimuli were presented in randomized order.

In the study/encoding phase, name and prime stimuli were presented in Arial font, sized to be approximately 1.5 cm vertically on screen, coloured white against a black background. A pre-stimulus cue consisted of two rows of white single dashes separated by spaces (“-   -”), to indicate the central position where the name stimuli would appear. Name and prime stimuli were presented at consistent positions centered on the screen, with the name above the prime, separated by a gap of approximately 0.75 cm. Participants sat approximately 60 cm from the screen. In the memory phase, single names were presented centrally in the same white Arial font, with a size of approximately 2.5 cm vertically.

Procedure

The basic study design for this and subsequent experiments is presented in Figure 3. In the study/encoding phase, a trial began with the cue presented for 500 ms. This cue was replaced with a male or female name. After a 100 ms stimulus onset asynchrony (SOA) the prime (‘male’ or ‘female’) word was presented directly under the name. Each stimulus was given a consistent exposure time of 1000 ms, after which they disappeared from the screen. Participants were instructed to categorize the name as typically male or female as quickly and accurately as possible while ignoring the prime. Responses for the male/female alternatives were mapped to the 'Z' and the '/' keys on a standard QWERTY keyboard, and participants responded using left and right index fingers. Response mapping was counterbalanced across participants. An intertrial interval of 2000 ms (blank screen) separated the offset of the prime and the presentation of the cue beginning a subsequent trial. The study/encoding phase stimuli were presented in four blocks of 40 trials each, for a total of 160 trials. An initial practice block was presented with an additional 12 trials and these were not considered for the later memory test or analysis. Trials with RT faster than 300 ms or slower than 1500 ms were excluded from data analysis (less than 0.5% of all trials).

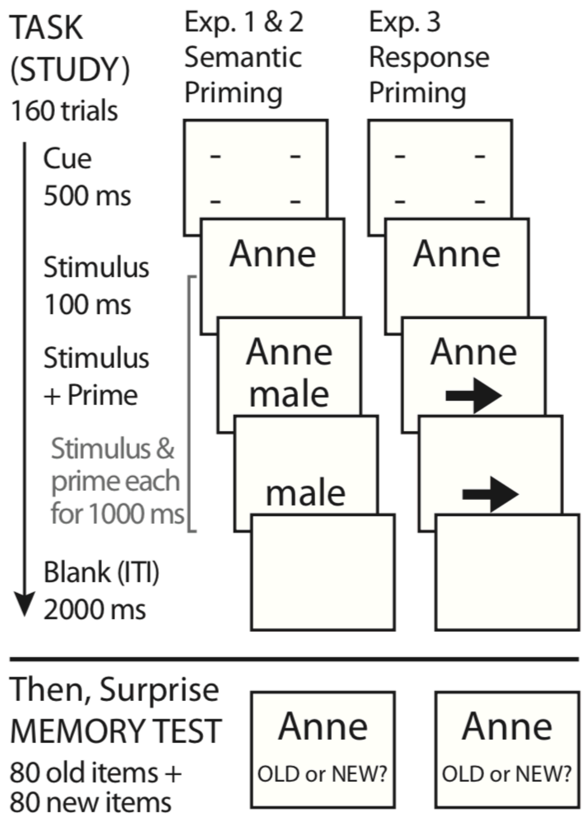

Figure 3. Task design and procedure for Experiments 1-3. Participants first performed a name gender classification task, with semantic or response priming. They then performed an old/new recognition memory test for name stimuli. ITI = Inter-trial interval.

After the completion or the study/encoding phase, participants were given 2 minutes rest before proceeding to the surprise memory test. The stimuli for the memory test consisted of 80 old names shown during the encoding phase and 80 new unseen names. Participants were instructed to classify each name as 'old' or 'new' in relation to whether they had seen that name during the encoding phase task. Test phase names remained on screen until a response was given. Responses were made by pressing the 'Z' key for old words or '/' key for new words on the computer keyboard. A blank screen of 1000 ms separated participants' responses and the subsequent memory stimulus. Trials consisted of 5 blocks of 32 trials, with self-paced breaks in between.

Results

Encoding phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 4. A 2x2 repeated measures ANOVA for RT data, with semantic congruency (congruent, incongruent) and previous trial congruency (previous congruent, previous incongruent) as factors, revealed a main effect of semantic congruency, $F(1, 49) = 9.58$, $p = 0.003$, $\eta p^2 = 0.16$, with slower RTs for incongruently primed trials reflecting the expected task difficulty influence on initial task performance. The main effect of previous trial congruency was also significant, $F(1, 49) = 9.47$, $p = 0.003$, $\eta p^2 = 0.16$, with relatively slower RTs when the previous trial was incongruent. Importantly, there was no evidence of an interaction, $F(1, 49) = 0.26$, $p = 0.611$.

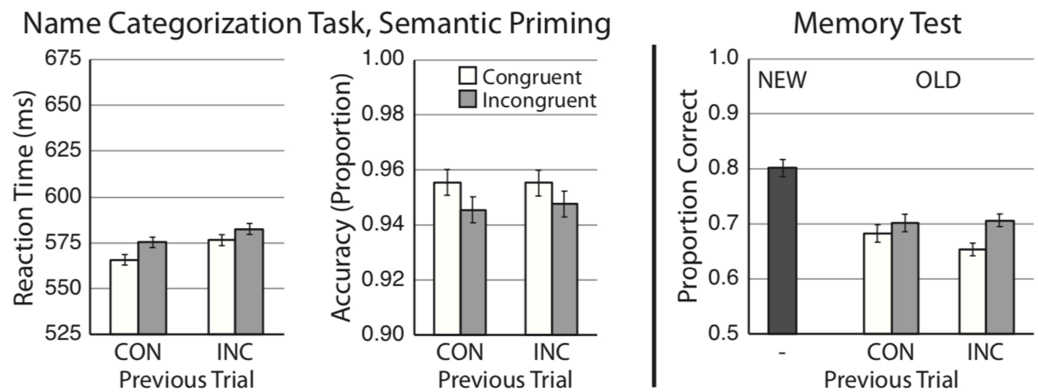

Figure 4. Data for Experiment 1. Basic congruency effects from these data were originally reported in Ptok, Thomson, Humphreys, and Watter, (2019), Experiment 5; new analyses here focus on sequential congruency effects. Semantic incongruency conflict produced costs on initial performance, and improved item memory at later test. Semantic priming and sequence conflict showed additive RT effects, suggesting effects at separate processing stages. Sequence conflict showed no conflict-encoding benefit for later memory. Error bars represent within-subjects SEM for the difference of condition means for associated congruent/incongruent condition pairs.

For mean accuracy data, congruent trials were numerically more accurate then incongruent trials, in keeping with an expected difficulty manipulation, but this main effect did not reach significance, $F(1, 49) = 2.62$, $p = 0.112$, $\eta p^2 = 0.05$. There was no suggestion of a sequence effect, $F(1, 49) = 0.04$, $p = 0.848$, nor of an interaction, $F(1, 49) = 0.09$, $p = 0.763$. These results are consistent with RT analyses where incongruent trials elicit more conflict or difficulty at encoding.

Memory phase

Figure 4 (right half) shows the mean recognition memory performance (proportion correct) for old and new items at test, excluding items that the participant incorrectly responded to at study. A 2x2 repeated measures ANOVA for old items revealed an expected main effect of congruency, indicating better memory for items incongruently primed at study, $F(1, 49) = 7.02$, $p = 0.011$, $\eta p^2 = 0.13$. There was no main effect for previous trial congruency, $F(1, 49) = 0.74$, $p = 0.394$, and no interaction, $F(1, 49) = 1.42$, $p = 0.239$.

Discussion

These data have previously been reported (in Ptok et al., 2019, Experiment 5) to show semantic incongruency priming imposing costs on categorization task performance (slower RT) and also leading to better later recognition memory performance for task stimuli. The present analyses restate those findings, and in addition assess the influence of sequential congruency and modulation of control. Following predictions from our stage-specific conflict-encoding model, we observed no CSE-related memory benefit, with the effect of sequential congruency on memory numerically worse for trials following high-conflict incongruent trials. This is opposite to the general prediction from Verguts and Notebaert (2009) and related models, that high conflict trials should lead to better encoding for task information. These conflict sequence effects on later memory, as well as the observed additive RT effects of semantic priming and sequence congruency, are consistent with predictions from our stage-specific conflict-encoding model following Ptok et al. (2019; see Figure 2).

Given that our CSE manipulation for semantic priming does not produce typical Gratton-like RT effects (as for Stroop or flanker effects), and that we are hoping to make claims about the meaningfulness of the absence of CSE-related memory influences, it is important for us to be able to re-demonstrate these same categorization RT and memory effects with this semantic priming manipulation. To that end, we conducted a new study as Experiment 2, to directly replicate the methods from Experiment 1 with a new and larger sample, the goal being to extend and confirm the predictions and data found in Experiment 1. We reserve further discussion of results from Experiment 1 to consider these together with Experiment 2 results below.

Experiment 2

Experiment 2 aimed to replicate both the within-task semantic incongruency priming effects from Ptok et al.'s (2019) Experiment 5 (here our Experiment 1), and also the CSE-related effects from the new analyses of those data above. We used the exact same methods, and aimed to approximately double the sample size. We predicted that we should again observe additive RT effects for semantic categorization and CSEs, and that only within-task semantic incongruency and not CSE-related conflict should produce later memory benefits.

Method

Participants

Eighty first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained, and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision and normal or corrected-to-normal visual acuity and spoke English fluently. We adopted a recruitment stopping rule of 80 or more participants, assessed at the end of each week's data collection. Following data exclusion methods used throughout Ptok et al. (2019), data from two participants were excluded due to low encoding phase accuracy (< 75%), and data from one other participant were eliminated due to large reversed RT priming during the encoding/study phase (> 50 ms incongruency benefit). In addition, data from one participant were eliminated due to not performing the memory task as instructed (84% False Alarm rate for new items, at-chance Hit rate for old items, strongly negative d-prime), and data from one other participant were excluded for having participated in a similar prior study with the same name stimuli. A total of 75 participants were included for reported data analysis.

Apparatus, Stimuli, and Procedure

Methods were identical to Experiment 1.

Results

Encoding Phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 5. A 2x2 repeated measures ANOVA for RT data treated semantic congruency (congruent, incongruent) and previous trial congruency (previous congruent, previous incongruent) as factors. As expected, we observed a strong main effect of response congruency, $F(1, 74) = 14.97$, $p < 0.001$, $\eta p^2 = 0.17$, with slower RTs for incongruently primed trials reflecting the expected task difficulty influence on initial task performance. The main effect of previous trial congruency was also significant, $F(1, 74) = 17.07$, $p < 0.001$, $\eta p^2 = 0.19$, indicating slower RTs when the previous trial was incongruent. Again, there was no evidence of an interaction, $F(1, 74) = 0.05$, $p = 0.819$.

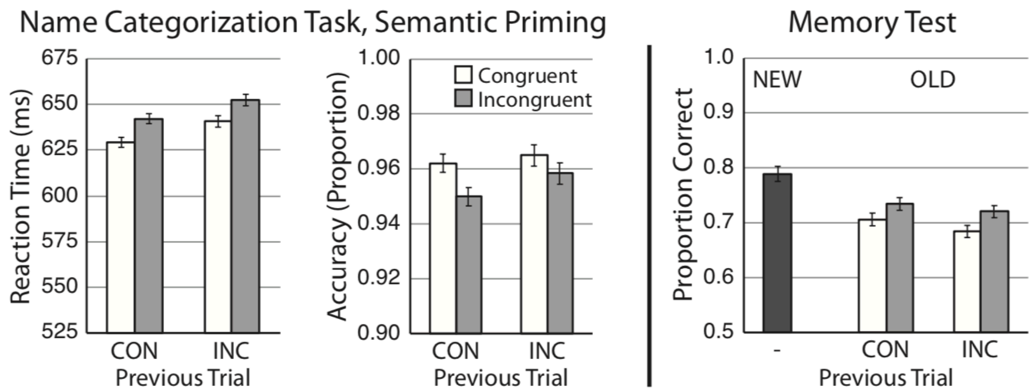

Figure 5. Data for Experiment 2. Semantic incongruency conflict produced costs on initial performance, and improved item memory at later test. Semantic priming and sequence conflict showed additive RT effects, suggesting effects at separate processing stages. Sequence conflict showed no conflict-encoding benefit for later memory. These data directly replicate Experiment 1. Error bars represent within-subjects SEM for the difference of condition means for associated congruent/incongruent condition pairs.

Accuracy results showed a significant main effect of congruency, $F(1, 74) = 5.92$, $p = 0.017$, $\eta p^2 = 0.07$, with congruent trials more accurate than incongruent trials, in keeping with expected effects of trial difficulty. There was no main effect of previous trial congruency, $F(1, 74) = 1.46$, $p = 0.231$, and no evidence of an interaction, $F(1, 74) = 0.70$, $p = 0.404$.

Memory Phase

Figure 5 (right half) shows the mean recognition memory performance (proportion correct) for old and new items at test, excluding items the participant incorrectly responded to at study. A 2x2 repeated measures ANOVA for old items revealed a main effect of congruency, $F(1, 74) = 7.16$, $p = .009$, $\eta p^2 = .09$, indicating better memory for items incongruently primed at study. Again, there was no significant main effect for previous trial congruency, $F(1, 74) = 1.38$, $p = .243$, $\eta p^2 = .02$, and no significant interaction, $F < 1$.

Combined Data Analyses

Given that our Experiment 2 was a direct methodological replication of Ptok et al.'s (2019) Experiment 5 (here, with additional analyses of CSE effects, as Experiment 1), we reanalyzed the combined data, adding Experiment as a between-subjects factor. Combined data for RT and memory for Experiments 1 and 2 are shown in the upper right section of Figure 2. For RT data, we observed strong main effects of congruency, $F(1, 123) = 20.82$, $p < 0.001$, $\eta p^2 = 0.15$, and of previous trial congruency, $F(1, 123) = 24.57$, $p < 0.001$, $\eta p^2 = 0.17$, with no evidence of an interaction, $F(1, 123) = 0.29$, $p = 0.588$. These combined data show a strong pattern of additive RT effects, suggesting that the semantic congruency manipulation used in this task influences a separate processing stage than the effect of sequential conflict/control (presumably response selection). There was a notable between-experiments main effect for RT, with participants in our Experiment 2 having overall slower RTs by a mean of approximately 65 ms overall. This experiment difference did not interact with any other factors, *F*s < 1.1.

Combined accuracy results showed a clear main effect of congruency, $F(1, 123) = 7.88$, $p = 0.006$, $\eta p^2 = 0.06$, with greater accuracy for congruent trials, but no effect of previous congruency, $F(1, 123) = 0.90$, $p = 0.345$, and no interaction, $F(1, 123) = 0.59$, $p = 0.443$. While mean accuracy scores in our Experiment 2 were numerically higher, consistent with our observed slower RTs, this between-Experiments accuracy difference was not significant, $F(1, 123) = 1.35$, $p = 0.248$, and did not interact with any other factors, *F*s < 0.5.

Combined recognition memory data for Experiments 1 and 2 showed a strong main effect of congruency, $F(1, 123) = 13.68$, $p < 0.001$, $\eta p^2 = 0.10$, with better memory for items seen with high conflict incongruent semantic primes at study. Memory performance appeared numerically worse for trials following incongruent versus congruent prior trials, though this difference did not reach significance, $F(1, 123) = 1.88$, $p = 0.173$, and there was no significant interaction, $F(1, 123) = 1.45$, $p = 0.231$. Overall memory performance did not differ between experiments, $F(1, 123) = 1.17$, $p = 0.281$, and there was no interaction of Experiment with any other factors, Fs < 0.6.

Discussion

Results from Experiment 2 directly replicated findings from Experiment 1. We again observed a clear memory benefit for stimuli from classification trials with high-conflict incongruent semantic priming, but no evidence of any CSE-related memory benefit (in fact a numerically reversed effect) for stimuli on trials following high-conflict prior trials. This is opposite to the general prediction from Verguts and Notebaert (2009) and related models, that high conflict trials should lead to better encoding for task information, but is consistent with predictions from our stage-specific conflict-encoding model shown in Figure 2. For these data and also in Experiment 1, we note that we observe this absence of any CSE-related memory effect within an experiment that does show a different incongruency-related encoding benefit (from immediate within-trial semantic priming), suggesting that our study design is in principle sensitive enough to observe this kind of conflict-encoding effect on memory.

As in Experiment 1, reaction time data showed strict additivity for our manipulations of within-task semantic congruency and the sequential effects of congruency/conflict. While interactive patterns of RT might be interpretable in a range of ways, strict additivity when the speed of one manipulated process is considerably faster than the other can be much more confidently interpreted as the result of two task factors independently manipulating two separate processing stages (McClelland, 1979). This is strong evidence that our semantic/category priming manipulation really is targeting a category representation process, and that the sequential effect of prior trial conflict from semantic interference is being implemented on the subsequent trial at a separate processing stage, most likely response selection. As such, these RT data provide direct converging evidence along with the conflict-encoding memory data, of semantic/category incongruency priming benefiting later memory but response selection modulation from CSEs showing no conflict-encoding benefit on later memory, as predicted and in keeping with Ptok et al. (2019).

Analysis of combined data from Experiments 1 and 2 confirmed the findings discussed above. While there was an apparent difference in speed-accuracy criterion between experiments, the lack of any evidence of interactions between Experiment and any other factor is supportive of the replicated main effects in RT and memory performance. We do note the non-significant trend in both experiments for worse memory for trial information following high-conflict incongruent trials. Ptok et al. (2019) predict that a cost to memory under high-conflict response priming may occur if conflict/control at response selection is sufficiently strong to cut short central attentional focus on semantic item information. In our current experimental design, we should expect to see this possibility with CSE-related memory outcomes, assuming that elicited sequential conflict/control is implemented at response selection on a subsequent trial. We discuss this issue further below, considering data from our entire series of experiments here.

Experiment 3

Experiments 1 and 2 have provided evidence for semantic congruency priming and sequential congruency-related conflict having their effects at separate processing stages, and demonstrate semantic incongruency conflict-encoding benefits while showing an absence of any benefit for CSE-related conflict on later memory. These novel findings are contrary to general predictions of conflict-encoding benefits from Verguts and Notebaert (2009) and related models, but are directly predicted from the stage-specific conflict-encoding model from Ptok et al. (2019) and extended to congruency sequence effect predictions here (see Figure 2). It would be a powerful demonstration, and we believe a necessary one, to show the elimination of these conflict-encoding effects and a return to more typical interactive Gratton-like RT effects when using a response congruency priming manipulation within the same categorization task, as predicted in the lower half of Figure 2.

To that end, we consider data from another previous congruency priming experiment very similar to Experiments 1 and 2 here, previously reported by Ptok, Hannah, and Watter (submitted). This study did not assess CSE-related issues, and focused solely on immediate semantic and response congruency priming effects, in addition to assessing pupil dilation responses under those various conditions. Here as our Experiment 3, we reanalyze their Experiment 2 data, which used response congruency priming (left and right arrow primes) with the same gender name task as in our previous experiments here. We focus on the previously unexamined CSE-related effects within these data, to assess the response priming predictions of within-task versus sequence congruency effects as predicted by our stage-specific congruency-encoding model. From Figure 2, we predict that RT should show an interactive pattern typical of Gratton-like effects for response congruency versus CSE factors, given they are both affecting a common response selection stage. Given that both of these factors focus central attention away from item information, however neither factor should show a memory benefit under high conflict conditions.

Method

Participants

Thirty-three first-year McMaster University students participated in this experiment for course credit. Informed written consent was obtained, and McMaster's Research Ethics Board approved the study. All participants reported normal colour vision, normal or corrected-to-normal visual acuity, and spoke English fluently. This experiment (and others from this broader study) used a recruitment stopping rule of 24 participants assessed at the end of each week's data collection.

Apparatus, Stimuli, and Procedure

Methods were identical to Experiments 1 and 2, aside from the following changes. Instead of semantic primes "female" and "male", primes were left and right arrows presented in the same position beneath name stimuli, to produce congruent and incongruent conditions relative to the correct left/right manual responses for the categorization task (see Figure 3). Stimuli were presented in a green colour against a grey background to achieve approximate isoluminant conditions to better study event-related pupil dilation measures (compared to white stimuli on a black background in Experiments 1 and 2 here).

Results

Encoding Phase

Data for encoding phase mean RT for correct trials, and mean accuracy, are shown in the left half of Figure 6. As for previous experiments, a 2x2 repeated measures ANOVA treated response congruency (congruent, incongruent) and previous trial congruency (previous congruent, previous incongruent) as factors. We observed a strong main effect of response congruency, $F(1, 32) = 185.85$, $p < 0.001$, $\eta p^2 = 0.85$, with slower RTs for incongruently primed trials reflecting the expected task difficulty influence on initial task performance. There was no main effect of previous trial congruency, $F(1, 32) = 0.13$, $p = 0.726$. However, here with response priming there was a strong interaction of congruency and sequence congruency, $F(1, 32) = 16.66$, $p < 0.001$, $\eta p^2 = 0.34$, with the pattern of mean RTs showing typical Gratton effects – the response congruency effect (congruent versus incongruent RT difference) was substantially smaller following an incongruent trial, typically interpreted as the influence of enhanced elicited control following a previous high-conflict incongruent trial.

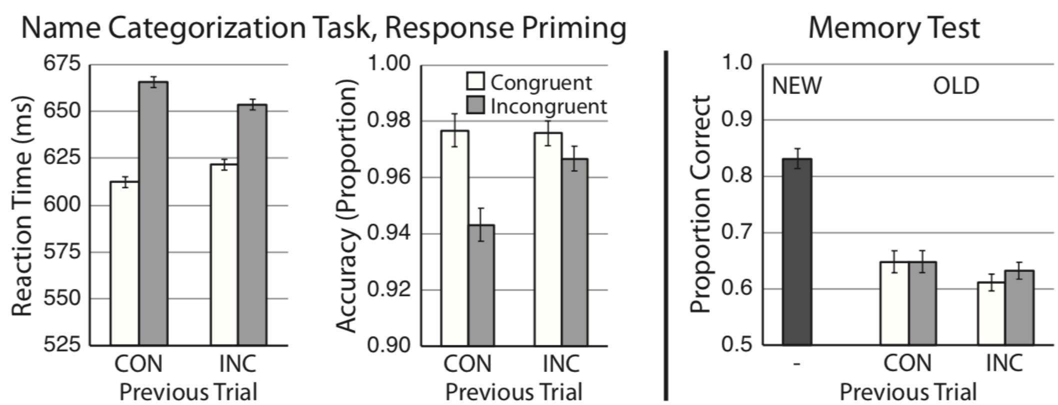

Figure 6. Data for Experiment 3. Basic congruency effects from these data were originally reported in Ptok, Hannah, and Watter (submitted), Experiment 2; new analyses here focus on sequential congruency effects. Response incongruency conflict produced costs on initial performance, but showed no benefit for item memory at later test. Response priming and sequence conflict showed typical interactive Gratton-like RT effects, suggesting effects at a common response selection stage. Sequence conflict showed no conflict-encoding benefit for later memory. Error bars represent within-subjects SEM for the difference of condition means for associated congruent/incongruent condition pairs.

Accuracy results were consistent with RT results. We observed significant main effects of congruency, $F(1, 32) = 14.91$, $p = 0.001$, $\eta p^2 = 0.32$, and previous trial congruency, $F(1, 32) = 8.01$, $p = 0.008$, $\eta p^2 = 0.02$, modified by a significant interaction, $F(1, 32) = 6.45$, $p = 0.016$, $\eta p^2 = 0.17$, again consistent with a reduction of congruency effects following previous high-conflict incongruent trials.

Memory Phase

Figure 6 (right half; see Figure 2 for a comparison of all experiments) shows the mean recognition memory performance (proportion correct) for old and new items at test, excluding items that the participant incorrectly responded to at study. A 2x2 repeated measures ANOVA for old items revealed no main effect of response congruency, as previously reported with these response priming data (Ptok, Hannah, & Watter, submitted), $F(1, 32) = 0.29$, $p = 0.592$. Memory performance appeared numerically worse for trials following incongruent versus congruent prior trials, but this effect was not significant, $F(1, 32) = 1.98$, $p =$ 0.170, $\eta p^2 = 0.06$. There was no interaction, $F(1, 32) = 0.49$, $p = 0.490$.

Discussion

These data have previously been reported (in Ptok, Hannah, & Watter, submitted, Experiment 2) to show that while response incongruency priming imposes expected costs on categorization task performance (slower RT), response incongruency conflict has no benefit on later recognition memory performance for task stimuli. The present analyses restate those findings, and in addition assess the influence of sequential congruency and modulation of control, in this case under response priming conditions.

Again, following predictions from our stage-specific conflict-encoding model (see Figure 2, lower half), we observed no CSE-related memory benefit, with the effect of sequential congruency on memory again numerically worse for trials following high-conflict incongruent trials. This is opposite to the general prediction from Verguts and Notebaert (2009) and related models, that high conflict trials should lead to better encoding for task information. In this experiment, we observe this same lack of CSE-related conflict-memory effects along with more typical Gratton-like RT effects from congruency priming involving response selection representations. These data fill out the full set of predictions for sequence conflict effects on immediate task performance and later memory effects from our stage-specific conflict-encoding model, shown in Figure 2.

General Discussion

Across three experiments, we observed no evidence of any memory benefit from elicited sequential control from prior trial conflict. We showed this lack of CSE-related memory benefit against a backdrop of clear and direct evidence that this kind of sequential control is being elicited by both semantic and response congruency priming manipulations, and is predictably influencing RTs within a categorization task. Our model in Figure 2 lays out a basic set of stage-specific processing predictions for within-task effects and across-task sequential effects of semantic and response congruency priming, which directly predict both RT and conflict-encoding memory consequences, for which we show confirmatory data here.

Our model here is conceptually in keeping with the general idea from Chiu and Egner (2015), that if task requirements focus selective attention away from relevant task stimulus information under high-conflict situations, then conflict will not lead to better memory for task information. Our model follows and extends the stage-specific conflict-encoding model from Ptok et al. (2019), that in turn extends and constrains the general idea from Chiu and Egner (2015) to demonstrate more specific predictions and constraints on when and where increased task conflict should (and should not) lead to better later memory for task stimulus information.

Our current study directly considers CSE-related effects with respect to where this control is *implemented* on a current trial, namely response selection. Consistent with Ptok et al. (2019), we have demonstrated that conflict-encoding memory benefits are only produced when additional control is focused on to-be-tested stimulus information. Because sequential control is implemented at response selection, we argue that this kind of elicited sequential control always diverts central attentional processing away from, central representations of stimulus information, and as such does not lead to improved later memory for stimulus information for trials following a previous high-conflict trial.

Sequential Conflict-Encoding Effects Across Experiments

We note several other patterns in our data overall, that are consistent with our stage-specific congruency-encoding model. Ptok et al. (2019) demonstrated substantial memory costs for high-conflict incongruent response priming with particularly strong response primes (in their Experiment 1, using backward compatibility effect response activation), and also simply an absence of congruency-related memory effects with less powerful incongruent response priming (in their Experiment 2, using response-relevant word primes “left” and “right”). They argued that conflict processing that diverts attention away from a focus on to-be-tested item information will not lead to a memory benefit for high-conflict trials; however, the degree to which this diversion of central controlled processing might cut short or compete with central attention to item information (and hence produce a relative encoding cost under high conflict conditions) should depend on the degree of elicited response-focused control.

In each experiment, in the present study, we observed a non-significant numerical trend of worse memory for trials following high-conflict incongruent prior trials. This is opposite to the general conflict-encoding prediction of Verguts and Notebaert (2009) and similar models, but is predicted from our stage-specific model if elicited sequential control at response selection is substantial enough to divert or cut short central focus on stimulus information within a current trial. From our model in Figure 2, this sequential incongruency cost on later memory should most reliably be observed on current congruent trials – this should avoid the possibility of incongruent semantic priming eliciting greater attentional encoding effects, possibly biasing memory data from other sources of encoding enhancement. This analysis of current congruent trials under both semantic and response priming most cleanly asks whether implemented sequential control at response selection has an effect on later memory, in the absence of other conflict on a current trial.

To this end, we assessed memory data for congruent trials across all three experiments with a repeated-measures ANOVA, with a within-subjects factor of previous trial congruency (congruent, incongruent) and a between-subjects factor of Experiment (1, 2, 3). Memory was significantly worse following high-conflict incongruent trials, $F(1, 155) = 5.58$, $p = 0.019$, $\eta p^2 = 0.04$. The main effect of Experiment was marginal, $F(2, 155) = 2.38$, $p = 0.096$, $\eta p^2 = 0.03$, with memory performance with response priming (Experiment 3) numerically worse than for semantic priming in Experiments 1 and 2. Importantly, the lack of any evidence of an interaction, $F(2, 155) = 0.13$, $p = 0.882$, supports the observation of the same costs of sequence conflict effects on memory under both semantic and response priming situations.

These memory costs of sequence conflict are consistent with memory costs of response selection conflict in Experiment 1 of Ptok et al. (2019), and predictions from the stage-specific conflict-encoding model. We suggest these findings are generally consistent with similar locus-of-attention conflict-encoding views such as Chiu and Egner (2015), but provide some strict limitations on the generalizability of conflict-encoding models such as Verguts and Notebaert (2009) and Botvinick (2007). We also note that these data replicate recently reported sequential congruency memory data from Davis et al. (2019), who similarly showed worse memory for congruent trial stimuli that followed prior incongruent trials versus prior congruent trials, from a combined analysis of a series of their interleaved words tasks. Davis et al. (2019) argued that these sequence memory effects did not easily align with other ideas about how proactive or reactive control ought to influence recognition memory; we suggest that these effects (along with our own data here) are directly explainable and predictable based on our stage-specific conflict-encoding model.

Assessment of the categorization RT data for the same current congruent trials across our experiments may also lend additional support to the idea that sequential control is implemented at response selection in our semantic priming experiments. Again, these current congruent trials allow a relatively cleaner assessment of categorization task performance with and without CSE-related control, independent of semantic or response incongruency conflict. Assessing RT performance for congruent trials as for memory trials above (by previous congruency and Experiment), we observed a strong main effect of previous trial congruency, $F(1, 155) = 19.04$, $p < 0.001$, $\eta p^2 = 0.11$, with slower RT following previous incongruent versus congruent trials, as expected. While a main effect of Experiment, $F(2, 155) = 8.48$, $p < 0.001$, $\eta p^2 = 0.10$, showed overall differences in mean RT between experiments, there was no evidence of any interaction, F(2,

155) = 0.06, $p = 0.939$, suggesting extremely similar RT costs of high versus low sequential control under both semantic and response priming conditions, in the absence of any current trial conflict. Although these data are far from conclusive, they are consistent with predictions of our stage-specific conflict-encoding model, and add to our confidence in our description of cognitive control as being potentially elicited immediately by a number of different sources, but being implemented in a longer-term sequential control fashion as a modulation of response selection.

Implications for Cognitive Control Models

While our current results provide strong limitations on the generalizability of conflict-encoding models of cognitive control (e.g., Botvinick, 2007; Verguts & Notebaert, 2009), we do not intend to suggest that these models are generally incorrect. One very important distinction between the associative learning through conflict approach typified by Verguts and Notebaert (2009) and the studies of conflict-encoding effects on later memory (e.g., Krebs et al., 2015a, 2015b; Rosner et al., 2015; Ptok et al., 2019), may be the kind of information each approach is focused on. Verguts and Notebaert (2009) focus on the associative binding of activated stimulus and response information within a single trial, where the same stimulus-response pairs are experienced and repeated many times over within a single experiment. In contrast, studies of later memory effects typically use a large number of unique stimuli, often with a simple categorization task. In the latter case, the activation of a small number of task-relevant category representations from unique stimuli (e.g., female/male category representations in our present work), with the associative binding of consistent and repeated *category*-response pairs, may be more akin to the stimulus-response binding described by Verguts and Notebaert (2009).

This description suggests that unique stimulus items will not be the primary focus of this kind of associative binding of activated stimulus and response information described by Verguts and Notebaert (2009), when a task requires many items to be categorized and responded to relative to shared category features. Semantic category information is rapidly activated from typical and relatively automatically processed stimuli, with usual task structure to select the correct response given the emerging semantic category representation. In this situation, sequential conflict implementation at response selection might enhance binding of activated category-response information, but may not do a good job of binding unique and changing stimulus features, especially when the particular stimulus features (e.g., individual name stimuli) become rapidly irrelevant to the task at hand once a task category has been resolved. To enhance memory for individual stimulus items, selective attention and control needs to be directed toward relevant stimulus information – we argue that encoding of this unique stimulus information is not generally enhanced by response conflict, given that category-response associations are the focus of the task, and become the associated information by which future task automaticity is driven. Previous divided attention work has shown evidence of this kind of automaticity of task-relevant category-response activation arising from unique semantic stimuli (Thomson, Watter, & Finkelshtein, 2010), and we would predict other kinds of so-called item-specific and context-specific associative learning modulations of control (e.g., proportion congruency effects; Crump, Gong, & Milliken, 2006; Crump & Milliken, 2009) to have their effects on category-response and not stimulus-response associations in these kinds of circumstances.

Conclusions

This paper provides a simple and coherent framework to explain and predict when processing conflict should (and should not) lead to better memory for task stimuli. The foundation of this stage-specific conflict-encoding model was laid out by Ptok, Thomson, Humphreys, and Watter (2019). We confirm and replicate those main findings here, and extend this model to show that it predicts both RT and later memory effects of sequential task conflict and related cognitive control modulation. We suggest that current prominent conflict/control models (e.g., Botvinick, 2007; Verguts & Notebaert, 2009) are being interpreted much too broadly in the emerging conflict-encoding literature with respect to implications of conflict on later memory for task stimuli, and argue that the within-task locus of processing conflict and how this directs selective attention relative to task requirements will be vital in determining whether conflict leads to better later memory for task stimuli.

Finally, the present results may offer further insight to the broader literature of desirable difficulty (Bjork & Bjork, 1992, 2011; Bjork, 1994). Kühl and Eitel (2016) have recently reviewed disfluency effects on encoding within the perceptual desirable difficulty literature, and have argued for a greater focus on understanding mechanism rather than continuing with the current hit-and-miss record of searching for task manipulations that might show disfluency-encoding benefits. Similarly, from reviewing related literature, Dunlosky and Mueller (2016) have suggested that disfluency-encoding effects may be more fundamentally due to attentional modulation, and recommend more focused approaches to understanding potential mechanisms.

We suggest that our current stage-specific conflict-encoding model is a very good candidate here, and may provide considerable insight with respect to predicting and constraining perceptual desirable difficulty effects. More generally, we see our stage-specific conflict-encoding model as providing a framework by which we can better understand cognitive control effects on later memory. By combining a task analysis of how participants engage with a task and what information they are drawn to focus on, coupled with better encoding of information that is in the particular stage-specific focus of conflict-elicited attention/control, we can better predict whether task stimuli should see benefits (or possibly costs) from various kinds of task conflict. Given the strong applied potential for better understanding and operationalization of desirable difficulty effects on memory, we suggest that this stage-specific conflict-encoding model might serve as a useful starting point to better understand and predict a wider range of conflict-encoding phenomena.

CHAPTER 5: General Discussion

There has been great interest in understanding conditions where optimal learning takes place. Additionally, recent work in the field of cognition has given some insight into situations where an increase in selective attention on task-relevant features leads to better incidental encoding compared to when attention is directed away from task-irrelevant information (e.g., Botvinick, 2007; Krebs et al., 2015; Rosner et al., 2015a; Verguts & Notebaert, 2008). Additional work gives evidence for how response inhibition – a key component of executive control – directs attention away from memory encoding leading to poorer memory. These examples fit with the general idea that processing difficulty during encoding results in better memory. However, there are many examples of where general processing difficulty does not lead to this increased memory benefit (e.g., Eitel et al., 2014; Miele et al., 2013; Yue et al., 2013). Therefore, to be more specific, this work might point to another shared observation: The information that is the recipient of selective attention processes is also the information that gets remembered later on. Based on the work presented throughout these chapters, I would argue there is more to this story.

The goal of the current thesis was to better understand the specific conditions under which incongruency priming leads to better incidental encoding. More specifically, I was interested in further investigating whether the mechanisms involved are more stage-specific in nature or are task-general, as previous research has assumed. Additionally, the previous examples mentioned may fit into a class of "desirable difficulty" effects whereby additional work/difficulty at encoding leads to better incidental memory. However, to date the term "desirable difficulty" has been descriptive in nature without pointing to a specific mechanism (Dunlosky & Mueller, 2016). This thesis was not an attempt to pinpoint the mechanisms involved but, rather, acts as an attempt to begin the search for possible mechanisms to better operationalize the term.

In Chapter 2, initial experiments on the stage-specific mechanisms of incongruency priming were reported. Across six experiments, a novel finding was observed: Better memory for incongruent items only when selective attention was directed at the to-be-remembered information. This effect was seen through semantic priming directed toward the semantic stage of processing (Experiments 4, 5, and 6). Whenever the difficulty effect of the incongruency manipulation directed attention away from the to-be-remembered semantic information such as toward response selection (Experiments 1 and 2) no memory benefit was found. When task difficulty directed processing towards semantic representation, but required more elaborative processing (Experiment 3), all trials (both congruent and incongruent) received more deliberate focus and effort due to the evaluative nature of the task; this eliminated the memory difference observed in less demanding semantic tasks between low-demand congruent trials and high-conflict control-eliciting incongruent trials.

Chapter 2 provided evidence in support of the idea that *where* the conflict directs attention is critical for later memory. Chapter 3 built upon this idea by examining whether the *amount* of difficulty/attention is important. This was measured with pupil dilation in an attempt to give us a good indication of cognitive effort within our difficulty manipulation. It was hypothesized that the amount of difficulty in a task is not as important to later memory compared to where the difficulty is directing our selective attention. Pupil dilation and RT measures provided evidence in support of increased difficulty for incongruent stimuli directed at both semantic representation (Experiment 1) and response selection (Experiment 2). However, better later memory was only seen for the semantic categorization task. Experiment 3 showed that having participants deliberately focus their attention with more effort during the encoding task – as indicated by a large equal pupil dilation response to both congruent and incongruent stimuli – these memory benefits were eliminated, conceptually replicating the high-task-demand semantic priming results from Chapter 2, Experiment 3, which also found equivalent memory results. These results show additional support and converging physiological evidence for a more selective mechanism of these effects. They also show that observing conflict-encoding benefits may be dependent on situations with more automatic or less evaluative performance.

Chapter 4 explored the stage-specific account more closely by examining the trial-to-trial modulation of attentional control processes (congruency sequence effects; CSEs) that occurs in the incongruency priming tasks. It was hypothesized that CSEs are driven by response conflict (Botvinick et al., 2001; Jentzsch &

Leuthold, 2005), and memory effects are driven by conflict directed at the semantic state of processing. Results confirmed the processing stage separation of these two effects (Experiments 1 and 2). The purpose of Experiment 3 was to show elimination of these effects through the use of a response selection priming task which is typically used when investigating CSEs (e.g., Stroop, flanker, etc.). Results confirmed these predictions showing typical RT Gratton effects (Gratton, Coles, & Donchin, 1992) at study where the congruency effect (the congruent versus incongruent trial RT difference) is reduced following incongruent trials. Additionally, no memory effects were observed from within-task response priming or CSE conflict. These results provide further evidence that memory encoding effects are only produced when congruency priming induces additional attention and control at a processing stage that is focused on the to-be-remembered stimulus information. In other words, these experiments provide additional evidence for the stage-specific nature of conflict-encoding memory benefits.

The results of the empirical chapters in this thesis all explore the stage-specific nature of conflict-encoding benefits. This work suggests that for difficulty to result in a later memory benefit, selective attention/cognitive control must be directed toward task-relevant stimulus information. In contrast, any situation in which selective attention/control is directed away from these representations should not lead to better memory for stimulus information. Next, I will turn to a more detailed discussion regarding these effects and the support for this framework, as well as the connection of these effects to the desirable difficulty literature.

The role of engagement

The framework outlined in this thesis can speak to the mechanisms driving the beneficial memory effects with difficulty at encoding. One interesting finding is the requirement for how central the decision-relevant features for the classification task are. In other words, any additional evaluative processing inhibits the memory effect. As seen in Chapter 2, Experiment 3 with the relative size comparison task – here participants needed to classify non-canonically big or small items in relation to the size of the computer monitor – extra evaluative work led to greater control in processing to resolve the categorization decision. This extra work led to greater attention directed at both congruent and incongruent stimuli, leading to similar encoding for both conditions. These results suggest that the conflict-encoding benefit we see is a result of conflict attracting greater attention and control toward the relevant stimulus information with incongruent priming, leading to better encoding, versus relatively less engaged automatic engagement for congruent items.

On the other hand, if stimuli have strong semantic features that are activated relatively automatically, then the relevant information needed to resolve the categorization would be activated from semantic memory with little deliberate effort. In this situation, the extra attentional control elicited by the incongruent priming trials focuses attention on the essential task-relevant information leading to better incidental memory for those items. This was the case in Chapter 2, Experiment 6 where participants completed a size categorization big/small task with canonically big and small stimuli. Additionally, this could also be seen in Experiment 4 where we used the same stimuli as Experiment 3 but, had participants classify the items based on animacy (which we suggested elicits a relatively essential and automatic dimension). Both these tasks demonstrated a strong incongruency effect along with better later memory for those difficult items.

A recent example within the literature using perceptually blurry versus clear word stimuli illustrates this prediction nicely. Work done by two different groups (Yue et al., 2013; Rosner et al., 2015b) examined whether reading blurry compared to clearly presented words would lead to a later memory benefit. Over a series of experiments, Yue et al. (2013) did not find any evidence of an encoding benefit on memory, whereas Rosner et al. (2015) found beneficial memory effects for blurry versus clear words. The difference between the two studies was that Yue et al. (2013) required participants to make "judgments of learning" (JOL) for both clear and blurry word stimuli. Rosner et al. (2015b) on the other hand, simply had participants say the blurry and clear words aloud, a task requiring minimal extra evaluative processing especially during the low-conflict (clear) trials. However, Rosner et al. (2015b) included an experiment where they added a JOL by having participants evaluate how likely they would remember stimuli on a later memory test. This eliminated the memory benefit seen in their other experiments.

Rosner et al. (2015b) also discussed other studies within related memory literature that have also found similar disruptions to memory when adding item-by-item JOL tasks to their procedures (see Soderstrom, Clark, Halamish, & Bjork, 2015). These item-by-item JOL results are discussed in comparison to aggregate JOLs which have been found to be less likely to influence the processing of individual trials, leaving the beneficial memory effect intact. These effects have been found over a number of studies. For example, item-by-item JOLs have eliminated the well-documented generation effect (Begg, Vinski, Frankovich, & Holgate, 1991; Matvey, Dunlosky, & Guttentag, 2001) and have also eliminated perceptual interference effects in comparison to the aggregate JOL which has left this effect intact (Besken & Mulligan, 2013, 2014). Together, these results all point to the finding that item-by-item JOLs interfere with desirable difficulty effects (see also Rhodes & Castel, 2008, 2009).

Based on these results, it is argued that the degree of engagement required for this evaluative JOL task is greater than simply reading the word as was done in Rosner et al. (2015b). Therefore, any differences that would be present in the absence of such an evaluative task are unlikely to lead to additional attentional allocation toward central stimulus representations at study. This prediction would strongly suggest that in situations where we observe a conflict encoding benefit, the effect is demonstrating a relative cost to encoding in low-conflict conditions where the effect of automaticity is present. This is in contrast to the idea that there is a special enhancement to encoding under high-conflict conditions resulting in more controlled attentional processing.

As seen above, eliciting more engagement by having more demanding evaluative processing in task demands eliminates the difference between incongruent and congruent conditions. We have also observed that other kinds of manipulations to general engagement have the same kind of effect. Chapter 3, Experiment 3 provides evidence for this effect. When participants were instructed to sit forward in their chair with their face placed in a chin rest, this encouraged greater engagement in the classification task. Pupil dilation was significantly increased for both sets of stimuli (i.e., congruent and incongruent), giving a good indication of increased cognitive control/engagement compared to the previous two experiments in that paper.

Similar to the argument for high-demand task requirements above, if participants are endogenously more engaged (in a colloquial sense, "trying harder"), they are boosting engagement for *all* trials, and so we see less of a difference between congruent and incongruent trials in terms of attentional allocation. However, when participants are not required to focus as much or to "try hard" (i.e., Experiments 1 and 2), we see a relative encoding benefit for incongruent trials. Therefore, when endogenous engagement is low (as in Experiments 1 and 2), the priming conflict elicits transient attentional bursts when incongruent trials are present. This increased attention toward task-relevant information produces better memory for incongruent trials only, again compared against relatively low-engagement congruent trials.

Generality of conflict-encoding mechanisms

The findings of the present thesis provide a more detailed framework for the underlying mechanisms of conflict-encoding effects and fit well with recent work on the memory effects of inhibitory control (Chiu & Egner, 2015). In line with the predictions of this thesis, these authors predict that if control demands direct the focus of selective attention away from stimulus processing, a relative memory cost of control will be observed. These findings propose a challenge to the generality of the conflict-encoding model of Verguts and Notebaert (2008, 2009). Although this model is adapted from the conflict monitoring model proposed by Botvinick et al. (2001), Verguts and Notebaert (2009) took a different approach to how conflict adaptation is implemented. They argued that when conflict is detected, a Hebbian learning signal is sent throughout the brain which strengthens all active representations, including both task-relevant and task-irrelevant information.

While the Verguts and Notebaert (2009) model makes good predictions, it mostly makes predictions about better learning of stimulus-response bindings for high versus low levels of conflict. The present work uses many specific instances of unique semantic items, to isolate instances of semantic versus response conflict. Conversely, these manipulations have given insight into how the allocation of cognitive control toward specific representations is important for determining what does and does not get encoded. Therefore, our data argue against a general task-wide difficulty prediction and in favour of a more specific set of within-task requirements for conflict-encoding benefits. Chapter 4 (see General Discussion) discusses how the associative binding through conflict idea from Verguts and Notebaert (2009) mainly describes category-response associative learning at central response selection, where individual stimuli are essentially stimulus categories with only a small number of repeated stimuli (e.g., as in a typical Stroop task). The stage-specific conflict-encoding model presented in this thesis broadens the scope of the Verguts and Notebaert (2009) model to account for memory consequences for unique stimuli, and conflict arising at other processing stages.

Implications of stage-specific mechanisms for the desirable difficulty effect

This thesis presents a series of experiments demonstrating selective attention-related encoding benefits which may be highly relevant to the broader desirable difficulty literature (Bjork & Bjork, 1992, 2011; Bjork, 1994). This principle is not just observed in educational context examples such as the spacing effect (for a review, see Cepeda et al., 2006), interleaving (Rohrer and Taylor, 2006; Kornell & Bjork, 2008), and the test-enhanced learning literatures (Roediger & Karpicke, 2006). Across many experiments, better memory has been observed for stimuli that are more difficult to process, such as with better recognition for masked compared to intact words (Hirshman & Mulligan, 1991; Hirshman, Trembath, & Mulligan, 1994; Mulligan, 1996; Nairne, 1988), for low frequency than high frequency words (Glanzer & Adams, 1985; Gregg, 1976), for incongruent than congruent stimuli (Krebs, Boehler, De Belder, & Egner, 2015; Rosner, D'Angelo, MacLellan, & Milliken, 2015), and for blurry than clear stimuli (Rosner et al., 2015b; but see Hirshman et al., 1994; Yue, Castel, & Bjork, 2013).

This work can help clarify some of the present issues within the literature. First, this research can help explain situations where desirable difficulty manipulations do not lead to a memory benefit and possible reasons why. For example, perceptual disfluency is proposed to provide its advantage by causing deeper, more effortful processing. However, many recent studies have found a lack of this effect (e.g., Eitel & Kuhl, 2016; Magreehan, Serra, Schwartz, & Narciss, 2016; Rummer, Schweppe, & Schwede, 2016; Strukelj, Scheiter, Nystrom, & Holmqvist, 2015). Bjork and Yue (2016) suggest one simple explanation is that comprehension, storage, and access to to-be-remembered information happens after the perceptual encoding of the items. Research by Rhodes and Castel (2008), who looked at the effects of font size on recall found that increasing font size resulted in higher predictions of later recall but had no actual effects on recall – leading to a similar conclusion. The experiments in this thesis take this one step further and predict when particular kinds of task conflict should and should not lead to encoding benefits in a range of congruency/control and desirable difficulty paradigms. More specifically, incidental memory encoding benefits elicited by task difficulty occur only when the difficulty directs selective attention toward the to-be-remembered information.

This work can also help clarify the argument that difficulty benefits on later memory tests arise simply due to an increase in time on task. The idea here is that the additional time required to respond to high-conflict stimuli compared to low-conflict stimuli directly produces additional encoding because of the longer exposure. As can be seen in all Chapters of this thesis, in all experiments, high-conflict incongruent trials led to extra time on task. However, experiments which focused on response priming stages of processing led to a lack of incidental memory benefits, whereas those that focused attention toward the semantic/categorization stages of processing led to conflict-encoding benefits on later memory. Enhanced memory is not apparent for all difficult selective attention conditions, but depends on the particular stage of processing at which the additional difficulty occurs.

Future directions

There are still many avenues to explore regarding the stage-specific mechanisms of congruency priming/desirable difficulty effects. Given that this thesis provides some of the only examples of these stage-specific mechanisms involved with these effects, there is still much that is unknown about these effects on memory. For example, congruency effects on memory performance have been studied almost exclusively using recognition tasks (e.g., Krebs et al., 2015; Rosner et al., 2015). It would be beneficial to see whether such effects would extend to other types of memory tasks. This is an important issue as it may help clarify which processes of the memory representations are being enhanced. For example, free recall is assumed to encompass different processes in comparison to recognition memory. Free recall depends on relational processing as well as the retrieval of item-specific information (Hunt & Einstein, 1981; Hunt & McDaniel, 1993; Kintsch, 1970; McDaniel & Bugg, 2008), whereas recognition is primarily dependent on the stimulus-driven retrieval of item-specific information. Previous research has suggested that difficult-to-process information and unusual stimuli involve the encoding of item-specific information (Mulligan, 1999; McDaniel & Bugg, 2008). This evidence would suggest that processing difficulty effects might be favoured in recognition tasks. Given these predictions, it would be useful to extend this work out to other types of memory performance.

Although the findings in this thesis are consistent with the desirable difficulty principle and even help conceptualise the term, the present research does have strong ties to the cognitive control literature. We anticipate that this work will improve our understanding of fundamental cognitive mechanisms of divided attention and central information processing and will begin the process of developing a mechanistic view of how memory is influenced by moment-to-moment attention and cognitive control demands. The conflict monitoring model (Botvinick et al., 2001) is a prominent theory of cognitive control. According to this model, the anterior cingulate cortex (ACC) detects response conflict (multiple competing responses), leading to an activation of the dorsolateral prefrontal cortex

(DLPFC) and an increase in cognitive control. We generally agree with accounts in the literature suggesting that conflict resolution involving top-down attention should facilitate memory for that information (e.g., Botvinick et al., 2001; Egner & Hirsch, 2005), and these models suggest that conflict from incongruent trials might up-regulate learning and memory processes (see Egner, Delano, & Hirsch, 2007; Kiesel, Kunde, & Hoffmann, 2006; Sapapé & Hommel, 2008; Verguts & Notebaert, 2008), which lead to better memory (e.g., Krebs et al., 2013; Rosner et al., 2015). However, our work shows an important constraint on this kind of effect where this encoding benefit is stage-specific, and only occurs when there is additional control directed toward the processing of task-relevant information.

Krebs, Boehler, De Belder, & Egner (2015) investigated DLPFC activity using functional magnetic resonance imaging during the study phase of their experiment. They observed higher DLPFC activity for remembered compared to not-remembered incongruent items, but no difference for congruent items. These results support the idea that DLPFC activation due to conflict leads to adjustments in cognitive control which influence later memory. It would be useful to extend such findings using our stage-specific predictions for tasks which focus on categorization compared to response selection stages of processing. In this sense, it would be valuable to investigate our prediction that these conflict/encoding benefits might be limited to situations where task engagement is relatively automatic rather than resulting from cognitive control elicitation having some additional encoding benefit in all situations. We see evidence of these predictions in Chapter 3 with our pupillometry data. Here we see that the critical consideration is what information ends up being the focus of central attention rather than the degree of conflict in general.

Based on this, we also predict that many of the purely perceptual desirable difficulty manipulations will focus central attention on the to-be-tested stimulus information. As long as these perceptual manipulations do not require too much effortful or evaluative work to access relevant stimulus meaning, we would expect there to be memory benefits in these cases against a background of relatively fluent/automatic performance in low-conflict conditions. Again, these predictions come from our interpretations of what is happening in the Rosner et al. (2015b) and Yue et al. (2013) studies. If would be valuable for future work to look into these predictions further.

Finally, the results of the present thesis should be investigated further from a desirable difficulty perspective. It would be beneficial to extend this research to make better predictions about how and where these kinds of desirable difficulty effects should occur. I encourage researchers to use the findings that we already have from cognitive psychology for guidance when investigating these effects. It would be valuable to extend this stage-specific model of conflict in application-based classroom settings.

Conclusion

In summary, this thesis describes an attempt to find possible mechanisms for situations where initial task difficulty leads to a later memory benefit.

Moreover, these results are offered to help better operationalize the term "desirable difficulty." According to these results, difficulty at encoding will lead to a later memory benefit when attention/cognitive control is directed toward the to-be-remembered representations of the stimuli regardless of finding the 'optimal' level of difficulty for the task. Additionally, if the difficulty elicited by the task directs attentional resources away from these representations, then we predict there should be no memory benefit, and with sufficiently strong redirection we predict relative costs to memory under high conflict conditions, similar to typical divided attention effects.

I anticipate that this work will improve our understanding of fundamental cognitive mechanisms of divided attention and central information processing and will begin the process of developing a mechanistic view of how memory is influenced by moment-to-moment attention and cognitive control demands. These results are in agreement with ideas where conflict resolution directing top-down attention toward to-be-remembered information will lead to better later memory (e.g., Botvinick et al., 2001; Egner & Hirsch, 2005). In many cases, task demands serve to do exactly this. On the other hand, the variability of outcomes in the broader desirable difficulty literature, not to mention that desirable difficulty itself is still a somewhat novel and surprising effect (given psychology's long history of divided attention costs), suggest that simply being task- or stimulus-directed might not be sufficient. These results suggest that it should be possible to make better predictions about how and where desirable difficulty effects should occur, and that fundamental ideas and knowledge we already have within cognitive psychology could provide more guidance than we may have suspected.

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