2006

Exploring the role of visual selective attention in synesthesia

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Exploring the role of visual selective attention in *synesthesia*

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Co-majors: Psychology; Neuroscience

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Iowa State University
Ames, Iowa
2006

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ABSTRACT

Individuals with *grapheme-color synesthesia* perceive colors, called concurrents, when processing alphanumeric stimuli. Concurrents may arise from cross activation between cortical language and color processing areas. Two experiments used an attentional blink (AB) paradigm to test whether production of concurrents is an automatic or attention-demanding process. Two experiments used a visual-short-term-memory paradigm to test whether working memory (WM) representations of concurrents are capacity demanding. When target color was incongruent with concurrent color but color did not define targets, a synesthete (S1) showed delayed AB recovery compared to controls. When color defined targets and target color was congruent with concurrent color, the ABs of S1 and controls were similar. It appears that concurrent production is involuntary (automatic), but requires resources (attention demanding). WM capacity of S1 and controls was similar. WM representations including concurrents required no more capacity than representations without concurrents. Thus, although production of concurrents requires resources, maintenance does not.

CHAPTER 1: INTRODUCTION

Overview

In this dissertation, a series of behavioral experiments were conducted to explore the relation between attention and grapheme-color synesthesia. Four experiments were designed to contribute to the understanding of the processing of synesthetic experiences. In the synesthesia literature, there are basically two camps of researchers, those that posit that the activation of synesthetic experiences are automatic and those that posit that controlled processing is needed (i.e., attention is required) for their activation. This dissertation consists of a literature review of empirical research on synesthesia and the cognitive science of attention, followed by two experiments testing the temporal limits of attention and two experiments testing the visual short term memory in an individual with grapheme-color synesthesia.

Synesthesia

The current line of research investigates the role of visual selective attention in synesthesia. The actual word synesthesia comes from the Greek *syn* (union) + *anesthesis* (sensation), meaning the union of the senses "joined-sensation." Cytowic (2002) defined synesthesia as the involuntary physical experience of a cross-modal association. Examples include the ability to hear colors, taste shapes, or experience other equally strange sensory fusions. For synesthetes stimulation of one sensory modality reliably causes a perception in one or more other sensory modalities (Cytowic, 2002). In some cases just thinking about a concept (that has the ability to induce synesthesia) can elicit a synesthetic experience (Smilek, Dixon, Cudahy, & Merikle, 2000). The majority of synesthetes have developmental synesthesia; that is, the synesthesia was present during early childhood. The cause of synesthesia is not known. Attempts have been made to correlate synesthesia with an autosomal dominant or X-linked dominant genetic factor (Bailey & Johnson, 1997), but recent reports have found that monozygotic twins experience diverse synesthesia (Smilek & Dixon, 2002) and that synesthesia may skip generations (Ramachandran & Hubbard, 2003).

Grossenbacher and Lovelace (2001) suggested that synesthetic experiences can be categorized into at least two types: synesthetic experiences induced via perceptions and synesthetic experiences induced via concepts. *Synesthetic perception* is the perception of an induced sensory experience in one sense that is the consequence of the perception in another sense. For example, the perception of a particular sound may induce the perception of color. The induced perception is commonly referred to as a concurrent. In the example above, the *inducer* is the sound and the *concurrent* is the perception of color. *Synesthetic conception* occurs when simply thinking about a particular concept induces a concurrent. For example, periods of time may be conceptualized in a spatial layout (Grossenbacher & Lovelace, 2001) or thinking about particular stimuli (e.g., alphanumeric stimuli) may invoke concurrents (e.g., colors) (Dixon, Smilek, Cudahy, & Merikle, 2000). The key difference is that synesthetic conception does not require a physical stimulus to elicit the concurrent. Important for the present purposes, individuals with synesthesia report that the concurrents, or the vivid induced *sensory perceptions,* occur automatically (Grossenbacher & Lovelace, 2001).

The most common form of synesthesia is grapheme-color synesthesia (Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996). The prevalence of grapheme-color synesthesia is estimated to be around 1 in 200 individuals among the general population (Ramachandran & Hubbard, 2001). Individuals with grapheme-color synesthesia experience colors when they perceive alphanumeric stimuli. Some synesthetes experience colors for all letters and digits, but it is also the case that some synesthetes only experience colors for certain alphanumeric stimuli (e.g., digits but not letters). An interesting aspect of synesthesia is that the concurrent percepts can be idiosyncratic and systematic at the same time. Concurrent experiences are idiosyncratic in that each synesthete has a unique set of inducers and concurrents. For example, the digit two may be blue for one grapheme-color synesthete and it may be red for another. However, both synesthetes will display a systematic association for their set of inducers and concurrents.

According to Laeng, Svartdal, and Oelmann (2004), the concurrent synesthetic colors do not produce the same neural activation that typically occurs during an early stage of visual processing for colors (e.g., visual cortex area V4). However it is difficult to make such a claim because the neural basis of synesthesia is not well understood. In fact, Ramachandran and Hubbard (2001) proposed that synesthetic experiences may result from a failure of neural pruning or a type of disinhibition. Specifically, they suggested that individuals with synesthesia have excess anatomical neural connections that in normal individuals would have been pruned during development. Ramachandran and colleagues suggested that grapheme-color synesthesia may arise from direct cross activation between the visual word form area (VWFA; for review see McCandliss, Cohen & Dehaene, 2004) and color processing regions in V4 (Wade, Brewer, Rieger, & Wandell, 2002), which are adjacent brain regions. Thus, cross activation leads to reproducible, involuntary, and systematic synesthetic perceptual experiences (Ramachandran & Hubbard, 2003). The majority of neuroscience studies of grapheme-color synesthesia suggest that the color-selective region V4 of the visual cortex is involved in the experience of concurrent colors; nevertheless, the studies are inconsistent in determining the functional significance of such V4 activation and whether other early visual areas are also involved (Hubbard & Ramachandran, 2005).

Behavioral Evidence for the Perceptual Reality of Synesthesia

Cognitive research has shown that the fundamental mechanism(s) underlying synesthesia is poorly understood and what research exists tends to be inconsistent. Cognitive studies of synesthesia, which incorporate modified Stroop interference paradigms, visual search tasks, and masking-related tasks, provide conflicting conclusions about the underlying mechanism(s) that contribute to the perceptual experience of concurrents. On the one hand, some theories suggest that concurrents are invoked automatically (Cytowic, 2002). On the other hand, some theories propose that attention is required for the binding of the inducer and the concurrent (Laeng, Svartdal, & Oelmann, 2004; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002). Automatic here means that no attentional resources are needed to experience a concurrent. Thus, when attention or effortful processing is necessary for the experience of a concurrent it is not considered an automatic process.

Stroop effect. In a standard Stroop paradigm (Stroop, 1935), color names are presented in colored ink, such as the word BLUE in blue ink (a congruent stimulus) or the word BLUE in green ink (an incongruent stimulus) and the task is to name the color of the ink. Typical results show that participants have slower response times to incongruent trials than to congruent trials (MacLeod, 1991). The effect is assumed to occur when interference from reading the word slows down the color naming response. In the modified Stroop task, synesthetes are presented with stimuli that are in congruent or incongruent ink colors for each concurrent experience. For example, if an individual sees green for the number eight, then a congruent stimulus is the number eight in green ink and an incongruent stimulus is the number eight in red ink. Just as for individuals in the original Stroop task, when synesthetes are asked to name the ink color in this modified Stroop task, they show interference on incongruent trials. Mattingley, Rich, Uellan, and Bradshaw (2001) showed that during the modified Stroop task, induced synesthetic colors could not be consciously suppressed even when they were disadvantageous for successful completion of the task. Hubbard and Ramachandran (2005) suggested that the interference found in synesthetes is evidence that concurrent colors are produced automatically. Here automaticity refers to not being under voluntary control. Mattingley et al. (2001, Exp. 2) showed that if the inducers are briefly presented and are masked, making the inducers unavailable for conscious report, then the concurrent effects of synesthesia are no longer obvious in the response times to the congruent and incongruent trials. Their data suggest that attention and awareness maybe necessary for the binding of inducers and concurrents in color-grapheme synesthesia.

Visual search. Visual search tasks have been extensively used to examine the role of attention in processing different aspects of a stimulus (e.g., Triesman & Gelade, 1980; Wolfe, 2003). In a typical visual search task, participants are shown a display of stimuli consisting of distractors (e.g., slanted bars) and a target (e.g., a vertical bar). The task is to search for the different stimulus target (i.e., the vertical bar in the example described). The ease of the search depends on the nature of the difference between the target and the distractors. Searching for a target that varies from distractors in color is quite easy. For example, finding a green vertical bar embedded in red slanted bars (rotated between $\pm$ 20 deg from vertical) is easy compared to finding a green vertical bar among green slanted bars. The latter is very difficult (Wolfe, 2003).

Another difficult visual search task is searching for a 2 embedded in 5s when the digits are presented in a straight line font in which the only difference between 2 and 5 is whether the top and bottom vertical bars are on the right and left (2), or left and right (5). For a synesthete, searching for a 2 embedded in 5's in such a font should be a relatively easy task if the 2 and 5 induce different concurrents, but if the concurrent is the same, then the task should be more difficult. Palmeri et al. (2002) demonstrated that when the color concurrents were different, detection of a 2 or 5 target was a relatively easy visual search task. In their experiment, a visual array consisting of white digits 2 and 5 were presented and the task was to make a target present/absent judgment as soon as possible without making mistakes. The controls in this experiment showed no difference in search times as a function of the targets and distractors used because all stimuli appeared in only one color. In the beginning of the experiment, the synesthete commented to the researchers that the target digits appeared to "pop-out" because to him targets were always in a different color than distractors. However, Palmeri et al. noted that the pop-out effects were not as efficient as the pop-out effects found with true colors. Palmeri et al. further concluded that the binding of inducers and concurrents most likely does not occur as a parallel process across the visual field and thus concurrents must be bound to the visual form as the form is being recognized. Given that their synesthete was 500 ms faster than normal controls at the largest set size, Palmeri et al. suggested that concurrents likely influence the target selection process.

As can be seen in the visual search examples, the nature of the target and distractor stimuli in a visual search task plays an important role in determining the type of processing associated with the target detection. When a visual search task is extremely easy so that the number of distractors does not affect performance, researchers typically conclude that the ease of search represents parallel processing. On the contrary, when a visual search task is difficult so that more distractors slow performance, researchers typically conclude that serial processing is required. Unfortunately not all visual search tasks clearly distinguish between parallel and serial processing. The search data for the synesthetes in Palmeri et al. did not clearly fall into either processing category.

Neurological Correlates of Attention

Although most research on attention has used behavioral paradigms, it is also important to understand the neural mechanisms of attention. As neuroscience techniques have become more sophisticated, researchers have revealed how populations of neurons, neural pathways, and brain structures can account for different stages of information processing. Just as type of stimulus in a visual search affects the behavioral outcome, the complexity of visual spatial *attention* is also revealed when different neural activation results as a function of the type of task used. For example, spatial cueing tasks typically show activation of cells in area V4 of the occipital cortex (Luck, Chelazzi, Hillyard, & Desimone, 1997), attentional selection based on object identity requires activity in inferotemporal cortex (Chelazzi, Duncan, Miller, & Desimone, 1998), and under different conditions a cued spatial location may engage neurons from prefrontal cortex (Everling, Tinsley, Gaffan, & Duncan, 2002).

More generally, Posner and colleagues (Posner, 1980; Posner, Inhoff, Friedrich, & Cohen, 1987) have demonstrated that attention involves at least three distinct processes, each with its own neural correlates. These components of visual attention can be isolated through use of a spatial cueing task (Posner, 1980). Moving attention from one location to another requires that attention *disengage* from its current target, *shift* to its new location, and *engage* its new target. Studies of patients with brain damage indicate that the disengage operation is associated with parietal cortex (Friedrich, Egly, Rafal, & Beck, 1998; Posner, Walker, Friedrich, & Rafal, 1984, 1987), the move operation is associated with midbrain regions (Posner, Cohen, & Rafal, 1982), and the engage operation is associated with thalamic structures (Rafal & Posner, 1987).

Cognitive Science & Attention

What is attention? Attention is a concept that has many definitions because researchers in the field of attention have not come together to agree on a single definition. Researchers have provided several definitions throughout the years. One of the most quoted definitions was provided by Williams James (1890); it focuses on attention as selection.

> Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought... It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state ... (1890, p.404).

The field of attention continues to be widely researched. Attention is studied at the cognitive, neuroanatomical, molecular, synaptic, and most recently at the genetic level, so in some sense it is not surprising that disagreement in the field prevails. The lack of agreement on the definition of attention among *attention researchers* may be due in part because it is extremely difficult to classify attention as a single mechanism, a single function, or even a single set of mechanisms.

The nature of the disagreement concerning the definition of attention is partially attributable to the widespread use of the distinction between automatic and controlled processing. Controlled processing requires attention, and automatic processing does not. But many different dimensions have been used to discriminate between controlled and automatic processing. For example, Schnieder, Dumais, and Shiffrin (1984) listed 12 dimensions. Kahneman and Treisman (1984) noted that there is general agreement among researchers on two criteria by which processes can be termed automatic. An automatic process 1) is involuntary because it can be triggered without intention and once it has started it cannot be intentionally stopped and 2) does not require general resources and it is not subject to interference from attended sources. That is, an automatic process does not interfere with another process that does require attention. However, as noted by Paap and Ogden (1981), although the literature on automaticity often assumed that when a process met one criterion, it would meet the other, the two criteria are separable. They demonstrated that the early perceptual components of letter encoding are in fact involuntary or obligatory but they are resource demanding. So, the early perceptual processing was "automatic" on one dimension, but not the other.

Cognitive Models of Information Processing

Information processing models (e.g., Broadbent & Broadbent, 1987; Chun & Potter, 1995) suggest that the temporal limits of attention are a result of the dynamic nature of the stages of processing that may reflect two types of processing, one of which requires attention and one of which does not. In these models stage 1 is a relatively capacity free process responsible for the initial detection of stimulus features and stage 2 is a more resource demanding and capacity-limited process resulting in consolidation and stimulus identification. Thus, stage 1 processing is automatic and stage 2 processing is controlled. These stages occur in a serial fashion such that stage 1 must be completed before a stimulus undergoes stage 2 processing. During stage 1 a stimulus is processed on the basis of independent features such as color, contrast, or letter case (Chun & Potter, 1995). The initial stage 1 processes may also include detection of target status on the basis of categorical identity. That is, Chun and Potter claimed that the categorical identity of stimuli presented very rapidly, at a rate of 10 items per second, is most likely briefly available and serves as the basis of selection into stage 2 processing. Given that stage1 and stage 2 occur serially, the representations which result from early levels of stage 1 processing are transferred to stage 2 for subsequent processing that result in full identification.

In accord with stage 1 and stage 2 information processing models, some of my previous work has provided evidence for the serial nature of target processing. In this experiment participants were briefly flashed a masked object and after a period of time were asked to identify the object. Participants could recognize a feature of the object as being part of the previously viewed object even when they could not explicitly identify the object (Langley, Ramos, & Cleary, *submitted*). During stage 2, a stimulus becomes available for conscious report as it is consolidated into a durable memory representation (i.e., memory consolidation allows identification of a stimulus). Stage 2 only occurs after stage 1 is completed (Chun & Potter, 1995). Thus, in the above example the object was not consolidated, as shown by the deficit in identification. Two outcomes could be responsible for the lack of identification, one is that stage 2 may have begun but was not completed and the other is that the stimulus was never transferred to stage 2. The key in the information processing models is that stage 2 is necessary for memory consolidation and stimulus identification.

Model of attention. Clearly not all stimuli that are projected to the retina can be fully processed to the point of reaching awareness; otherwise the system would be overwhelmed with stimulation. There are several different models of attention that attempt to describe the limits of visual awareness. One example is Cavanagh's hierarchical model of vision routines, which proposes that attention is not a resource (Cavanagh, 2004). Instead, Cavanagh considers attention as one aspect of a hierarchy of routines that contain visual routines, attention routines, and cognitive routines. In Cavanagh's hierarchical model, visual routines (i.e., processing pathways) are not accessible to awareness or introspection and occur automatically. Attention routines are voluntarily initiated and the outputs are available for conscious report, but nothing from the intermediate (preoutput) states is reportable. Cognition routines include multiple stages in which intermediate stages are accessible to introspection (e.g., counting, cooking). This hierarchical model does not characterize attention as limited in capacity. Rather, limitations are a consequence of representing the initial and final states of the attention routine in awareness. According to Cavanagh's hierarchical model it is awareness that is limited in capacity, which may be the result of the limitations of working memory.

Model of working memory & attention. In contrast, there are models that consider attention as a subcomponent of working memory (WM), which is limited in capacity. According to the information processing model originally proposed by Baddeley and Hitch (1974), WM is a limited-capacity memory system in charge of short-term retention and manipulation of information (Baddeley 1998; Baddeley & Hitch 1974). WM has an attentional control or central executive system that operates in conjunction with two subsidiary systems: the phonological loop, concerned with auditory (i.e., verbal in nature) information, and the visuospatial sketchpad, responsible for visual and spatial information. These two "slave" systems are relatively independent from one another and, thus, constitute separate resource pools. The experiments reported in this dissertation were conceived within this model. They assume that attention is a substrate of working memory (WM). Specifically, the current set of experiments examined both the temporal limits of attention at one spatial location and the limits of WM consolidation in the production of concurrents.

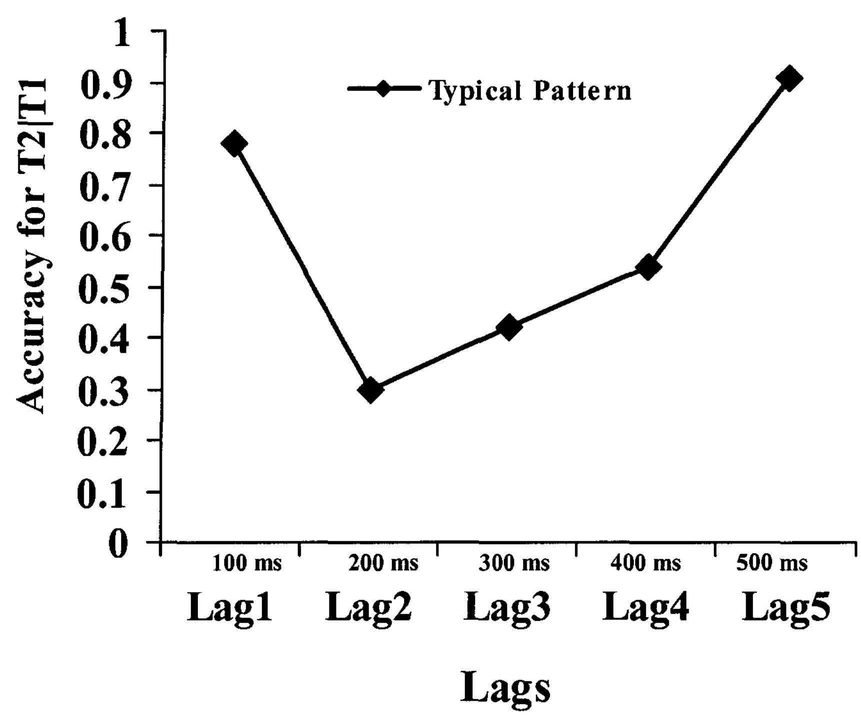
Correct identification and hence awareness of the most behaviorally relevant stimuli is an important adaptive role of the visual information processing system. As previously described, there are many restrictions to the system that limit the number of objects that can be processed at a given time (Marois & Ivanoff, 2005). The system can only selectively attend to a limited amount of information within a set amount of time. The capacity limitations of the information processing system include at least two widely investigated types of limitation (for review see Marois & Ivanoff, 2005). One limitation is that only three to four independent stimuli can be maintained in visual short term memory (VSTM; Luck & Vogel, 1997; Vogel, McCollough, & Machizawa, 2005; Sperling, 1960), although Alvarez and Cavanagh (2005) described this limitation in terms of the overall amount of detail to be held in memory. A second limitation is a temporal one: it takes time to consolidate a stimulus in VSTM in order to consciously identify the stimulus (Chun & Potter, 1995).

Temporal Limits of Attention: Attentional Blink

The temporal constraint of attention is attributed to the fact that selection and consolidation take approximately 500 ms (e.g., Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992), as demonstrated by the *attentional blink* (AB) paradigm. Typically, in the AB paradigm, participants are asked to detect two targets embedded in a rapid serial visual presentation (RSVP) stream of stimuli (e.g., letters, words or symbols). Results have consistently demonstrated that given identification of the first target (T1), identification of the second target (T2) is severely degraded if its temporal proximity to the T1 is between 150 ms to approximately 500 ms (Raymond et al., 1992). Hence, Raymond et al. have labeled the T1-triggered effect on T2 an AB because it is as if the attentional system blinks and cannot process T2. If T2 occurs immediately after T1, then identification for both targets is high. This increased identification of T2 given T1 (T2|T1) at lag 1 was labeled the Lag 1 sparing effect and it contributes to the U-shaped pattern of results found in AB studies as shown in Figure 1.

Raymond et al. further hypothesized that the processing time necessary for correct identification of the first target must exceed a T1 to T2 interval of 450 ms because the onset of the second target before then showed a deficit. They assumed that the deficit was the result of interference from attentional suppression. Attentional suppression, in their view, can be conceptualized via the analogy of a shut-and-locked attentional gate. Selection of T1 leads to shutting the gate, which remains closed for several hundred milliseconds. According to Raymond et al., the attentional gate is closed between 150-300 ms after T1 is presented and this shutting of the gate is responsible for the T2|T1 deficit. Raymond et al. explained Lag 1 sparing by stating that T1 and T2 are processed together (i.e., both get through the gate before it is shut). Furthermore, because at some time after 300 ms the gate can be reopened, recovery from the AB is produced and there is an increased probability of correct identification of T2 when presented at the reopening of the attentional gate.

Figure 1. Typical Attentional Blink U-Shaped Pattern for T2|T1 as a Function of Lag.



Several other explanations of the AB have focused on impairments in VSTM consolidation that is assumed to occur serially (e.g., Chun & Potter, 1995; Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005). These explanations suggested that T2 does not undergo consolidation because T1 is still undergoing consolidation. From this view, Awh, Serences, Laurey, Dhaliwal, vander Jagt, and Dassonville (2004) provided three crucial conditions that need to be met in order to produce an AB: (1) The T1 task must demand sufficient resources to deny subsequent stimuli access to stage 2 processing, (2) the T2 task must require sufficient resources to show the effects of the T1 processing load, and (3) T1 and T2 must be adequately masked. In this account, what determines the magnitude of the AB is the extent to which these three conditions are met. For example, a more difficult T1 task should increase the magnitude of the AB whereas failure to fully mask T1 should decrease the magnitude of the AB. The two-stage model can also account for Raymond and colleagues' interpretations of the AB in that it too suggests that when T2 is a lag 1 item, then both targets are likely to be processed together. Regardless of which model best explains the AB deficit, there is no argument about the U-shaped pattern it typically produces (see Figure 1). This reliable AB pattern lends itself as a tool for exploring the temporal limits of attention without testing the spatial limits of attention.

Experimental Design Overview

In this dissertation, I use the term *attention* to mean something associated with the mechanism(s) of selection into conscious processing. With behavioral paradigms, determining if a stimulus gained access to awareness is accomplished by requiring report of the stimulus. A series of behavioral experiments were conducted in order to more thoroughly explore this direct relation between attention and awareness in grapheme-color synesthesia, as measured via conscious report.

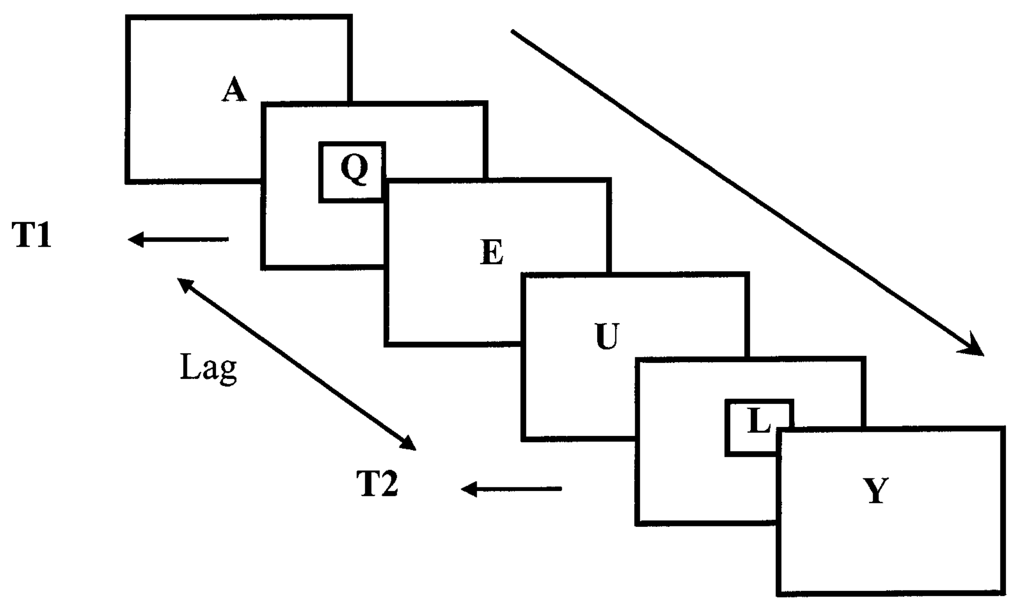
Specifically, in a set of experiments I examined the role of temporal attention and memory consolidation in the production of *concurrents* for an individual with grapheme-color synesthesia by manipulating the stimulus characteristics used in an AB paradigm and a VSTM change detection paradigm. The AB experiments (Experiments 1 and 2) examined the effects of temporal attention (selection and identification) on the processing of inducer stimuli. The VSTM experiments (Experiments 3 and 4) examined the memory for non-inducer and inducer stimuli under different types of memory load. The AB and VSTM experiments were used to provide an understanding of the memory consolidation process for inducer stimuli.

CHAPTER 2: EXPERIMENT 1

The focus of the AB experiments was on testing the temporal limits of attention for an individual with grapheme-color synesthesia. The AB phenomenon is a useful tool for researchers exploring the temporal limits of attention for information presented in one spatial location (i.e., in RSVP procedures all stimuli occur at one spatial attention location, but the nature of the stimuli and the temporal characteristics of the RSVP stream can vary). Two AB experiments were conducted. Experiment 1 was specifically designed to measure the magnitude of the standard AB for a grapheme-color synesthete. In a typical AB task, participants must search for two colored (e.g., red) letters that are embedded in a stream of black letters. However, presentation of physically colored targets (e.g., the letter *A* presented in red ink) among black distractors (e.g., letters of the alphabet presented in black ink) poses a problem with synesthetes because the ink color of the targets may or may not be congruent with the concurrent colors induced by the targets and the black distractors also will produce concurrent colors. Therefore, a different task was developed to measure the standard AB for the synesthete. In Experiment 1, controls and synesthetes were asked to identify the two black letters in an RSVP stream of black letters that were surrounded by a red box as shown in Figure 2. Letters that induce the color red for the synesthete were not used as targets or distractors for Experiment 1.

The duration of the AB could be informative about whether production of concurrents is a stage 1 or stage 2 process. Theoretically, it is possible for concurrent processing to occur prior to target identification. If *inducers* and *concurrents* are bound entities before synesthetes attend to and become aware of the inducer stimulus (i.e., the concurrent is a result of stage 1 processing), then the duration of the AB, which represents stage 2 processing, should not differ between synesthetes and controls. Similarly, if the concurrent is simply a feature represented in stage 1, like physical features are represented, then it would be consolidated along with the physical features. Luck and colleagues have shown that the number of features to be consolidated has no impact on consolidation time, so synesthetes should not differ in AB duration from controls (e.g., Luck & Vogel, 1997). It is also possible that the binding of *inducers* and *concurrents* is an automatic result of identification and therefore occurs after stage 2. An example of a post identification automatic process is automatic spread of activation after word identification (Neely, 1991). If this is the case, then the post identification activation of *concurrents* should not affect the duration of the AB. Finally, if concurrents are produced during the memory consolidation process (i.e., they are the result of stage 2 processing), then the memory consolidation process may be lengthened, which would affect the duration of the AB. That is, theoretically it is possible that the binding of *inducers* and *concurrents* requires additional stage 2 resources. Thus, a longer AB should occur only if concurrent processing is part of the identification process.

Figure 2. Schematic Representation of the Procedure used in Experiment 1.



Experimental Predictions

The letter to letter stimulus onset asynchrony (SOA) was set at 106 ms so that the resulting lag durations would fall within those typically used in AB studies. That is, performance for T2|T1 should be the highest at lags 1 and 5, the worst at lags 2 and 3, and it should begin to recover by at least lag 4. If production of concurrents requires a certain level of conscious attention (i.e., it reflects post stage 2 processing), then when the target is indicated by a surrounding box, the concurrent colors should not influence performance given that it is not necessary for successful completion of the task; that is, no difference is expected between individuals with synesthesia and controls because both should demonstrate a typical U-shaped AB pattern. If concurrents are activated as part of stage 1, then because the concurrent color does not place any limitations at stage 2, no difference between individuals with synesthesia and controls should be observed. However, if processing of concurrents occurs during stage 2, it could change the AB pattern in synesthetes even though the concurrent color is irrelevant to the task.

Method

Participants

Synesthete participant. One individual (S1) who has color-grapheme synesthesia for letters and digits volunteered as a participant. S1 is a left-handed male who is 31 years old. To assess S1's synesthetic concurrent experiences, S1 was asked to report the particular colors that matched the color concurrents on two separate testing sessions. The concurrents are shown in Figure 3. The testing sessions were separated by one week. Color matching was completed using a Pantone color palette available in ABOBE PHOTOSHOP 6.0 (Adobe Systems, Mountain View, CA). S1 also completed a structured synesthesia questionnaire developed by Rich, Bradshaw, and Mattingley (2005) to determine the relative frequency and characteristics of different types of synesthesia that S1 had experienced. The completed questionnaire is presented in Appendix A. S1 reported that sounds, temperature, smells, taste, and alphanumeric characters elicited his synesthesia for colors. S1 is classified as a developmental synesthete because has been aware of his synesthesia for as long as he can remember. S1 reported that he is unable to control his synesthesia. That is, S1 claimed that he is unable to prevent the concurrents from occurring. S1 was a native English speaker and had corrected to normal vision.

Figure 3. S1 Concurrent Colors for Letters and Digits.

B C D E

F

M

P Q

R S T

V W X Y Z

2 3 4 5 6 8 9

Control group. Thirty-one Iowa State University undergraduate students (16 men and 15 women, mean age = 24.5 years, *SD* =5.01) who reported not having synesthesia participated in the study in exchange for course credit. [1] All were native English speakers and had normal or corrected to normal vision.

Stimuli & Procedure

The stimuli consisted of letters from the English alphabet. Each participant was seated 60 cm in front of the computer screen. A chin rest was used to avoid head movements. At the start of each trial a fixation cross appeared at the center of the screen to indicate the beginning of a trial. The fixation cross remained on the screen for 200 ms and was followed by an RSVP stream of letters. Letters were presented in Courier New 18 point black font. Each letter was presented for 35 ms with an Inter-Stimulus-Interval (ISI) of 71 ms. Thus, the SOA or lag between letters was 106 ms. The length of the RSVP stream varied from 13 to 21 letters per stream. No letter was repeated within the stream. The T1 position in the RSVP stream varied between position 2 and 4. Five lags were used between T1 and T2: 106 ms (lag 1), 212 ms (lag 2), 318 ms (lag 3), 424 ms (lag 4), and 530 ms (lag 5). A red square box that extended two degrees around the target letters served as the target identifier. The red box was positioned two degrees from the targets in order to minimize masking effects. As an additional masking control, the red box and the letter targets always offset together (Enns, 2004). The RSVP stream consisted of black letters presented on a white background screen.

The task was to report the two letters (T1 and T2) surrounded by the red square boxes. Thus, at the end of the RSVP stream participants reported the identity of T1 and immediately after reported the identity of T2. Participants indicated their responses using a standard keyboard. The E-Prime software package (Psychology Software Tools, Inc., www.pstnet.com) was used for stimulus presentation and response collection. Instructions stressed keeping one's eyes focused on the center of the screen, which was the location of the RSVP stream.

Participants completed 15 practice trials. In the subsequent 105 experimental trials (21 trials at each lag), participants received accuracy feedback. Trials were self paced such that short breaks were allowed between blocks of five trials. Each block had one trial at each lag; the order of lags within a block was random. The entire session took approximately 30 minutes.

Results and Discussion

Plan of Analysis

An alpha level of .05 was used in this and all subsequent experiments. For each experiment, both analyses of variance (ANOVAs) and *Pairwise* t-test comparisons with *Bonferroni* adjustments for multiple comparisons were used for analyzing the control group data. These analyses established whether the expected pattern was found in the control group. Because an AB can only occur if T1 is identified for the AB experiments the main dependent variable was T2|T1 accuracy. In Experiment 1, the analyses answered three questions. First, did an AB occur? This was tested by assessing whether performance at lag 5, which represents non-blinked performance, was higher than performance at lag 2. Lag 5 was then compared to lag 3 to see if the AB was still occurring and, if necessary, to lag 4. Second, at what point does recovery from the AB begin? This was tested by assessing whether performance at lag 2 was lower than performance at lag 3 and, if necessary, at lag 4. Third, was there Lag 1 sparing? This was tested by assessing whether performance at lag 1 was better than at lag 2. All questions were directional and therefore all tests were one-tailed.

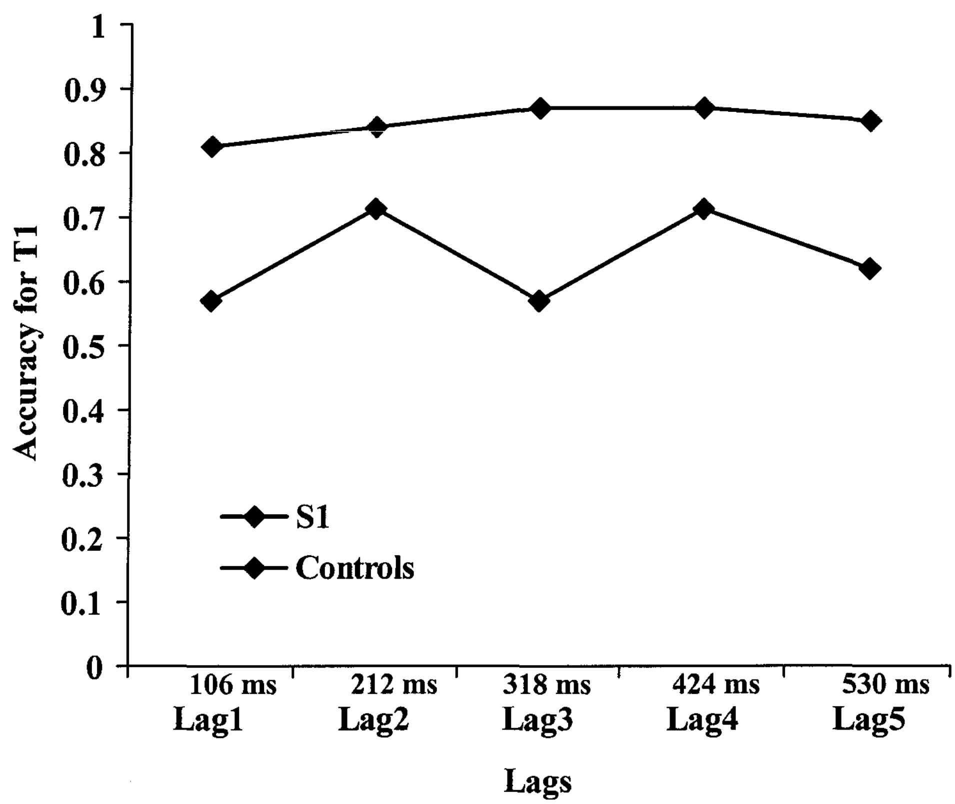
After examining the control group data, the synesthete data were examined using a within subject modified *t-test* to see if S1 showed the same pattern as the controls. For all these S1 comparisons, the standard deviation from the parallel comparison for the controls was used to compute the error term. The formulas are presented in Appendix B. This is an extremely conservative approach. For that reason, comparisons involving the synesthete data that yielded p values greater than .05 but less than .10 will be described as indicating a trend. The use of the control group standard deviation assumes that the variability in a synesthete group should be that same as the variability among controls. There is no theoretical reason to assume otherwise.

T1 Accuracy

Controls. Figure 4 shows identification of T1 as a function of T2 lag. A repeated measures ANOVA with lag as the independent variable showed no effect of lag. No effect was expected.

Synesthete. As shown in Figure 4, for S1 there appeared to be some variability in T1 accuracy over lag, but there were no reliable differences. T1 accuracy was analyzed to determine if there were any differences between the controls and S1. There was a trend for an overall T1 performance difference between S1 (M=.64) and controls (M=.85), t (30) = -1.74, SE= 0.12, $.05 < p < .10$, suggesting that the controls had higher T1 identification than S1. A difference between the groups in overall T1 identification was not expected. However, a post hoc explanation can be derived from the comments of S1. S1 reported that the task was "so overwhelming that it caused me a headache because letters and concurrents were flashing so rapidly." It appears that the presence of the concurrents made the task more difficult for S1.

Figure 4. Experiment 1 T1 Accuracy for Controls and S1 as a Function of Lag.



T2|T1 Accuracy

Controls. Figure 5 shows that correct identification of T1 produced a lag-dependent deficit in identifying T2 for the controls. A repeated measures ANOVA with lag as the independent variable was computed for T2|T1. There was a reliable main effect of lag, F (4, 120) = 37.46, MSe = 0.033, p < .0001. *Planned* comparisons examining the lag effect are reported in Table 1. As predicted, an AB was found for identification of T2|T1 at Lag 2 as indicated by the reliable difference between lags 5 and 2, $t\ (30) = 6.05, p < .0001$. There was also an AB at lag 3, $t\ (30) = 7.05, p < .0001$, and lag 4, $t\ (30) = -6.05, p < .001$. The AB was recovering at lag 3 because performance at lag 3 was greater than at lag 2, $t\ (30) = 7.05, p < .0001$. A Lag 1 sparing effect was also found for the control group such that accuracy for T1|T2 was higher at lag 1 than lag 2, $t\ (30) = 5.60, p < .0001$.

Synesthete. Visual inspection of the T1|T2 data shown in Figure 5 suggested a different pattern of results for S1 than for the controls: S1 did not appear to recover from the AB by lag 5. To test whether the AB recovery function varied between the synesthete and controls, the planned contrasts among the different lags were computed for S1 and are shown in Table 1. Lag 5 performance was higher than lag 2 performance, indicating the presence of an AB, $t\ (30) = 1.71, p < .05$. However, lag 5 performance was not reliably greater than lag 3 performance, which technically means that there was no AB at lag 3. However, performance at lag 3 was not reliably greater than performance at lag 2, nor was lag 4 performance reliably greater than at lag 2, both suggesting that recovery had not begun. Finally, performance at lag 1 was not reliably greater than performance at lag 2.

These statistical results are contradictory to the pattern observed and they may not provide a good explanation of the obtained pattern of performance across lags. Consider Lag 1 sparing. It was not reliable in the analysis, but clearly the difference between lags 1 and 2 is larger than the difference for controls. Basically, the test for Lag 1 sparing has no power. The lags 1 and 2 comparison has such a large error term that a difference score of at least .51 would be required for the difference to be considered reliable. That is, the size of the differences for S1 must be almost twice as the large as the difference for controls in order to be detected. Although a conservative test did not find a reliable Lag 1 sparring effect in the pattern of the S1's data, I compared S1's performance at lag 1 and at lag 2 to performance of the controls. There was no difference between controls and S1 at either lag, suggesting that there was Lag 1 sparing. The conservative test analysis suggests that there was an AB for S1, but that he is not recovered at 500 ms. That is, the recovery function of the AB observed is different for S1 as compared to the more typical AB pattern found in the controls and in previous AB studies in which recovery is pretty much complete at 500 ms.

Figure 5. Experiment 1 T2|T1 Accuracy Results for Controls and S1 as a Function of Lag.

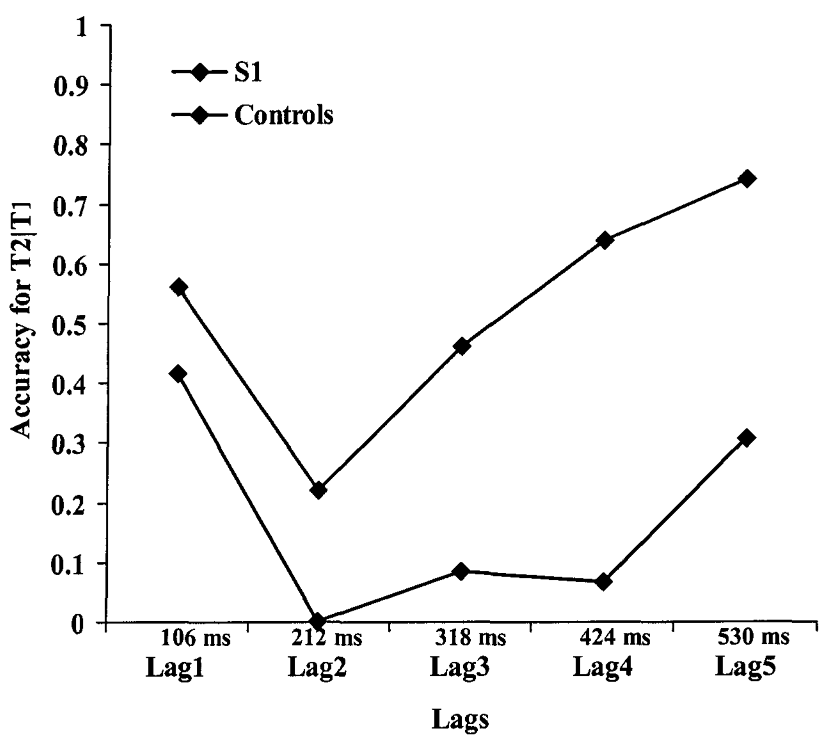


Table 1. Experiment 1 Planned Pairwise Comparisons for T2|T1.

Type of Test		*Controls*** Mean Difference	*Controls*** Std. Error	*Synesthete**** Mean Difference	*Synesthete**** Std. Error
AB Period					
5	2	.523*	.05	.308*	.18
	3	.282*	.04	.224	.25
	4	.106*	.03	.241	.15
AB Recovery					
2	3	-.242*	.04	-.083	.21
	4			-.067	.16
Lag 1 Sparing					
1	2	.336*	.06	.417	.30

**The mean difference is significant at the .05 level, one-tailed.*
***Bonferroni adjustment for multiple comparisons.*
****Modified t-test comparisons.*

Experiment 1 Replication & Extension for S1

The data of Experiment 1 suggested that S1 may have had a delayed AB recovery. In order to find the temporal parameters of the AB recovery for S1, S1 repeated the same task with an additional 3 lags (i.e., lags 1-8). Except for the addition of lags 6 (636 ms SOA), 7 (742 ms SOA), and 8 (848 ms SOA), no other changes were made. S1 completed a total of 168 trials, 21 trials at each lag, and 15 practice trials. As shown in Figure 6, the results from S1's new data replicated the delayed AB recovery shown by S1 in Experiment 1. A comparison between lag 8 of S1 and lag 5 of the control group showed no reliable difference, suggesting that S1 had completely recovered at lag 8. Lag 8 was used as the complete recovery point in the new comparisons. Because in Experiment 1 the controls showed an AB pattern with complete recovery at lag 5, the error term for the S1 comparisons involving lag 8 in the replication was the error term from the controls for lag 5.

Comparisons for S1 were computed and are shown in Table 2. There was an AB such that performance at lag 8 was reliably higher than at lag 2, $t\ (30) = 2.59, p < .01$. Performance at lag 8 was also higher than at lag 3, $t\ (30) = 2.46, p < .01$, lag 4, $t\ (30) = 2.22$, $p < .02$, lag 5, $t\ (30) = 2.73, p < .01$, lag 6, $t\ (30) = 2.22, p < .02$, and lag 7, $t\ (30) = 2.66, p < .01$. The tests to determine when the AB recovery began showed that performance at lag 2 was not reliably lower than at lags 3, 4, 5, 6, and 7. Thus, the comparisons confirmed the pattern suggested in Figure 5: S1 recovers from the AB at lag 8. The comparison testing whether S1 had a Lag 1 sparing effect (i.e., whether performance at lag 1 was greater than lag 2) was not reliable. However, as with the first experiment, when performance at lags 1 and 2 were compared to the control group, which did show Lag 1 sparing, there was no difference.

As in Experiment 1, the test for Lag 1 sparing was extremely conservative and with little power.

Figure 6. Replication and Extension of Experiment 1: Accuracy for T2|T1 for S1 as a Function of Lag with Control Data from Experiment 1.

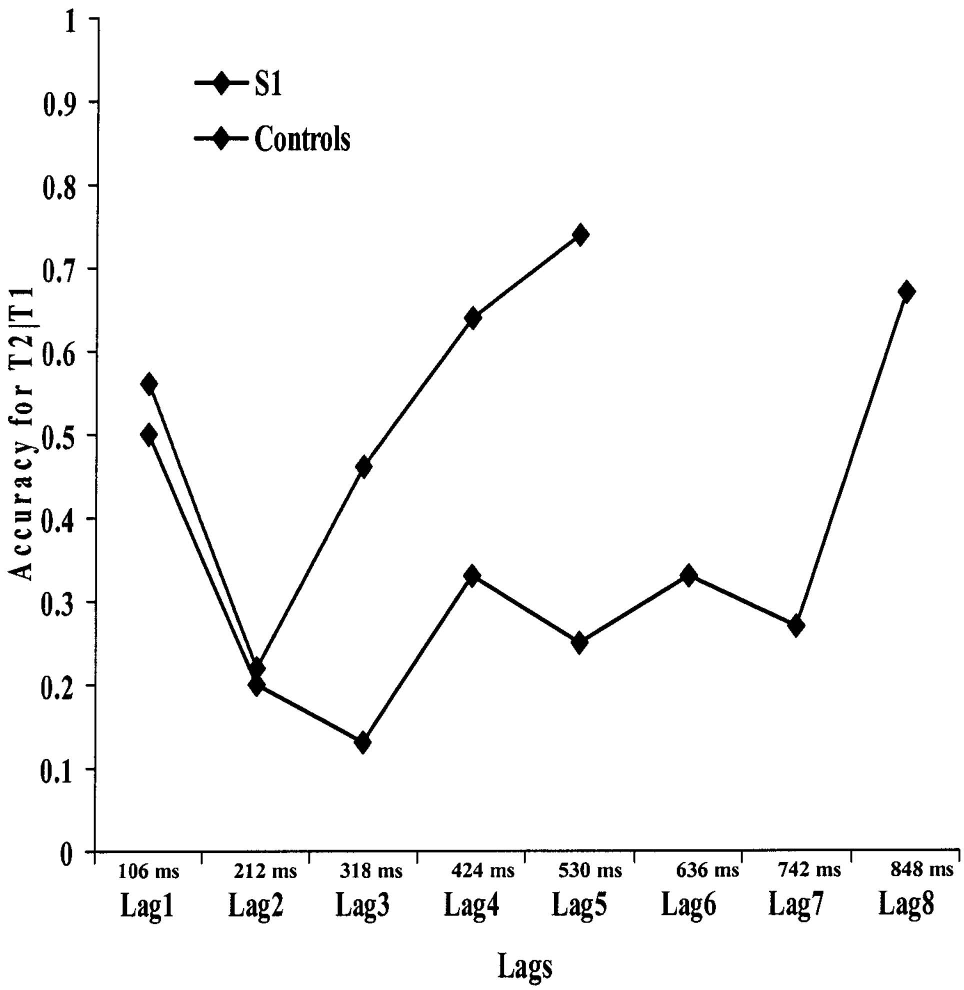


Table 2. Replication and Extension of Experiment 1: Planned Pairwise Comparisons for T2|T1.

		*Synesthete***	
Type of Test		*Mean Difference*	*Std. Error*
AB Period			
8	2	.467*	.18
	3	.542*	.22
	4	.333*	.15
	5	.417*	.15
	6	.333*	.15
	7	.400*	.15
AB Recovery			
2	3	.075	.21
	4	-.133	.18
	5	-.05	.18
	6	-.133	.18
	7	-.066	.18
Lag 1 Sparing			
1	2	.300	.30

**The mean difference is significant at the .05 level, one-tailed.*
***Modified t-test comparisons.*

Results for S1 from Experiment 1 and its replication and extension showed a longer AB period. Such results suggest that if targets are processed in a stage fashion, then concurrent processing is part of stage 2 processing. If concurrent processing were part of stage 1 so that concurrents automatically activated even when the concurrent was irrelevant to the task, then no difference should have been observed in the AB pattern because stage 1 processing has no limitations. The AB deficit is typically described as a post-perceptual deficit, that is, one that occurs after the completion of stage 1. Similarly, if concurrent processing occurred after stage 2, then no difference would have been observed in the pattern of the AB. Therefore a longer AB suggests concurrent processing is a stage 2 process. It is possible that the production of concurrents made the task more difficult for the synesthete. The increased difficulty may have produced a longer AB period.

Experiment 1 findings suggest that concurrents are obligatorily processed. The processing of concurrents does not appear to be interference free. That is, concurrent processing is not under voluntary control but it does demand resources. Concurrent processing does in fact demand some resources at the expense of other dimensions of more complex task demands. Paap and Ogden (1981) showed that obligatory processing and interference-free processing can be dissociated from what is typically referred to as an automatic process. The distinction needs to be made because the intentionality and capacity-free criterion that are typically used to characterize automaticity do not always co-occur. That is, a process maybe obligatory and yet capacity demanding. Concurrent processing in synesthetes (at least in S1) appears to be an obligatory and capacity demanding process.

CHAPTER 3: EXPERIMENT 2

Experiment 2 was designed to examine the role of concurrent color congruency in the AB. According to the two-stage models of information processing, T2 cannot be consolidated while T1 is still undergoing consolidation (Chun & Potter, 1995). However, as the interval between T1 and T2 increases, T1 consolidation is more likely to be completed before the onset of T2 in the RSVP stream. The results of Experiment 1 suggested that color-grapheme synesthetes may have an extended AB. The delay was attributed to production of concurrents during stage 2. In Experiment 1, target color was irrelevant to target status because target status was indicated by a box. An interesting question is whether the same pattern would occur in a more traditional AB task in which the targets were the two colored digits in an RSVP stream. Of particular interest is whether targets presented in colors that are congruent or incongruent with the concurrents for synesthetes would differently affect the consolidation process.

In Experiment 1, all letters were presented in black ink, so except for F and Z, whose concurrents were black, targets and distractors were presented in "incongruent" colors. In Experiment 2, half of the targets in the RSVP stream were presented in their congruent-to-the-concurrent ink colors and half were presented in an incongruent-to-the-concurrent ink color. Participants were asked to identify two colored digits embedded in an RSVP stream of black digits, which themselves can be considered as being in an incongruent-to-the concurrent color. The colors of the incongruent target digits were chosen randomly from the set of concurrents reported by the synesthete in the experiment. Target digits were presented in nine different colors: one color for each digit because each digit induced a unique color for the synesthete.

Congruency was manipulated to examine the processing of inducer stimuli when they are presented in the congruent or incongruent concurrent color. Congruency of targets should not affect the pattern of the AB for controls because controls do not have any concurrents. Therefore, the AB pattern for controls should be similar to the U-shaped AB pattern observed in Experiment 1. The results of Experiment 1 suggested that for S1, concurrent processing is part of stage 2 processing. As already noted, almost all distractors and targets in Experiment 1 were in incongruent-to-the-concurrent in color. It is possible that the resulting incompatibility between physical color and concurrent color may have produced Stroop-like interference, resulting in delayed consolidation. It also has been hypothesized that the interference found in the Stroop effect may be due to an increase in the attentional dwell time on the stimulus as a result of the incongruency (MacLeod, 1991). So the longer AB could be the result of taking more time to disengage from incongruent targets. Regardless of the cause of the interference, if the interference is responsible for the delay, no delay should occur when the target is presented in a congruent-to-the concurrent color. In fact, presentation of a stimulus in its concurrent color for a synesthete may facilitate concurrent processing or consolidation time or both. If so, then S1 should not have a delayed AB recovery for congruent targets; S1 and the control group should show the same AB pattern. For incongruent targets, however, S1 should continue to show the delayed recovery reported in Experiment 1.

Experimental Predictions

Experiment 2 was designed to test the effects on the AB of concurrent color congruency of targets. Theoretically, if concurrents are produced as part of stage 1, then the duration of the AB for congruent targets should not vary between controls and S1. If it is the production of the concurrent in stage 2 and not the incongruency that is responsible for the delayed AB recovery found in Experiment 1, then these should be an extended AB and target congruency should have no effect on performance. If it is dealing with the fact that there are two incongruent colors that produces the delayed AB recovery, perhaps by increasing attentional dwell time, then S1 and controls will be similar on T1 congruent trials but not T1 incongruent trials. That is, a longer AB period than the controls should be observed for S1 when T1 is incongruent regardless of T2 congruency. If congruent concurrent color targets are easier to process than incongruent targets for S1, then a more similar AB pattern among controls and S1 should be observed when T1 is congruent, regardless of T2 congruency.

Method

Participants

Synesthete participant. The same color-grapheme synesthete as in Experiment 1 volunteered as a participant. S1 reported concurrents for digits, which are shown in Figure 3.

Control group. Eighteen Iowa State University undergraduate students (10 men and 8 women, mean age = 27.5 years, *SD* =7.01) who reported not having synesthesia participated in the study in exchange for course credit. All were native English speakers and had normal or corrected to normal vision.

Stimuli & Procedure

The stimuli consisted of digits ranging from one to nine. Zero was not used as either a target or a distractor because it induced a clear transparent type of white color in S1. All digit distractors were presented in black ink. Targets were presented in either their congruent-to-the-concurrent ink colors or incongruent-to-the-concurrent ink colors, so that there were four conditions: T1 Congruent – T2 Congruent, T1 Congruent – T2 Incongruent, T1 Incongruent – T2 Congruent, and T1 Incongruent – T2 Incongruent. An incongruent color was randomly selected from the set of colors serving as congruent colors for the remaining digits.[2] The digit number two was not used as a target because it induced a black concurrent color for S1. There were 12 to 22 digits in the RSVP stream. T1 randomly occurred in position 6 - 10 of the stream and T2 was always followed by four distractors. The digit distractors were randomly selected with the constraint of not repeating any digits during the T1 – T2 intervals and never immediately repeating a digit. Target digits were not used as distractor digits on any given trial. The task was to report the two colored digits embedded in an RSVP stream of digits presented in black ink.

The same experimental parameters were used as those in Experiment 1 except that digits were used as stimuli and digit color rather than a surrounding box indicated the targets. In addition, the background display was set to gray in order to enhance the differences among the colors. Instructions stressed keeping one's eyes focused on the center of the screen, which was the location of the RSVP stream. Participants completed 15 practice trials. Controls completed 280 experimental trials (70 trials per congruency condition, 10 at each lag) and S1 completed 420 trials (105) per congruency condition, 15 at each lag). Participants received accuracy feedback on each trial. Trials were self paced such that short breaks were allowed between blocks of 28 trials (one at each combination of lag and congruency condition). The order of trials within blocks was random. The entire session took approximately 50 minutes for controls and 90 minutes for S1.

Results and Discussion

Plan of Analysis

The same general plan of analysis as in Experiment 1 was used; however, additional analyses were included to test for congruency effects. A 2 (T1: congruent concurrent, incongruent concurrent) x 2 (T2: congruent concurrent, incongruent concurrent) x 7 (Lag: 1, 2, 3, 4, 5, 6, 7) repeated measures ANOVA was computed for the control group data. For the controls, no congruency effects were expected. Therefore, after confirming that none occurred, the data from all conditions were collapsed over both T1 and T2 congruency. The collapsed data were analyzed. As in Experiment 1, three hypotheses were tested: Was there an AB? When does recover from the AB begin? Was there Lag 1 sparing? The collapsed control data were used in comparisons involving S1. The original plan was to look at S1 performance as a function of both T1 and T2 congruency. However, as will become apparent, the task was very difficult, yielding many fewer than expected T2|T1 data points for each condition. Given that *a priori* predictions for S1 were made about the effects of T1 congruency on the AB pattern, the S1 data were examined collapsing over T2 congruency.

T1 Accuracy

Control group. Figure 7 shows T1 accuracy as a function of lag for the control group and S1. A repeated measures ANOVA for T1 identification for controls showed a reliable main effect of lag, $F\ (6, 102) = 5.40$, $MSe = 0.06$, $p < .0001$. No lag effect was predicted. Post hoc comparisons showed that T1 performance at early lags (i.e., lags 1 ($M = .43$) and 2 ($M = .44$)) was lower than at the later lags (i.e., lags 5 ($M = .54$) and 7 ($M = .53$)). Also unexpected was the overall low level of T1 identification. Changing from letters to digits (so that it was necessary to repeat distractors) and defining targets in terms of color made the task much more difficult.

Synesthete. Figure 7 also shows S1 performance collapsed over congruency. Although there were no reliable differences between overall T1 accuracy for S1 (M =.43) and controls (M = .49), S1 showed somewhat more variability for T1 performance as a function of lag. Figure 8 shows T1 accuracy as a function of T1 congruency and lag for S1 and controls. Clearly, there was more variability in S1's T1 performance. However, it did not systematically vary as a function of lag. In fact, for S1 overall performance on T1 congruent trials (M = .44) was similar to performance to T1 incongruent trials (M = .42).

Before turning to the T2|T1, it should be noted that T1 accuracy was unexpectedly low. It appeared to be lower than in Experiment 1. Because digits were used, there were only 8 potential targets in this experiment while in Experiment 1, in which letters were used, there were 20 potential targets. While this means that participants were more likely to be correct from guessing, it also meant that there was repetition of digits within the RSVP stream, which may have increased difficulty. Another possibility is that the change in background from white to gray may have had an effect. The change was made so that the colors would be easier to see. It may be that while the colors were easier to see that the shapes (i.e., digits themselves) were not. Finally, in Experiment 1 all targets were indicated by the same set of features, a red box surrounding the target, in Experiment 2 the feature defining the targets was that they were not black. Each was in color, but the colors differed. The red box in Experiment 1 may have been a more salient target cue than the set of colors used in Experiment 2.

Figure 7. T1 Accuracy as a Function of Lag for Controls and S1.

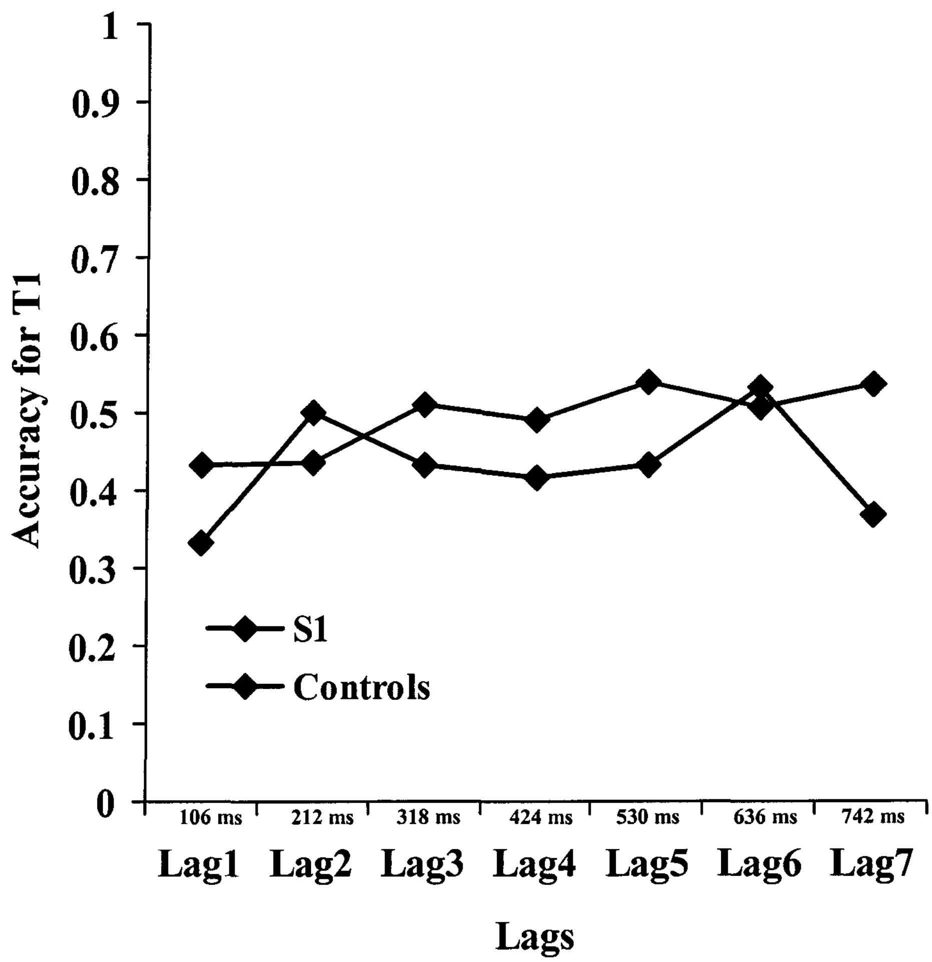
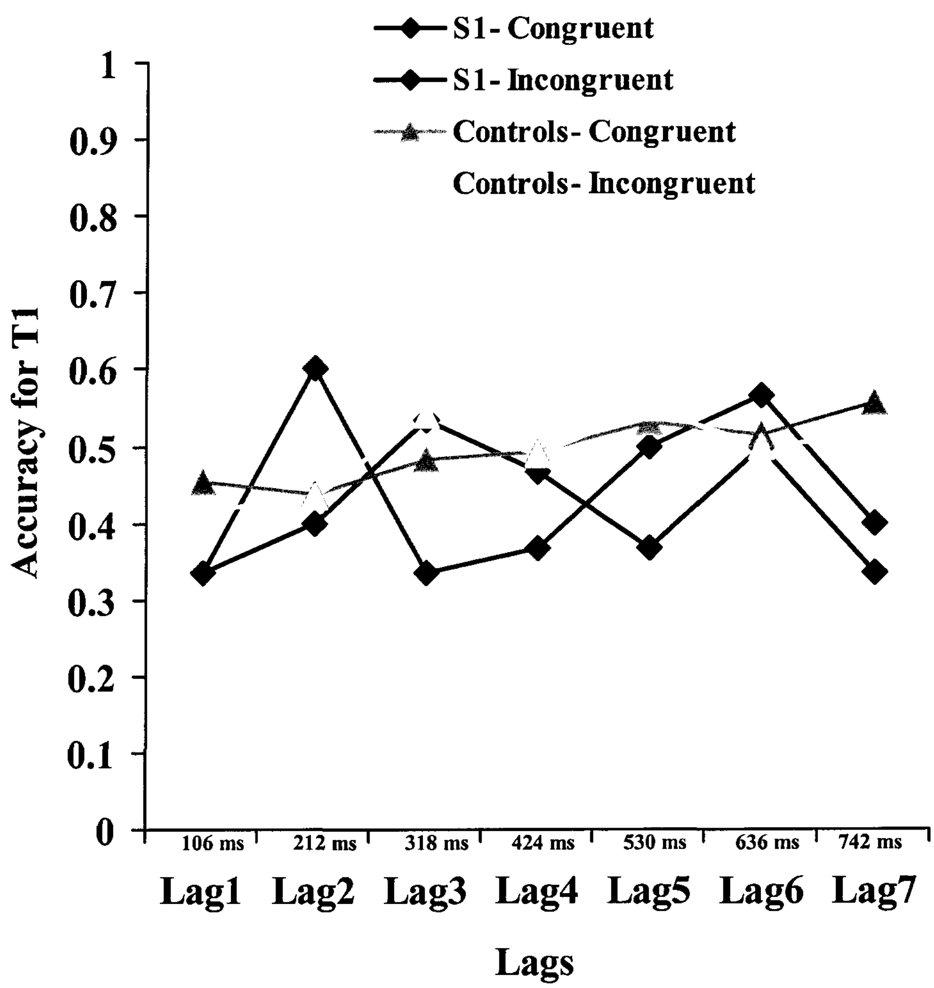


Figure 8. T1 Accuracy as a Function of Lag and T1 Congruency for Controls and S1.



T2|T1 Accuracy

Controls. Figure 9 shows T2|T1 accuracy as a function of lag for the control group. A 2 (T1: congruent, incongruent) x 2 (T2: congruent, incongruent) x 7 (Lag: 1, 2, 3, 4, 5) repeated measures ANOVA on the control group data showed a reliable main effect of lag, $F(6, 96) = 21.29$, $MSe = 0.06$, $p < .0001$. That is, correct identification of T1 produced an overall lag-dependent deficit for identifying T2 regardless of T1 and T2 congruency. As expected for the controls there were no reliable effects of either T1 or T2 congruency, so the pairwise comparisons were done on the collapsed data. Table 3 shows the pairwise comparisons that were computed to test for the AB period, for AB recovery, and for Lag 1 sparing. To test for an AB, lag 7, which should represent complete recovery, was compared to lag 2. Performance at lag 7 was reliably higher than performance at lag 2, $t(18) = 5.32$, $p < .0001$, establishing that there was an AB. Lag 7 was then compared to other lags to see when there was no longer a reliable AB. Performance at lag 7 was reliably higher at lag 3, $t(18) = 5.98$, $p < .0001$, and lag 4, $t(18) = 3.34$, $p < .001$, but not lag 5.

To test for the point at which AB recovery begins, lag 2 performance was compared to lag 3, then lag 4, and lag 5. Lag 2 performance was reliably lower than lag 5 performance, $t(18) = 6.03$, $p < .0001$. These comparisons revealed that controls had a delayed onset of recovery such that recovery appeared to begin at lag 5. This longer AB period is indicative of a more difficult target task for the controls. Finally, a Lag 1 sparing effect was found such that lag 1 performance was higher than lag 2 performance, $t(18) = 4.66$, $p < .0001$.

Figure 9. T2|T1 Accuracy for Controls Collapsed Across All Four Congruency Conditions as a Function of Lag.

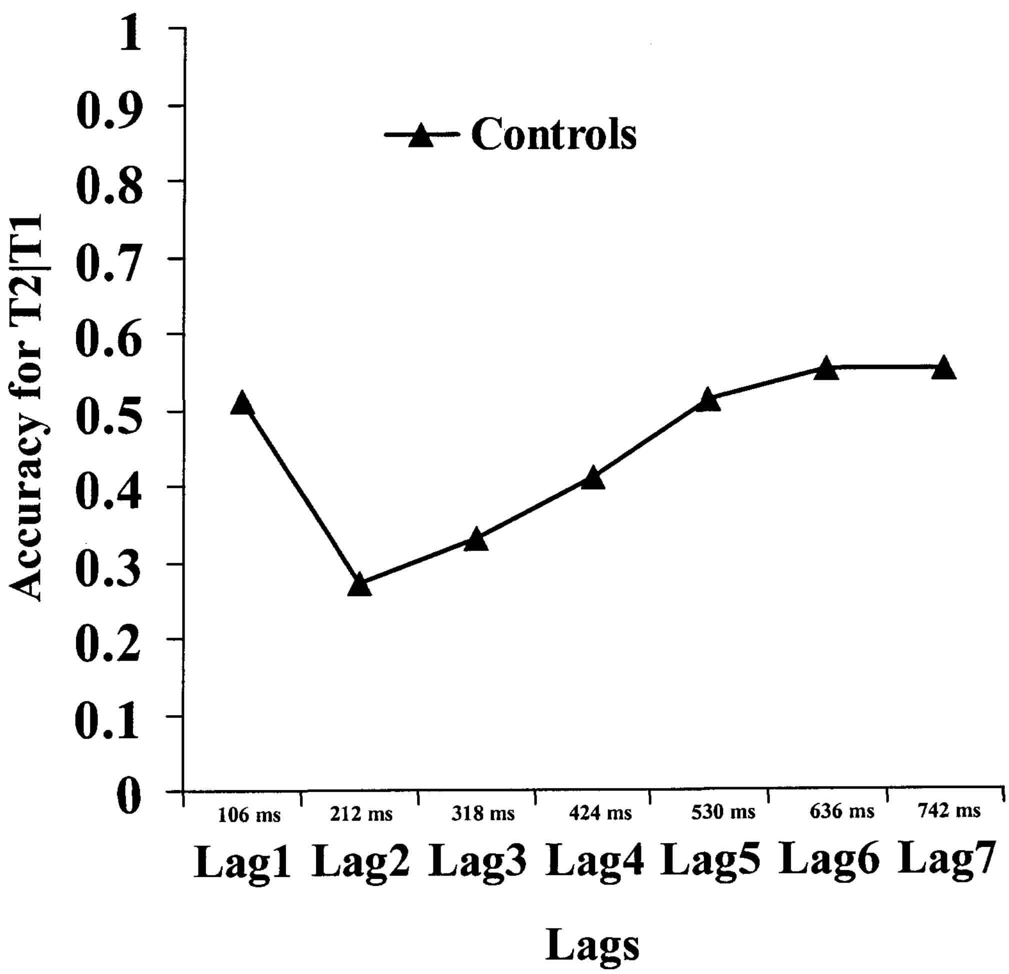


Table 3. Experiment 2 Planned Pairwise Comparisons for T2|T1 Accuracy for Controls Collapsed Across Conditions.

Type of Test		*Mean Difference*	*Std. Error*
AB Period			
7	2	.266*	.05
	3	.236*	.04
	4	.167*	.05
	5	.052	.03
AB Recovery			
2	3	-.040	.04
	4	-.108	.04
	5	-.241*	.04
Lag 1 Sparing			
1	2	.233*	.05

**The mean difference is significant at the .05 level, one-tailed.*
Bonferroni adjustment for multiple comparisons.

Synesthete. When the data were conditionalized as a function T1 and T2 congruency, S1 had very few trials per lag and the results showed inconsistent patterns with extremely high variability. S1's T2|T1 data as a function of the four combinations of T1 and T2 congruency are shown in Appendix C. In fact, the range of the number of observations per condition per lag was 2-10 out of the possible 15 trials for S1. Because the focus was on T1 congruency and different predictions were made about T1 congruent and T1 incongruent trials, the data were collapsed over T2 congruency. This increased the number of observations at each lag to a minimum of 10. This increase should increase the power to detect differences for S1 as a function of T1 congruency and lag.

Figure 10 shows T2|T1 accuracy as a function of lag and T1 congruency for S1 and the controls. The data are collapsed over T2 concurrent congruency (congruent, incongruent). Table 4 shows the planned comparisons for S1. As previously mentioned, the T2|T1 accuracy data collapsed over T1 and T2 congruency from the controls was used for all the comparisons for S1. However, the data for the controls are shown in Figure 10 as a function of T1 congruency to demonstrate that congruency does not affect performance for controls.

The first set of comparisons tested for an AB for S1 on T1 congruent trials. Performance at lag 7 was reliably higher than performance at lag 2, $t\ (18) = 5.32, p < .0001$, lag 3, $t\ (18) = 4.66, p < .0001$, lag 4, $t\ (18) = 4.66, p < .0001$, lag 5, $t\ (18) = 2.4, p < .0001$, and lag 6, $t\ (18) = 1.88, p < .04$. These results showed that for S1 the processing of targets presented in their concurrent colors produces an extended AB period. The second set of comparisons tested at what point recovery from AB began. Performance at lag 2 was not reliably lower than performance at lag 3, lag 4, lag 5, or lag 6, suggesting that recovery did not actually begin until lag 7. However, once again, the problem appears to be lack of power because S1's data are almost identical to those of the control group over lags 2 - 6. A Lag 1 sparing effect was found such that performance at lag 1 was higher than performance at lag 2, $t\,(18) = 1.84, p < .05$.

The data for S1 on T1 incongruent trials showed quite an unexpected pattern. The prediction was that S1 generally would have more difficulty on T1 incongruent than T1 congruent trials and that the pattern would replicate the pattern found in Experiment 1. Neither prediction was statistically confirmed. Performance at lag 7 was not reliably different than performance at lag 2, $t\,(18) = 1.29, p > .10$, so statistically, there was no evidence of an AB for T1 incongruent trials. However, the shape of the curve suggests that an attenuated AB did occur, with recovery beginning at lag 3 and being complete at lag 5. More surprising is that overall T2|T1 performance on T1 incongruent trials was higher than on T1 congruent trials. When T1 was presented in an incongruent concurrent color, S1 appeared to recover faster from the AB. S1 was simply better at the task when T1 was in an incongruent-to-the-concurrent color than when T1 was in a congruent-to-the-concurrent color.

Clearly, for both controls and S1 when they used colors to select a target the processing of targets was not the same as it was in Experiment 1 when color was not a defining target characteristic. The task became much more difficult. The finding that performance for a synesthete is enhanced when T1 is in an incongruent color, however, is perplexing. Further research is needed to replicate these effects.[2] An experiment in which all targets and distractors are presented in different colors and the defining target characteristic is not color needs to be conducted. Such an experiment would test the effects of target color congruency without having to use the actual color as the feature that defines target status.

Figure 10. T2|T1 Accuracy for S1 and Controls Collapsed Across T2 Congruency as a Function of T1 Congruency and Lag.

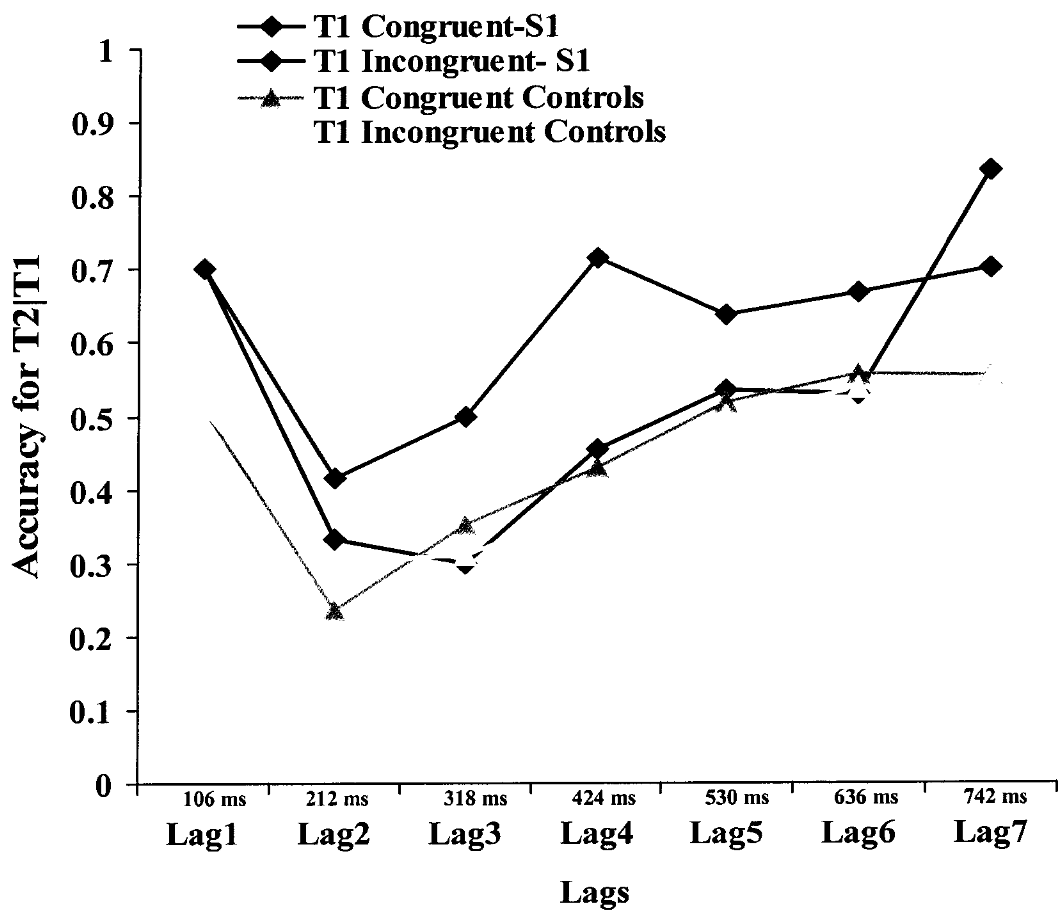


Table 4. Experiment 2 Planned Pairwise Comparisons for T2|T1 as a Function of T1 Congruency and Lag for S1.

		T1 Congruent		***T1 Incongruent***	
Type of Test		*Mean Difference*	*Std. Error*	*Mean Difference*	*Std. Error*
AB Period					
7	2	.500*	.22	.283	.22
	3	.533*	.15	.200	.15
	4	.379*	.19	-.014	.19
	5	.300*	.14	.064	.14
	6	.300*	.16	.034	.16
AB Recovery					
2	3	.033	.17	-.083	.17
	4	-.121	.19	-.298	.19
	5	.200	.19	-.220	.19
	6	-.196	.16	-.250	.16
Lag 1 Sparing					
1	2	.367*	.20	.283	.20

**The mean difference is significant at the .05 level, one-tailed. Modified t-test comparisons.*

Results from the AB experiments suggest that consolidation of inducer stimuli for synesthetes is different from consolidation for nonsynesthes and that for synesthetes consolidation of inducer stimuli presented in incongruent concurrent colors is different than consolidation of inducer stimuli presented in congruent concurrent colors. In Experiment 1 target stimuli were presented in black ink and therefore were incongruent except for the two letters that induced black concurrents. Under these conditions, S1 showed delayed recovery from the AB, which was interpreted as indicating a longer consolidation time. The AB results of Experiment 1 provide evidence that when stimuli are presented at a known location but under conditions testing the temporal limits of attention, concurrent activation demands resources even at the expense of the task demands. Experiment 1 was indicative that concurrent processing is a stage 2 process, that is, concurrent processing requires attention. In Experiment 2, targets were presented in the ink color that was congruent with the concurrent color on half of the trials and on those trials the recovery function for S1 looked like the recovery function for the controls. That is, when S1 processes stimuli under conditions more similar to those experienced by the control group, who do not have concurrents, S1 performs similarly to the control group.[3]

In Experiment 2, target color was important because the task was to report the identity of two colored digits embedded in an RSVP stream of black digits. The change between Experiments 1 and 2 in how target status was determined affected performance for both the controls and for S1: Identification of T1 was more difficult than it was for Experiment 1. In fact, the control group showed an overall longer AB period than the one found in Experiment 1. Although no direct statistical comparisons were made between experiments, the comparisons showed that recovery began for controls at lag 3 in Experiment

1 and at lag 5 in Experiment 2. Awh et al. (2004) also showed an extended AB as a function of increased T1 difficulty.

In Experiments 1 and 2, the AB procedure was used to examine the temporal limits of selective attention. Target consolidation time was measured when it was necessary to select the targets from a set of distractors. In Experiments 3 and 4 target selection is no longer required because there are no distractors. All stimuli are targets; only consolidation and maintenance of targets is required. Specifically, in the next two experiments the focus changed to examining the capacity of WM, that is, measuring how many consolidated items can be maintained at once. The question was whether the more demanding consolidation process apparent in synesthetes produces a more capacity demanding representation. In order to determine whether synesthetes vary from controls in the number of items that can be maintained in WM when no distractors are present, the change detection paradigm employed by Vogel et al. (2001) was used. Experiments 3 addressed whether the WM capacity for S1 and controls is the same when inducers are not involved. Experiment 3 established that the capacity of WM is the same for S1 and controls when no concurrents are involved for S1. Experiment 4 examined whether the latter is true when concurrents are involved. That is, Experiment 4 addressed whether the synesthete has the same WM capacity as controls when the representations include inducer stimuli for S1.

CHAPTER 4: EXPERIMENT 3

Based on data from the AB paradigm, it has been argued that WM consolidation for each target selected from the AB stream takes approximately 500 ms under conditions in which the temporal limits of selective attention are tested (Chun & Potter, 1995; Raymond et al., 1992). Vogel, Woodman, and Luck (2001) suggested that using the duration of the AB as an estimate of consolidation time for several objects may overestimate the actual time. It may be that more items could be consolidated within 500 ms if each item was encoded without the need for selection among distractor items. Rather, one needs to examine how many items that are presented at once and that are fully encoded can be consolidated WM. Vogel and colleagues recommended using a visual change detection paradigm to determine a better estimate of the number of items that can be consolidated into durable WM representations.

In an effort to provide corroborating evidence about the role of visual selective attention and WM in synesthesia, two VSTM experiments were designed. The VSTM experiments were specifically designed to estimate the number of items that can be consolidated by an individual with grapheme-color synesthesia and to determine whether there is a difference when the items being consolidated are inducer stimuli. The objective of Experiment 3 was to obtain the relative number of items that are not *inducers* that can be consolidated in durable WM representations under experimental parameters that are typically used to estimate WM capacity. The objective of Experiment 4 was to obtain the relative number of *inducer* items that can be consolidated in durable WM representations when the verbal and visual-spatial substrates of WM are loaded with another task. The primary aim was to determine if the numbers of items that can be consolidated is the same for *"physical* *colors"* as it is for stimuli that induce *"concurrent colors."* In Experiments 3 and 4, the number of items that can be of consolidated information was measured with a change detection paradigm.

The VSTM task developed by Vogel et al. (2001) was used to test the capacity of WM. In the Vogel et al. VSTM task, participants were presented with a sample array of one to eight colored squares (100 ms), followed by a 900-ms blank interval, and a 2000-ms test array that was the same as the sample array on 50% of the trials and on the remaining 50% of the trials the test array was the identical except for one feature change (e.g., a blue square turned into a red square). Only a color change was possible and not a location change. Participants were then asked to make a same-different judgment to the test array. In addition, 1000 ms before the onset of the sample array, participants were shown two digits (500 ms presentation) and were encouraged to subvocally rehearse the digits in order to report them at the end of the test array. Results in this task showed that VSTM has a storage capacity of three to four items and that the verbal load did not interfere with memory for the test array of colored squares. These results were consistent with Baddeley's WM model (Baddeley, 1998), which suggests that verbal WM and visual-spatial WM can operate independently without interference.

Experiment 3 was a replication of the Vogel et al. (2001) experiment with one exception. Instead of rehearsing digits, participants were asked to rehearse two four-letter words. The words were selected from a set of ten that had been used previously to assess verbal memory capacity (Dark & Benbow, 1991). The words were needed instead of digits because using digits would presumably activate concurrent colors for the synesthete and the concurrent colors may interfere with the processing of the colored squares. The two four-letter words, which were used in place of the digits from the original VSTM paradigm, should be stored in verbal WM just as digits would be. Therefore, just like the digits, a memory load of two words should not interfere with the same/different judgment about the test array.

Experimental Predictions

Based on Vogel et al. (2001), it was predicted that there should be no difference on the same/different test array judgment when holding two or three colored squares in WM and that accuracy should be very high. Accuracy for the test array should begin to decline at a set size of four and accuracy should be the lowest when holding eight colored squares in WM. No differences between the controls and the grapheme-color synesthete were expected for the same/different judgments on the test array. That is, controls and the grapheme-color synesthetes should have similar WM capacities. There is no theoretical reason to assume differences exist in WM capacity between the normal population and individuals with grapheme-color synesthesia for stimuli that do not induce concurrents.

Method

Participants

Synesthete participant. S1, who has color-grapheme synesthesia for digits, also volunteered as a participant.

Control group. Sixteen Iowa State University undergraduate students (5 men and 11 women, mean age = 23.5 years, *SD* = 4.0) who reported not having synesthesia participated in the study in exchange for course credit. All were native English speakers and had normal or corrected to normal vision.

Stimuli & Procedure

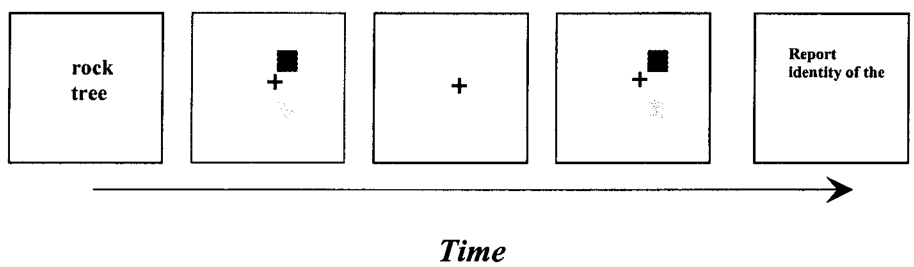
Colored squares that extended 0.65° x 0.65° of visual angle were used as stimuli. The colors used for each of the squares were chosen from the set of synesthetic concurrent colors induced from digits, as reported by S1, see Figure 3. The number of squares presented on any given trial varied randomly between a set size of 2, 3, 4, and 8 colored squares. This experiment was a replication of Vogel et al. (2001) with one exception: At the beginning of each trial instead of presenting two digits, two four-letter words appeared at the center of the screen for 500 ms (i.e., there was verbal memory load). As in Vogel et al., participants were encouraged to rehearse the words so that they would be able to report them at the end of the trial. The pair of words was selected from a pool of ten words that were matched for word frequency and concreteness and had previously been used to compare word span to digit span (Dark & Benbow, 1991). The set of words is shown in Table 5. The set consisted of only ten words so that across the experiment each word would be repeated as many times as would a set of 10 digits, which is what was used in the Vogel et al. study.

At the start of each trial, two words were presented for 500 ms, followed by a 200-ms presentation of a sample array of colored squares. The sample array was replaced by a black fixation cross (Courier New 18 point font) that remained at the center of the screen for 900 ms. The fixation cross was used to encourage participants to maintain eye fixation at the center of the screen. After the fixation, the test array of colored squares was presented for 2,000 ms. Figure 11 depicts the displays on a trial. On half of the trials, the test array was identical to the sample array. On the remaining half of the trials, one of the squares in the test array had a changed color. The location of the square and the set size of the array did not change, only the color. Participants were instructed to make a same/different response as quickly as possible while minimizing mistakes. Responses were recorded via a keyboard that had the number 1 key labeled "same" and the number 2 key labeled "diff." Immediately after the same/different judgment participants were prompted to type in the two words that were presented at the beginning of the trial. Participants completed 4 same and 4 different trials for each set size for a total of 32 trials (trial types were randomly ordered). In addition, participants completed 16 practice trials with accuracy feedback. The entire experiment was completed in 30 minutes. Participants were allowed to take breaks at any time between trials.

Table 5. Words used in Experiments 3 and 4.

	Mean	
	Concreteness	Frequency
Set Size		
Coin	581	10
Star	574	25
Rock	598	6
Nail	606	31
Door	600	75
Slip	448	19
Bowl	575	23
Tree	604	59
Book	609	193

Figure 11. Schematic Representation of the Procedure used in Experiment 3.



Results and Discussion

Plan of Analysis

In Experiment 3, set size was the independent variable and the dependent variables were accuracy for the test array and accuracy for the memory load task. The main hypothesis tested was whether the number items stored in WM affects performance differently for S1 and the controls. To test this hypothesis, first an ANOVA with set size (2, 3, 4, & 8) was computed for the controls to establish the expected pattern. Comparisons were then computed for set size. That is, set size 8, which was expected to be the most difficult, was compared with set sizes 2, 3, and 4. Next, S1's performance was compared to the control group for each set size, using a modified t-test employed in neuropsychology single case studies. It was developed for comparing a single case (e.g., neuropsychology patient) with a control sample (Crawford & Garthwaite, 2002).

Test Array Accuracy.

Control group. Figure 12 shows the set size effect for the controls and S1. For the controls, the mean accuracy to the test array was analyzed with an ANOVA with set size (2, 3, 4, & 8) as the independent variable. There was an overall effect of set size, $F\,(1, 45) = 9.70$, $MSe = 0.009$, $p < .0001$. As seen in Table 6, comparisons showed reliable differences between set size 8 and set size 4, $t\,(15) = 3.73$, $p <.001$. As in the Vogel el al. (2001) experiment, there was no reliable difference between set sizes 2 and 3. That is, participants can easily hold in memory 2 or 3 colored squares. Set size 4 did not differ from set size 3. Accuracy did not reliably decrease until set size 8. These results suggest that WM capacity under the conditions employed was not between 3 and 4, but likely between 4 and 8.[4] More levels of the set size variable would be needed to show an exact WM capacity.

Synesthete. The purpose of this experiment was to compare the WM capacity of S1 to the control. S1's performance was compared to the control group using the modified t-test. As predicted, S1's WM capacity was similar to that shown by the controls. Although, S1 was numerically higher than the controls at all set sizes, there were no reliable differences between S1 and the control group. Digit span was not measured for controls, but based on normative data, digit span is typically 7 + 2. S1 had a digit span of 10 which is at the upper range of the norms.

Figure 12. Accuracy for Test Array as a Function of Set Size for S1 and Controls.

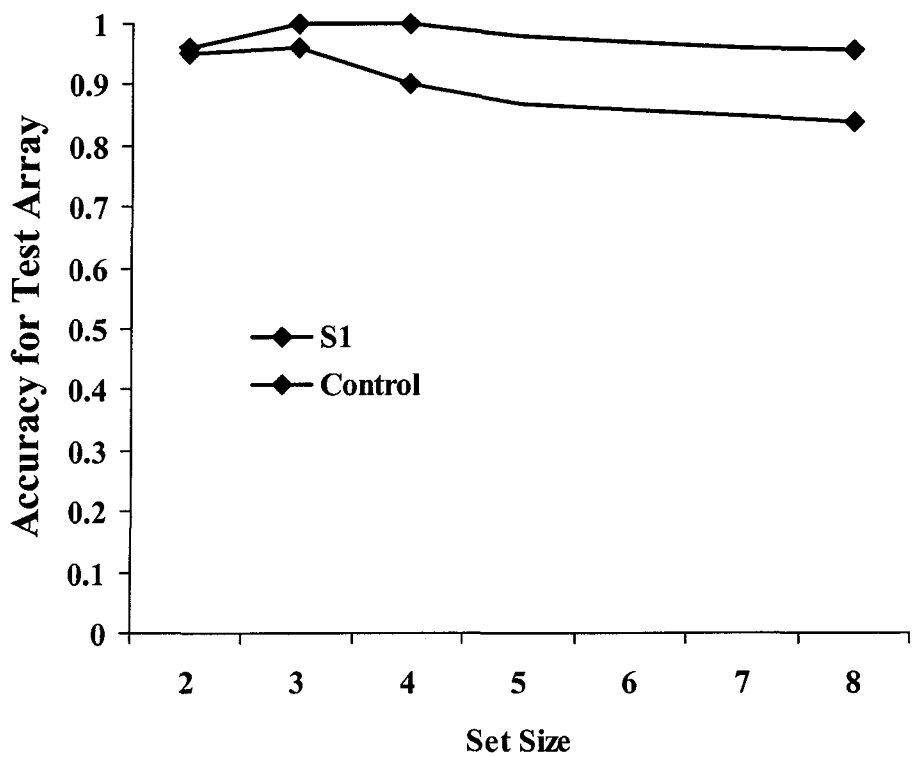


Table 6. Experiment 3 Pairwise Comparisons for Test Array Accuracy as a Function of Set Size.

		Controls	
Set Size	Set Size	*Mean Difference*	*Std. Error*
8	2	-.112*	.03
	3	-.122*	.03
	4	-.068*	.02
4	2	-.044	.03
	3	-.055	.03
2	3	-.010	.02

**The mean difference is significant at the .05 level.*
***Bonferroni adjustment for multiple comparisons.*

Verbal Memory Load Accuracy

Controls. Table 7 shows the mean word report accuracy for the controls and S1. To assess whether set size influenced memory for the two words for the controls, the mean accuracy was analyzed with an ANOVA with Set Size (2, 3, 4, & 8) as the independent variable. There was no effect of set size, $F\ (1, 45) = 0.06$, $MSe = 0.00$, $p > .40$.

Synesthete. There was no reliable difference between S1 and the normal controls for the verbal memory load as function of set size.

Table 7. Accuracy for the Verbal Memory Load Task.

	Control Group		S1
	Mean	(SD)	Mean
Set Size			
2	.99	0.03	.96
3	.99	0.03	1.00
4	.99	0.02	1.00
8	.99	0.02	1.00

Experiment 3 results provide evidence that there is no reliable difference in the ability to hold colored squares in WM between controls and S1. Participants can easily consolidate and maintain in WM up to four colored squares while holding two words in verbal WM. These results are similar to the results obtained by Vogel et al., which showed that accuracy begins to decrease at set size 4 with a gradual decrease on higher set sizes. Luck and Vogel (1997) concluded that errors at set sizes 4-12 reflect limitations in storage capacity. Thus, the storage capacity of WM for colored squares is similar for normal controls and S1.

CHAPTER 5: EXPERIMENT 4

Verbal descriptions of synesthetic experiences make it easy to assume that for them inducer stimuli are always bound to concurrents. However, the empirical evidence for this description is quite inconsistent. It is unclear whether for synesthetes the representation of inducer stimuli is different in nature from the representations for non-inducer stimuli. Therefore, Experiment 4 was a modified version of Experiment 3 such that the sample arrays consisted of digit stimuli (*inducers*) instead of colored squares. The digit sample and test arrays replaced the colored squares arrays. For controls this should change the nature of the task from a primarily visual-spatial task to a more verbal task. For S1 this was a task in which both the physical shape (i.e., digit identity) and concurrent color be used to complete the task, but for controls only the physical shape could be used. That is, if concurrent color were part of the WM representation and if concurrents function like physical colors, then synesthetes could use matches between either the concurrent color or the identity of digits to make the same/different judgment unlike controls who could only use the identity of the digit. Therefore, this task could be more difficult for controls.

The digits 1-9 were used because those digits induced synesthetic experiences (concurrents) for S1, see Figure 3. As in Experiment 2, the digit zero was not used because it induced a clear transparent color that is extremely difficult to replicate on a computer monitor. The question examined was whether synesthetes hold concurrents in WM in addition to the identity of the digit (e.g., Is the digit 7 stored as simply a 7 or is it stored as a yellow 7?). If they do, then it is possible that the additional information changes the numbers of items that can be maintained in WM. Because it is not clear whether concurrents would use resources from visual-spatial WM or verbal WM, two memory load tasks were used.

According to Baddeley's WM model (Baddeley, 1998), if visual-spatial WM is used to represent and maintain concurrents induced from digits, then the synesthete should show greater interference from the visual-spatial memory load than from the verbal memory load. However, if verbal WM is used to represent and maintain concurrents induced from digits, then the synesthete should show greater interference from the verbal memory load. The verbal memory task was the same as in Experiment 3. The task used for the visual-spatial memory load was modeled after the task used by MacPherson, Sala, and Logie (2004). The visual-spatial memory load task consisted of a same/different judgment of the location of six dots in a 3 x 4 grid.

Experimental Predictions

If concurrents for alpha-numeric stimuli rely primarily on visual-spatial memory, then greater interference from a visual-spatial memory load task is expected when S1 has to hold inducer stimuli in WM. However, if concurrents rely primarily on verbal WM, then greater interference is expected from a verbal memory load task when S1 has to hold inducer stimuli in WM. For the controls in Experiment 4, it should be more difficult to hold digit stimuli in WM when the memory load task is verbal as compared to when the memory load task is visual-spatial. An overall effect of set size is expected, such that as the number of digits held in memory increases, accuracy on the test array should decrease.

Method

Participants

Synesthete participant. S1 who has color-grapheme synesthesia for digits volunteered as a participant.

Control group. Fourteen Iowa State University undergraduate students (9 men and 5 women, mean age = 21.0 years, *SD* = 3.0) who reported not having synesthesia participated in the study in exchange for course credit. All were native English speakers and had normal or corrected to normal vision.

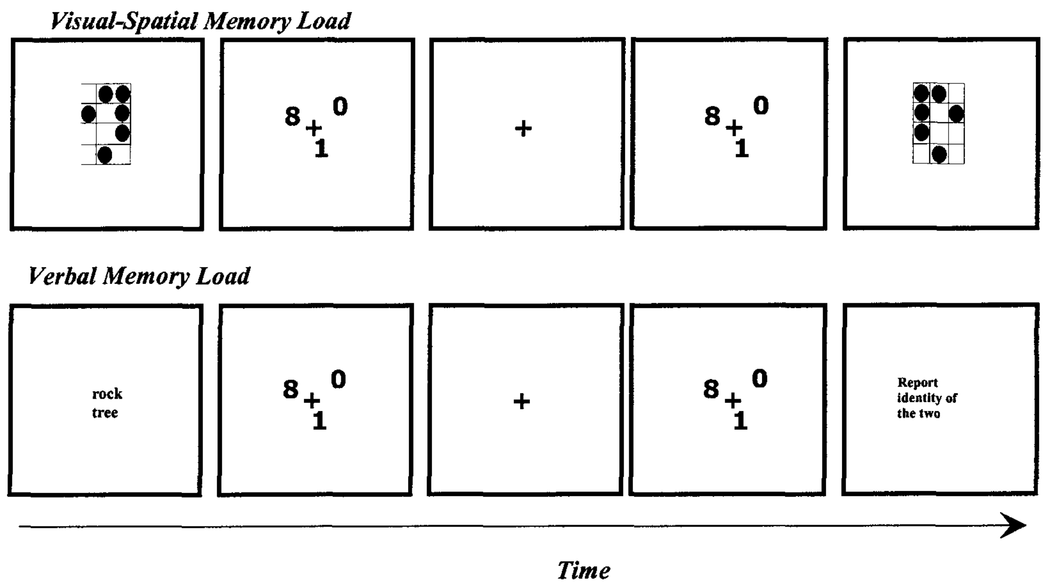
Stimuli & Procedure

The temporal parameters for the sample and test arrays were identical to Experiment 3. The sample and test array stimuli consisted of the digits 1-9. The digits were presented in Arial Black 20 point font and were placed among the parameters of the squares from Experiment 3 (0.65° x 0.65°). The number of digits presented on any given trial varied between a set size of 2, 3, 4, and 8. On half of the trials, the test array was identical to the sample array. On the remaining half of the trials, one of the digits in the test array changed and thus was replaced by another digit. For S1, this change represented a change in the identity of the digit and the concurrent color because no two digits produced the same concurrent color. For the controls, the only change was in digit identity (or shape). For all participants, the location of the digits and the set size of the sample and test array did not change, only the physical digit. No digits were repeated on any given array.

Participants were instructed to perform the digit comparison task while maintaining either verbal or visual-spatial information in memory. For the visual-spatial memory load trials, at the beginning of each trial a 3x4 grid that had a black dot in six randomly selected locations on the grid appeared at the center of the screen for 500 ms as shown in the top half of Figure 13. This grid was replicated from one previously used to load visual-spatial WM in a dual-task paradigm (MacPherson et al., 2004). The actual grid was always presented; the location of the dots on the grid was what could change. Participants were instructed to hold the location of the dots in memory until the end of the trial when a same/different judgment was to be completed. Immediately after the first grid presentation, the sample digit array was presented followed by a fixation, the test array, and the second presentation of a grid. The task was to make same/different judgments first for the digit array and then for the grid via a key press labeled "same" or "diff." On half of the visual-spatial memory load trials (the grid trials), for the second presentation of the grid, the location of the dots was identical to the first presentation. On the remaining half of the visual-spatial memory load trials, the location of the dots was different from the first presentation. On these trials a mirror image of the first grid was presented to increase the difficulty of the same/different judgment. For the verbal memory load trials, the same procedure as in Experiment 3 was used, such that participants held in memory two four-letter words while processing and responding to the digit sample and test arrays.

The visual-spatial memory load trials and the verbal memory load trials were randomly intermixed. Participants completed 3 same and 3 different trials for each type of memory load across all set sizes for a total of 48 experimental trials. The order of trials was random, so trials for each type of memory load and set size were intermixed. Participants were allowed to take self-paced breaks between trials. At the beginning of the experiment participants completed 16 practice trials. The entire session was completed in approximately 50 minutes.

Figure 13. Schematic Representation of the Procedure used in Experiment 4.



Results and Discussion

Plan of Analysis

In Experiment 4, set size and memory load type were the independent variables and the dependent variables were accuracy for the digit test array, accuracy on the visual-spatial memory load, and accuracy on the verbal memory load. Three different questions were examined: What was performance on the visual-spatial memory load and does it vary between controls and S1? What was performance on the verbal memory load and does it vary between controls and S1? Does memory load type differently affect the number of items stored in WM and does the effect differ between S1 and the controls? To test these questions, three separate ANOVAs were computed for the controls. The first ANOVA used test array set size (2, 3, 4, & 8) as the independent variable and accuracy for the visual-spatial memory load as the dependent variable. The second ANOVA used test array set size as the independent variable and accuracy for the verbal memory load as the dependent variable. The third ANOVA used test array set size and memory load type (visual-spatial, verbal) as the independent variables and accuracy for the test array as the dependent variable. After each ANOVA, planned comparisons were computed for the controls and then S1 was compared to the controls. Test array set size 8, which was expected to be the most difficult, was compared with set sizes 2, 3, and 4. The control group and synesthete data were compared at each set size using a modified t-test employed in neuropsychology single case studies.

Visual-Spatial Memory Load Accuracy

Control group. Accuracy on the visual-spatial memory load task (grid task) is shown in Table 8 for both the control group and S1. An ANOVA on the control data in which test array set size (2, 3, 4, & 8) was the independent variable showed a reliable main effect of set size, $F\ (3, 15) = 26.01$, $MSe = 0.01$, $p < .0001$. Comparisons showed that performance at set size of 8 was lower than at set sizes 2, $t\ (13) = -22.40$, $p < .0001$, and 3, $t\ (13) = -14.47$, $p < .0001$. However, there was no difference between set size 4 and 8 (see Table 9). There also was no difference between set sizes 2 and 3. These results suggest that at set sizes 2 and 3 participants can equally perform the visual-spatial memory load task and that they do so with relative ease. Conversely when the set size increases to 8, participants perform less accurately on the visual-spatial memory load task.

Synesthete. A modified t-test comparing accuracy on the visual-spatial memory load task between S1 and the controls for all set sizes did not reveal any differences. This lack of difference demonstrates that accuracy for the visual-spatial memory load task is similar for both controls and S1.

Table 8. Accuracy for the Visual-Spatial Memory Load Task as a Function of Test Array Set Size.

	Control Group		S1
	Mean	(SD)	Mean
Set Size			
2	.97	.03	1.00
3	.96	.05	.92
4	.72	.19	.67
8	.53	.05	.46

Table 9. Experiment 4 Pairwise Comparisons for the Visual-Spatial Memory Load Task as a function of Test Array Set Size

		Controls	
Set Size	Set Size	*Mean Difference*	*Std. Error*
8	2	-.448*	.02
	3	-.434*	.03
	4	-.198	.07
4	2	-.250	.08
	3	-.236	.08
2	3	-.014	.02

**The mean difference is significant at the .05 level, one-tailed.*
***Bonferroni adjustment for multiple comparisons.*

Verbal Memory Load Accuracy

Control group. Accuracy for the verbal memory load task is shown in Table 10 for both the control group and S1. An ANOVA on the control data which test array set size (2, 3, 4, & 8) was the independent variable showed a reliable main effect of set size, $F(3, 15) = 21.05$, $MSe = 0.01$, $p < .0001$. Comparisons showed that accuracy for verbal memory load at a set size of 8 was different than at set sizes 2, $t(13) = -10.85$, $p < .001$ and 3, $t(13) = -10.33$, $p < .001$. However, there was no difference between set size 8 and 4. Accuracy was lower on set size 4 than at set sizes 2, $t(13) = -3.54$, $p < .05$, and 3, $t(13) = -4.27$, $p < .05$.

Synesthete. A modified t-test comparing accuracy on the verbal memory load task between S1 and the controls for all set sizes did not reveal any differences. This lack of difference demonstrates that accuracy for the verbal memory load task is similar for both controls and S1.

Table 10. Accuracy for the Verbal Memory Load Task as a function of Test Array Set Size.

	Control Group		S1
	Mean	(SD)	Mean
Set Size			
2	.99	.11	1.00
3	.97	.03	1.00
4	.67	.17	.87
8	.55	.09	.55

Table 11. Experiment 4 Pairwise Comparisons for the Verbal Memory Load Task as a function of Test Array Set Size.

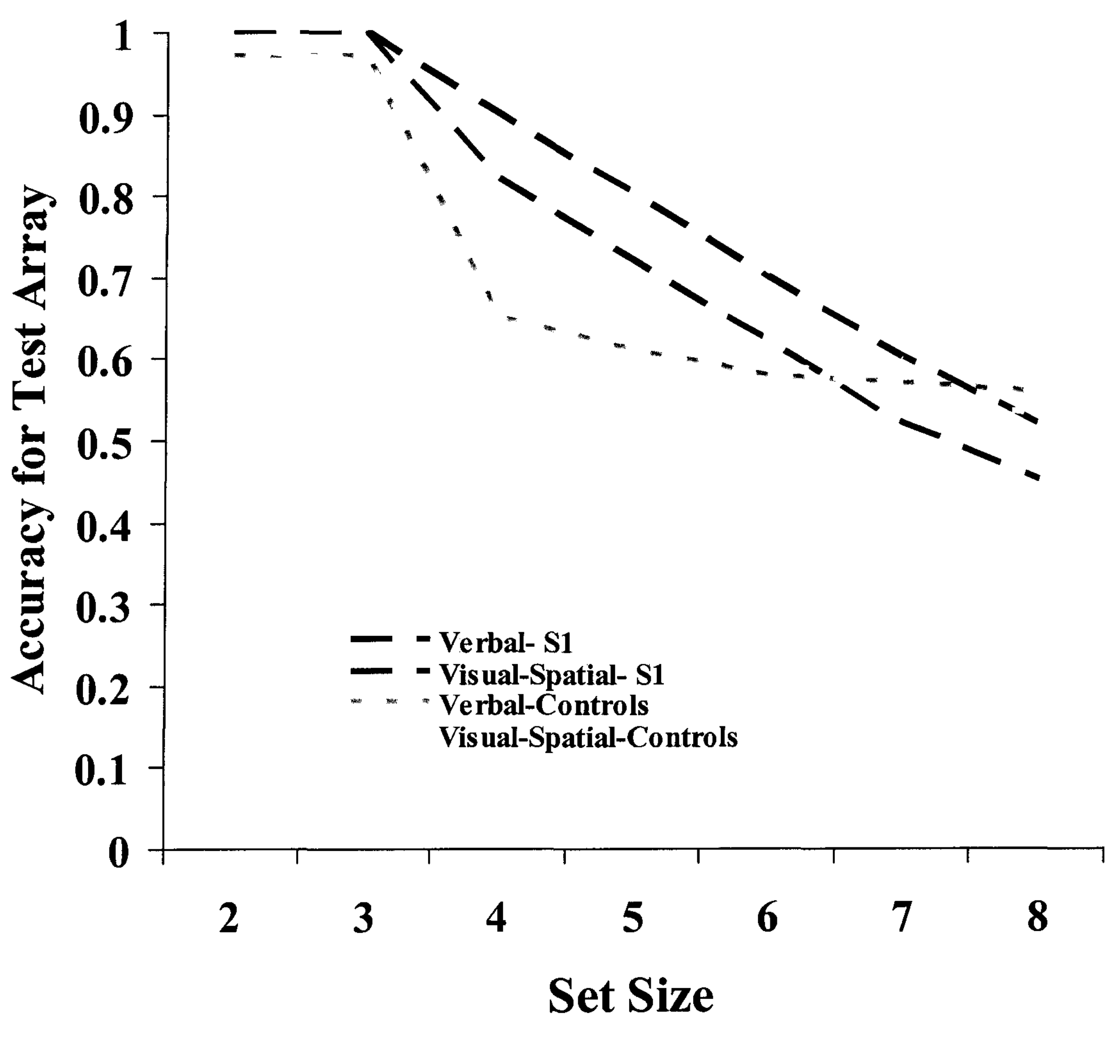
		Controls	
Set Size	Set Size	*Mean Difference*	*Std. Error*
8	2	-.434*	.04
	3	-.413*	.04
	4	-.115	.08
4	2	-.319*	.09
	3	-.299*	.07
2	3	-.021	.05

**The mean difference is significant at the .05 level, one-tailed.*
***Bonferroni adjustment for multiple comparisons.*

Test Array Accuracy

Control group. Figure 14 shows the overall accuracy for the test array as a function of memory load type. To examine the effects of memory load type on accuracy for the digit test array, only trials on which the correct response was given on the memory load task (visual-spatial or verbal) were analyzed in a 2 (memory load type: visual, verbal) x 4 (test array set size: 2, 3, 4, & 8) repeated measure ANOVA for the control data. A reliable main effect of set size was found, F (3, 15) = 29.83, MSe = 0.02, p < .0001. Contrary to the predictions, there was neither a main effect nor an interaction involving memory load type. That is, the verbal memory load did not produce poorer performance than the visual-spatial memory load. Comparisons showed that overall accuracy, regardless of memory load type for set size 8 was different than accuracy for set size 2, t (13) = -43.00, p <.0001, and 3, t (13) = -21.25, p <.0001. As shown in Table 12 there were no differences on overall accuracy between set sizes 2 and 3 or between set sizes 4 and 8.

Figure 14. Accuracy for the Test Array as a Function of Test array set Size for S1 and Controls



Synesthete. Figure 14 shows accuracy for the test array at each set size as a function of memory load and set size. A set of comparisons were computed between S1 and controls for performance on the digit test array for accurate trials on the visual-spatial memory load task. There were no reliable differences between S1 and controls as a function of memory load and set size. A separate set of comparisons were computed between S1 and controls for performance on the test array for the visual-spatial memory load trials. S1's performance did not reliably vary from the controls regardless of memory load type. Although the comparisons did not show reliable differences, it should be noted that the pattern of means did suggest a difference. For S1, performance was numerically higher with the verbal task at higher set sizes (4 and 8) but the reverse was true for the controls.

Table 12. Experiment 4 Pairwise Comparisons for the Test Array Set Size Regardless of Memory Load Type

		Controls	
		Mean Difference	*Std. Error*
Test array set Size			
8	2	-.430*	.01
	3	-.425*	.02
	4	-.143	.07
4	3	.282	.07

**The mean difference is significant at the .05 level, one-tailed.*
***Bonferroni adjustment for multiple comparisons.*

The results did not vary as a function of memory load type, suggesting that both types of memory load tasks produced similar amounts of interference on the digit test array. Because the sample and test arrays were comprised of digits, it was expected that the verbal memory load would produce more interference. There are two possible explanations. One is that the two memory load tasks did not interfere differently because they were too easy and thus only allowed the effects of set size to emerge. If this explains the control data, then it should also account for S1's data. To test this possibility as a function of group, multiple modified t-tests were computed for performance on the digit test array between controls and

S1 for digit test array and no differences were observed. As second possibility is that because the digit test array included a spatial dimension (i.e., digits were distributed across the visual field) the same/different judgments required some level of visual-spatial memory representation. Thus, the digit test array could have used both verbal and visual-spatial memory. To rule out this possibility future experiments should sequentially present digits at one spatial location.

Contrary to the predictions, memory for digits did not vary as a function of the type of memory load (visual-spatial or verbal). It was expected that controls would show greater interference from the verbal memory load than from the visual-spatial load given that digits are typically thought to be rehearsed in verbal WM; however, controls showed the same level of performance for set size 8 regardless of type of memory load. When the digit-task difficulty increased to a set size of 4, then there was a trend for controls to perform better during the visual-spatial memory load than for the verbal memory load. The pattern of results was not the same for S1 whose performance for the digit test array was somewhat higher during the verbal memory load than during the visual-spatial memory load.

Contrary to the predictions about the nature of memory storage of *concurrents,* S1 did not show more interference from one type of memory load task, thus suggesting that S1 may code for digits much in the same way as controls. WM capacity for controls was the same as for S1, but the task should have been easier for S1 because he had two upon which to base his judgments, the digits and the concurrent. The fact that S1 was not more accurate implies that VSTM for S1 may store integrated *inducer* and *concurrent* features of objects (e.g., digit identity and color) rather than individual physical and concurrent features. This integrated form of object storage is consistent with Luck and Vogel's (1997) results, which demonstrated that memory for a one feature object and for an object containing several feature conjunctions is identical, regardless of the additional features present in objects with feature conjunctions.

CHAPTER 6: GENERAL DISCUSSION

Summary of Results

The first two experiments used an AB task. In Experiment 1, participants were instructed to detect two letters surrounded by a red square that were embedded in an RSVP stream of letters that did not include a red square. The only unique target identifying feature was the red square. In Experiment 2, the targets were the two colored digits in an RSVP stream of black digits. Typically, when T2 is presented within a few hundred ms after T1, participants are unable to accurately report T2 when T1 is correctly identified (Raymond et al., 1992). The lower report of T2 is assumed to reflect the fact that stimuli presented during the AB period do not undergo memory consolidation and thus are not available for report (Chun & Potter, 1995).

In Experiment 1, letter inducer stimuli were used as targets and distractors in order to evaluate the stages of processing of concurrents for a synesthete. One aim was to explore whether the binding of *inducers* and *concurrents* is occurring prior to stage 2, after stage 2, or during stage 2 when *concurrents* are task irrelevant. The task used in Experiment 1 did not require processing of letter color, and in fact, letters did not vary in terms of ink color. Because letter ink color was irrelevant to identification of targets, there was no theoretical basis for assuming that concurrent color would affect performance. Theoretically, S1 was not required to attend to his concurrents for correct target identification. Therefore, it was predicted that if concurrent activation is automatic in that binding of the inducer and concurrent occurs as part of stage 1 and, therefore, does not require effortful processing for activation, then S1 should display the same AB pattern as controls.

For the controls, the results showed the typical U-shaped AB pattern with recovery beginning by lag 3 (318 ms) and completed by lag 5 (530 ms). The lag effect demonstrated that with the current experimental parameters, an AB can be observed. S1 showed a longer AB duration in which recovery did not begin until lag 5 and in fact he did not appear to have completely recovered from the AB at lag 5. For this reason, S1 completed the same task with an additional three lags for a total of 8 lags (out to 848 ms). The results replicated the extended AB effect. That is, S1 showed a T2|T1 deficit at lags 5-7 with recovery only at lag 8, whereas the controls showed recovery at lag 5.

The most parsimonious explanation for an extended AB period for S1 is that it reflects that fact that T1 processing took longer for S1 than for the controls. If inducers and concurrents were simultaneously bound before full identification of the inducer, there would have been no difference between S1 and controls. That is, if the two-stage model is assumed, then the synesthetic binding of colors and letters is not part of stage 1. In an RSVP stream, stimuli appear in one spatial location within the focus of attention. Participants are always actively searching for targets amongst distractors. Because processing of concurrents does not increase the likelihood of target identification, synesthetes should ignore concurrents in order to successfully complete the task. They should be able to do this if the concurrents occur post stage 2. However, the data suggest that S1 (and possibly synesthetes in general) was unable to actively ignore the concurrents. This result suggests that concurrents are not produced in a strategic manner after the full identification of the stimulus. That is, they are not the result of post-target identification controlled processing.

The fact that production of concurrents cannot be controlled, but that production appears to require resources is somewhat problematic for Chun and Potter's two-stage model for the attentional blink. Stage 1 is supposedly capacity free, but stage 2 is not. Processing of concurrents requires limited capacity resources and is therefore stage 2. But the inability to control a process has been associated with the term "automatic", which in the two-stage model is associated with stage 1. The current data suggest that concurrent processing has characteristics of both automatic (stage 1) and controlled (stage 2) processing. In order to handle the data, the two-stage model would have to allow "automatic" effects to occur in both stages.

In Experiment 2, target status was indicated by color. Based on the finding in the modified version of the Stroop task that synesthetes were slower at naming a color patch if it was preceded by an inducer with an incongruent concurrent color (Mattingley et al. 2001), it was assumed that target identification for digits presented in an ink color incongruent to the concurrent color should produce a *Stroop-like* interference effect for S1. This was basically the explanation for the difference between S1 and controls in Experiment 1: Targets presented in an incongruent concurrent color are more difficult to process and thus require more attentional resources from stage 2, producing a longer AB period. In contrast, it was predicted that S1 would show an increase in target identification for targets presented in the ink color congruent to the concurrent color because targets presented in their congruent concurrent color would be more easily processed than targets in incongruent colors. That is, it was predicted that with congruent targets the AB pattern for S1 would be more like the AB pattern for controls.

Results showed that task was more difficult for both controls and for S1. That is, everyone showed a longer AB period. Results also showed that for the T1 congruent trials, S1's AB pattern did resemble the AB pattern found for controls. Lag 1 sparing was observed for S1 and recovery onset was delayed. Therefore, when there was no mismatch between the target ink color and the concurrent color, target processing for a synesthete is more like it is for controls without synesthesia. However, the explanation in terms of the contribution of congruency to the ease of target processing cannot handle the results for T1 incongruent trials. For S1, T2|T1 accuracy was higher and both the AB and Lag 1 sparing were attenuated. Paradoxically, the presence of an incongruent T1 appeared to increase alertness and make the task easier.

In Experiment 3, a VSTM change detection paradigm was used to estimate the number of items that could be held in WM. The influential Luck and Vogel (1997) paradigm motivated the design of this experiment and thus their temporal parameters were used. The items were colored squares. However, instead of rehearsing digits, for the verbal WM load, participants were asked to rehearse a pair of four-letter words. Digits were not used because digits induce concurrents for S1. The results replicated the established set size function. That is, accuracy was very high at set sizes of 2 and 3 showing that WM can successfully hold the information. As was predicted, at set size 8 WM is clearly taxed and participants showed a reliable decrease in accuracy. The results also showed that there were no differences in WM capacity between the control group and S1. Furthermore, the results showed that S1 does not have any WM capacity deficits.

In Experiment 4, a modified version of the Luck and Vogel (1997) change detection paradigm was used to examine the number of inducer items that could be held in WM. The temporal parameters remained the same as those in Experiment 3. Two changes were made: digits replaced colored squares and there were two types of memory load. On half of the trials a verbal memory load was used while on the remaining half of the trials a visual-spatial memory load was used. This experiment was designed to explore the nature of memory consolidation for concurrents. Because the type of memory representation for digit inducers is unknown, two types of memory load were used to examine if any interference would be observed for the consolidation of an array of digits. It was predicted that if synesthetes form memories for their concurrent colors as part of the representation of the inducer stimulus, then S1 would show more interference from the visual-spatial memory load than the verbal memory load in the consolidation of the inducer digits. The results showed no reliable differences between S1 and controls in memory representations of digits as measured in the VSTM change detection paradigm, although there was a trend which showed that S1 was overall more accurate at the digit test array regardless of memory load task and a suggestion that S1 was more affected by the visual-spatial memory load.

Attention, Automaticity, & Synesthesia

Among attention researchers there is no question regarding the perceptual reality of synesthesia; however, the role of attention for the activation of concurrents remains ambiguous. Many researchers have attempted to determine if synesthetes must attend to and be aware of the identity of the inducer before a concurrent is activated (e.g., Mattingley et al., 2001; Palmeri et al., 2002; Smilek et al., 2002). One strong claim is that concurrents are only elicited by attended inducers after they are available for conscious report (Mattingley et al.). Mattingley et al. view the activation of the concurrents as a serial process in that explicit identification of the inducer is needed in order to activate the concurrent. Within the two-stage model, the position is that concurrent activation only occurs after stage 2 processing is completed. If the inducer and concurrent binding occur after stage 2, then the binding would be a controlled process that synesthetes should be able to inhibit. If no concurrents were activated prior to stage 2 completion and if production of concurrents can be inhibited, then there should have not been any difference between S1 and controls. Results from Experiment 1 are not consistent with such a claim. If no concurrents were activated, then there is no mechanism(s) to explain the extended AB shown by S1 in both Experiment 1 and a replication. Results from Experiment 1 imply that the locus of the concurrent binding *bottleneck* is not likely to be after stage 2. It is likely that some identification of the inducer is needed; however the question should be whether what is needed is a level of identification that occurs during stage 1 or whether it is conscious awareness (i.e., full identification) that occurs at stage 2.

The controversy about whether synesthesia requires attention may be a result of the interdependencies present in the definitions of attention and automaticity. As previously mentioned convoluted arguments arise when defining attention and making a distinction between an attentional or controlled process and a truly automatic process because there are appeals to many different dimensions of differences. Thus, in this dissertation only certain dimensions of automaticity were considered. In the synesthesia literature there are basically two camps of researchers, those that posit that the activation of concurrents are automatic and those that posit that controlled processing is needed (i.e., attention is required). The current results suggest that both are right and both are wrong. Each camp characterizes *attention* as being under voluntary control and resource demanding and each camp defines *automaticity* as not being under voluntary control and not demanding resources. The problem arises because there is no single dichotomy. Rather, the dichotomies are separate. A process can be automatic in that it is not under voluntary control, but it also can demand resources (Paap & Ogden, 1981).

In this dissertation *automaticity* was used as an underlying mechanism to distinguish between involuntary and voluntary processing in a two-stage information processing model. Chun and Potter (1995) elaborated on Broadbent and Broadbent's (1987) results and Neisser's (1967) preattentive processes theories to guide in the development of a two-stage model that incorporated theories of spatial attention to explain the selective attentional processes at one spatial location. In Chun and Potter's two-stage model, stage 1 is responsible for rapid detection of features relevant to a target and it consists of short-lived target representations susceptible to rapid forgetting. The registration of features is relatively capacity free and not under voluntary control. Stage 2 is capacity limited and it is where target identification occurs. What gets selected into stage 2 can be controlled. If Chun and Potter's two-stage model is assumed, then automaticity must fall into stage 1 because stage 2 is capacity limited and full identification is reached. One of the theoretical arguments is whether synesthesia concurrents are automatic in that they are more of a stage 1 process, whether concurrents are a stage 2 process that requires attention, or whether concurrents are activated upon the completion of stage 2. The current AB experiments provide evidence that the automatic activation of concurrents does not fit well into the distinctions made by the two-stage model. However, if one had to categorize concurrent processing, then it would most likely represent a stage 2 process.

The Nature of Memory Representations Involving Concurrents

The VSTM paradigm has been used to assess the capacity of WM. One of the issues examined is the question of whether consolidation of more features into a WM representation takes more capacity. On the one hand, there is some evidence that the consolidation that leads to a durable WM representation may consume more resources when more features must be bound (Vogel et al. 2001; Wheeler & Treisman, 2002). On the other hand, Xu (2002) provided evidence that VSTM capacity is the same for multi-part objects and for single-part objects. The key difference in Xu's experiments is that the different feature dimensions are from different parts of an object (e.g., color is one dimensional change and orientation is a different dimensional change). However, Alvarez and Cavanagh (2005) suggested that each feature may be stored separately.

Although the paradigm from Experiment 4 has never been used with synesthetes in the past, one might assume that the addition of a concurrent would function like the addition of some other feature. For synesthetes, the change in features is not only in one dimension. Concurrents are not the same as what has traditionally been defined as a feature (e.g., physical color, straight edge), so a concurrent change may not be the same as a feature change. In the change detection paradigm, different trials for S1 produced both a digit change and a change in the concurrent color that was produced. That is, on different trials synesthetes have to process both a physical stimulus change and a concurrent color change. This is not the case for controls because they only process a physical stimulus change. Regardless of the stimulus feature change and the concurrent change, the WM capacity for representations of inducer stimuli and non-inducer stimuli does not appear to be different for an individual with synesthesia. That is, the results of Experiment 4 support the view that in a change detection paradigm when no encoding deficits are expected, durable WM representations can be formed for 3-4 items and this formation is similar for synesthetes and controls.

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FOOTNOTES

[1] Individuals without synesthesia will be referred to as controls in the remainder of the dissertation.

[2] After data analysis, a programming error was identified: When T1 was incongruent, the incongruent color was randomly selected from the set of other concurrent colors. There were no restrictions regarding the ink color or concurrent color of T2. Therefore, it is possible that the ink color of T1 was either the ink color of T2 or the concurrent produced by T2. Such matches would have occurred at random.

[3] Another synesthete participant completed Experiments 1 and 2. Her completed synesthesia questionnaire is shown in Appendix D. However, she only had concurrents for digits. She completed Experiment 1 and, as expected given that she had no concurrents for letters, her data are the same as the controls. For Experiment 2, S2's data are shown in Appendix E. Her data showed a pattern similar to the conditionalized pattern shown by S1. However, she was not included in the analyses because she also reporting having numerous strange "ESP" and out of body experiences. Her data for both Experiments 1 and 2 are shown in Appendix E.

[4] For Experiment 3 the mean response times showed the same pattern as the accuracy analysis, indicating that there was no speed-accuracy trade off. The data are shown in Appendix F.

APPENDIX A
COMPLETED SYNESTHESIA QUESTIONNAIRE FOR S1

Digit Span is 10.

Describe your Synesthesia

1. What kinds of things trigger or elicit your synesthesia?

- Sounds, temperature (cold or hot: for example if I burn my hand, then I feel a different pulse), smells, flavors (taste), letters, numbers.

2. Do these things always give the same experiences?

-YES

3. How long have you had synesthesia?

As long as I can remember.

4. How often do you experience your synesthesia? (e.g. daily, weekly, monthly, occasionally)

-Consistently all the time.

5. Are you able to control your synesthesia (e.g. can you stop it happening, or make it happen if you wish)?

- Can't stop it and don't want to stop it!

6. Does attention or lack of attention seem to affect the vividness of your synesthesia?

-If the sensation is great enough, then no. But if the sensation is weak, then yes.

7. Are there any circumstances when your synesthesia seems stronger, clearer, longer lasting; or weaker, shorter (e.g. under the influence of alcohol, medication, caffeine, tobacco, other drugs, fatigue, stress, time of the day)?

-Volume: high volume increase intensity of colors, or perception of distance, but the mappings do not change only the intensity.

8. Do you remember anything in the past that may have triggered the development of your synesthesia?

-No, it was always there.

9. Are there times when your synesthesia is advantageous?

-Yes, it helps me play my musical instruments better and gives me perfect pitch.

10. Are there times when your synesthesia is disadvantageous?

-No, because if I turn the music off then it is off too.

12. Do any other members of your immediate family experience synesthesia?

-No

This questionnaire was developed by Rich, Bradshaw, and Mattingley, 2005

APPENDIX B
MODIFIED T-TEST FORMULAS

Crawford and Garthwaite (2002) recommend formula

for comparing a single case to a sample.

$$t = \frac{X_1 - X_2}{S_2\sqrt{(N_2 + 1)/N_2}}$$

X_1 = the individual's score
X_2 = mean score in the normative sample
S_2 = standard deviation of scores in the normative sample
$N2$ = the number of persons in the normative sample

Modified t-test formula for a within subject comparison

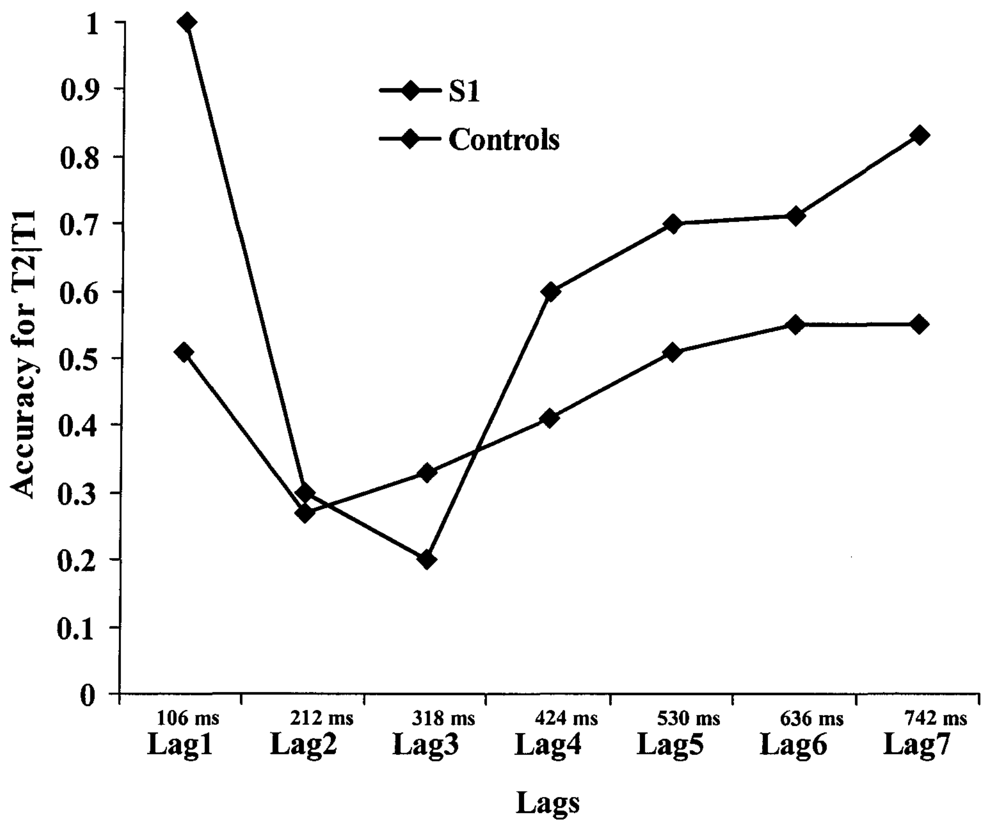
for 1 subject.

$$t = \frac{X_1 - X_2}{S_2/\sqrt{1}}$$

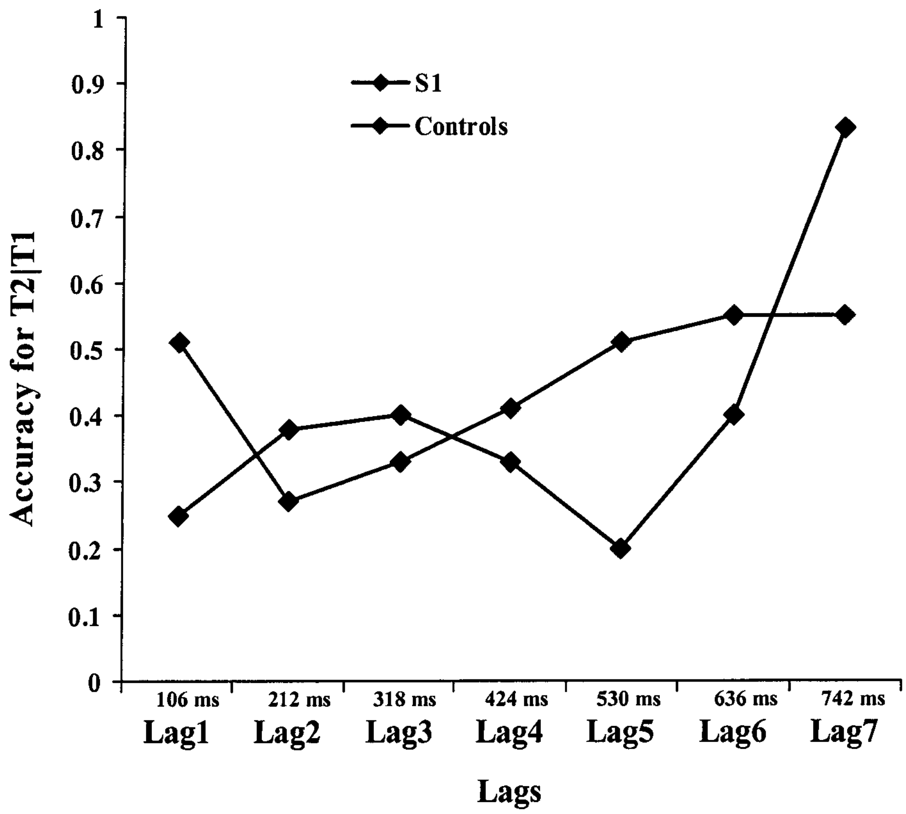
X_1 = an individual's score for condition (e.g., 1)
X_2 = an individual's score for condition (e.g., 2)
S_2 = standard deviation of the difference scores
(e.g., 1-2) for each comparison from the control group
df = N-1

APPENDIX C: ADDITIONAL STATISTICAL RESULTS FOR S1

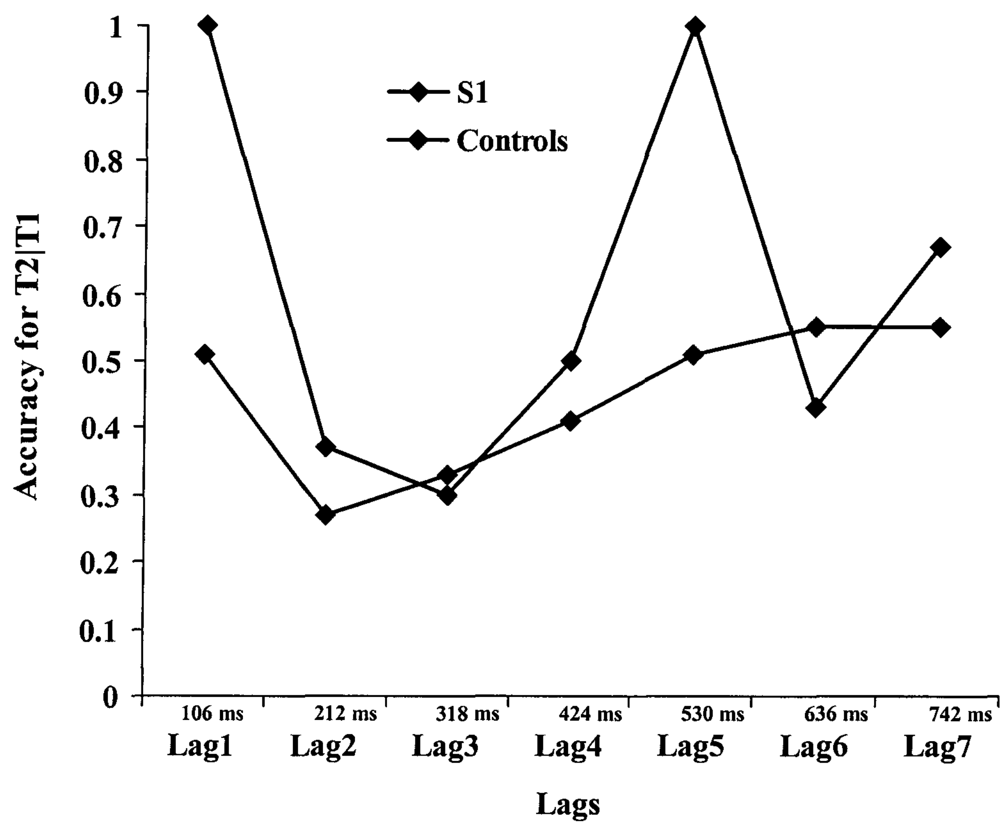
T1 Congruent - T2 Congruent for S1 and Overall Accuracy for Controls as a Function of Lag.



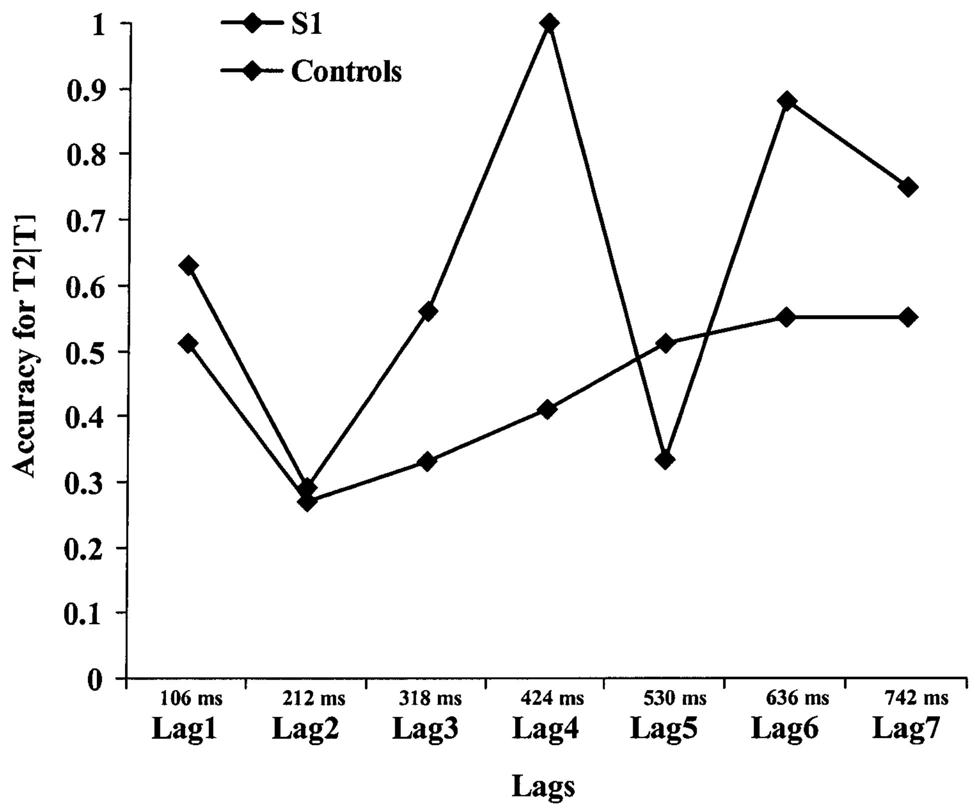
T1 Congruent - T2 Incongruent for S1 and Overall Accuracy for Controls as a Function of Lag.



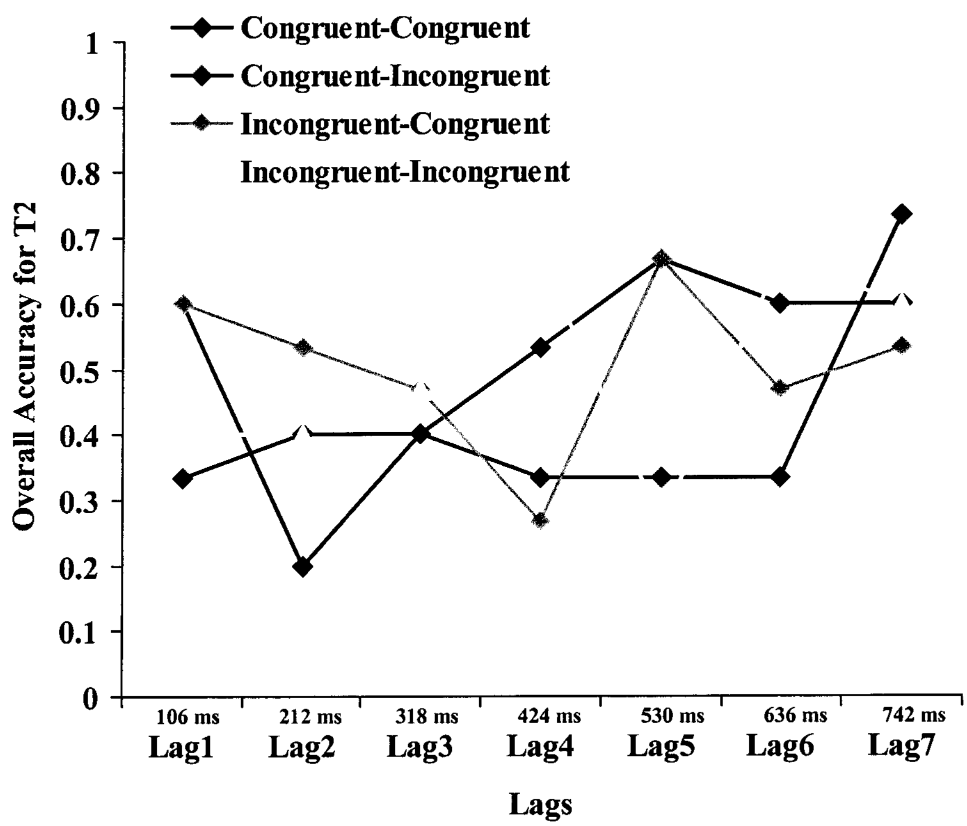
T1 Incongruent - T2 Congruent for S1 and Overall Accuracy for Controls as a Function of Lag.



T1 Incongruent - T2 Incongruent for S1 and Overall Accuracy for Controls as a Function of Lag.



Overall T2 Accuracy for S1 as a function of Lag and Condition (not conditionalized)



APPENDIX D: COMPLETED SYNESTHESIA QUESTIONNAIRE FOR S2

Digit Span is 8.
Describe your Synesthesia
1. What kinds of things trigger or elicit your synesthesia?
- Seeing or hearing, but mostly numbers.

2. Do these things always give the same experiences?
-Some letters are stable. Numbers are stable, except 1 which is white and also appears as a clear transparent color.

3. How long have you had synesthesia? ***Ever since I can remember.***

4. How often do you experience your synesthesia? (e.g. daily, weekly, monthly, occasionally)
-Daily and consistently. Some times I try not to think about it.

5. Are you able to control your synesthesia (e.g. can you stop it happening, or make it happen if you wish)?
- No.

6. Does attention or lack of attention seem to affect the vividness of your synesthesia?
-Yes, when I am less attentive in the afternoons I see my numbers more clearly.

7. Are there any circumstances when your synesthesia seems stronger, clearer, longer lasting; or weaker, shorter (e.g. under the influence of alcohol, medication, caffeine, tobacco, other drugs, fatigue, stress, time of the day)?
- Yes, in the afternoon. When I am stressed I loose the ability to work with numbers because I can only focus on the colors. Many times I can't even balance my check book. I loose the ability to think in numbers because I only see colors.

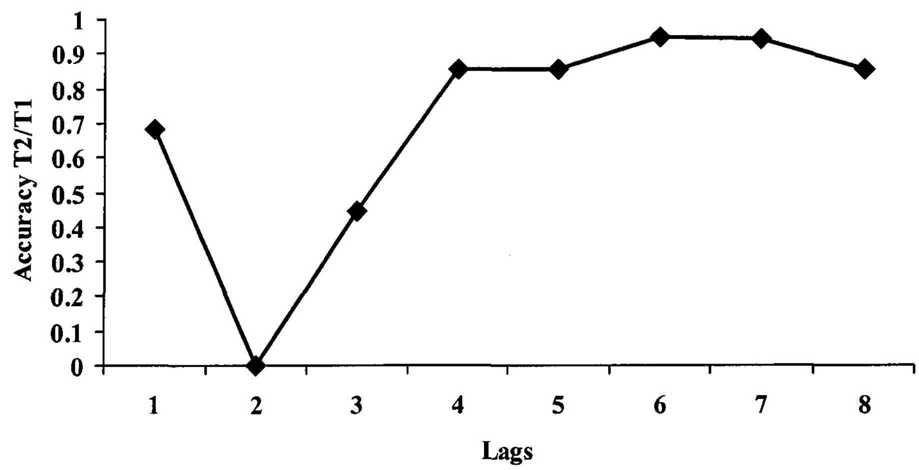
8. Do you remember anything in the past that may have triggered the development of your synesthesia?
-NONE

9. Are there times when your synesthesia is advantageous?
-Yes, it helps my art work and perception.
10. Are there times when your synesthesia is disadvantageous?
-Yes, my daily management of details dealing with numbers. I can't isolate numbers from the colors.
11. Do any other members of your immediate family experience synesthesia?
-Yes, my daughter.

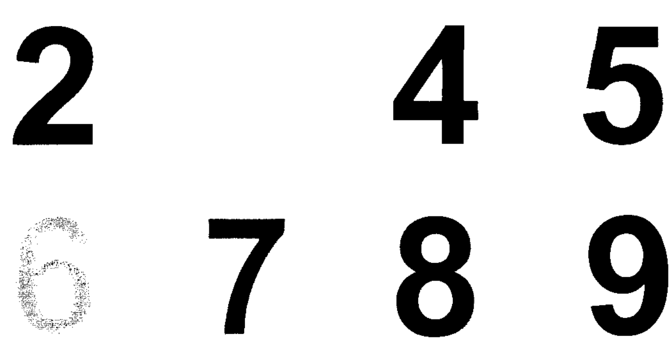
This questionnaire was developed by Rich, Bradshaw, and Mattingley, 2005

APPENDIX E. ADDITIONAL STATISTICAL RESULTS FOR S2

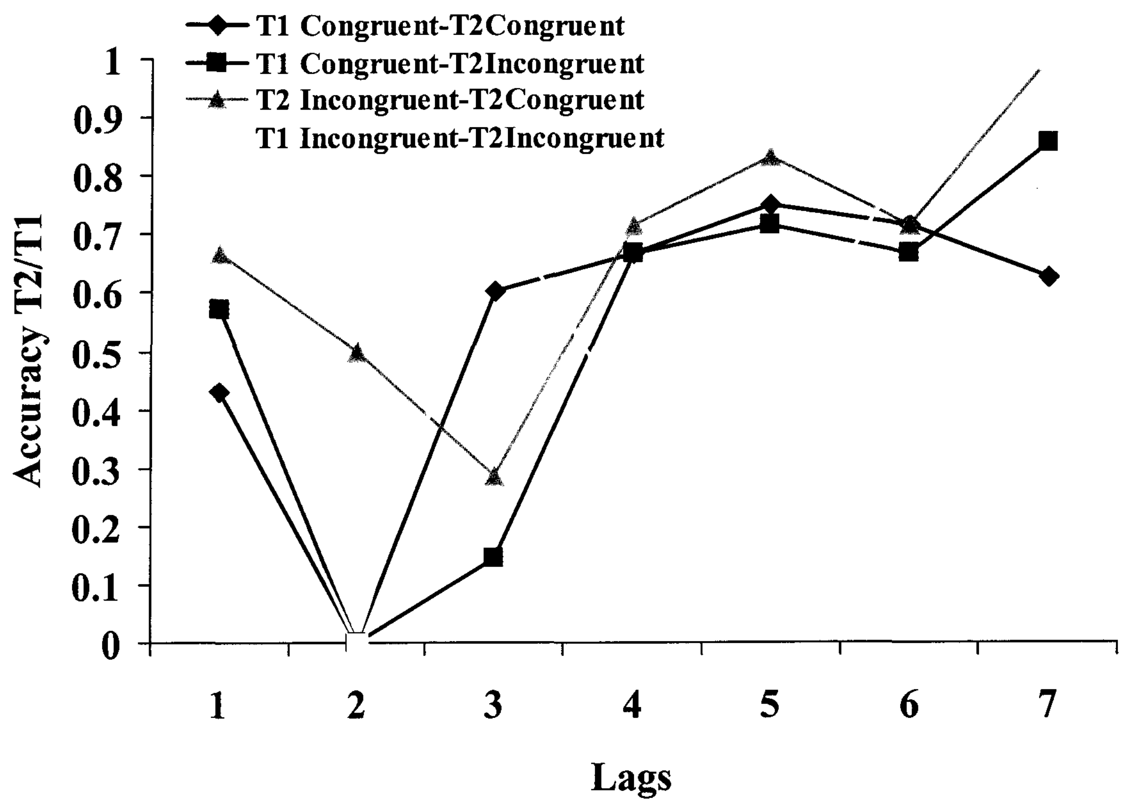
Experiment 1: T2|T1 Accuracy for S2 as a Function of Lag.



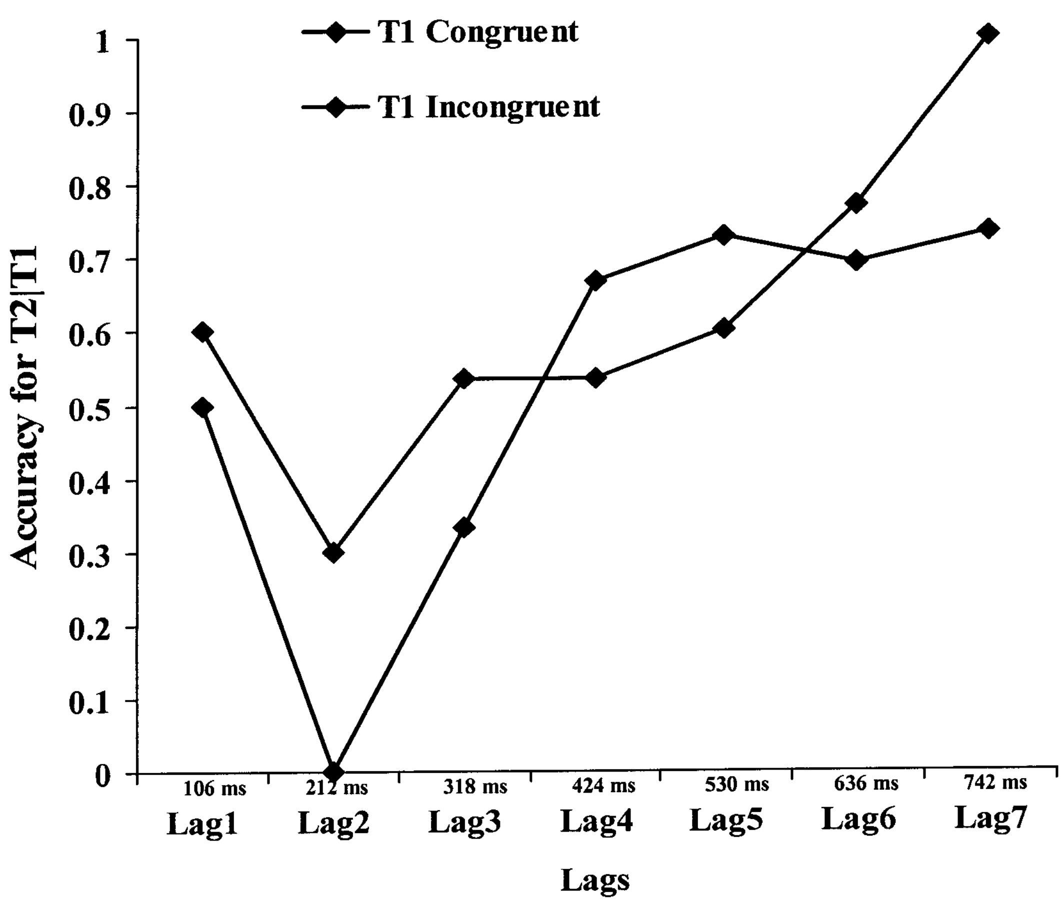
Digit- Color Concurrents.



Experiment 2: T2|T1 Accuracy for S2 as a Function of Lag.



Experiment 2: T2|T1 Accuracy for S2 Collapsed Across T2 Congruency as a Function of Lag.



APPENDIX E: ADDITIONAL STATISTICAL RESULTS FOR EXPERIMENT 3

Response Time Analyses. Mean response times for all trials for the controls were analyzed in an ANOVA with set size (2, 3, 4, & 8) as the independent variable. A main effect of set size was revealed, $F\,(3, 45) = 23.17$, $MSe = 2519.30$, $p < .0001$. As shown in the Table below, set size 8 showed the slowest response times and set size 2 showed the fastest response times. S1's mean response times showed a similar pattern as the controls.

Appendix D: Table 1. Mean Response Times for all Trials.

	Control Group		S1
	Mean	(SD)	Mean
Set Size			
2	786.66	154.63	718.63
3	819.06	178.79	750.29
4	853.87	173.96	797.92
8	927.49	191.16	932.17

ACKNOWLEDGEMENTS

This dissertation was supervised by Professor Veronica J. Dark in collaboration with Professor Eric. E. Cooper of the Department of Psychology and Interdepartmental Neuroscience Program at Iowa State University. Professor Dark's wonderful guidance was instrumental in the development of this research project. With her unwavering support Professor Dark was always eager to provide constructive comments and alternate aspects to investigate. I am forever grateful for the scientific knowledge that Professor Dark has shared with me over the years. She has impressed me with her theoretical ideas and her passion for science.

I would also like to thank Professor Gina M. Grimshaw of the Department of Psychology at California State University, San Marcos whose flood of immeasurable spontaneous contributions to my academic and personal development have transformed me into a scientist. Thanks for guiding me in discovering the scientist in me!

I would like to thank my Research Professor Lourdes Anllo-Vento of the Department of Neurosciences at the University of California, San Diego for taking me under her wing and advancing my technical and conceptual skills necessary to prevail in the field of Cognitive Neuroscience.

This dissertation was ultimately possible thanks to the moral and spiritual support I have received from my fantastic *familia* and my faithful companion Steve. My family has always inspired me to overcome barriers at any expense and that inspiration has motivated all of my success. Gracias!