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An examination of the stimuli used in and the theories behind the cross-modal Stroop task

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AN EXAMINATION OF THE STIMULI USED IN AND THE THEORIES BEHIND THE
CROSS-MODAL STROOP TASK

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Abstract

The classic Stroop task, during which one names the ink color of color words, has long been used as a measure of selective attention (Stroop, 1935). Selective attention generally refers to our ability to attend to one stimulus (a target) while ignoring another (a distractor). Since its initial creation, many variations of the classic Stroop task have been developed. One of these variations is cross-modal Stroop, which uses visual colored targets and auditory distractor color words. However, whether the same mechanisms and processes are used while completing the two tasks has yet to be determined. The following thesis examined cross-modal Stroop and the theories that have been developed in an attempt to explain the classic Stroop findings. Two experiments were conducted. In Experiment 1, different colored visual stimuli were used (e.g. color squares and @ symbols) to determine whether this had any impact on task performance. A row of X's induced significantly less interference, suggesting that they serve as an excellent neutral stimulus. In Experiment 2, the response times and accuracy levels for repeating auditory color words and visual colored items were examined with or without accompanying distractors. Although the classic Stroop task displays a very clear asymmetry between word reading and color naming, this asymmetry was not found for cross-modal Stroop. This finding suggests that the same processes and mechanisms may not be involved when completing cross-modal Stroop as classic Stroop, and furthermore, that some of the theories are better at explaining the cross-modal Stroop effect than others.

Chapter 1. Introduction

Since Stroop (1935) first recorded it, the so-called Stroop effect has become perhaps one of the most widely known and examined effects in psychology. However, despite the fact that this phenomenon is widely recorded, has been heavily examined, and would appear to be extremely robust, the mechanisms underlying this effect are not fully understood. Several different theories attempting to explain the effect have been posited; however, no theory is able to explain the effect completely. Additionally, many have had the basic assumptions upon which they stand disproved. Finally, the extent to which these theories can be extended to other versions of the Stroop task (e.g. cross-modal Stroop) is unknown in addition to whether or not these variations on the task are even measuring, examining, or using, the same processes or mechanisms. These issues will be examined in the current study.

1.1 The Stroop Task and Associated Terms

The classic Stroop task involves naming the ink color of congruent and incongruent color words and a non-verbal control stimulus such as a row of x's. Surprisingly, the original Stroop article did not use congruent words, and it was not until the 1960s that the congruent word and ink condition was first examined (Langer & Rosenberg, 1966; Dalrymple-Alford & Budayr, 1966). Nevertheless, congruent words have been used consistently since (e.g. Logan & Zbrodoff, 1979; Roelofs, 2005).

Within the incongruent condition, the written color word and ink color do not match. For example, the word "red" may be printed in green ink. As the task is to name the color of the ink, the correct answer would be "green." In the congruent condition, the color word and ink color are the same. The word "red," for example, would be presented in red ink, and this time the

correct answer would be "red." In control trials, one is essentially just naming the color of the ink of a non-word stimulus such as colored squares, a row of x's, #'s, etc.

Response times and accuracy results for the classic Stroop task are extremely consistent across participants and studies (MacLeod, 1991; Logan & Zbrodoff, 1979; Stroop, 1935). One such finding is that incongruent trials show slower response times and lower accuracy levels than control trials—or those with non-word stimuli. This is called *Stroop interference*. Furthermore, response times of congruent trials are generally faster than those of the control trials, and this is known as *Stroop facilitation*. The *Stroop effect* comprises both this facilitation and interference combined. Lastly, for the most part, little to no interference or facilitation is found when the task is to ignore the ink color and simply read the word (also known as *reverse Stroop*)—this is otherwise identified as the *color-word Stroop asymmetry* (Roelofs, 2005). By using black/white words and colored patches it has been found that interference and facilitation levels are highest when the word and color are presented simultaneously and in the same spatial location (MacLeod, 1991). The greater the temporal and spatial separation between the target and distractor, the less interference and facilitation is found until it disappears completely— approximately 150ms in the case of temporal separation (Glaser & Glaser, 1982).

These results have been found consistently and in participants of virtually all ages (children, college students, working adults, and the elderly). Stroop interference appears to be greatest in young children and rises to its highest level around grades 2 and 3 as reading skills develop. Interference continues to decline into adulthood as reading skills continue to improve but typically begins to increase again with advanced age (MacLeod, 1991). No sex differences in Stroop interference have been found at any age (MacLeod, 1991).

1.2 Variations of the Classic Stroop Task

Since Stroop's (1935) article, many different versions of the task have been developed. Some versions have been relatively close to that first proposed by Stroop and simply involve a white color word embossed on a strip or patch of color (e.g. Tecce & Dimartino, 1965; Dunbar & MacLeod, 1984). Others have incorporated a word and spatial location. In these versions of the task, a fixation point is presented and words such as "above" or "below" are presented in a position relative to the fixation point that is either congruent or incongruent to the word's semantic meaning with the goal being to ignore the word and name the location (e.g. Palef & Olson, 1975). Another popular version of the Stroop task is the picture-word interference task that involves naming a picture that has a congruent or incongruent word incorporated into the image (e.g. Glaser & Glaser, 1982; Glaser & Dungelhoff, 1984). For example, a line drawing of a sofa may have the word "sofa" in the middle of it—a congruent trial—or the word "table"—an incongruent trial.

Other versions of the Stroop task have sought to create a scenario that examines the auditory modality or when more than one modality is involved. In an auditory version of the Stroop task, participants heard the words "low" and "high" in a pitch that was either congruent or incongruent to the word heard (Hammers & Lambert, 1972). In a cross-modal version, Cowan and Barron (1987) explored having a visual color target and an auditory color word distractor.

All of the variations on the classic Stroop task listed above show varying degrees of interference and more or less facilitation. Whether or not these variations on the classic Stroop task involve the same mechanisms and processes, however, has not been definitively shown and has been examined very little. This is especially important as these variations are frequently

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used to test whether the assumptions underlying the theories of the Stroop effect are correct (e.g. Shimada, 1990).

1.3 Cross-Modal Stroop

As mentioned above, cross-modal Stroop involves naming the color of visual targets while ignoring auditory distractor words. Today this task is mainly used to help explore selective attention mechanisms—for example, is a distractor in a different modality to the target similar to a distractor in the same modality to the target. However, the authors who first explored this task, Cowan and Barron (1987), were more interested in whether or not we have a pre-speech buffer, what role selective attention could potentially play in this buffer, and to what extent auditory information can be ignored.

In their experiment, Cowan and Barron (1987) had participants name the color of the ink of an incongruent color word or control stimulus (in this case a row of x's) while hearing spoken color words, the alphabet, "the," music, or silence. Each of the different auditory and visual conditions was blocked, and the task was to name the ink color and ignore the accompanying visual item and auditory stimulus. As can be expected, Cowan and Barron (1987) found more interference when participants were naming the color of the ink of colored words than naming the color of the ink of a row of x's regardless of the auditory condition heard. Furthermore, there was more interference when spoken color words were heard than any of the other auditory conditions.

Cowan and Barron concluded that this was due to the competition of the names of both the visual and auditory colored items in the pre-speech buffer. This, in turn, meant that the auditory information was being processed to some degree, for if selective attention had been able to completely filter out the auditory information, the Stroop effect would not have occurred at

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all. These findings came under dispute, however, when Miles, Madden, and Jones (1989) attempted to replicate these findings and were unable to do so. There was much back and forth activity between the two groups (Cowan, 1989a; Miles & Jones, 1989; Cowan 1989b) with the matter dying down in a stalemate for many years.

Shimada (1990) continued the investigation of the cross-modal Stroop task, but as opposed to focusing on the potential role of a pre-speech buffer, he was more interested in using the task to explore the basic theories behind the Stroop effect. Shimada examined two theories, which he named the *automatic parallel-processing model* and the *feature integration theory*. The automatic parallel-processing model argued that the two processes—word reading and color naming—are carried out in parallel and that no attention is required in word reading due to the fact that subjects are asked to give their attention exclusively to the color dimension. Despite this, the word dimension is, nevertheless, still semantically processed, as it is the more automatic of the two tasks.

The feature-integration theory, however, states that Stroop interference is instead caused by the word dimension being attended. This theory suggests that the various features of the target (which in the classic Stroop task are generally spatially integrated) are all perceived, processed, and attended together. As such, this theory assumes that the semantic meaning of a word cannot be processed automatically and requires some attention. The Stroop effect occurs, therefore, when one finds it impossible to focus their attention solely on the color dimension. As the cross-modal Stroop involves a target and distractor that are not spatially integrated, any Stroop interference would mean that the feature-integration theory is incorrect.

Shimada (1990) used colored circles for his target and four auditory distractor conditions: Japanese color words (the experiment was conducted in Japan on Japanese students) that were

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either congruent or incongruent to the colored circles shown, silence, a buzzer, and "white." Shimada also varied the stimulus onsets so that the auditory distractor was either presented before the target (by +200ms or +100ms), simultaneously (0ms), or after the target (-100ms or -200ms). Like Cowan and Barron (1987), Shimada did find Stroop interference at all of the stimulus onset levels with the exception of +200ms and -200ms. The greatest level of interference was found when the target and distractor where presented at the same time, with a low, but still significant, amount of interference found for +100ms and -100ms. These findings suggest that the cross-modal Stroop task does lead to the Stroop effect and that feature-integration theory is not correct.

The question of whether or not the cross-modal Stroop task does lead to Stroop interference was finally put to rest by Elliott, Cowan, and Valle-Inclan (1998). Unlike the previous experiments in the 1980s (Cowan & Barron, 1987; Miles et al., 1989; Miles & Jones, 1989; Cowan, 1989a; Cowan, 1989b) Elliott et al., like Shimada (1990), were able to directly control the onset of the visual and auditory stimuli. In the 1980s, researchers had used sheets of roughly 100 visual targets and cassette tapes with recorded auditory distractors. The time it took one to get through the entire sheet was recorded, as opposed to the response time for each trial. Elliott et al. (1998), on the other hand, were able to look at the response times for each trial and ensure exactly when the auditory and visual stimuli were heard and seen.

Elliott et al. asked participants to name the colors of patches on a computer screen while hearing incongruent color words, silence, and non-color words (these were not included in Shimada (1990) and were used as an additional control). Stimulus onset asynchrony (SOA) was also examined with the distractor being presented either 500ms before the target or presented with it simultaneously. In the first experiment, the auditory conditions were all intermixed. In

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the second experiment, the auditory conditions were presented in blocks. However, although the blocked version of the experiment led to shorter response times in all of the conditions, both the intermixed and blocked presentation led to equal amounts of interference.

Stroop interference was found when the target and distractor were presented simultaneously. It was not found, however, when the distractor was presented 500ms before the target. This finding most likely explains why in the past the effect was found sometimes but not others, due to less precise experimental methodologies. Also, color words only had a larger effect on response time than the non-color words when the target and distractor were presented simultaneously. There was no significant difference between the color words and non-color words at the 500ms SOA. However, while this experiment did show that cross-modal Stroop interference is replicable, it also called into doubt the original theory used to explain the cross-modal Stroop effect involving a pre-speech buffer. If the pre-speech buffer was responsible for interference, one would expect the largest amount of interference when the distractor is presented first as this would allow for the distractor responses to interfere with the target responses. This appears, though, not to be the case.

1.4 The Stroop Task and Working Memory Capacity

Since its initial creation, researchers have examined why the Stroop effect occurs. It is generally agreed that the task involves inhibition and selective attention in that one has to inhibit the distractor information in order to focus on and respond to the target. Also, the Stroop task is believed to tap into goal maintenance, as one needs to keep in mind which dimension is the target and which is the distractor while completing the task (Kane & Engle, 2003). Failure to do so can lead to an error when responding, at least for incongruent trials. As such, researchers have examined what effect varying the number of incongruent to congruent trials has on

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response times and accuracy levels, and whether or not there is any relationship between performance on the Stroop task and working memory—how well one is able to control, regulate, and maintain the activation of task-relevant information (Cowan, 1995).

As working memory is generally assumed to be a system capable of storing and manipulating multiple pieces of information at one time, it is generally assumed to be limited in capacity (Becker & Morris, 1999). As such, multiple tests have been developed to measure one's working memory capacity. Unlike short-term memory which is measured by having participants recall a list of words, numbers, etc. in the order in which they were heard, working memory measures have participants recall a list of words, numbers, etc., which they have learned while completing another task (e.g. sentence comprehension) or by manipulating the information they have just heard by, for example, repeating the words in the order of smallest to largest (size-judgment span; Cherry, Elliott, & Reese, 2007). As such, working memory measures generally require participants to keep the task goal in mind (Cowan, 1985).

When Logan and Zbrodoff (1979) explored varying congruency proportions in a series of three experiments, they found that compatible stimuli were processed faster when conflicting trials were rare (conflicting approximately 20% of the time) and that incompatible stimuli were processed faster when they were frequent (conflicting approximately 80% of the time). Extending this manipulation to working memory capacity, Long and Prat (2002) conducted 2 experiments to investigate whether individual differences in working memory capacity, as measured by a complex span task, reflect limitations in the ability to inhibit task-irrelevant information and/or maintain a goal in the face of distracting or interfering events. Long and Prat (2002) used the classic Stroop format involving colored words printed in colored inks and a row of X's for a control stimulus. They looked specifically at whether individuals measured to have

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high or low working memory capacity differed in the susceptibility to Stroop interference, as well as individual differences in strategies for minimizing interference.

Long and Prat (2002) found that high capacity individuals showed interference when conflicting trials were infrequent (20%) and almost no interference when conflicting trials were common (80%). Low-capacity individuals, however, showed substantial interference regardless of the proportion of congruent trials. High capacity individuals did experience substantial negative priming, however, or slow responses when the to-be-named color was the irrelevant word on the previous trial. Long and Prat suggested that inhibition plays a role in the Stroop effect and that high-capacity individuals employ a suppression strategy.

Kane and Engle (2003) re-examined the relationship among working memory capacity, congruency proportions, and the Stroop task in a series of five experiments. Again, Kane and Engle were interested in the importance of goal maintenance and selective attention and used congruency proportions of 0% and 75% with the exception of Experiment 4 which used 20% and 80%. Kane and Engle hoped that by increasing the number of congruent trials, goal neglect would become more likely—especially in participants with low span scores.

Overall, like Logan and Zbrodoff (1979) interference was larger for the 75% and 80% congruent conditions as opposed to the 0% and 20% congruent ones. Furthermore, compared to participants with high span scores, those measured as low spans only showed larger interference and committed more errors on incongruent trials in the 75% congruent condition. In addition, the response times for incorrect incongruent trials committed by low span participants were faster than correct responses from high span participants. This finding suggests that the errors committed by the low spans were due to reading the word as opposed to naming the ink, which

would be neglecting the goal of the task. This in turn highlights the important role goal maintenance appears to play in the Stroop task.

Due to this strong relationship between working memory capacity and classic Stroop, experimenters in recent years have tried to determine whether the different versions of the Stroop task have similar relationships with working memory capacity. If the different versions of the Stroop task are testing the same cognitive processes and using the same mechanisms, one would predict that this would be so. The findings so far, however, have suggested that this may not be the case.

Morey, Elliott, Wiggers, Eaves, Shelton, and Mall (2012) recently attempted to examine the relationship among classic Stroop, cross-modal Stroop, and working memory. They were able to demonstrate a relationship between classic Stroop and working memory, but they were unable to determine any relationship between cross-modal Stroop and working memory capacity.

The authors concluded that the relationship between cross-modal Stroop and working memory capacity may be hard to find as one is constantly reminded of the goal of the task in the cross-modal version. The visual stimulus (the target) remains present until the participant answers. The auditory stimulus, however, comes and then is not heard again. Furthermore, when looking at the visual stimulus typically used in cross-modal Stroop, one is not really able to do anything else but name the color of the square visible. When looking at the visual stimuli in classic Stroop, one can name the word or the ink color. For this task, a person has to keep in mind which dimension they should be attending. As such, there may not be as much of a goal maintenance aspect to cross-modal Stroop as classic Stroop.

In summary, there appears to be a relationship between working memory capacity and classic Stroop. Those with high spans seem to be better at maintaining the goal of the task

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(naming the ink color) than those with low spans when incongruent trials are infrequent. However, this relationship has yet to be found with cross-modal Stroop, which suggests that there may be something different about this version of the task. It may be that it is inherently easier to maintain the task goal in cross-modal Stroop, or perhaps different mechanisms and processes are involved.

1.5 Theories of the Stroop Effect

Over the years many different theories have been proposed to explain the Stroop effect. For the most part, however, all of these theories have a few things in common: something needs to be inhibited in order for a response to be made and/or one thing is faster than the other. What varies between the theories is what needs to be processed, how it is being processed, and what specific mechanisms are involved.

Relative processing speed theory. It is well known that words are read faster than colors are named (Cattell, 1886). According to the relative processing speed theory, this difference in the speed of color naming and word naming is due to the respective processing speeds of the two tasks (Morton, 1969; Morton & Chambers, 1973). Essentially, word reading takes less time to process than naming the color of ink. The Stroop effect arises, therefore, due to this difference in processing speed and a competition for response. When one is presented with a color word written in colored ink they have two options: to name the word or to name the color of the ink. According to the theory, stimulus analyzers for both the color of the ink and the color word work in parallel to create a response. If multiple responses are possible, however, the various responses will compete to be the exiting response. This idea is known as response competition and will lead to a time cost—interference. The direction of this interference is determined by the

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processing speeds of the various components. In the case of the Stroop task, the color word is processed faster; therefore, the color word interferes with naming the ink color.

This theory is able to explain a surprising amount of the research. Facilitation can be easily explained as the two congruent components could potentially prime one other and lead to faster processing, in addition to the fact that either response would be correct. Relative processing speed theory, however, cannot explain why direct manipulations in processing speed through reorientation or practice do not produce results consistent with this theoretical perspective (for more information see Dunbar & MacLeod, 1984; MacLeod & Dunbar, 1988). Also, the theory essentially states that interference should always be asymmetrical. This does not, however, have to be the case. One can theoretically change which response will be received first by altering the onsets of the stimuli. SOA studies have shown that interference is not an orderly function of processing speed, as exposing the slower dimension first does not lead to a clear reversal of the effect by allowing the the color name to "catch up" and interfere with the read word (Glaser & Glaser, 1982; Glaser & Glaser, 1989, Kahnemand & Chajczyk, 1983).

Automaticity of reading theory. Another theory, which follows along in a similar vein, explains the Stroop effect by assuming that reading is automatic. According to this theory, reading is automatic due to the fact that it is obligatory and does not require attention (Posner & Snyder, 1975). When one sees a word he or she will read it either voluntarily or involuntarily. In many situations this would not be a problem. This is an issue, however, when the person does not want to read the word but, for example, should name the color of the ink instead, as is the case in the Stroop task. The desire to name the ink color as opposed to the word leads to one having to inhibit the automatic reading response and leads to interference with the less automatic

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process (naming the ink color). Lastly, the more automatic process always interferes with the less automatic process but never vice versa, which can explain the asymmetry findings.

This theory is able to account for the results of many different analogous Stroop tasks and can explain why varying the SOA would have little to no influence on the effect due to the fact that reading would remain automatic and still need to be inhibited regardless of when it is presented. The main problem with the automaticity of reading theory is that reading may not, in fact, be automatic. If reading was completely automatic, strategy use should have no impact on the effect. As various strategies can be used to influence one's performance—thereby leading to a correlation between one's working memory capacity one's performance on the task—this does not appear to be the case. Furthermore, spatial separation should also have no effect, which is not what the research suggests.

Risko, Stolz, and Besner (2005) conducted three experiments combining Stroop and visual search tasks. In the first experiment, the participants were told to pick a colored word (the word was either incongruent or congruent to the ink color, or neutral) out of a set of white words (which in the colored color word condition were neutral and in the neutral colored word condition contained some color words) and to name the color of the colored word. The Stroop effect, however, was only present when the color and color word were integrated. In Risko et al.'s second experiment, the methodology was exactly the same, but this time instead of classifying the color the participants simply detected the presence or absence of a specific color, which did not lead to the Stroop effect. In the third experiment, the design was exactly the same as the first experiment except that a colored bar was used as the target (as opposed to a colored word) which was surrounded by congruent, incongruent, or neutral words, and again, no Stroop effect was found. All of this suggests that reading is not purely automatic and obligatory. It is

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possible, however, that automaticity is not strictly dichotomous and should instead be placed on a continuum (MacLeod & Dunbar, 1988).

Relative pathway strength theory. This theory was first developed by Cohen, Dunbar, and McClelland (1990) and got its current name from another researcher seeking to compare the various theories of the Stroop effect (Roelofs, 2005). The theory is based on the idea that automaticity is a continuum that develops with practice (for more information see MacLeod & Dunbar, 1988), and that processes differ in automaticity according to the amount of attention they rely upon.

This theory is based upon the principles of parallel distributed processing and is more heavily tied to neuroanatomy than any of the other major theories. The theory revolves around the idea of systems of connected modules, which comprise groups of elementary processing units. These units represent information as a pattern of activation. Processing, in turn, occurs by the spread of activation from one module to the next. A pathway, which is used for a particular process, is formed by a sequence of connected modules. The speed and accuracy with which information flows along the appropriate processing pathway determines the speed and accuracy with which a task is performed. The authors refer to this as the *strength* of the pathway.

Individual modules can, however, receive input from and send information to numerous other modules and can, therefore, participate in several different processing pathways. As a result, pathways can "interact" in that two or more pathways can rely upon a common module. If both of these processes are activated and the patterns of activation that each pathway generates are different, then interference will occur within that module and processing will be impaired in one or both pathways. If the patterns of activation are similar, however, this will lead to

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facilitation. In the cases where more than one response is possible, attention modulates which one is chosen.

It should be noted that since the theory's initial creation, another component has been added, that of the conflict monitor (Botvinick, Carter, Braver, Barch, & Cohen, 2001). Essentially, the anterior cingulate cortex (ACC) is believed to be responsible for this role. The ACC monitors the amount of interference and establishes a chain of events that leads to the allocation of attention. This helps to explain why more errors are not made when there are conflicts among the pathways.

As such, according to this theory, there is a word-naming pathway and color-naming pathway, which are assumed to share a common module. The word-naming pathway, however, is the stronger of the two due to the fact that it receives more practice. Thus, this word-naming pathway requires less attention and interferes with the weaker color-naming pathway when they are simultaneously activated with dissimilar information. When the two pathways are simultaneously activated with similar information, however, facilitation occurs.

This theory is able to explain Stroop interference and facilitation as well as many of the other general findings. The theory is not, however, able to explain all of the findings with varying SOA. While the theory can account for why manipulating the SOA does not cause a reversal in the asymmetry of the Stroop effect—the differences in the strengths of the color-naming and word-naming pathways would remain regardless of when they are activated— the theory cannot account for the fact that presenting a word sufficiently in advance of the color reduces interference. In fact, the theory actually predicts that the interference should be larger in this scenario than when the word and color are presented simultaneously.

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Tectonic theory. Another theory, the tectonic theory by Melara and Algom (2003), takes a slightly different approach to the Stroop effect. Melara and Algom examine the Stroop task in terms of what they call the *paradox of selection*. Essentially, this has to with the fact that the goal of avoiding distractions is contrary to our desire to process salient and related aspects of our environment. The Stroop task, therefore, exemplifies this paradox and the role that surprising, salient, and correlated information play on disrupting selective focus.

A Stroop trial consists of two corresponding perceptual representations, in this case the color and the word. However, according to this account, the Stroop effect arises due to the fact that the two dimensions present are imbalanced. During a trial, each part of the Stroop stimuli (the target—the color dimension—and the distractor—the word dimension) is perceptually activated, which, in turn, activates the corresponding long-term memory representations.

According to Melara and Algrom, long-term memory is organized by dimensions, which echo the structure of perceptual space. Furthermore, the efficiency with which we access these dimensions in long-term memory depends, in part, on an individual's developmental history with processing the separate values along these dimensions. The imbalance in the two dimensions of the Stroop task, therefore, is due to the fact that most individuals have numerous perceptual experiences with auditory and visual words (but not with colors), which establishes an optimal visual angle for viewing text. Thus, most of us are more efficient at discriminating between different values along the word dimension than the color dimension.

Lastly, the authors propose that there are two memory-based structures, which direct selection by processing the salient, surprising, and/or correlated information contained within and across the dimensions of a stimulus. Each of these structures moderates the amount of excitation to a target, buildup of inhibition to a distractor, and memories of previous stimuli. As

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such, as dimensional imbalance and dimensional uncertainty (the degree of surprisingness and correlation) increase, inhibition and excitation become less and less efficient. Therefore, impeding information about the more discriminable/salient and, in this case, irrelevant dimension, causes Stroop interference. Facilitation, meanwhile, is due to the fact that the information from the distracting dimension is relevant to the target dimension and aids in processing and discrimination. Although this theory is able to explain Stroop facilitation and interference, it is not clear exactly what the theory predicts in terms of SOA manipulations.

Word production architecture theory. According to this theory first put forth by Roelofs (1997) and again by Levelt, Roelofs, and Meyer (1999), the Stroop effect is due to the word production structure. Color naming is assumed to require conceptual planning and preparation of the spoken color name. This includes selecting a "lemma" (a representation of a word as a syntactic entity, which mediates word meaning and form) of the name and encoding the word form. Word naming, in contrast, is believed to be a relatively "shallow" process involving simple "form-to-form mapping of print onto the word form of the spoken color name" (Roelofs, 2005, p. 1326) which does not require lemma selection. Furthermore, a lemma only significantly activates the corresponding word form for color naming when one actually wants to name the color. Thus, the intricately produced color name will be affected by the shallowly produced word name, but not vice versa. Therefore, when the word and color representations are both activated close enough in time, this can cause either interference (if the representations are different) or facilitation (if the representations are the same).

Due to the fact that the word will always be processed in a shallow manner and the color a deep manner, the differences in processing between colors and words will remain with the pre-

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exposure of both the word and the color, consistent with the SOA findings. This theory is, therefore, able to explain why few studies have been able to provide evidence of reverse Stroop.

In summary, although all of the theories are able to account for some of the classic Stroop findings, it would appear that no theory is able to explain all of them, with most of the theories being unable to explain the results from manipulating SOA. How these theories relate to the cross-modal Stroop will be examined in detail later.

1.6 Differences Between Classic and Cross-Modal Stroop

Despite the fact that both classic and cross-modal Stroop exhibit interference, there are still some important and prominent differences in the results of the two. For instance, while both tasks produce interference, the interference found for the cross-modal version (around 25ms when there are no congruent trials presented) is considerably smaller than that found in the classic version (generally around 100ms). Furthermore, while facilitation is consistently found in the classic version of the task, it is less robust in the cross-modal version.

In addition, the response times in all of the conditions of cross-modal Stroop (silent, incongruent, congruent, and non-color) are faster than their respective conditions in classic Stroop. Lastly, as discussed earlier, unlike classic Stroop, there does not appear to be any relationship between working memory capacity and cross-modal Stroop. This last point in particular draws into question whether or not the two tasks involve the same processes and mechanisms, and more generally whether the distraction effects in one modality are similar to the effects in two modalities. As such, the current thesis will focus on how the theories discussed can be applied to cross-modal Stroop, with less of a focus on how cross-modal Stroop can expand the theories.

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1.7 How the Theories Relate to Cross-Modal Stroop

As cross-modal Stroop is a relatively new version of the task, it has not really been used to help develop the theories explaining the classic Stroop effect. Furthermore, the theories, for the most part, have not been applied extensively to the cross-modal version of the task. One main thrust has, instead, been on goal neglect and selective attention. Most of the theories, nonetheless, can be applied to the cross modal version; however, this generally leads to some assumptions of which the validity is not known and to the same problems that the theories have with the classic version.

Relative processing speed theory. If one does, in fact, process auditory information faster than visual information, this theory should be able to explain all of the aspects of the cross-modal Stroop that it can for the classic Stroop. However, it is not entirely certain that information in the auditory modality is processed faster than information from the visual modality, and the theory still has the problems with cross-modal Stroop that it does with the classic Stroop: it cannot account for the fact that presenting the distractor first (in this case the auditory word) does not lead to a reversal of the Stroop effect (Shimada, 1990; Roelofs, 2005).

Automaticity theory. This theory is able to explain most of the cross-modal findings such as interference and facilitation and the manipulations with SOA, assuming that listening is the more automatic process. This would make sense as research suggests that one cannot entirely ignore what he or she is hearing (Spence, Ranson, & Driver, 2000; Conway, Cowan, & Bunting, 2001; Beaman, 2004). The fact that the cross-modal Stroop effect exists at all supports this and suggests that listening would appear to be at least somewhat obligatory. In fact, cross-modal Stroop was even originally examined by Cowan and Barron (1987) to see whether one could not listen or be affected by what they were hearing.

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Relative pathway strength theory. Theoretically, there would be a word-repeating pathway and, again, a color-naming pathway. It would be assumed that as we hear spoken words more often than naming colors, the spoken word-repeating pathway would be the stronger of the two. Therefore, if both pathways shared a module, activation of the two pathways with dissimilar information would lead to interference, and activation with similar information would lead to facilitation. It is possible that there is less interference and facilitation in the cross-modal version of the Stroop task because the read-word naming pathway is stronger in comparison than the word-repeating pathway to the color-naming pathway. Whether or not word repeating is more automatic/faster/stronger then color naming, however, is not known. Also, as in the classic Stroop, this theory cannot explain why there is no Stroop interference if the auditory word is presented a reasonable amount of time before the to-be-named colored item.

Tectonic theory. According to this theory, spoken words are more dimensionally discriminable than colors due to the fact that we have more experience distinguishing them. This does seem reasonable as one is constantly distinguishing spoken words. Why there is less facilitation and interference in the cross-modal version of the task is unclear, however, given that research suggests that the processing of sounds is both automatic and obligatory (Spence et al., 2000; Conway et al., 2001; Beaman, 2004), while reading, some argue, would appear to only be automatic (Risko et al., 2005). Thus, if we truly are better at distinguishing spoken words from written words, one could conclude that the interference and facilitation should be greater, not less. Also, again, this theory is unclear about the findings with SOA in the cross modal version of the task.

Word production architecture account theory. If one assumes, again, that color naming involves conceptual planning and preparation, including the selection of a "lemma" and

encoding the word form and that spoken word naming simply involves form-to-form mapping, this theory is essentially able to explain everything in the cross modal version that it is able to do in the classic. However, the theory is not really able to explain why interference and facilitation are smaller in the cross-modal version of the Stroop task. One would assume, again, that we listen as much as, or possibly more than, we read. Therefore, one would assume we would process auditory words just as shallowly as written words. If this were the case, one would expect the same levels of interference. Also, this theory is not able to explain the findings involving spoken color words and written color words. When Cowan and Barron (1987) first conducted cross-modal Stroop they used auditory and written color words. As the interference with written words and color is greater than that for spoken words and color, it would suggest that written words are processed in a shallower manner than spoken words. Why is it, then, that spoken words interfere with written words? Roelofs (2005) has argued that two shallowly processed dimensions can interfere with one another, but then why do these two shallowly processed dimensions lead to unequal amounts of interference?

1.8 The Current Experiments

Two experiments were conducted to examine how well the classic Stroop theories explain the findings of cross-modal Stroop. The first experiment explored what effect a visual stimulus can have on interference. The visual stimuli were, therefore, chosen to represent a continuum of how much color the item displays, frequency of appearance, and semantic complexity. The visual stimuli that produce the greatest semantic activation and provide the least amount of the color would be expected to produce the greatest amount of interference. However, it is also possible that the visual stimulus may have no impact on interference levels, as it would play such a small role in the process.

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The second experiment sought to examine the theories of classic Stroop in the context of the cross-modal Stroop task by examining whether there is an asymmetry in naming colors and listening to spoken words. The speed at which individuals named the color of an item was compared to repeating auditory color words when each task was completed alone and with the other dimension present as a distractor at varying SOAs. As such, both a "traditional" cross-modal Stroop paradigm was tested in which one named the color of the visual item while ignoring auditory distractors, and a "reverse" cross-modal Stroop paradigm during which one saw colored items while repeating auditory words.

If there is an asymmetry in that repeating words is not affected by seeing colors but naming colors is harmed by hearing words, all of the theories will be upheld and it would suggest that similar processes are taking place in the cross-modal and classic versions of the task. If this pattern does not occur, it would suggest that most of the theories are not applicable to the cross-modal Stroop task and that the same processes and mechanisms used for classic Stroop are most likely not involved when completing cross-modal Stroop.

Chapter 2. Experiment 1

Although previous cross-modal Stroop experiments have used an array of visual stimuli, a direct assessment of the degree of interference based on the type of visual stimulus has not been conducted. For example, Elliott et al. (1998) and Hanauer and Brooks (2003) used colored patches while Elliott, Morey, Morey, Eaves, Shelton, and Lutfi-Proctor (2013) experimented with a row of four colored @ symbols. Dots and circles have been used by Cowan (1989) and Shimada (1990) respectively. Roelofs (2005) has used color words that were read (whether they were black or colored is unclear), and strings of x's and colored color words were used in the original cross-modal Stroop experiment conducted by Cowan and Barron (1987). The following experiment, therefore, examined and compared the impact different stimuli have on the magnitude of Stroop interference in the cross-modal version of the task. The results will also help to determine whether some of the theories of classic Stroop are more applicable to cross-modal Stroop than others.

Colored squares, symbols (@, *, and ~), numbers (4s), and letters (X's), as well as black color words were used. Black color words that were read were chosen as opposed to colored color words due to the fact that this condition has since become known as multimodal Stroop and displays an unusual pattern of results (see Elliott et al., 2013 for more information). Black color words that were read allow us to examine what occurs when the two supposedly dominant dimensions (written and spoken words) are placed in conflict. Some of the theories (e.g. automaticity account) could be said to argue that little to no interference should be found for this stimulus due to the fact that it is so shallowly processed. Other theories argue that some interference will probably occur, but to what extent is unclear.

Based on a summation of all of the theories, two sets of hypotheses are posited for the colored visual stimuli. According to the word production architecture and automaticity theories, there should be no difference in the amount of interference seen for any of the visual stimuli (@ = 4 = * = X = ~ = squares). The auditory word would always be shallowly processed, and the automatic process (listening) would always interfere with the less automatic process (color naming). However, according to the other three theories, the more complex colored visual stimuli (the symbols, letters, and numbers) will lead to the largest amounts of interference (@ > 4 > * > X > ~ > squares). The meaning of the actual stimulus would either activate another pathway, lead to a faster or slower processing of the color, or contain less of the color so as to be less discriminable. The simple colored visual stimuli (the color patch) would also lead to interference, but less than the more complex stimuli due to the fact that it is more discriminable and does not lead to additional activation or slower processing. The pattern that black words that are read will display is unclear at this time.

2.1 Methods

Participants. A total of 61 Louisiana State University undergraduates participated for course or extra credit. The mean age of the participants was 20.32 ($SD = 1.93$). Participants were not eligible to participate if they reported abnormal hearing, color vision, mind-altering medications, abnormal uncorrected vision, or a first language other than English. Due to these restrictions, 2 participants were excluded from all data analyses. Of the 59 participants examined, the majority of participants were female (74.6%) with a mean age of 19.56 ($SD = 2.01$).

Materials. This experiment utilized a 2 (test type) x 2 (auditory condition) x 7 (visual condition) mixed-factor design. Incongruent and silent auditory conditions were employed

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within-subjects as well as the different visual stimuli, while there were two versions of the experiment (test type), which were between-subjects. In one test version, the seven different visual stimuli were intermixed and presented randomly in two sets (the integrated version), while in the second version the different types of visual stimuli were presented in individual blocks (the blocked version). This manipulation was done to determine the effect of having to switch from one visual stimulus to the next from trial to trial, versus having a set visual stimulus that was consistent within a block of trials.

In addition, the black words, which were read, should lead to a task switch in the integrated version of the experiment. Participants are switching from the task of naming colors to reading words from trial to trial. In the blocked version, the task goal for each section is clear. Participants read words for one block of trials. After that section is complete, participants never had to read a word again. This format is similar to that of Elliott et al. (1998), which found that presenting the different types of trials in blocks (non-color words, incongruent, etc.) led to less interference than presenting the different types of trials randomly.

Whereas previous cross-modal Stroop experiments employed one type of visual stimulus that varied from one experiment to the next, the visual stimuli in this experiment consisted of a row of four colored @ or ~ symbols, 4s, asterisks, X's, or a colored square, as well as color words written in black which were to be read. The visual stimuli were chosen based on their use in past experiments (@ symbols, X's, colored squares, and colored color words) and so as to provide a continuum of frequency of appearance, degree of semantic activation, and visual complexity.

The visual stimuli and auditory distractors were presented simultaneously for the incongruent (the auditory word was not the same color as the visually presented stimuli) and

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neutral/silent (the visual stimulus was presented by itself without any auditory stimuli) conditions. Congruent trials were not examined in this design, as facilitation is quite rare in the cross-modal version of the Stroop task and, some have argued, due to different factors than those responsible for interference (MacLeod, 1991). As the main focus of this experiment was the effect of different visual stimuli on Stroop interference, only incongruent and neutral trials were used.

The experiment was presented using E-Prime 2.8 software (Schneider, Eschman, & Zuccolotto, 2002) on a Dell Dimension desktop computer with a 17-inch monitor. A headset microphone connected to a response box logged the vocalization onsets and recorded the participants' response times. The auditory distractors used (the words red, blue, and green) were a recorded female voice and presented through headphones at a comfortable volume with the volume of the words being subjectively equal. The task was completed in approximately 25 minutes in a room with only the participant and the experimenter.

Procedure. In the integrated version, the participants received instructions, and then saw 21 practice trials at the beginning of the first set (3 trials of each of the 7 visual stimuli), while using the microphone to name the visual stimuli without any auditory distractors. The experimental portion consisted of two sets of 168 randomly ordered trials (for a total of 336 trials) with an optional five-minute break between the two sets. There were an additional 7 practice trials at the beginning of the second set so the microphone could be adjusted if the optional break was used. In the experimental trials, each type of visual stimulus was presented for a total of 48 trials between the two sets with 24 incongruent and 24 neutral/silent trials. There were 6 possible incongruent combinations each presented an equal number of times: *red-blue*, *red-green*, *blue-red*, *blue-green*, *green-red*, and *green-blue*.

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The blocked version of the experiment was exactly the same as the integrated experiment except that the visual stimuli were presented in blocks as opposed to being randomly intermixed. Three practice trials were presented before each of the seven blocks of different visual stimuli (leading to a total of 21 practice trials), and the blocks were presented in random order.

Each trial began with a fixation cross in the center of the screen for 500ms. The target was presented on the screen with or without an accompanying sound through the headphones. In trials with sounds, the onset of the visual and auditory stimuli was simultaneous. The visual stimuli remained on the screen until the microphone detected a response. The participant named the color of the presented stimulus or read the black word as quickly and accurately as possible. The experimenter then used the keyboard to respond to three questions following each trial: the color word said by the participant, whether a false start had taken place (the participant essentially triggered the microphone with an incomplete response), and whether any errors were made by the experimenter in answering the first two questions.

2.2 Results

Mixed model and repeated-measures ANOVAs were used to analyze response times (RTs), accuracy, and false starts. Overall, 1.81% of trials contained an inaccurate response, 2.74% involved a false start, and the experimenter made an error responding 0.41% of the time. For all analyses $\alpha = .05$, and the Bonferonni correction was used for all appropriate follow-up tests. In all cases where sphericity was violated and the results were significant, the Greenhouse-Geisser correction was used.

Response times. Means of medians were used to examine RTs, and a 2 (test type) x 2 (auditory condition) x 7 (visual condition) mixed-model ANOVA was use to analyze overall RTs across the two versions of the experiment, after removing the trials with errors, as indicated

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above. There was a main effect of auditory condition, $F(1, 57) = 351.26$, $p < .01$, and visual condition, $F(6, 342) = 19.27$, $p < .01$. Although the auditory condition by test version interaction was not significant, the visual condition and test version interaction was, $F(6, 342) = 3.61$, $p < .05$. However, the auditory by visual condition interaction was not significant, nor was the three-way interaction. Due to differences in results that were supported by the significant two-way interaction, the integrated and blocked versions of the experiment were analyzed and reported separately.

2.3 Results from the Integrated Version.

Overall, the percentage of trials including inaccurate responses (1.84%), false starts (1.74%), and experimenter errors (0.12%) was quite low. RTs, accuracy levels, and false starts were all analyzed using repeated-measures ANOVAs and are reported separately.

Response times. A 2 (set) x 2 (auditory condition) x 7 (visual stimuli) repeated-measures ANOVA was used to analyze the remaining RTs. The data were analyzed across the two sets of trials separately, as set had an impact on interference levels.

It was found that there was no significant main effect for set. However, there was a significant main effect of visual condition, $F(6, 162) = 16.81$, $p < .01$, $\eta_p^2 = .38$ (see Appendix A). In addition, there was a significant main effect for auditory condition, $F(1, 27) = 208.90$, $p < .01$, $\eta_p^2 = .89$. The RTs for incongruent trials were significantly slower than the RTs for neutral trials, meaning that the experiment did induce cross-modal Stroop interference. Furthermore, there was a significant set and auditory condition interaction, $F(1, 27) = 10.73$, $p < .01$, $\eta_p^2 = .28$, with a larger amount of interference found in the first set of the experiment than the second (see Figure 1).

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The set and visual condition interaction was not significant, nor was there an auditory and visual condition interaction. However, although sphericity was violated, there was a three-way interaction of auditory condition, visual condition, and set, $F (4.49, 121) = 2.50, p < .05, \eta_p^2 = .09$. Due to this significant three-way interaction, two separate 2 (auditory condition) x 7 (visual condition) repeated-measures ANOVAs were then run for each set.
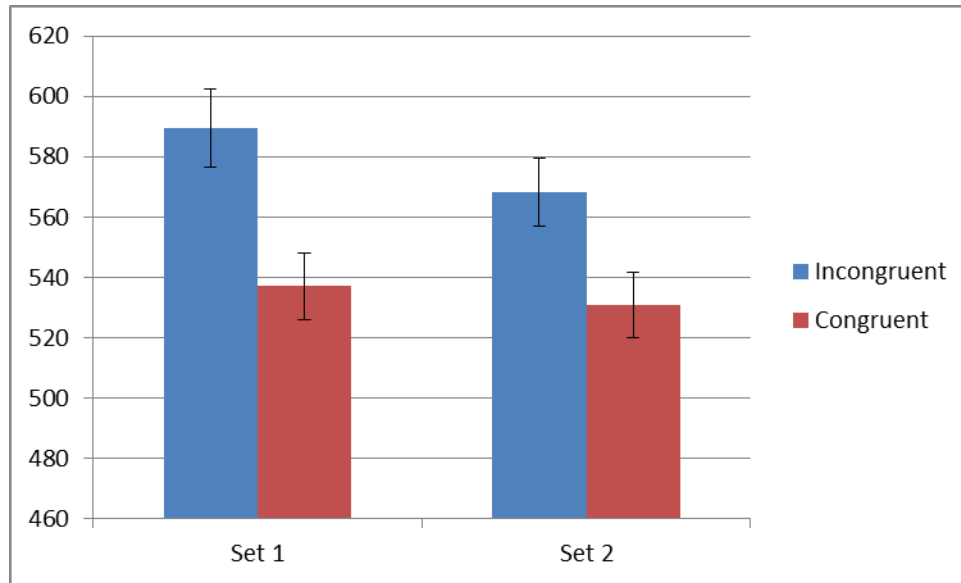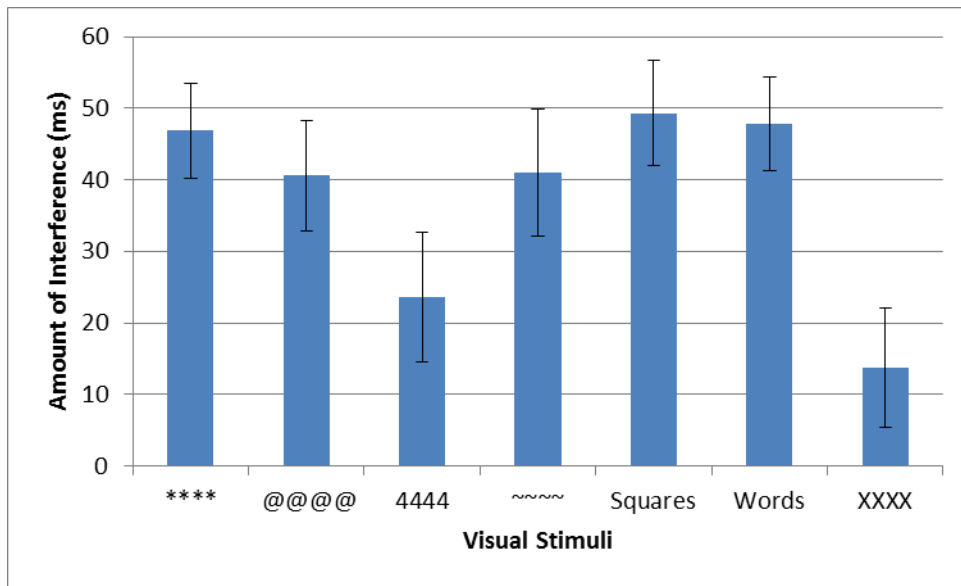

Figure 1. RTs by auditory condition for block 1 and 2 of the integrated version of experiment 1. Error bars represent standard error. The interaction was significant, $p < .01$.

For set one, there was again a main effect of visual condition, $F (6, 162) = 6.95, p < .01, \eta_p^2 = .21$, and a main effect of auditory condition, $F (1, 27) = 155.36, p < .01, \eta_p^2 = .85$, meaning the experiment induced cross-modal Stroop interference; though once again, the auditory and visual condition interaction was not significant, $F (6, 162) = 1.4, p > .05, \eta_p^2 = .05$. However, in the second set, there was a main effect of auditory condition, $F (1, 27) = 117.52, p < .01, \eta_p^2 = .81$, and, although they both violated sphericity, a main effect of visual condition, $F (3.9, 105.26) = 13.83, p < .01, \eta_p^2 = .34$, and a visual and auditory condition interaction, $F (3.83, 103.5) = 3.22, p < .05, \eta_p^2 = .11$, were found, indicating that the different visual stimuli led to varying amounts of interference in the second set.

Interference scores were then created for set 2 only by taking each participant's mean neutral RT score and subtracting it from their mean incongruent RT score for each individual visual stimulus type. This led to each person having an interference score (or a measure of how much cross-modal Stroop interference they displayed) for all of the visual conditions. A repeated-measures ANOVA was then run on these interference scores. Although sphericity was violated, there was a significant difference in the amount of interference induced by the different visual stimuli, $F (3.83, 103.5) = 3.22$, $p < .05$, $\eta_p^2 = .11$ (see Figure 2). Although there was a range of interference for the various stimuli, only x's were significantly different in that they produced significantly less interference than the @, *, and ~ symbols, words, colored squares, and 4s.

Note: X was significantly different from the @, $p < .01$

Figure 2. Interference scores for block 2 of the integrated version of Experiment 1. Error bars represent standard error.

Accuracy. Overall, a total of 1.84% of the trials induced an inaccurate response. A 2 x 2 x 7 repeated-measures ANOVA was used to determine whether there were any significant

differences among the sets, auditory conditions, or visual stimulus types; however, none of the conditions produced any differences in accuracy levels.

False starts. Once again, a 2 x 2 x 7 repeated-measures ANOVA was used to determine whether there were any significant differences among the two sets, two auditory conditions, or seven visual stimulus types. However, there was no significant main effect of set or auditory condition. Nor were any of the interactions significant. However, although sphericity was violated, there was a main effect of visual condition, $F(4.42, 119.44) = 5.42$, $p < .05$, $\eta_p^2 = .52$. Those trials that used colored 4s as the visual stimulus produced significantly more false starts than those trials that displayed colored asterisks, tildes, squares, or black words (see Table 1).

Table 1. False start percentages and standard errors by visual condition in the integrated version of Experiment 1.

Visual Stimulus	False Starts	Standard Error
****	0.01	0.002
@@@@	0.02	0.004
4444	0.03*	0.006
~~	0.01	0.005
Squares	0.01	0.003
Words	0.01	0.003
XXXX	0.02	0.005

*Significantly different from asterisk, square, and word, $p < .01$, and tilde, $p < .05$

2.4 Results from the Blocked Version.

The percentage of trials including inaccurate responses (1.78%), false starts (3.34%), and experimenter errors (0.7%) for the blocked version of the experiment was roughly equivalent to the integrated version, although the number of false starts was slightly higher. RTs, accuracy

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levels, and false starts were all analyzed using repeated-measure ANOVAs and are reported separately.

Response times. Trials containing inaccurate responses, false starts, and experimenter errors were removed from all RT analyses leading to a total removal of 5.82% of trials. Means of medians were used in a 2 (auditory condition) x 7 (visual stimuli) repeated-measure ANOVA.

It was found that there was there was a significant main effect of visual condition, F (4.28, 128.25) = 11.13, $p < .01$, $\eta_p^2 = .27$ (see Table 2). In addition, there was a significant main effect for auditory condition, F (1, 30) = 158.39, $p < .01$, $\eta_p^2 = .84$. The RTs for incongruent trials were significantly slower than the RT for neutral trials, indicating that the experiment did induce Stroop interference (see Figure 3). However, there was no auditory by visual condition interaction; thus, interference scores will not be reported for this version of the experiment.

Table 2. Overall mean RTs and standard errors for the visual stimuli in the blocked version of Experiment 1.

Visual Stimulus	Mean RT	Standard Error
****	516.73	10.27
@@@@	520.71	12.82
4444	532.88	13.98
~~	506.77	11.30
Squares	511.81	11.42
Words	459.67*	12.23
XXXX	523.22	19.10

*Significantly different from asterisk, @ symbols, 4's, ~ symbols, squares, and X's, p < .001
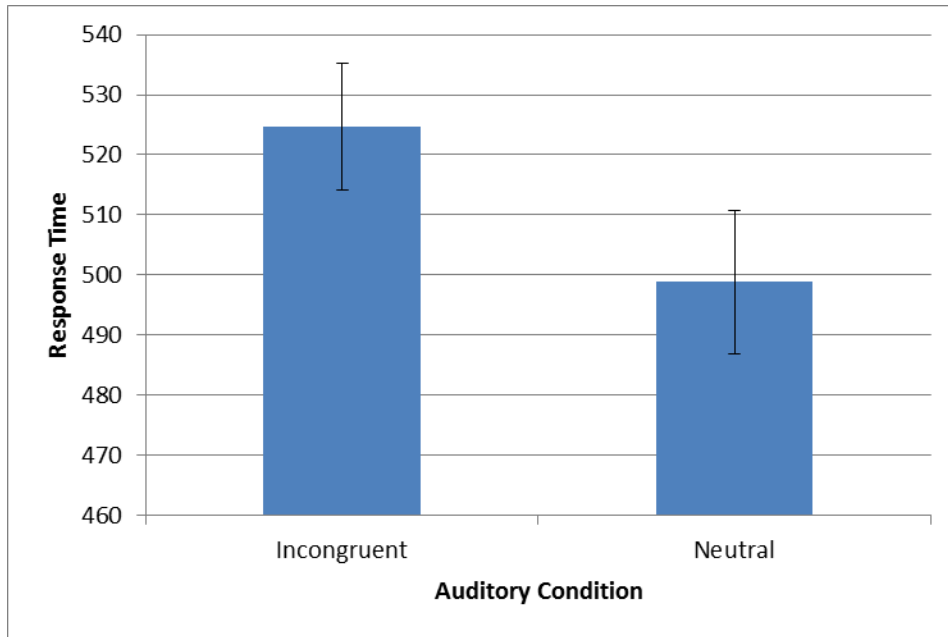
Note: Incongruent and congruent trials were significantly different from one another, *p* < .01

Figure 3. RTs by auditory condition for the blocked version of experiment 1. Error bars represent standard error.

Accuracy. Overall, a total of 1.78% of the trials induced an inaccurate response. A 2 (auditory condition) x 7 (visual condition) repeated-measures ANOVA was used to determine whether there were any significant differences in accuracy. There was a significant main effect of visual condition, $F (6, 180) = 2.48$, $p < .05$, $\eta_p^2 = .08$ (see Table 3), but no main effect for auditory condition, nor was there a significant visual and auditory condition interaction.

False starts. Overall, a total of 3.34% of the trials contained a false start. Once again, a 2 (auditory condition) x 7 (visual condition) repeated-measures ANOVA was used to determine whether there were any significant differences in the rate of false starts while responding. None of the main effects or interactions was significant.

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Table 3. Inaccuracy percentages and standard errors for the blocked version of Experiment 1.

Visual Stimulus	Inaccurate Trials	Standard Error
****	0.02	0.005
@@@@	0.02	0.005
4444	0.02	0.004
~~	0.02	0.004
Squares	0.02	0.005
Words	0.01*	0.002
XXXX	0.02	0.004

* Significantly different to asterisks, $p < .05$, and close to significantly different to tildes, $p = .091$

2.5 Discussion

All of the different visual stimuli in both versions of the experiment (integrated and blocked) were able to induce interference, regardless of the fact that there were overall differences in the RTs for the different visual stimuli. However, one goal of the current study was to determine if the magnitude of Stroop interference would differ based upon the visual stimulus. The only instance of an interaction between the auditory and visual conditions occurred during the second set of the integrated version of the experiment. This finding is interesting as the overall level of interference actually decreased in the second set compared to the first. It is possible that while the participants were getting better at reducing the amount of interference being induced, they were still becoming fatigued and so the differences in interference caused by the different visual stimuli began to become apparent. This may also help to explain why a visual and auditory condition interaction was not found in the blocked version of the experiment, as any effects caused by fatigue would have been washed out due to the random order of the blocks across participants.

Within the second set of the integrated version, only a row of colored X's produced a significantly different amount of interference, leading to an average of only 13ms. This suggests that a row of X's would perhaps serve as an excellent neutral stimulus in the future. Interestingly, this is how Cowan and Baron (1987) used X's in the very first cross-modal Stroop experiment. More work needs to be done, however, to ensure that switching to a different visual stimulus on neutral trials does not lead to additional interference.

Although not significantly different, it is interesting to note that there was a trend in that both the colored squares and black words induced the largest amounts of interference in the integrated version, especially since it is also these two stimuli that produced the shortest overall RTs. Why the stimuli that are most easily named may also lead to the largest amounts of interference is unclear at this time; however, it is possible that the ease of naming suggests something about pathway strength, which is consistent with the relative-pathway strength account.

The fact that reading a color word while ignoring auditory color words led to any interference is surprising due to the assumptions of some of the theories. While one could argue that the interference found for the words in the integrated version of the experiment could be due to task switching—one had to switch from the task of naming colors to reading a word—the fact that words produced interference in the blocked version of the experiment suggests this is not the case. Regardless, whether this interference is being caused by the same mechanisms responsible for the Stroop effect is not clear, it is still a significant finding, as it suggests that a "stronger" dimension is capable of being interfered with. Furthermore, the only difference in accuracy levels found for any of the conditions in both versions of the experiment was seen for words in the blocked version. Participants had significantly less errors for words. This suggests that

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while participants were very good inhibiting the correct response, they could not prevent themselves from being slowed by the presence of an incongruent auditory color word. Roelofs (2005) examined a similar scenario in which participants read color words while ignoring auditory words and was only able to find evidence of facilitation in RTs and no significant results in terms of accuracy across different auditory conditions; however, the differences in results may be due to the fact that Roelofs (2005) also manipulated SOA.

Finally, it is not clear why a row of colored fours led to significantly more false starts in the integrated version of the experiment. It is possible that it was simply an anomaly. The fact that this finding was not replicated in the blocked condition suggests that this may be so.

In summary, the different visual stimuli did lead to varying amounts of interference under certain conditions. This is counter to the predictions of the word production architecture and automaticity account; furthermore, the fact that X's led to the lowest levels of interference is hard to rectify with the relatively processing speed and tectonic theories. The fact that words produced significant levels of interference is hard to rectify with the tectonic theory and the word-production architecture account. Although the word-production architecture account argues that it can account for the interference found for words, this leads to some apparent inconsistencies in the theory. The second experiment will provide an additional method for contrasting the views of the classic Stroop task, and their application to cross-modal Stroop. Experiment 2 examined the response times and accuracy levels of naming a visual color and repeating an auditory word both when distractors were and were not present. In classic Stroop, written words always interfere with colors but colors never interfere with written words. Whether or not this asymmetry is apparent for cross-modal Stroop is unclear. Previous research

suggests that there is indeed an asymmetry (Roelofs, 2005); however, it may not be the same

asymmetry found in classic Stroop.

Chapter 3. Experiment 2

Experiment 2 was conducted to examine RTs and accuracy levels for naming a visually presented color when an auditory distractor is present and for repeating a spoken color name when a visual distractor is present. As such, this experiment consisted of two parts, a baseline portion and an experimental portion. In Part A, participants named the color of squares in one set of trials, and repeated auditory color words with no distractors in a separate set of trials, to determine the rate of information processing in the auditory and visual channels. According to the theories reviewed above, the stronger dimension should display shorter RTs and higher accuracy levels than the weaker dimension when tested separately. Words are read faster and more accurately than colors are named in the visual modality. Whether auditory words are repeated faster than colors are named is unclear.

In Part B of this experiment, whether or not one can reverse the Stroop effect in the cross modal version of the task was examined (see also Roelofs, 2005). As an asymmetry between the two processes involved (e.g. naming a color and reading a word, or naming a color and hearing a sound) is necessary in order for most of the theories to remain valid in the cross-modal version, it is important to determine whether the cross-modal Stroop effect is actually the result of an imbalance between the modalities involved. If seeing color squares does lead to a difference in repeating color words, it would suggest that the auditory and visual dimensions interfere with each other and that this imbalance does not exist for the cross-modal Stroop task as it does in the classic task

3.1 Methods

Participants. Sixty-eight Louisiana State University undergraduates were tested for course or extra credit (age *M* = 20.32, *SD* = 1.93). Again, participants were not eligible to

participate if they reported abnormal hearing, color vision, mind-altering medications, abnormal uncorrected vision, or a first language other than English. Four participants were excluded from all analyses for not fulfilling these requirements. One participant was removed due to missing data, and another due to a lack of receiving all of the instructions (the final $N = 62$)

Materials. This experiment consisted of two parts, A and B, which each contained two tasks. All manipulations were within subjects. Part A consisted of two tasks, which were counterbalanced: Naming Colors and Repeating Colors. In the Naming Colors task, participants named the color of a square as quickly and accurately as possible. Squares were chosen based upon the results of Experiment 1, and popular usage in the previous literature. In the Repeating Colors task, participants repeated an auditory color word as quickly and accurately as possible. In both tasks, only the colors *red*, *blue*, and *green* were used. The auditory color words took approximately 280ms (blue), 270ms (Green), and 340ms (red) to be heard in their entirety. The colors were presented quasi-randomly, an equal number of times.

Part B consisted of two tasks, which were also counterbalanced: Traditional Cross-Modal (CM) Stroop and Reverse Cross-Modal (CM) Stroop. In traditional CM Stroop, participants completed the traditional cross-modal Stroop task in which they named the color of squares while hearing incongruent and congruent words, silence, and catch trials (the word "tall"). In reverse CM Stroop, participants completed a reverse cross-modal Stroop task in which they named the color of spoken words while seeing color squares which were an incongruent or congruent color to the spoken color word, a blank screen, or visual catch trials (a black circle). Catch trials were included in order to ensure that participants were looking at the screen during reverse CM Stroop. We were concerned that participants would simply look away from the screen so as to avoid the distracting information. Because catch trials were necessary in reverse

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CM Stroop, they were also included in traditional CM Stroop to provide an equivalent experience for both tasks.

For both Stroop tasks, the stimulus onset asynchrony (SOA) was also varied so that the auditory stimulus was presented 500ms before (500ms or sound first), simultaneously with (0ms or simultaneous), and 500ms after (-500ms or square first) the visual stimulus. This manipulation led to a 3 x 4 repeated-measures design for both Stroop tasks with three levels of the SOA condition and 4 levels of the auditory/visual condition (neutral, incongruent, congruent, and catch), referenced henceforth as congruency. Congruent trials were examined so as to provide a more direct comparison to the findings in classic Stroop (Glaser & Glaser, 1989).

The entire experiment was presented using E-Prime 2.10 software (Schneider, Eschman, & Zuccolotto, 2002) on a Dell Dimension desktop computer with a 17-inch monitor. Again, a headset microphone connected to a response box logged the vocalization onsets and recorded the participants' response times. The auditory words used were a recorded female voice presented through headphones. The volume of the different color words were subjectively equal and presented at a comfortable volume. The task was completed in approximately 30 minutes in a room with only the participant and the experimenter.

Procedure. Every trial in Part A began with a fixation cross in the center of the screen, which remained onscreen for 500ms. For the Naming Colors task, the visual targets were then presented on the screen and remained until the microphone detected a response. The experimenter used the keyboard to answer three questions: what response the participant has given, whether or not a false start has taken place (the participant essentially triggers the microphone with an incomplete response), and whether the experimenter had made an error in answering the first two questions. The Repeating Colors task was essentially identical except

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that participants heard a color word after the presentation of the fixation cross instead of seeing a color square (the screen remained blank until the microphone was triggered). Once the microphone was triggered, the experimenter responded to the same 3 questions described for the previous task.

For Part A, each task began with 6 practice trials with each of the three possible colors—*red*, *blue*, and *green*—presented an equal number of times (two). The practice trials were then followed by 45 experimental trials with each color being presented 15 times. All experimental trials were presented in random, intermixed order, and the order of the two tasks was counterbalanced across subjects.

After completion of Part A of the experiment, participants then began Part B. For traditional and reverse CM Stroop, each trial began with a fixation cross in the center of the screen for 500ms. Depending on the SOA condition, the auditory and visual stimuli were then either presented simultaneously (0ms), with the auditory stimulus being heard and then the visual stimulus appearing (500ms), or with the visual stimulus present on screen followed by the auditory stimulus (-500ms; see Figures 4-6).

For each task, incongruent, congruent, and neutral trials were used and presented an equal number of times. Furthermore, each of the 6 possible incongruent combinations were shown the same number of times (9): *red-blue*, *red-green*, *blue-red*, *blue-green*, *green-red*, and *green-blue*. The same was also true of the congruent trials (18): *red-red*, *blue-blue*, and *green-green*, and neutral trials. Both of the conditions—SOA and congruency—were intermixed and randomly presented. Finally, the traditional and reverse CM Stroop tasks were counterbalanced across subjects.

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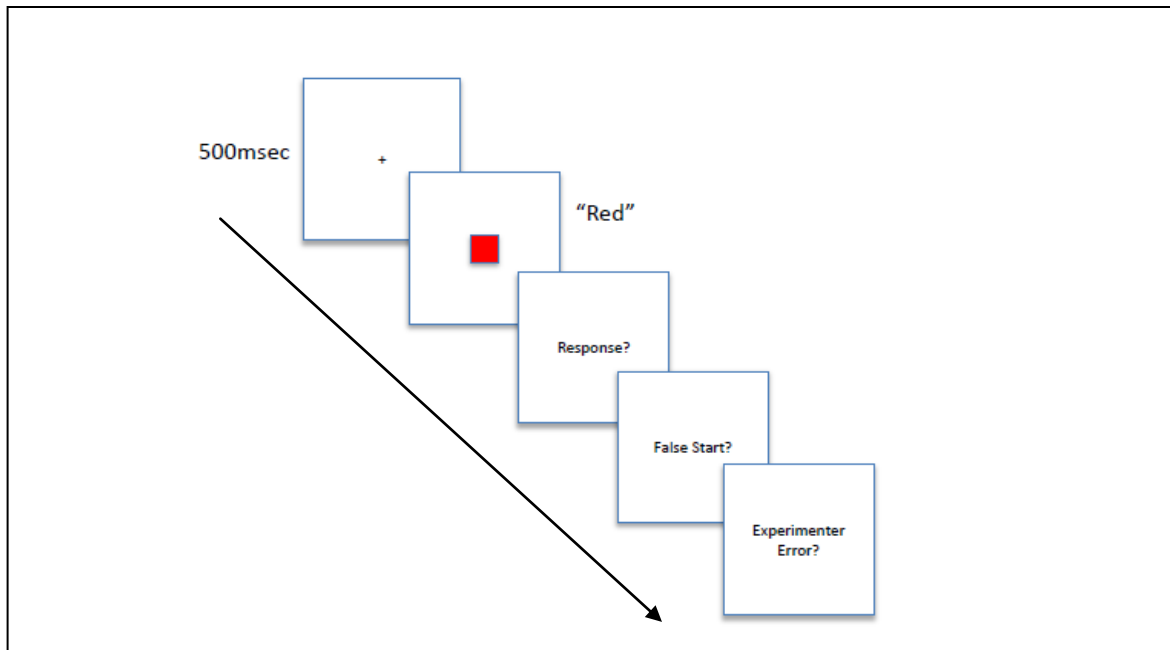
Figure 4. Example of a simultaneous auditory and visual stimulus onset (0ms or simultaneous). This type of trial was presented in the same way for both the Traditional and Reverse CM Stroop versions of the experiment.
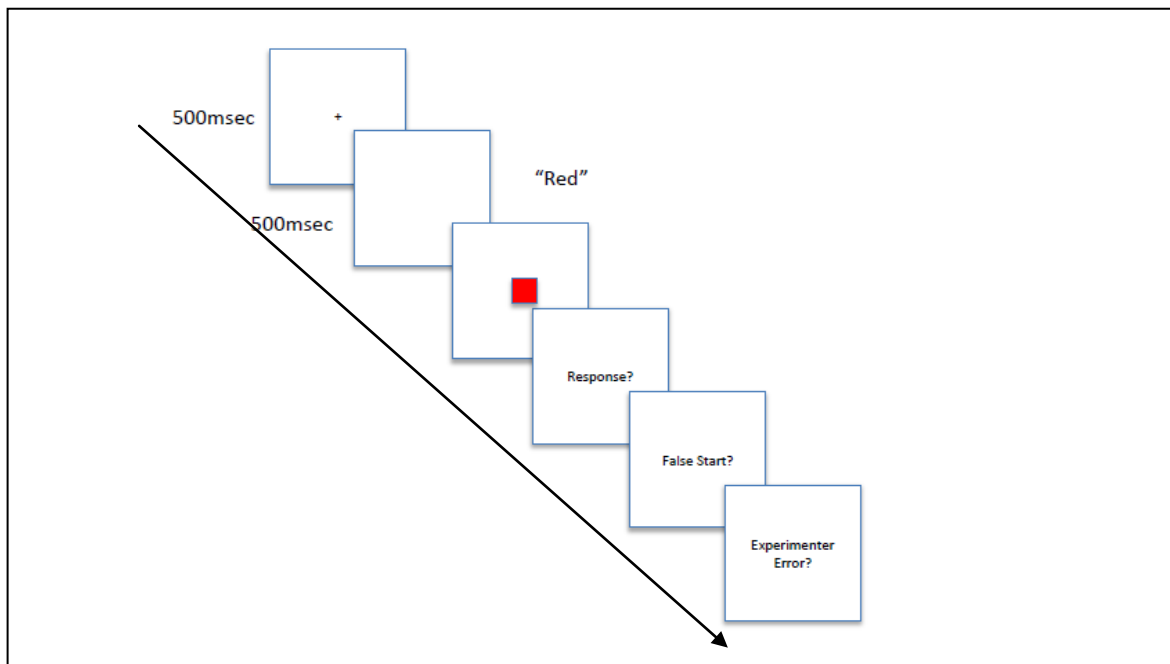
Figure 5. Example of a trial in which the onset of the auditory stimulus was 500ms before the onset of the visual stimulus (500ms or sound first). This type of trial was presented in the same way for both the Traditional and Reverse CM Stroop versions of the experiment.
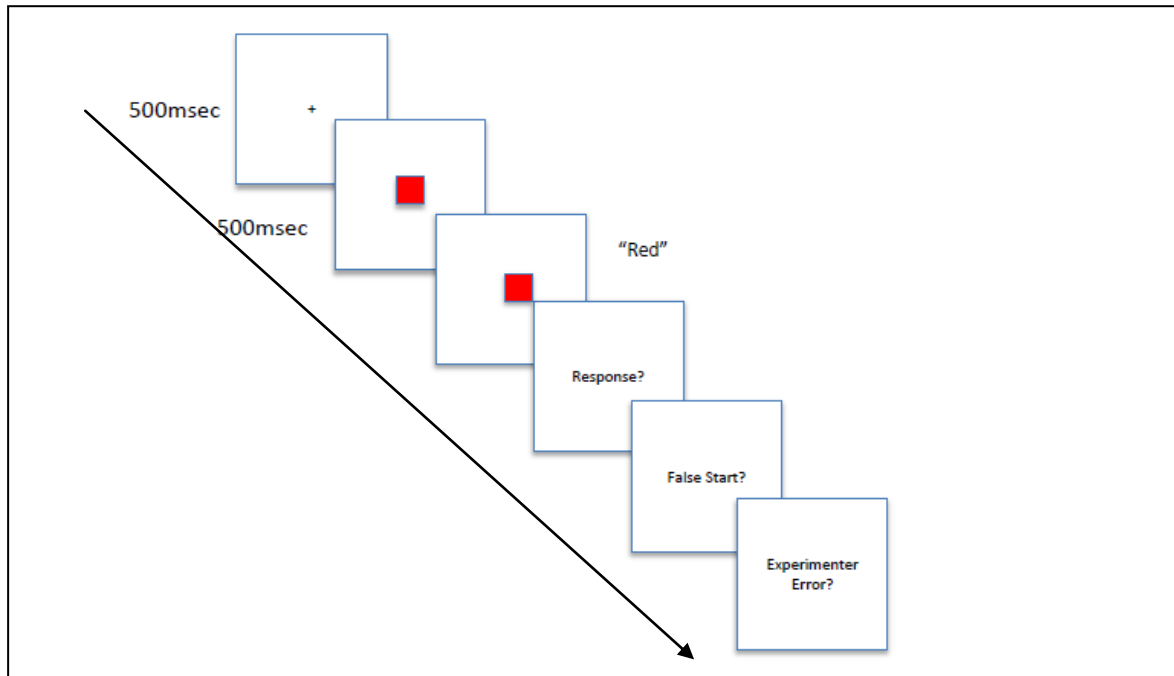
Figure 6. Example of a trial in which the onset of the visual stimulus was 500ms before the onset of the auditory stimulus (-500ms or square first). This type of trial was presented in the same way for both the Traditional and Reverse CM Stroop versions of the experiment.

In the traditional CM Stroop task, participants named the color of a visual stimulus, while hearing a spoken congruent or incongruent color word, silence, or a non-color word ("tall"). The participants were told to name the color of the stimulus as quickly and accurately as possible except for when they heard the non-color word. These non-color word trials will be referred to as auditory catch trials from this point on. When participants heard these catch trials, their task was to repeat the non-color word that they heard instead of the color of the stimulus presented (see Figure 7).

Participants completed 9 practice trials involving both the visual and auditory stimuli with varying SOA, and then 171 experimental trials that consisted of 9 catch trials, 54 incongruent trials, 54 congruent trials, and 54 neutral/silent trials. In addition, each SOA condition (0ms, 500ms, and -500ms) was presented 57times, with each SOA condition

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Figure 7. Traditional CM Stroop examples of each congruency condition trial type. containing 3 catch trials and 18 trials of each of the congruency conditions. Each colored stimulus was also presented an equal number of times. The numbers for each type of trial were held constant for the reverse CM Stroop version of the task.

In the reverse CM Stroop task, participants heard a spoken color word (either "red," "green," or "blue") while seeing a blank screen, a colored stimulus (which was also red, green, or blue), or a black circle. The spoken color words were either congruent or incongruent to the colored stimulus seen on the screen. Participants were told to repeat the word they heard as quickly and accurately as possible except for when they saw a black circle (from this point on, these trials will be referred to as visual catch trials). When participants saw a black circle, they were told to say "circle" instead of the color word they heard (see Figure 8).

For both tasks, the visual stimulus remained on screen until the microphone recorded a response. The one exception to this was in the rare case when a participant gave their response before the visual stimulus appeared in the sound first (500ms) SOA condition. In these cases, the color square never appeared; however, due to the fact that participants were repeating the word, this scenario did not lead to an error. Once again, the experiment recorded the responses, false starts, and experimenter errors.

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	9 Catch Trials	54 Incongruent Trials	54 Congruent Trials	54 Neutral Trials
See	(black circle)	(red square)	(green square)	Blank
Hear	"Green"	"Blue"	"Green"	"Red"
Correct Response	"Circle"	"Blue"	"Green"	"Red"

Figure 8. Reverse CM Stroop examples of each congruency condition trial type.

3.2 Results

Due to the way the experiment was programed, the response times for the square first (-500) reverse Stroop trials had to be corrected. The program started recording as soon as the square appeared; however, participants were not supposed to give their answers until the auditory word was sounded 500ms later. Due to this, 500ms was subtracted from each square first reverse Stroop trial. From this corrected raw data, all trials with an RT less than 200ms were dropped and the median for each person calculated. This correction enabled a more direct comparison to the other trial types, which started recording only as soon as the target item appeared.

Mixed-model and repeated-measures ANOVAs were used to analyze the means of medians of RTs, and the count of inaccurate trials, false starts, and catch trials, and the effect of the counterbalance order. For Part A (color naming and repeating baseline), a total of 0.86% trials were removed due to an inaccurate response, 0.73% because they contained a false start, and 0.02% for experimenter error. For Part B (reverse and traditional cross-modal Stroop), a total of 1.98% trials were removed due to an inaccurate response, 0.92 % because they contained a false start, and 0.03% for experimenter error. For all analyses $\alpha = .05$, and the Bonferonni correction was used for all appropriate follow-up tests. In all cases where sphericity was violated

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and the results were significant, the Greenhouse-Geisser correction was used. The results of Parts A and B are reported separately, and additionally divided by RTs, accuracy, false starts, and catch trials.

3.3 Results Part A: Color Naming and Color Repeating Baseline

Mixed-model ANOVAs were used to analyze the effect of the counterbalance order (between-subjects) on the RTs, accuracy levels, and number of false starts for the two different tasks (within-subjects).

Response times. There was no significant main effect of the order of the tasks, nor was there a significant task and order interaction. However, there was a main effect of task, F (1, 60) = 138.43, $p < .01$, $\eta_p^2 = .70$, with participants taking significantly longer to repeat an auditory word, $M = 671.54$ (SD = 137.32) than to name the color of a square, $M = 514.71$ ($SD = 85.71$).

Accuracy. Again, there was a significant main effect of task, F (1, 60) = 19.13, $p < .01$, $\eta_p^2 = .24$. Participants made more errors when they were naming the color of a square than when repeating a color word. However, while there was no significant main effect of order, there was a significant task and task order interaction, F (1, 60) = 4.66, $p < .05$, $\eta_p^2 = .07$ (see Table 4). Participants always produced more errors on the second task; however, this increase in errors was largest when they named colors first and repeated words second.

Table 4. Inaccuracy levels for color naming and color repeating by task order

	Color Naming First	Word Repeating First
Color Repeating	663.91 (140.92)	679.68 (135.29)
Color Naming	520.63 (100.86)	508.40 (67.06)

Note: Standard errors displayed in parentheses

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False starts. There was a significant main effect of task, $F(1, 60) = 8.28$, $p < .01$, $\eta_p^2 = .12$, with participants producing less false starts when they were repeating a word (see Table 5). The order of the tasks had no impact on the number of false starts produced as neither the main effect of order nor interaction terms were significant.

Table 5. False start levels for color naming and color repeating

Task	M	SD
Color Repeating	0.37	1.05
Color Naming	1.08	2.11

3.4 Results Part B: Traditional and Reverse Cross-Modal Stroop

Separate 2 (task order) x 2 (task) x 3 (auditory condition) x 3 (SOA) mixed-model ANOVAs were used to analyze the effect of the counterbalance order (between-subjects) on the RTs, accuracy levels, and number of false starts for the two different tasks (within-subjects). The overall results from these analyses are displayed in Table 6 and are reported separately below.

Response times. The order of the tasks did have some effect on performance in terms of RTs. While there was no main effect of task order, there was a significant three-way interaction of task, auditory condition, and task order, $F(2, 122) = 4.17$, $p < .05$, $\eta_p^2 = .07$. In order to examine this interaction, each task order was analyzed separately with a 2 (task) x 3 (auditory condition) x 3 (SOA) mixed-model ANOVA for RTs. Both task orders displayed the same patterns of results (see Appendix B). Due to these similarities, the task order was removed from further analyses and a repeated-measures ANOVA was run to analyze the remaining RTs.

Table 6. Significant and non-significant results of the mixed-model ANOVAs for each dependent variable

_____

Main Effect/Interaction	RTs	Accuracy	False Starts
Task	no significance	significant	significant
Order	no significance	no significance	no significance
SOA	significant	no significance	significant
Auditory	significant	significant	significant
SOA * Order	no significance	no significance	no significance
Task * Order	no significance	no significance	no significance
Auditory * Order	no significance	significant	no significance
Task * SOA	significant	significant	no significance
SOA * Auditory	significant	no significance	no significance
Task * Auditory	significant	significant	no significance
Task * SOA * Auditory	significant	significant	no significance
Task * SOA * Order	no significance	no significance	no significance
Task * Auditory * Order	significant	significant	no significance
SOA * Auditory * Order	no significance	no significance	no significance
Task * SOA * Auditory * Order	no significance	no significance	no significance

Thus, the next step in the analyses was to conduct a 2 (task) x 3 (SOA) x 3 (auditory condition) repeated-measures ANOVA. The main effect of task was not significant; however, the main effects of SOA, $F (1.46, 89.32) = 77.3$, $p < .01$, $\eta_p^2 = .56$, and auditory condition, $F (1.49, 90.97) = 27.37$, $p < .01$, $\eta_p^2 = .31$, were. The task and SOA interaction was significant, $F (1.33, 81.36) = 43.54$, $p < .01$, $\eta_p^2 = .42$, as was the task and auditory condition interaction, $F (1.43, 87.04) = 11.98$, $p < .01$, $\eta_p^2 = .16$, SOA and auditory condition interaction, $F (2.95, 179.96) =$

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14.25, $p < .01$, $\eta_p^2 = .19$, and the task, SOA, and auditory condition interaction, $F (3.07, 187.11)$ = 15.82, $p < .01$, $\eta_p^2 = .21$ (see Table 7).

In order to analyze the three-way interaction, two separate repeated-measures ANOVAs were run for each task. For the reverse cross-modal Stroop task there was a main effect of SOA, $F (1.57, 95.49) = 7.49$, $p < .01$, $\eta_p^2 = .12$, with RTs for trials with simultaneous onsets > sound first = square first. There was also significant main effect of auditory condition, $F (1.57, 95.78)$ = 39.66, $p < .01$, $\eta_p^2 = .39$, with RTs for congruent trials = incongruent trials < neutral trials (see Figure 9). The interaction was not significant. These results demonstrate neither Stroop interference nor facilitation.

For the traditional cross-modal Stroop task the main effect of auditory condition was also significant (incongruent > neutral = congruent), $F (1.44, 87.86) = 12.05$, $p < .01$, $\eta_p^2 = .17$, as was the main effect of SOA (sound first < simultaneous < square first), $F (1.25, 75.97) = 78.76$, $p < .01$, $\eta_p^2 = .56$, and the interaction, $F (2.7, 164.09) = 19.04$, $p < .01$, $\eta_p^2 = .24$ (see Figure 9). When the SOA was simultaneous there was interference but no facilitation, congruent = neutral < incongruent. However, when the sound was presented 500ms before the target, pattern of results was very similar to that found in Reverse CM Stroop, congruent < incongruent < neutral. When the square was presented first, congruent = incongruent < neutral.

Errors

A 2 (task order) x 2 (task) x 3 (auditory condition) x 3 (SOA) mixed-modal ANOVA was used to examine the number of errors. Once again, there was a three-way interaction among task, auditory condition, and task order, $F (2, 122) = 3.69$, $p < .05$, $\eta_p^2 = .06$. Two repeated-measures ANOVAS were run for each task to examine this. Unlike for response times, the pattern of results was not identical across the two tasks when task order was taken into account;

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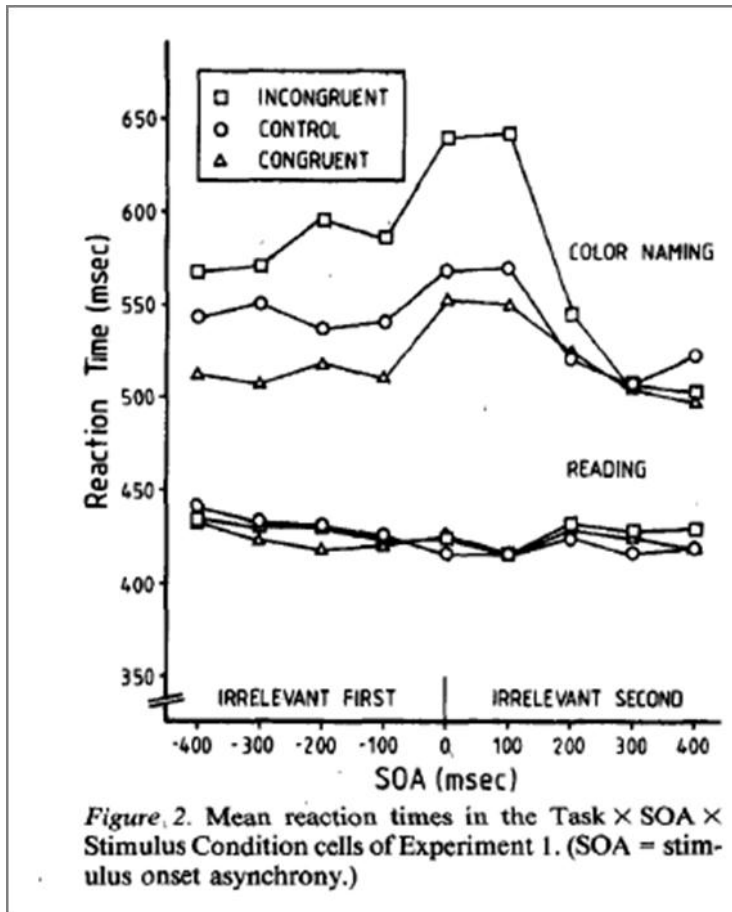
Note: figure from Glaser & Glaser, 1982, p. 880   Note: Error bars display standard error
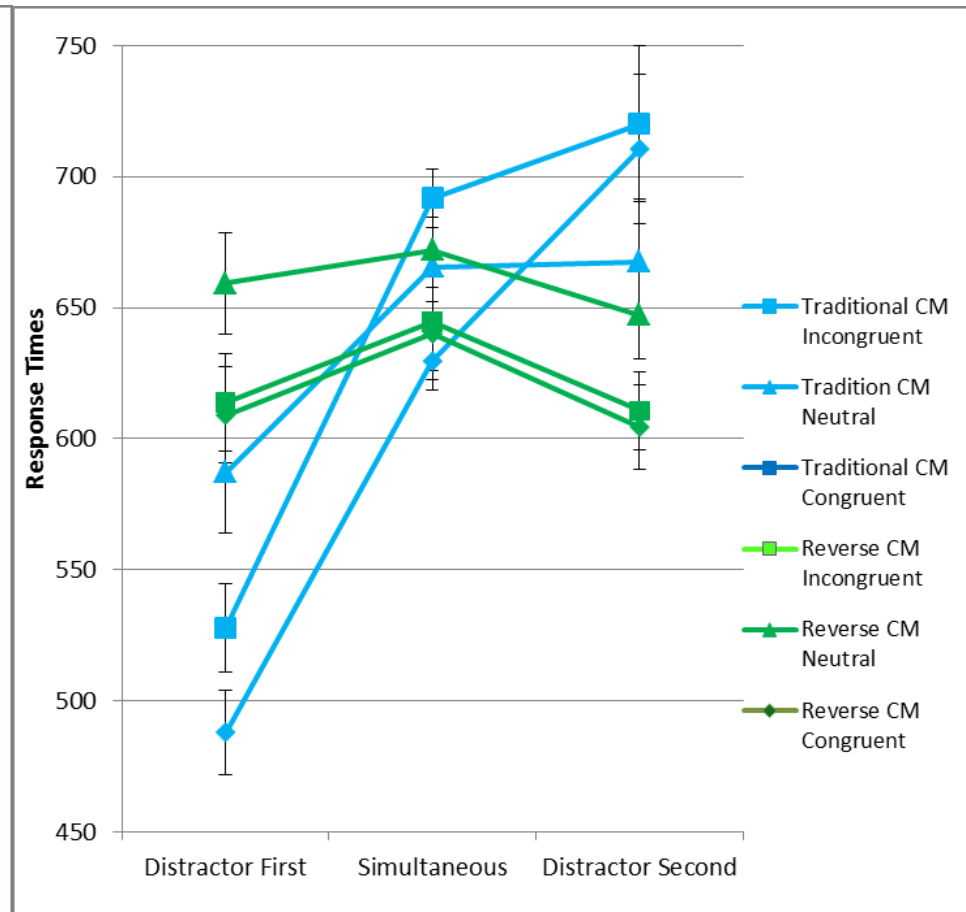
Figure 9. RTs for reverse and traditional CM Stroop by SOA and auditory condition with a comparison to the classic Stroop asymmetry. For reverse CM Stroop, the distractor first means that the color appeared on the screen and was then followed by the auditory color word. For traditional CM Stroop, the distractor first means that the onset of auditory word started 500ms before the color patch appeared on the screen.

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Table 7. RTs by task, task order, and auditory condition

	Reverse CM Stroop First		Traditional CM Stroop First	
	Reverse CM Stroop	Traditional CM Stroop	Reverse CM Stroop	Traditional CM Stroop
Incongruent	611.02 (23.65)	658.56 (24.78)	635.35 (23.99)	635.00 (22.90)
Neutral	628.34 (24.61)	654.09 (30.36)	627.02 (29.39)	690.62 (23.83)
Congruent	599.16 (24.30)	611.73 (24.31)	607.27 (23.54)	636.58 (23.53)

Note: Standard deviations are in the parentheses

therefore, the results reported below are from the mixed-model ANOVA and the resulting follow-up tests.

There was no significant main effect of SOA, but there was a main effect of task, $F(1, 60) = 16.74$, $p < .01$, $\eta_p^2 = .22$. Participants made more errors in the traditional cross-modal Stroop than in the reverse version. In addition, there was a significant main effect of auditory condition, $F(1.65, 98.72) = 7.34$, $p < .01$, $\eta_p^2 = .11$, with neutral = congruent < incongruent trials. There was also a significant task and auditory condition interaction, $F(1.7, 101.71) = 4.56$, $p < .05$, $\eta_p^2 = .08$, and task, auditory condition, SOA interaction, $F(3.31, 198.65) = 5.11$, $p < .01$, $\eta_p^2 = .08$ (see Table 8).

In order to analyze the three-way interaction, separate repeated-measures ANOVAs were run for each task (reverse and traditional CM Stroop). For the reverse cross-modal Stroop task, there was no significant main effect of SOA or auditory condition, and the interaction was not significant. For the traditional Stroop task, there was no main effect of SOA, but the main effect of auditory condition was significant, $F(1.5, 120.78) = 6.11$, $p < .01$, $\eta_p^2 = .09$, as was the interaction, $F(3.34, 203.77) = 4.8$, $p < .01$, $\eta_p^2 = .07$. With a simultaneous onset, incongruent > neutral = congruent in terms of the number of inaccurate trials. When the square was first, incongruent trials were still more likely to lead to an inaccurate response than neutral trials, but congruent trials were not significantly different from either. There were no significant differences in accuracy when the sound came first.

To examine the effect of the task order, a mixed-model ANOVA for each task order was completed. When the traditional cross-modal Stroop task was completed first, there was a main effect of task order, $F(1, 31) = 6.25$, $p < .05$, $\eta_p^2 = .17$. As in Part A, participants made more errors in the second task (reverse cross-modal Stroop) than in the first (traditional cross-modal

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Table 8. Errors by task, task order, auditory condition, and SOA

		Reverse CM Stroop First		Traditional CM Stroop First	
		Reverse CM Stroop	Traditional CM Stroop	Reverse CM Stroop	Traditional CM Stroop
	Incongruent	0.59 (0.33)	1.22 (0.45)	1.13 (0.51)	0.56 (0.32)
Simultaneous	Neutral	1.24 (0.55)	0.59 (0.33)	0.77 (0.46)	0.38 (0.45)
	Congruent	0.20 (0.20)	0.39 (0.27)	1.11 (0.42)	0.93 (0.39)
	Incongruent	0.20 (0.20)	3.93 (1.11)	1.71 (0.57)	0.92 (0.38)
Sound First	Neutral	1.67 (0.58)	1.20 (0.54)	0.38 (0.26)	0.56 (0.32)
	Congruent	>.01 (>.01)	4.07 (1.52)	2.11 (0.52)	0.78 (0.78)
	Incongruent	0.20 (0.20)	0.59 (0.33)	1.19 (0.68)	0.95 (0.49)
Square First	Neutral	0.39 (0.27)	1.11 (0.75)	1.54 (0.57)	0.37 (0.26)
	Congruent	0.20 (0.20)	>.01 (>.01)	1.10 (0.41)	0.37 (0.26)

Note: Standard deviations are in the parentheses

Stroop). This was most likely due to fatigue. Neither the main effect of SOA or auditory condition was significant nor were any of the interactions.

However, there was a different pattern of results when the reverse cross-modal Stroop task came first. Once again there was a main effect of task, $F (1, 29) = 10.28$, $p < .01$, $\eta_p^2 = .26$. The second task (traditional cross-modal Stroop this time) had more inaccurate trials than the first task (reverse cross-modal Stroop). This time there was also a main effect of auditory condition, $F (1.41, 40.83) = 7.17$, $p < .05$, $\eta_p^2 = .2$, incongruent > congruent = neutral. The main effect of SOA was not significant; though, the three-way interaction among task, auditory condition, and SOA was significant, $F (2.46, 71.26) = 4.88$, $p < .05$, $\eta_p^2 = .14$, in addition to the task and auditory condition interaction, $F (2, 58) = 3.75$, $p < .05$, $\eta_p^2 = .12$, and the task and SOA interaction, $F (1.90, 55.06) = 6.04$, $p < .05$, $\eta_p^2 = .17$,

Two repeated-measures ANOVAs for each task order, separately by task, were then run to analyze the three-way interaction. For the reverse cross-modal Stroop task, when it was run first there were no significant results. When the reverse cross-modal Stroop task was completed second, however, there was a main effect of SOA, $F (2, 58) = 5.84$, $p < .01$, $\eta_p^2 = .17$, (see Table 8). In terms of errors, simultaneous = sound first < square first. Participants seem to have had a harder time keeping their task goal in mind when reverse cross-modal Stroop was completed after traditional cross-modal Stroop and the square was presented first.

For the traditional cross-modal Stroop task, when it was completed first, neither of the main effects nor the interaction was significant. When the traditional cross-modal Stroop task was completed second, there was a main effect of auditory condition, $F (2, 58) = 7.20$, $p < .01$, $\eta_p^2 = .20$. Congruent trials had significantly less inaccurate responses than neutral and incongruent trials. In addition, although the main effect of SOA was not significant, the auditory

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condition and SOA interaction was, $F(2.69, 77.88) = 3.38$, $p < .05$, $\eta_p^2 = .10$ (see Table 7).

When the SOA was simultaneous, incongruent trials > neutral = congruent. When the sound was

first, incongruent trials had more errors than neutral, and there were no differences when the

square came first. Overall this pattern of results suggests that participants were fatigued by the

time they started on the second task and that their performance on the second task suffered as a

result. However, performance suffered to a greater degree when the traditional CM Stroop task

was completed second.

False starts. The task order had no effect on the number of false starts produced. Task

order was therefore removed and a 2 (task) x 3 (auditory condition) x 3 (SOA) repeated-

measures ANOVA was used to analyze the data. There was a significant main effect of task, F

$(1, 61) = 17.5$, $p < .01$, $\eta_p^2 = .22$. The traditional cross-modal Stroop task led to more false starts

than the reverse. There was also a main effect of SOA, $F(2, 122) = 4.0$, $p < .05$, $\eta_p^2 = .06$. The

sound coming first led to more false starts than it being presented simultaneously with the color.

Lastly, the main effect of auditory condition was significant, $F(2, 114) = 5.94$, $p < .01$, $\eta_p^2 = .09$,

congruent = neutral < incongruent (see Table 9). None of the interactions were significant

Catch trials. On the whole, participants performed very well on the catch trials. The

high number of reverse cross-modal Stroop catch trials suggests that participants were looking at

the screen during the task and were most likely not improving their performance by looking

elsewhere. A repeated-measures ANOVA was used to analyze any potential differences in the

number of catch trials participants correctly identified. There was a significant main effect of

task, $F(1, 61) = 220.16$, $p < .01$, $\eta_p^2 = .78$, and SOA, $F(2, 122) = 119.71$, $p < .01$, $\eta_p^2 = .66$, as

well as a significant task and SOA interaction, $F(2, 122) = 143.94$, $p < .01$, $\eta_p^2 = .7$ (see Table9).

Two separate 3 (auditory condition) x 3 (SOA) repeated-measures ANOVAs were

Table 9. False Starts by task, auditory condition, and SOA

		Traditional CM Stroop	Reverse CM Stroop
Simultaneous	Incongruent	0.90 (0.35)	0.20 (0.14)
	Neutral	1.66 (0.44)	1.01 (0.42)
	Congruent	0.49 (0.26)	0.71 (0.37)
Sound First	Incongruent	2.90 (0.56)	0.39 (0.19
	Neutral	2.10 (0.55)	1.33 (0.46
	Congruent	1.35 (0.44)	1.19 (0.82
Square First	Incongruent	1.56 (0.31)	0.10 (0.10)
	Neutral	1.51 (0.58)	0.49 (0.56)
	Congruent	0.87 (0.48)	0.10 (0.10)

Note: Standard errors displayed in parentheses

then run for each task. It was found that there was no significant main effect of SOA for reverse

CM Stroop; however, there was a significant main effect of SOA for traditional CM Stroop, F (2,

122) = 153.08, $p < .01$, $\eta_p^2 = .7.15$, with all of SOAs being significantly different from one

another (see Table 10).

Table 10. Count of Catch Trials by task and SOA

Task	Simultaneous	Sound First	Square First	Total
Reverse	2.90 (0.04)	2.90 (0.04)	2.94 (0.03)	8.70 (0.54)
Traditional	2.42 (0.10)	2.92 (0.05)	0.76 (0.12)	6.10 (1.43)

Note: Standard errors in parentheses

3.5 Discussion

The results of the baseline manipulation (Part A) suggest that it takes longer to repeat a

color word than it does to name a color. This is in contrast to the classic Stroop task in which

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reading a word takes less time to complete than naming a color (Stroop, 1935). However, it is possible that this is being driven by the fact that one has to let the word finish unfolding before he or she can determine what exactly the word is.

Furthermore, the expected asymmetry between the auditory and visual modalities was not found (although see Roelofs, 2005). The classic Stroop task with printed stimuli shows a very clear pattern of results across varying SOAs in terms of RTs. When completing the classic Stroop task, the greatest impact of color words on ink naming is found the closer the ink and word are presented together in time and when the ink color and word are incongruent (Glaser & Glaser, 1982). Furthermore, when examining reverse classic Stroop, the color of ink never has an impact on reading, regardless of the congruency of the ink color and word or the SOA at which they are presented.

For reverse CM Stroop (repeating the auditory word while ignoring visual colored distractors), the SOA did lead to differences in RTs (see Figure 9). Simultaneous trials were longer overall than trials in which the visual distractor or auditory word came first. In addition, whether the trial was incongruent, congruent or neutral also had an impact. Neutral trials were significantly slower than both congruent and incongruent trials. This could potentially be due to the fact that participants (regardless of instructions) could not stop themselves from waiting for the visual distractors to appear before making their responses (Roelofs, 2005). However, this is unlikely as the average RT for simultaneous neutral trials is no different from when participants where repeating a word without any distractions at the beginning of the experiment. Why visual stimuli, even incongruent visual colors helped people to repeat words faster is also unclear as this occurred even when the distractor was presented 500ms after the word and simultaneously. It is possible that the visual colors are helping to prime the auditory dimension even when the visual

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color is not the same as that being heard. The fact that the incongruent visual colors did not then appear to lead to any more errors is, therefore, even more intriguing.

This improvement of incongruent and congruent words on repeating colors is not unique to this study. Roelofs (2005) examined the cross-modal Stroop asymmetry across experiments and used a manual response for his "catch trials", to ensure his participants were simply not looking at the computer screen. Nonetheless, Roelofs (2005) argued that neutral trials displayed longer RTs because participants were waiting for the color to appear to respond. As a clear baseline was taken from the participants in the current study at the very beginning of Experiment 2 that was equal to the neutral trials in both traditional and reverse CM Stroop, this does not appear to be the case. In additional Roelofs did not find a main effect of SOA, whereas Experiment 2 did. However, Roelofs only examined an SOA of up to 300ms and presented the various SOAs in separate blocks. The current study used 500ms, which may have allowed more time for patterns of responding to emerge.

For traditional CM Stroop, interference was only found when the sound (distractor) and target were presented simultaneously. Facilitation never reached significance at any of the SOAs. Interestingly, when the square was presented first, the presence of any auditory word increased response times, regardless of whether the spoken word was congruent or incongruent. The sound being presented first had the opposite effect: neutral words were the slowest in terms of RTs followed by incongruent and then neutral trials. This suggests that in this condition the auditory word served as a cue. Similar evidence for an auditory warning effect has been shown in previous literature (Elliott et al., 1998).

Like Roelofs (2005), Shimada (1990), and Elliott (1998), the greatest impact of auditory color words on color naming was when they were presented simultaneously. However, Shimada

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(1990) did not look past an SOA of 200ms and Roelofs (2005) past an SOA of 300ms. Furthermore, Shimada (1990) found facilitation across all of the SOAs he examined with the exception of when the auditory word was presented 200ms after the color. Elliott et al. (1998) did look at an SOA of 500ms (the auditory dimension was presented first only) and found that at this SOA auditory color words did not induce any more interference than non-color words (interference was induced for both); however, Elliott et al. did not include congruent trials. Why we did not find any facilitation is unclear. As mentioned earlier, facilitation is less robust in cross-modal Stroop, which may explain why neither we nor Roelofs (2005) were able to find any evidence of it.

While the task order did not make any important contributions to RTs, it did for accuracy. Performance on traditional CM Stroop was impaired to a greater degree by fatigue than reverse CM Stroop. Also, participants made more errors during traditional CM Stroop, and were most likely to do so when a trial was incongruent and the color and color word presented simultaneously.

Traditional CM Stroop also induced more false starts than reverse CM Stroop and people were most likely to produce a false start when a trial was incongruent or the target and distractor had simultaneous onsets. In terms of catch trials, participants were very good at noticing them overall but were more successful during reverse CM Stroop. Participants were the least likely to answer correctly on the traditional CM Stroop catch trials in which the auditory word was presented after the color and were frequently in the midst of their answer when they heard the word.

In summation, although we found the expected asymmetry between the word repeating and color naming dimensions for accuracy and false starts, the significant results for RTs found

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for reverse CM Stroop suggests that the asymmetry pattern found in classic Stroop may not occur in cross-modal Stroop. Furthermore, the fact that it took longer for participants to repeat auditory words than to name colors implies that the auditory dimension may not actually be the "stronger" dimension, as many of the theories argue that the "stronger" dimension should take less time to name by itself.

Chapter 4. General Discussion

The results from the two experiments suggest that cross-modal Stroop may not involve the same processes and mechanisms as classic Stroop. Different types of visual stimuli were contrasted in Experiment 1, and the finding of significantly different interference with one type of visual stimulus is not easily explained by extant theories of the classic Stroop effect. Furthermore, Experiment 2 demonstrated that the cross-modal Stroop task does not appear to display the asymmetry pattern seen in the classic Stroop task (i.e., colors do not impact word repeating in any SOA in classic Stroop). Visual colored items did impact word repeating, and this interacted with the SOA for cross-modal Stroop.

Experiment 1 suggested that not all colored visual stimuli lead to the same levels of interference. The fact that the different visual stimuli lead to different RTs overall is also interesting as it was the color of the visual stimulus that was named, not the stimulus itself. This implies that the complexity of the visual stimulus and the amount of color it provides can impact color naming performance. Together, these findings imply that some of the Stroop theories may be better at explaining cross-modal Stroop than others.

As mentioned in the introduction, the various theories could be broken down into supporting either one of two general hypotheses: 1) all of the visual stimuli would lead to roughly equal amounts of interference; or 2) the more complex stimuli would lead to larger amounts of interference as the more complex stimuli would activate an additional pathway, memory representation, etc. Although Experiment 1 did suggest that maybe not all visual stimuli lead to equivalent levels of interference, some of the stimuli predicted to display the highest levels of interference based on semantics (e.g., X's) actually produced the lowest levels.

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The fact that the there were apparent differences in the amount of interference the various visual stimuli produced is inconsistent with the word production architecture account and the automaticity theory (Levelt et al., 1999 and Posner & Snyder, 1975, respectively). If listening was simply processed more shallowly or automatically, the visual stimuli used should have had no effect. The fact that color squares led to some of the largest amount of interference (although not significant) and that a fairly complex stimuli (x's) led to the least can also not be explained by the tectonic, relative pathway strength, or relative processing speed theories.

Also, why words that were read caused interference is unclear when examining the tectonic theory and possibly inconsistent with the word-production architecture account. In terms of the word-production architecture account, as mentioned earlier, it is because the distracting dimension is so shallowly processed that it requires little effort and is processed without thinking. This is how the word-production architecture theory is able to account for the findings with SOA. Roelofs (2005) has also argued, however, that as both written and spoken words are activated automatically, interference should be induced when both dimensions are pitted against one another. Why repeating words takes longer than reading words and why the same amount of interference is not found in classic and cross-modal Stroop is, therefore, unclear, according to this theory.

The relative pathway strength account is one of the few (along with the automaticity theory) that is able to explain why words caused interference. As the word naming pathway and word repeating pathway are both quite strong, it is very likely that activating both simultaneously would lead to large amounts of interference. In terms of the automaticity theory, it is possible that two automatic processes may interfere with one another when placed in conflict. Whether this creates the same type of interference as found in the Stroop task, however, is unclear. The

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same is true with the relative processing speed theory. What occurs when two quickly processed dimensions are placed in conflict and is this the same as Stroop interference?

The finding that the complexity of the visual stimulus and the amount of color it provides can impact our color naming performance may be a similar to the findings in classic Stroop when only one letter of the word is colored. For this version of the Stroop task, most of the letters are presented in a neutral color (e.g. black) and one letter is presented in a color congruent or incongruent to the color word (Monahan, 2001; Brown, Joneleit, Robinson, & Brown, 2002; Mamurck, 2003; Besner, Stolz, & Boutilier, 1997). Neutral trials usually consist of non-color words that, again, only contain one colored letter (e.g. Brown et al., 2002). Stroop interference is generally still found, but it is considerably smaller than the interference found when the whole word is presented in a color. However, this shrinking in the Stroop effect is not due to the RTs of incongruent trials speeding up. Rather, the neutral trials are slowing down (Monahan, 2001). This is usually assumed to be due to automaticity being more like a continuum than a dichotomy—the color word is being activated to a lesser degree due to the change in focus so it is easier to suppress (Mamurck, 2003; Kuper & Heil, 2012)—or because there is less of the color to discriminate (Monahan, 2001). Together, these findings imply that some of the Stroop theories may be better at explaining cross-modal Stroop than others, namely those that consider the amount of color activation and automaticity involved.

In order to examine this idea of a continuum of automaticity, MacLeod and Dunbar (1988) conducted three experiments that varied the amount of practice participants received for an analog of the Stroop color-word task. Every participant experienced four phases: (1) naming four familiar colors, (2) training using specific colors as names for novel shapes, (3) naming the colors when they appeared in the form of the learned shapes, and (4) naming the shapes when

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they appeared in color. In Experiment 1, participants received up to 2 hours of shape naming training. Afterwards when tested, colors were named faster than shapes and interference was only found in phase 4 (naming shapes which were colored). In Experiment 2, participants received five hours of training. With increased training, not only did shape naming RTs increase (they were still slower than color naming) but there was symmetrical interferences during phases three and four as well. In Experiment 3, participants received 20 hours of training which reversed the original asymmetry so that interference was only found during phase three (naming the colors of shapes). Together, these results imply that with practice, dimensions become more automatic which in turn leads to stronger interference and asymmetries; however, a dimension does not have to be purely automatic in order to do so.

As for the current Experiment 2, it is unclear why the same asymmetry pattern found in classic Stroop (Glaser & Glaser, 1982) does not appear for cross-modal Stroop. The word-production architecture account argues that a clear asymmetry should be found for cross-modal Stroop and that spoken words should interfere with visual color naming, but visual colors should have no impact on word repeating at any SOA. The Stroop effect arises due to the fact that words are processed shallowly and other dimensions, such as color, take more effort and processing. As such the SOA and presence of distractors should have no impact on the dominant dimension. Although colors did not interfere with word repeating, they did improve RTs and lead to facilitation, even when they were incongruent. How this finding fits in with this theory, therefore, is unclear.

The same is true of the automaticity and the relative processing speed theories. According to the automaticity theory, words (written and auditory) are processed automatically while colors are not. The non-automatic process can always be interfered with by an automatic

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process, but not vice versa. In terms of the relative processing speed theory, words (written and spoken) are processed faster than colors, which leads to the presence of a competing response. Why distractors led to facilitation is unclear when examine the automaticity theory and why incongruent trials did not lead to more errors in reverse CM Stroop is inconsistent with the relative processing speed theory.

The only theory that may be able to account for these asymmetry findings is the relative pathway strength account and, possibly, the tectonic theory. The tectonic theory argues that interference and facilitation is caused by memory representations and dimension discriminability. It may be that the nature of these relationships for auditory words and colors is not the same as those for written words and colors. The relative pathway strength account is based upon the idea of a continuum of automaticity and states that interference may occur in one or both of the involved pathways depending on the strength of the pathways and which one is being primarily attended to. However, this theory cannot account for why incongruent words would help performance in reverse cross-modal Stroop in terms of response times and not produce more inaccurate responses; furthermore, if the auditory dimension is actually the stronger dimension, why did it take participants longer to repeat a color word than to name a color? Nonetheless, the results suggest that theories that view automaticity as a continuum may be the best at explaining cross-modal Stroop.

It is also possible that auditory words may appear to be processed slower due to the fact that one has to wait for the word to unfold in order to be able to repeat it. As such, by the time the word has finished, the actual time to process it is quite short. However, this hypothesis is not consistent with the results from traditional CM Stroop. Even when the sounds were presented 500ms after the square (very shortly before a response was given), they still hindered RTs

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despite the congruency of the word. This finding is inconsistent with previous research (Roelofs, 2005; Shimada, 1990); though, as mentioned earlier, Roelofs (2005) and Shimada (1990) did not examine SOAs of 500ms.

In terms of the differences between traditional and reverse CM Stroop, there was an asymmetry. It simply was not the asymmetry found in classic Stroop. When the distractor was presented first, trials in which a distractor was presented were faster in terms of RTs than those in which it was not. For reverse CM Stroop, congruent and incongruent distractors led to equal amounts of facilitation, while for traditional CM Stroop, congruent distractors led to greater facilitation than incongruent ones. This suggests that the distractors served as a warning and helped participants to prepare their answers. It is interesting that this apparent warning does not appear to be found in classic Stroop.

When the target and distractor were presented simultaneously, congruent and incongruent distractors again led to facilitation in reverse CM Stroop though RTs overall were slower. For traditional CM Stroop, however, incongruent trials led to interference, and congruent trials did not produce significant levels of facilitation. When the distractor was presented second, the distractor had opposite effects on reverse and traditional CM Stroop. Once again, any distractor decreased RTs for reverse CM Stroop, but the presence of a distractor in traditional CM Stroop increased RTs even when it was congruent. These findings together suggest that (1) there is something inherently different about auditory distractions (Spence et al. 2000; Conway et al. 2001; Beaman, 2004) and (2) that a distractor in a different modality can serve as a warning cue.

There were some limitations with the current experiments. Experiment 1 only looked at interference, which while being more robust than facilitation in cross-modal Stroop, is only half of the picture. Therefore, it is important to replicate Experiment 1 with congruent trials to

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determine if this may lead to a greater impact of the visual stimulus on interference levels as has been seen in research with classic Stroop. Interference levels tend to increase as the proportion of congruent trials increases. As the relationship between working memory capacity and classic Stroop is only found when congruency proportions are high (Logan & Zbrodoff, 1979; Long & Pratt, 2002; Kane & Engle, 2003; Morey et al. 2012), it is possible that congruent trials will lead to a greater impact of the visual stimulus.

Lastly, it is possible that the built in spatial separation in the cross-modal version of the task could have some effect on the results. In the classic Stroop paradigm, the target and distractor are generally presented in the same location in space (e.g. Stroop, 1935). The color and the word are in the same location on the computer screen or piece of paper. The separation of the target and distractor has been shown to lessen the amount of interference and facilitation found in classic Stroop (McLeod, 1991). In cross-modal Stroop, the target is always presented on the screen while the distractors come from headphones on the participants' heads (Elliott et al, 1998). This spatial separation of auditory and visual stimuli has been shown to impact the perception of visual targets with visual targets being harder to distinguish when auditory distractors appear to be coming from the same location (Botvinick et al., 2001). As such, it is possible that a manipulation of the spatial integration of the target and distractor in cross-modal Stroop would lead to results more similar to those found in classic Stroop.

In summary, the current experiments demonstrated that different visual stimuli led to varying amounts of interference in cross-modal Stroop and that cross-modal Stroop does not display the same asymmetry as that found in classic Stroop. As such, it seems that the theory that is best able to explain cross-modal Stroop is one based upon a continuum of automaticity. Although this study examined many things, it raised several questions that have yet to be

answered. Why is it that congruent and incongruent stimuli improve response times for repeating an auditory color word? Why do auditory color words interfere with color naming when they seem to take longer to process? In conclusion, it would appear that the same mechanisms and processes are not involved in cross-modal Stroop as in classic Stroop. One candidate for this difference may be the modality of presentation; it may be that the effect of a distractor in the same modality as the target item is not the same as a distractor in a different modality (Spence et al., 2000).

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Appendix A

Mean RTs and Standard Errors for the Visual Stimuli in the Integrated Version of the Experiment

Visual Stimulus$_1$	Visual Stimulus$_2$	Mean RT	Standard Error	P Value
****		557.75	9.91	
	@@@@			$p > .05$
	4444			$p < .05$
	~~			$p > .05$
	Squares			$p < .01$
	Words			$p < .01$
	XXXX			$p > .05$
@@@@		563.31*	11.47	
	****			$p > .05$
	4444			$p > .05$
	~~			$p > .05$
	Squares			$p < .01$
	Words			$p < .01$
	XXXX			$p > .05$
4444		576.69	11.49	
	****			$p < .05$
	@@@@			$p > .05$
	~~			$p < .01$
	Squares			$p < .01$
	Words			$p < .01$
	XXXX			$p > .05$
~~		551.86	10.34	
	****			$p > .05$
	@@@@			$p > .05$
	4444			$p < .01$
	Squares			$p < .05$
	Words			$p > .05$
	XXXX			$p < .01$
Squares		539.22	11.49	
	****			$p < .01$
	@@@@			$p < .01$
	4444			$p < .01$
	~~			$p < .05$
	Words			$p > .05$
	XXXX			$p < .01$
Words		538.43	10.89	
	****			$p < .01$
	@@@@			$p < .01$
	4444			$p < .01$
	~~			$p > .05$
	Squares			$p > .05$
	XXXX			$p < .01$
XXXX		567.70	11.59	
	****			$p > .05$
	@@@@			$p > .05$
	4444			$p > .05$
	~~			$p < .01$
	Squares			$p < .01$
	Words			$p < .01$

Appendix B

Pattern of RT Results for Experiment 2 Part B Displaying the Significant Main Effects and
Interactions for Task, SOA, and Auditory Condition for the Two Task Orders

Main Effect/Interaction	Reverse CM Stroop First	Traditional CM Stroop First
Task	no significance	no significance
SOA	significant	significant
Auditory	significant	significant
Task * SOA	significant	significant
SOA * Auditory	significant	significant
Task * Auditory	significant	significant
Task * SOA * Auditory	significant	significant

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Appendix C

IRB Approval

<u>Application for Exemption from Institutional Oversight</u>

LSU

Institutional Review Board
Dr. Robert Mathews, Chair
131 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu
lsu.edu/irb

Unless qualified as meeting the specific criteria for exemption from Institutional Review Board (IRB) oversight, ALL LSU research/ projects using living humans as subjects, or samples, or data obtained from humans, directly or indirectly, with or without their consent, must be approved or exempted in advance by the LSU IRB. This Form helps the PI determine if a project may be exempted, and is used to request an exemption.

-- Applicant, Please fill out the application in its entirety and include the completed application as well as parts A-F, listed below, when submitting to the IRB. Once the application is completed, please submit two copies of the completed application to the IRB Office or to a member of the Human Subjects Screening Committee. Members of this committee can be found at http://research.lsu.edu/CompliancePoliciesProcedures/InstitutionalReviewBoard%28IRB%29/item24737.html

-- A Complete Application Includes All of the Following:
   (A) Two copies of this completed form and two copies of parts B thru F.
   (B) A brief project description (adequate to evaluate risks to subjects and to explain your responses to Parts 1&2)
   (C) Copies of all instruments to be used.
       *If this proposal is part of a grant proposal, include a copy of the proposal and all recruitment material.
   (D) The consent form that you will use in the study (see part 3 for more information.)
   (E) Certificate of Completion of Human Subjects Protection Training for all personnel involved in the project, including students who are involved with testing or handling data, unless already on file with the IRB. Training link: (http://phrp.nihtraining.com/users/login.php)
   (F) IRB Security of Data Agreement: (http://research.lsu.edu/files/item26774.pdf)

1) Principal Investigator: Danielle Lutfi-Proctor   **Rank:** Graduate Student

Dept: Psychology   **Ph:** 758-7460   **E-mail:** dlutfi1@tigers.lsu.edu

2) Co Investigator(s): please include department, rank, phone and e-mail for each
   *If student, please identify and name supervising professor in this space

Emily Elliott, Associate Professor, 225-578-7460, eelliott@lsu.edu

IRB# *E6082* LSU Proposal # _____

☑ Complete Application

☑ Human Subjects Training

3) Project Title: Investigating Auditory and Visual Processes

Study Exempted By:
Dr. Robert C. Mathews, Chairman
Institutional Review Board
Louisiana State University
203 B-1 David Boyd Hall
225-578-8692 | www.lsu.edu/irb
Exemption Expires: *9/4/2015*

4) Proposal? (yes or no) no   **If Yes, LSU Proposal Number** _____

Also, if YES, either   ○ This application <u>completely</u> matches the scope of work in the grant
              OR   ○ More IRB Applications will be filed later

5) Subject pool (e.g. Psychology students)   Psychology Students
   *Circle any **"vulnerable populations"** to be used: (children <18; the mentally impaired, pregnant women, the ages, other). Projects with incarcerated persons cannot be exempted.

6) PI Signature *[signature]*   **Date** 8/27/2012   (no per signatures)

** I certify my responses are accurate and complete. If the project scope or design is later changes, I will resubmit for review. I will obtain written approval from the Authorized Representative of all non-LSU institutions in which the study is conducted. I also understand that it is my responsibility to maintain copies of all consent forms at LSU for three years after completion of the study. If I leave LSU before that time the consent forms should be preserved in the Departmental Office.

Screening Committee Action: Exempted ✓ Not Exempted _____ Category/Paragraph *2*

Signed Consent Waived?: Yes / No
Reviewer *Mathews*   **Signature** *[signature]*   **Date** 8/5/12

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Vita

Danielle Lutfi-Proctor was born in Amman, Jordan, to Candice Proctor and Tony Lutfi. Soon after her birth, her parents moved to Australia where she lived until the age of 11 when she moved to New Orleans, Louisiana. Danielle attended undergraduate at Eckerd College in Saint Petersburg, Florida and graduated summa cum laude in 2011 with a B.A. in psychology and a minor in classical humanities. She will complete her master's degree in psychology at Louisiana State University in 2013 and will continue to work towards her Ph.D. at the same university.