PSYCHOLOGY

# DIAGNOSING SERIAL AND PARALLEL PROCESSING OF CUES AND TARGETS IN THE EXPLICIT TASK-CUING PROCEDURE

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Thesis under the direction of Professor Gordon D. Logan

The current studies used the explicit task cuing procedure in which subjects performed parity and magnitude judgments on target number words as indicated by a cue word that appeared on each trial. In two task switching experiments, we independently degraded the cue words and target number words in two ways—reduced brightness and contrast (Experiment 1) and character substitution (Experiment 2)—and manipulated cue-target interval (CTI) to determine if the serial processing assumption common to models of executive control is valid. Experiment 1 exhibited a significant interaction between cue and target degradation and non-significant interaction between CTI and stimulus degradation. Experiment 2 exhibited a non-significant interaction between cue and target degradation but a significant interaction between CTI and cue degradation. These different results suggest that processing of cues and targets depends upon degradation and the amount of time subjects have to prepare for the second stimulus.

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DIAGNOSING SERIAL AND PARALLEL PROCESSING OF CUES AND TARGETS

IN THE EXPLICIT TASK-CUING PROCEDURE

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To my darling husband, Joshua, who is my source of strength and inspiration

and

To my family who has always believed in me

and

To the God who I adore

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# CHAPTER I

# INTRODUCTION

Executive control processes are thought to govern goal-directed behaviors, allowing us to regulate task specific behavior, switch between tasks, form strategies, choose and execute these strategies, and monitor performance (Logan, 1985, 2003; Monsell, 1996; Norman & Shallice, 1986). The involvement of executive control processes in task switching is controversial, with some experimental results necessitating the role of executive control processes (Mayr & Kliegl, 2000; Monsell, Yeung, & Azuma, 2000) while other results eliminate or drastically reduce its involvement (Arrington & Logan, 2004; Logan & Bundesen, 2003; Schneider & Logan, 2005). The aim of the current research is not to reconcile the differing ideas of executive control processes during task switching but rather to determine whether subordinate processes, such as cue encoding and target processing, occur serially or in parallel with one another. We ask how cues and targets are processed to test the validity of the serial processing assumption that is a component of common models of executive control (Arrington & Logan, 2004; Meiran, 1996; Mayr & Kliegel, 2000; Logan & Bundesen, 2003, 2004; Rogers & Monsell, 1995; Schneider & Logan, 2005).

We investigate cue encoding and target processing using the task switching paradigm, a procedure commonly used to test aspects of executive control (Logan & Bundesen, 2005; Monsell, Sumner, & Waters, 2003; Schneider & Logan, 2005; Yeung & Monsell). In the current studies, we used the task switching paradigm to determine if cues and targets are processed serially as assumed by executive control models. Task switching is a procedure used to study executive control because it promises to provide a simple measure of the duration of control processes that influence behavior between trials and between tasks (Jersild, 1927; Logan & Gordon, 2001; Rubenstein, Meyer, & Evans, 2001). To evaluate the time required to switch between tasks, the response time (RT) from trials when the task alternates is compared to the RT on trials when the task repeats; this difference is referred to as a *switch cost.* There are different ways to interpret switch costs, but we will refrain from discussing the interpretations further because the focus of the current research is the processing of cues and targets in the explicit task cuing procedure.

## Explicit Task Cuing Procedure

The explicit task cuing procedure provides a cue on each trial that denotes a specific task to perform on a target. In the current experiments, subjects performed parity judgments (odd or even) and magnitude judgments (higher or lower than 5) on numbers presented as words. The target number word THREE, for example, would be judged as odd if the cue words were ODD-EVEN and judged as low if the cue words were HIGH-LOW. Using two cues per task instead of only one cue per task avoids confounding task alternation with a cue change and task repetition with a cue repetition. Three transitions are created using two cues per task— *cue repetitions*, in which the cue and the task repeat; *task repetitions*, in which the cue changes but the task repeats; and *task alternations*, in which the cue and the task both change. As will be discussed in the results sections, analyzing the data within these transitions provide information on how the processing of cues and targets, either in series or in parallel, could be influenced by potential RT benefits when the cue repeats or when the task repeats and the lack of those benefits when the task alternates.

The explicit task cuing procedure has become a very common method of investigation because of its ability to manipulate cue-target interval (CTI), the interval of time between the appearance of the cue and the appearance of the target. A number of past experiments have manipulated CTI using the explicit task cuing procedure (Logan & Bundesen, 2003, 2004; Meiran 1996; Schneider & Logan, 2005, 2006). RT measurement begins once both stimuli have been presented. Consequently, short CTIs provide less time for processing of the first stimulus before the second stimulus appears; this usually results in a longer RT because the processing of the first stimulus is less likely to be complete (or near completion) and contribute more to RT. Long CTIs, however, provide more time for the processing of the first stimulus before the second stimulus appears; this usually results in shorter RTs because the processing of the first stimulus is more likely to be complete (or near completion) and contribute less to RT.

The current study had three different CTIs in each experiment: -500 ms CTI condition, at which the target appeared before the cue, 0 ms CTI condition, at which the cue and target appeared simultaneously, and 500 ms CTI condition, at which the cue appeared before the target. To be clear on which stimulus comes first for a particular CTI condition, a positive CTI suggests that the cue came first and a negative CTI suggests that the cue came second. In the -500 ms CTI condition, the impact of target processing on RT should be reduced because target processing can take place during CTI. In the 500 ms CTI condition, the impact of cue processing on RT should be reduced because cue processing can take place during the CTI. In the 0 ms CTI condition, RT should include both cue encoding and target processing.

We justify our selection of CTI with previous results from task switching and psychological refractory period (PRP) experiments that manipulate stimulus onset asynchrony (SOA), the interval between the onsets of the two stimuli or tasks; such research suggests that we should observe measurable differences in RT between 0 ms and 500 ms SOA (Logan & Bundesen, 2003; Carrier & Johnston, 1995). In the task switching literature, Logan and Bundesen (2003) estimated the mean cue encoding time by fitting mathematical model equations under conditions of variable SOA ranging from 0 ms to 950 ms. They observed a 300 ms decrease in RT between SOAs of 0 ms and 500 ms, with RTs decreasing with increasing SOA. Additionally, Carrier and Johnston (1995) used SOA conditions ranging from 0 ms to 1200 ms and observed the largest change in RT2 between the 0 ms and 500 ms SOA conditions, after which the change in RT2 was negligible. These results suggest that using our CTI should also produce measurable effects.

Serial Processing Assumption in Common Models of Executive Control

Serial processing of cues and targets is an assumption made by many models of executive control including *task set reconfiguration theory* and *priming theory of explicit task cuing*. Both of these theories assume that cues and targets are processed serially but make this assumption for different reasons. Task set reconfiguration models assume that subjects must fully encode the cue to know if the *task set*, the appropriate mental state of preparation that guides mental processes, should persist or be *reconfigured* so a response can be made on the target (Meiran, 1996; Mayr & Kliegel, 2000; Rogers & Monsell, 1995; but see Logan, Schneider, & Bundesen, 2007). Without fully encoding the cue, subjects would not know how to modify the current task set, a step that must be completed for target processing and response selection to occur.

*Priming theory of explicit task cuing* also assumes serial processing of cues and targets (Arrington & Logan, 2004; Logan & Bundesen, 2003, 2004; Schneider & Logan, 2005). This theory postulates that learned associations between the cues and targets can facilitate performance. When tasks repeat on consecutive trials, residual activation from the previous trial persists to the current trial to facilitate cue encoding and reduce RT. When tasks do not repeat on consecutive trials, there is little or no residual activation, which results in a lack of facilitation for cue encoding on that trial.

The serial processing assumption of cues and targets is expressed in the equations that model the performance predictions of the priming theory of explicit task cuing. Overall RT is determined by summing the time for cue encoding and target processing. The following equation is a general version of the various mathematical expressions used by the model:

$$RT = RT_{Base} + \mu_c \exp [-CTI/\mu_c] \quad (1)$$

$RT_{Base}$ represents the time required for target processing and other "residual processing", $\mu_c$ represents the time required for cue encoding, and CTI represents the interval of time between the cue and the target. The manipulation of CTI does not alter how target processing and cue encoding are combined serially.

The aim of the current experiments is to determine if the serial processing assumption common to models of executive control is valid. Priming theories assume serial processing of cues and targets because it simplifies the equations and parameter estimations of the models. However, if the current experiments observe parallel processing of cues and targets, more complex methods may be necessary for models to more accurately predict performance.

## Serial and Parallel Processing

Serial processing has been notoriously difficult to distinguish from parallel processing—the simultaneous processing of cues and targets—because one type of processing type can easily mimics the other. There are a few diagnostic tools that allow researchers to make the distinctions (Townsend, 1971; 1990; Townsend & Fifić, 2004). A common way to determine whether processes are serial or parallel is to examine interactions between experimental factors that selectively prolong the processes in question (Besner & Risko, 2006; Egeth & Dagenbach, 1991; Logan, 2002; Townsend, 1971, 1990; Townsend & Schweickert, 1985; Townsend & Wenger, 2004). Diagnosing serial and parallel processing through interactions, as suggested by Townsend (1984), requires the selective manipulation of experimental factors that prolong each process, and measurement of their effect upon RT at all levels of each experimental factor. Additive joint effects of the factors are interpreted as evidence of serial processing and under-additive joint effects of the factors are interpreted as evidence of parallel processing. To determine whether cues and targets are processed in series or in parallel, we manipulated the duration of cue encoding and target processing through cue and target degradation under three different CTI conditions.

Degradation as a Diagnostic Tool for Serial and Parallel Processing

We prolonged cue encoding and target processing by degrading the cues and targets through reducing brightness and contrast and by substituting pound signs for characters to analyze the interaction between cue degradation and target degradation. These two stimulus degradation methods have consistently increased difficulty level and RT in a number of previous experiments (Besner & Risko, 2005; Broadbent & Broadbent, 1975; Egeth & Dagenbach, 1991; Giddings & Carmean, 1989; Logan & Bundesen, 2003; Oriet & Jolicoeur, 2003; Pashler, 1994; Sternberg, 1969).

Reducing the brightness and contrast of the stimuli, as in Experiment 1, was used in the experiments of Sternberg (1969) in which he observed an increase in RT, which he interpreted as reflecting the extra time needed for subjects to "clean up" the representation of the stimulus. In a visual search study, Egeth and Dagenbach (1991) manipulated contrast and observed an increase in RT when the stimulus degradation. Besner and Risko (2006) reduced the brightness and contrast of digits and also observed an increase in RT.

In Experiment 2, we used character substitution, in which half of the letters in the cue words and target words are replaced with pound signs. Broadbent and Broadbent (1975) used a similar method, in which they deleted half of the letters in their stimuli, and observed an increase in error rate. Logan and Bundesen (2003) replaced half the letters in the cue words of their task switching experiment with pound signs (#) and observed an increase in RT. We expect to observe a similar increase in RT.

Unlike Besner and Risko (2005) who degraded only targets and Logan and Bundesen (2003) who degraded only cue words, the current experiments apply the degradation manipulations to both the cue words and the target words. This procedural difference is necessary to interpret the joint effects of cue and target degradation (additive or under-additive) so that we can determine whether the serial processing assumption is valid. We evaluate this interaction between CTI and stimulus degradation at each CTI but of particular importance is the interaction between cue and target degradation at the 0 ms CTI condition. The 0 ms CTI condition is most informative to our diagnosis of serial and parallel processing because the simultaneous presentation of the cue and target ensure that cue and target processing will overlap temporally, providing information on how the cue encoding occur in relation target processing.

Predictions for Interaction between Cue and Target Degradation

We chose two different degradation manipulations—reduction in brightness and contrast and character substitution—because of the different ways in which they could affect information processing, helping to provide a more complete account of how cues and targets are processed. In Experiment 1, we degraded cues and targets by reducing the brightness and contrast. Sternberg (1969) demonstrated that manipulating brightness and contrast affected a perceptual encoding phase, which took place early in information processing during a stage that processes in parallel (Carrier & Pashler, 1995). Consequently, we expect degrading the cue and target by reducing brightness and contrast to produce under-additive joint effects, which would indicate that the perceptual stages of cue and target processing can go on in parallel. Although we analyze the interaction between cue and target degradation at each CTI condition, the 0 ms CTI condition will be the most informative because the cue and target processing overlap temporally whereas in the other two CTI conditions, it is less likely that cue and target processing overlap.

In Experiment 2, we degraded the stimuli by character substitution. Broadbent and Broadbent (1975) degraded their stimuli through character deletion. Character deletion, and character substitution, is a manipulation that is thought to affect memory retrieval because of its effect on the match between the current stimulus and the representation of that stimulus in memory (Sternberg, 1969). Memory retrieval has been found to process in series and take place late in information processing (Carrier & Pashler, 1995; but see Logan & Delheimer, 2001). Consequently, we expect degradation by character substitution to produce additive joint effects of cue and target degradation, providing evidence for serial processing of later stages of cue and target processing. As in the case for Experiment 1, we analyze the interaction between cue and target degradation at each CTI but expect the 0 ms CTI condition to be the most informative in our diagnosis of serial or parallel processing because of the temporal overlap of cue and target processing at the 0 ms CTI condition.

## Cognitive Slack

The locus of slack technique is a method commonly used in psychological refractory period (PRP) experiments to determine whether stages of processing are located before or after the single-channel bottleneck, the stage during which processing is limited to one stimulus (Pashler & Johnston, 1989). This central processing stage, thought to process portions of each task that require the bottleneck, is preceded and followed by pre-central and post-central stages that are thought to process information in parallel (Pashler, 1994, 2000; Pashler & Johnston, 1989). In PRP studies, manipulations are performed to selectively affect different processing stages to determine whether a manipulation affects pre-central processes on the one hand or central or post-central processes on the other.

The PRP procedure presents two stimuli, S1 and S2, in rapid succession and requires subjects to make one response (R1) to the first stimulus and another response (R2) to the second stimulus. Usually, there is a difficulty manipulation applied to either one or both stimuli and SOA is varied to manipulate the temporal overlap between S1 and S2. When S1 and S2 are presented at a short SOA, S2 can not be fully processed until processing of S1 has gone beyond the single-channel bottleneck. The period during which S2 is postponed is referred to cognitive slack. During cognitive slack, difficulty manipulations that affect pre-bottleneck stages of S2 can be absorbed and their effect on RT reduced or eliminated. However, when S1 and S2 are presented at a long SOA, there is less competition between S1 and S2 for access to the single-channel bottleneck because S1 can be fully processed before S2 appears. Consequently, there is no slack and S2 processing is not postponed.

In the PRP procedure, the way in which the difficulty manipulation interacts with SOA depends on whether the difficulty manipulation affects pre-central processing or central (or post-central) processing. S1 manipulations that prolong pre-central processing affect RT2 and should produce over-additive joint effects of degradation and SOA. At a short SOA, the effects of an S1 manipulation will carry forward to prolong RT2. The S1 difficulty manipulation would postpone central and post-central S2 processing and increase RT2. At a long SOA, the effects of an S1 manipulation will not prolong RT2.

At a long SOA there would be no overlap of central processing to postpone S2 processing. Putting these arguments together, we would observe over-additive joint effects between pre-central manipulation and SOA because the effects of manipulation would be observed at a short SOA but not at a long SOA. However, regardless of short or long SOA, S1 manipulations that prolong central or post-central process will effect RT2 and produce an additive interaction between S1 manipulation and SOA.

S2 manipulations that prolong pre-central processing affect RT2 and should produce under-additive joint effects of manipulation and SOA; degradation effects will be absorbed in the slack with a short SOA but not with a long SOA. S2 manipulations that prolong central or post-central processes will not affect RT2 and should produce additive joint effects with SOA; their effects will not be absorbed in slack.

Application of Cognitive Slack to Explicit Task Cuing

This logic can be applied to the current research to determine how cues and targets are processed, and determine the loci of effects for the two stimulus degradations. Similar to the two tasks in the PRP experiments, the current experiments involves two stimuli, cues and targets, to which subjects must respond. In the PRP experiments, the responses are separate. In the explicit task cuing procedure, the two responses are integrated such that subjects make one response to both the cue and target. The diagnostic tools used in PRP studies to determine the locus of effect for stimulus degradation and how stimuli are processed are also employed in the current research. We too, use different CTI conditions and analyze the interaction between CTI and stimulus degradation to address our question of serial or parallel processing and to identify the loci of effects for our stimulus degradations.

To apply the locus of slack logic to the current experiments, we make three key assumptions about cue and target processing: (1) pre-central processing, such as perceptual processing, of the cue and of the target can take place in parallel (Sternberg, 1969; Pashler & Johnston, 1989), (2) central processing, such as memory retrieval, occurs in series because of the psychological limitation of the single-channel bottleneck which processes only one stimulus at a time (Carrier & Pashler, 1995), and (3) central processing occurs in series because information from central processing of the cue (i.e. the task to perform on the target) is necessary for central processing of the target (i.e. how to judge the target according to the cue; Besner & Care, 2003). The remainder of the thesis will focus on the first two assumptions because we believe that the degradation manipulations we used—reduced brightness and contrast and character substitution—affect the pre-central process of perceptual processing and the central process of memory retrieval, respectively.

With these assumptions about cue and target processing in place, we made predictions about how cue and target degradation effects would vary at different CTIs. We based our predictions on a contrast that assess the interaction between degradation and the 0 ms and 500 ms CTIs and a contrast that assesses the interaction between degradation and the 0 ms and -500 ms CTIs. These predictions address our question about serial and parallel processing of cues and targets; the predictions also identify possible loci of effects for the two degradation manipulations—reduced brightness and contrast and character substitution—we used in our experiments.

Predictions for interactions between CTI and Cue Degradation

There are two contrasts that allow an examination of the interaction between CTI and cue degradation. The contrasts are between cue degradation effects at the 0 ms versus 500 ms CTI conditions and between cue degradation effects at the 0 ms and -500 ms CTI conditions. Of the two contrasts, the contrast between cue degradation effects at the 0 ms and -500 ms CTI conditions is the most informative to our investigation of serial or parallel processing of cues and targets. We make the comparison between these -500 ms CTI condition and 0 ms CTI condition because (1) the RT at the -500 ms CTI condition provides a full measurement of cue encoding because the cue appears after the CTI and (2) the 0 ms CTI condition presents cues and targets at the same time and thus RTs capture both cue and target processing. We can compare the observed degradation effects when the cue and target are presented together (0 ms CTI condition) to the effects when the cue and target have less temporal overlap. From these comparisons, we can make predictions about serial and parallel processing based upon whether degradation effects are large (not absorbed into target processing or slack) or small (absorbed into target processing or slack). The difference between these CTI conditions should reflect how cue processing occurs (either in series or in parallel) in relation to target processing and determine how CTI affects this relationship.

*Cue degradation and the 0 ms vs. 500 ms CTI*

The interaction between CTI (0 ms and 500 ms) and cue degradation does not provide diagnostic information regarding our question of serial or parallel processing of cues and targets. However, we still have predictions of how the degradation manipulations will affect pre-central and post-central processes. If cue degradation affects pre-central processes, we expect over-additive joint effects – the degradation effects would be absorbed by the CTI in the 500 ms CTI condition but not in the 0 ms CTI condition.

If the cue degradation affects central or post-central processes, we also expect over-additive joint effects: for 500 ms CTI condition, cue degradation effects would be reduced because effects would be resolved during CTI whereas for 0 ms CTI condition, degradation effects would be observed because degrading the cue postpones target processing and thus increases RT. The contrast between CTI (0 ms and 500 ms) and cue degradation does not provide useful information about the main question of whether cues and targets are processed in series or in parallel because regardless of pre-central or central manipulation, the predictions are the same.

*Cue degradation and the 0 ms vs.- 500 ms CTI*

The interaction between CTI (0 ms and -500 ms) and cue degradation is the critical interaction to determine whether cues and targets are processed in series or in parallel: if cues and targets are processed in series, we expect additive joint effects of CTI (0 ms and -500 ms) and cue degradation; if cues and targets are processed in parallel, we expect additive joint effects of CTI (0 ms and -500 ms) and cue degradation. If cue degradation affects pre-central processes, we expect under-additive joint effects between cue degradation and CTI. We expect under-additive joint effects because at the 0 ms CTI condition, there is slack to absorb the effects of cue degradation whereas in the -500 ms CTI condition, there is no slack to absorb the effects of cue degradation. The reduced cue degradation effect in the 0 ms CTI condition compared to the cue degradation effects in the -500 ms CTI condition would produce the under-additivity expected for this contrast.

If the cue degradation affects central or post-central processes, we expect additive joint effects. We expect additive joint effects because the effects of cue degradation could not be absorbed in the CTI of the -500 ms CTI condition. Instead, the degradation would cause an RT increase because of the time needed to resolve the cue, encode the cue, and make a response that could not take place during the CTI. A similar increase in RT would also be observed in the 0 ms CTI condition because the degradation would postpone target processing and response selection. The degradation would cause an RT increase because of the time needed to resolve the cue, process the cue, resume processing of the target, and make response. Even though there are more processes to take place in the 0 ms CTI condition for response selection to occur, the magnitude of the degradation effects is no different from degradation effects observed in the -500 ms CTI condition due to the overlap in cue and target perceptual processing that can take place in the 0 ms CTI condition. The similarity in the magnitude between the degradation effects in the -500 ms and 0 ms CTI condition produces the additive joint effects that we predict for this interaction.

Additive joint effects of CTI (0 ms and -500 ms) and cue degradation indicate that the central processing stage is the locus of effect for the degradation manipulation. Central processes are thought to occur in series; therefore, we can conclude that cues and targets are processed in series under degradation manipulations that selectively prolong central processes. Under-additive joint effects of CTI (0 ms and -500 ms) and cue degradation indicate a pre-central manipulation. Pre-central processes are thought to occur in parallel; therefore, we can conclude that cues and targets are processed in parallel under degradation manipulations that selectively prolong processes that prolong pre-central processes.

Predictions for interactions between CTI and Target Degradation

There are two contrasts that allow an examination of the interaction between CTI and target degradation. The contrasts are between target degradation effects at the 0 ms and -500 ms CTI conditions and between target degradation effects at the 0 ms and -500 ms CTI conditions. The interaction between CTI (0 ms and 500 ms) and target degradation is the critical interaction to determine how targets are processed: if cues and targets are processed in series, we expect additive joint effects of CTI (0 ms and 500 ms) and target degradation; if cues and targets are processed in parallel, we expect additive joint effects of CTI (0 ms and 500 ms) and target degradation. We make the comparison between the 500 ms CTI condition and 0 ms CTI condition because the 500 ms CTI condition presents the target word first and thus RTs captures all of target processing; comparing this to the 0 ms CTI condition when the cues and targets are presented at the same time be able to diagnosis how targets are processed, (either in series or in parallel) with the cue.

*Target degradation and the 0 ms vs.- 500 ms CTI*

The interaction between CTI (0 ms and -500 ms) and target degradation does not directly address our investigation of serial or parallel processing of cues and targets. However, we form predications of the joint effects of target degradation and CTI if the degradation effects were pre-central or post-central manipulations. If target degradation affects pre-central processes, we expect over-additive joint effects with CTI: the target degradation effect would be absorbed during the CTI in the -500 ms CTI condition whereas the target degradation effect would not be absorbed in the 0 ms CTI condition. If target degradation affects central or post-central processes, we also expect over-additive joint effects: because central processing of the target does not depend upon central processing of the cue, the target degradation effects would be absorbed in the -500 CTI condition but not absorbed in the 0 ms CTI condition. Regardless of a pre-central or central manipulation, our predictions are the same. Therefore, the contrast between CTI (0 ms and -500 ms) and target degradation is not informative in our diagnosis of serial or parallel processing of cues and targets.

*Target degradation and the 0 ms vs.500 ms CTI*

The interaction between CTI (0 ms and 500 ms) and target degradation provides diagnostic information regarding our question of serial or parallel processing of cues and targets: if cues and targets are processed in series, we expect additive joint effects between CTI and target degradation; if cues and target are processed in parallel, we expect under-additive joint effects of CTI and target degradation. If target degradation affects pre-central processes, we expect under-additive joint effects between target degradation and CTI: for the 0 ms CTI condition, cue processing is the rate limiting process which produces slack that can absorb the effect of target degradation whereas in the 500 ms CTI condition, there is less slack and thus less absorption of target degradation effects. If target degradation affects central or post-central processes, we expect additive joint effects because in both CTI conditions, the manipulation takes place after the CTI and is not absorbed.

## Summary

The two degradation manipulations used in the current research are thought to have different loci of effects that will produce different results. The brightness and contrast manipulation in Experiment 1 is thought to affect perceptual processing that takes place prior to the single-channel bottleneck (Egeth & Dagenbach, 1991; Pashler & Johnston, 1989; Miller, 1979). Because this manipulation affects a pre-central process, we expect under-additive joint effects between cue and target degradation, CTI (0 ms and -500 ms) and cue degradation, and CTI (0 ms and 500 ms) and target degradation. The character substitution manipulation in Experiment 2 is thought to affect memory retrieval, a process that some research has concluded occurs after the bottleneck (Carrier & Pashler, 1994; for an alternate account, see Logan & Delheimer, 2001). Because character substitution affects a central process, we expect additive joint effects between cue and target degradation, CTI (0 ms and -500 ms) and cue degradation, and CTI (0 ms and 500 ms) and target degradation.

# CHAPTER II

# EXPERIMENT ONE

The goal of the first experiment was to test the validity of the serial processing assumption by reducing the brightness and contrast of cues and targets independently with three different CTI conditions. If reduced brightness and contrast affects pre-central processing, we expect evidence for parallel processing of cues and targets. Our conclusion of parallel processing will be based upon under-additive joint effects of cue and target degradation, under-additive joint effects of CTI (0 ms and -500 ms) and cue degradation, and under-additive joint effects of CTI (0 ms and 500 ms) and target degradation. If reduced brightness and contrast affect central processing, we expected evidence of serial processing of cues and targets. Our conclusion of serial processing will be based upon additive joint effects of cue and target degradation, additive joint effects of CTI (0 ms and -500 ms) and cue degradation, and additive joint effects of CTI (0 ms and 500 ms) and target degradation.

## Method

### Subjects

Thirty-two students from the Vanderbilt University community participated in the experiment in exchange for course credit or pay.

Apparatus and Stimuli

The stimuli were displayed by Dell Dimension computers on Sony Trinitron monitors. The magnitude and parity judgments were each cued by two cue word for a total of four cue words in the experiment—MAGNITUDE and HIGH-LOW for magnitude judgments, and PARITY and ODD-EVEN for parity judgments. Two cue words—LOW-HIGH and EVEN-ODD—appeared in certain versions of the experiment to counterbalance mapping of responses onto response keys. The cue words were presented in 14-point Courier New font and were 0.3 cm tall. Cue word widths were 3.0 cm (PARITY), 4.0 cm (ODD-EVEN and HIGH-LOW), and 4.5 cm (MAGNITUDE). Non-degraded cue words appeared in white at a luminance of 72.4 cd/$m^2$; degraded cue words appeared in dark gray at a luminance of 2.33 cd/$m^2$. The black background remained constant at a luminance of 0.09 cd/$m^2$.

There were eight target number words—ONE, TWO, THREE, FOUR, SIX, SEVEN, EIGHT, and NINE. The number five was excluded because a magnitude judgment (lower or higher than five) could not be performed on this number. The target number words appeared in 14-point Courier New font and were 0.3 cm tall. Target number word widths were 1.4 cm (ONE, TWO, and SIX), 2.0 cm (FOUR and NINE), and 2.4 cm (THREE, SEVEN, and EIGHT). Non-degraded and degraded targets appeared at the same luminances as the non-degraded and degraded cues.

Cues and targets appeared in the center of the screen with the cue appearing one line above the target. There was a fixation display comprised of two plus signs (+) on each trial; one plus sign appeared one line above the position of the cue and the other plus sign appeared one line below the position of the target. The fixation display was presented in white on each trial. It remained on the screen for 500 ms. Depending upon the CTI, the cue appeared 500 ms after the target, at the same time as the target, or 500 ms before the target. The stimuli remained on the screen until subjects made a response.

Procedure

The experimental design was 3 (-500 ms, 0 ms, and 500 ms S0A) x 2 (non-degraded vs. degraded cue) x 2 (non-degraded vs. degraded target) x 4 (cue words) x 8 (target words) = 384 trials per block. The experiment was comprised of 2 replications of the basic experimental design for a total of 768 trials. At the beginning of the experiment, subjects completed 64 practice trials to expose them to all tasks, CTI conditions, cues, and cue and target degradation combinations. Cues and targets appeared in both non-degraded and degraded forms equally often and in random order; the CTI conditions also appeared equally often and in random order.

Subjects were tested individually. They were informed that their task was to judge the number words that appeared on the screen according to the cue words that appeared on each trial. Subjects were told that on some of the trials, the cue, the target, or both cue and target could appear at a reduced brightness and contrast. Subjects were also told that the order in which the stimuli appeared on the screen would vary such that the cue could appear after the target, at the same time as the target, or before the target. Subjects were instructed to make their judgments as quickly as possible without sacrificing accuracy.

Subjects made responses on a standard QWERTY keyboard. They used the Z key and the / key. One response from each task was mapped unto each response key. There were four counterbalanced response mappings: (1) ODD and HIGH mapped on the Z key; EVEN and LOW mapped on the / key, (2) EVEN and LOW mapped on the Z key; ODD and HIGH mapped on the / key, (3) EVEN and HIGH mapped on the Z key; ODD and LOW mapped on the / key, and (4) ODD and LOW mapped on the Z key; EVEN and HIGH mapped on the / key. After subjects made a response, there was an inter-trial period of 500 ms. There were rest periods after every 128 trials. Subjects could resume the experiment at any time during the rest period by pressing the spacebar.

## Results and Discussion

Mean RT was calculated for accurate responses that were less than 3000 ms. Accuracy was high, with a range of 91-100% correct and an average accuracy over all subjects of 97 %. The data were sorted into non-degraded and degraded trials, CTI conditions, and transitions. Two 3 (CTI: -500 ms, 0 ms, and 500 ms) x 2 (cue degradation: non-degraded vs. degraded) x 2 (target degradation: non-degraded vs. degraded) x 3 (transition: cue repetition, task repetition, and task alternation) analysis of variances (ANOVA) were conducted, one for accuracy and the other on RT. There was no evidence of speed accuracy tradeoff so subsequent analysis focused on RT.

### RT and CTI effects

Table 1 presents the accuracy and average RT for each CTI. RT varied with CTI. The mean RT was 912 ms at 500 ms CTI, 930 ms at -500 ms CTI, and 1198 ms at 0 ms

CTI. The main effect of CTI was significant, $F(2,62) = 145.58$, $p < 0.01$, $MSE = 9372496.62$. This result illustrates the benefit of processing the first stimulus in the absence of the second. The difference between RT when cues and targets were presented simultaneously (in 0 ms CTI condition) and when either the cue or target was presented first (in the 500 ms and -500 ms CTI conditions) suggest that some processing of the first stimulus occurred in the time interval provided by the CTI. Consequently, the processing does not contribute as much to RT as it does when stimuli are presented at the same time.

Regardless of target degradation, there was a 30 ms increase in RT due to cue degradation. The main effect of cue degradation was significant, $F(1,31) = 31.99$, $p < 0.01$, $MSE = 288757.89$. Regardless of cue degradation, there was a 33 ms increase in RT due to target degradation. The main effect of target degradation was significant, $F(1,31) = 30.41$, $p < 0.01$, $MSE = 319220.81$. The significance of the main effect for cue degradation and target degradation illustrates that our degradation manipulation successfully increased cue encoding and target processing time, which is crucial to our use of degradation to distinguish between serial and parallel processing of cues and targets.

Figure 1 plots the interaction between cue degradation and target degradation averaged over the CTI conditions. Target degradation increased RT by 53 ms when the cue was non-degraded and by 13 ms when the cue was degraded. The reduced effect of target degradation when both the cue and target were degraded indicates that the joint effects of cue degradation and target degradation were under-additive. The interaction between cue degradation and target degradation was significant, $F(1,31) = 13.48$, $p = 0.01$, $MSE = 221253.00$. We interpret this as evidence for parallel processing of cues and targets such that when both the cue and target were degraded, some of the effect of target degradation was absorbed into the time taken to encode and resolve the cue.

The three-way interaction between CTI, cue degradation, and target degradation was not significant, $F(2,62) = 0.83$, $p = 0.44$, $MSE = 15624.53$. Though the three-way interaction was not significant, we conducted planned comparisons to determine if cue degradation and target degradation interacted at each CTI. For the -500 ms CTI condition, we observed additive joint effects between cue and target degradation because target degradation effects were observed into the CTI and thus did not interact with cue degradation. The interaction was not significant, $F(1,62) = 0.08$, $p = 0.78$, $MSE = 15624.53$. For the 500 ms CTI condition, we observed under-additive joint effects between cue and target degradation because the cue degradation effects were absorbed during target processing; cue degradation effects were less when the target was degraded than when the target was non-degraded. The interaction was significant, $F(1,62) = 6.09$, $p = 0.02$, $MSE = 15624.53$. The RT pattern for the 0 ms CTI condition followed the same pattern of results as the 500 ms CTI condition in that the target degradation effects were reduced when the cue was degraded, suggesting that target processing took place during cue processing. The under-additive joint effects suggested by the RT results was supported by a marginally significant interaction between cue and target degradation, $F(1,62) = 3.69$, $p = 0.06$, $MSE = 15624.53$. The results of the cue and target degradation at each CTI condition lead us to conclude that cues and targets are processed in parallel when degraded when reduced in brightness and contrast.

The effects of cue degradation varied with CTI. Cue degradation increased RT by 58 ms at -500 ms CTI, 37 ms at 0 ms CTI, and -5 ms at the 500 ms CTI. The interaction between CTI and cue degradation was significant, $F(2,62) = 6.88$, $p < 0.01$, $MSE$ = 102322.39. When the cue was presented before the target, as in the 500 ms CTI condition, cue processing time and the effects of cue degradation were absorbed by the CTI interval. This was not the case for the other two conditions. When the cue appeared after the target in the -500 ms CTI condition, we observed the largest cue degradation effect of 58 ms: because the CTI elapsed before the cue was presented, none of the cue degradation resolution or cue processing could occur during that interval of time. When the cue and target appeared at the same time as in the 0 ms CTI condition, we observed a the cue degradation effect of 37ms: because the cue and target appear simultaneously, target processing could take place in parallel with cue encoding and absorb some of the degradation effects. We conducted pair-wise comparisons of the cue degradation effects for each CTI condition. The cue degradation effects at the -500 ms and 0 ms CTI conditions were not significantly different, $t = 1.29$, $p = 0.21$. The cue degradation effects at the -500 ms and 500 ms CTI conditions were significantly different, $t = 4.12$, $p = 0.00$. The cue degradation effects at the 500 ms and 0 ms CTI conditions were also significantly different, $t = 2.62$, $p = 0.01$.

The effects of target degradation also varied with CTI. Target degradation increased RT by 5 ms at -500 ms CTI, 33 ms at 0 ms CTI, and 61 ms at 500 ms CTI, an expected reverse in the pattern of degradation across CTI conditions observed for cue degradation. The interaction between CTI and target degradation was significant, $F(2,62) = 8.57$, $p = 0.01$, $MSE$ = 105733.88. When the target was presented before the cue, as in the -500 ms CTI condition, target processing time and the effects of target degradation were absorbed by the CTI interval. However, when the target was presented with the cue

(0 ms CTI condition) or after the cue (500 ms CTI condition), target degradation effects were higher (33 ms and 61 ms, respectively) because target processing could not be absorbed by the CTI interval. Also, the target degradation effect is less at the 0 ms CTI than at the 500 ms CTI. We attribute this 28 ms difference in target degradation effects to an increased probability of temporal overlap of cue and target processing in the 0 ms CTI condition relative to the 500 ms CTI condition. We conducted pair-wise comparisons of the target degradation effects for each CTI condition. The target degradation effects at the -500 ms and 0 ms CTI conditions were significantly different, $t = -2.49$, $p = 0.02$. The target degradation effects at the -500 ms and 500 ms CTI conditions were significantly different, $t = -3.51$, $p = 0.01$. The target degradation effects at the 500 ms and 0 ms CTI conditions were not significantly different, $t = -1.68$, $p = 0.10$.

Cue degradation and CTI contrasts

*Cue degradation and the 0ms vs. -500 ms CTI*

We conducted two contrasts between CTI (0 ms and -500 ms; 0 ms and 500 ms) and cue degradation. Figure 2 plots the interaction between CTI (0 ms and -500 ms) and cue degradation. The contrast between CTI (0 ms and -500 ms) and cue degradation provides information that directly addresses our question of how cues and targets are processed. At 0 ms CTI, cue degradation increased RT by 37 ms; at the -500 ms CTI, cue degradation increased RT by 58. The numerical pattern of the data suggests under-additivity of cue degradation effects and CTI. However, the interaction was not significant, $F(1,62) = 1.38$, $p = 0.25$, $MSE = 14881.98$. The results from this contrast are inconclusive because we do not have enough information to confidently accept or reject the null interaction. Consequently, we reserve judgment about this interaction.

*Cue degradation and the 0 ms vs. 500 ms CTI*

Figure 3 plots the interaction between CTI (0 ms and 500 ms) and cue degradation. The contrast was significant, $F(1,62) = 5.77$, $p = 0.02$, $MSE = 14881.98$. The under-additive joint effects of CTI (0 ms and 500 ms) and cue degradation provide no information for our diagnosis of serial and parallel processing because they were expected whether processing was parallel or serial

Target degradation and CTI contrasts

*Target degradation and the 0 ms vs. 500 ms CTI*

We conducted the same contrasts for CTI and target degradation. Figure 4 plots the interaction between CTI (0 ms and 500 ms) and target degradation. The contrast between CTI (0 ms and 500 ms) and target degradation provides information about whether cues and targets are processed in series or in parallel. At the 0 ms CTI condition, target degradation increased RT by 33 ms; at the 500 ms CTI, target degradation increased RT by 61 ms. This pattern of results suggests parallel processing of cues and targets because of the reduced effect of target degradation at the 0 ms CTI condition compared to the effect of target degradation at the 500 ms CTI condition. The under-additivity of the CTI (0 ms and 500 ms) and target degradation interaction was supported by a contrast that approached significance, $F(1,62) = 3.18$, $p = 0.07$, $MSE = 12334.11$. Again, we refrain from interpreting this interaction because of our inability to either accept or reject the null interaction despite the under-additive pattern in the mean RTs, which suggests parallel processing of cues and targets.

*Target degradation and the 0 ms vs. -500 ms CTI*

Figure 5 plots the interaction between CTI (0 ms and -500 ms) and target degradation. The interaction between CTI (0 ms and -500 ms) and target degradation was not significant, $F(1,62) = 3.12$, $p = 0.07$, $MSE = 12334.11$. The additive joint effects of CTI (0 ms and -500 ms) and target degradation are inconclusive because our prediction for this contrast was the same regardless of a pre-central or central manipulation. Consequently, we base our conclusion on how cues and targets are processed on the results from the contrast between CTI (0 ms and 500 ms) and target degradation; the statistical results were inconclusive while the pattern of results suggest parallel processing of cues and targets.

RT and Transition Effects

Table 2 presents the accuracy and average RT for each transition. RT varied with transition. The average RT was 940 ms for cue repetitions, 1037 ms for task repetitions, and 1040 ms for task alternations. The main effect of transition was significant, $F(2,62) = 31.446$, $p < 0.01$, $MSE = 1396905.51$. The significance of this main effect illustrates how RT performance benefited from the residual activation from the previous trial that facilitates cue encoding. This interpretation is supported by the large, 103 ms repeated cue encoding benefit, a finding that is consistent with other task switching experiments that used explicit task cuing procedure with multiple cues per task (Arrington & Logan, 2004; Logan & Bundesen, 2003; Schneider & Logan, 2005). There was little difference between task alternation and task repetition, resulting in a small task switch cost of 3 ms. The large cue encoding benefits and the small switch cost support associative and repetition priming as the cause for differences between transitions (Logan & Bundesen, 2003, 2004; Schneider & Logan, 2005).

Table 3 presents the accuracy and average RT for each transition for each CTI condition. The effect of transition varied for each CTI. Cue repetition was consistently faster than both task repetition and task alternation, across all CTI conditions. For the -500 ms CTI condition, cue repetitions were 107 ms faster than task repetitions and 91 ms faster than task alternations. For the 500 ms CTI condition, cue repetitions were 125 ms faster than task repetitions and 134 ms faster than task alternations. For the 0 ms CTI condition, cue repetitions were 77 ms faster than task repetitions and 93 ms faster than task alternations. This again illustrates the role of cue encoding benefits on RT when the cue repeats. Additionally, it illustrates that RT is reduced in the -500 ms and 500 ms CTI conditions by creating slack that absorbs cue and target processing. When the data were divided into the transitions, RT for -500 ms and 500 ms CTI conditions were still, on average, lower than the RT for 0 ms CTI. The interaction between transition and CTI was significant, $F(4,124) = 2.46$, $p = 0.05$, $MSE = 31094.16$. The significant interaction for transition and CTI is consistent with Logan & Bundesen (2003). In their experiment, there were several CTI conditions and as CTI increased, the differences between the transitions diminished. The interaction between transition and cue degradation was not significant, $F(2,62) = 0.52$, $p = 0.60$, $MSE = 9317.22$, and neither was the interaction between transition and target degradation, $F(2,62) = 1.62$, $p = 0.21$, $MSE = 23547.60$.

The three-way interaction between transition, cue degradation, and target degradation was significant, $F(2,62) = 4.58$, $p = 0.01$, $MSE = 44510.48$. We conducted planned comparisons for each transition type to determine if the interaction between cue degradation and target degradation held for each of the three transition types. Each transition presented a pattern of results that suggested parallel processing of cues and targets in that the target degradation effect was reduced on trials when the cue was degraded. However, the planned comparisons did not confirm the trend in the data: for cue repetitions, $F(2,62) = 1.80$, $p = 0.17$, $MSE = 44510.48$; for task repetitions, $F(2,62) = 0.50$, $p = 0.61$, $MSE = 44510.48$; and for task alternations, $F(2,62) = 0.04$, $p = 0.96$, $MSE = 44510.48$. We have no explanation of why this interaction was not significant.

The three-way interaction between transition, CTI, and cue degradation was not significant, $F(4,124) = 0.25$, $p = 0.91$, $MSE = 2903.71$ and neither was the interaction between transition, CTI, and target degradation, $F(4,124) = 0.78$, $p = 0.54$, $MSE = 8980.77$. The four-way interaction between transition, CTI, cue degradation, and target degradation was also not significant, $F(4,124) = 1.15$, $p = 0.34$, $MSE = 14815.31$.

## Conclusions

In this experiment, we reduced the brightness and contrast of cues and targets under three CTI conditions to test the validity of the serial processing assumption common to models of executive control. To assess how cues and targets were processed, we analyzed three critical interactions which promise to distinguish between serial and parallel processing, and determine the locus of effect for degradation manipulations: interaction between cue and target degradation, the interaction between CTI (0 ms and -

500 ms) and the interaction between cue degradation, and CTI (0 ms and 500 ms) and target degradation. We observed under-additive joint effects of cue and target degradation which we interpret as evidence for parallel processing of cues and targets. The under-additive pattern of results for the CTI (0 ms and -500 ms) and cue degradation, and CTI (0 ms and 500 ms) and target degradation contrasts suggest parallel processing of cues and targets and that reduced brightness and contrast affect pre-central processes, one that we believe to be perceptual processing. Based upon the results of these three critical interactions, we conclude that cues and targets are processed in parallel when reduced in brightness and contrast.

# CHAPTER III

# EXPERIMENT TWO

The goal of Experiment 2 was to test the validity of the serial processing assumption by using the same CTI conditions as Experiment 1 but using character substitution to independently degrade the cues and targets. If character substitution affects pre-central processing, we expect under-additive joint effects between cue and target degradation, under-additive joint effects between CTI (0 ms and -500 ms) and cue degradation, and under-additive joint effects between CTI (0 ms and 500 ms) and target degradation. If character substitution affects central processing, we expect additive joint effects between cue and target degradation, additive joint effects between CTI (0 ms and -500 ms) and cue degradation, and additive joint effects between CTI (0 ms and 500 ms) and target degradation.

## Subjects

Thirty-two students from the Vanderbilt University community participated in the experiment in exchange for course credit or pay. Subjects from Experiment 1 did not participate in Experiment 2.

## Apparatus and Stimuli

The apparatus and stimuli for Experiment 2 were the same as in Experiment 1, except that the cue words and target number words were degraded by substituting pound signs (#) for half of the letters in each stimulus.

For cue words, the number of pound signs in each degraded form was held constant by standardizing the length of the words to ten character positions. This word length was chosen so that the longest cue word, MAGNITUDE, would undergo the same level of degradation as the other cue words. The shorter cue words included spaces in some of the letter positions to maintain the ten character word length. The cue word PARITY, for example, could appear as #A#I#Y## .

A standard length of six character positions was chosen for the target words. The shorter target words included spaces to maintain a standard six character word length. A degraded form of the number word SEVEN would be S#V#N . In the case of both the cue words and the target number words, each degraded form was recognizable and distinct from any other letter/pound sign combination of other degraded cues or target words.

Trials that included degraded stimuli sampled from a pool of degraded cue words and degraded target words. Each cue word had 32 unique degraded forms. For each target number word, there were eight unique degraded forms. Each cue word and target number word appeared equally often in both its non-degraded and degraded form in each experiment.

## Procedure

The procedure for Experiment 2 was the same as Experiment 1, differing only by the degradation manipulations.

## Results and Discussion

Mean RTs were calculated for responses that were both correct and less than 3000 ms. Accuracy ranged from 92 to 99% correct, with an average accuracy of 96% correct over all subjects. The data were sorted into non-degraded and degraded trials, CTI conditions, and transitions. Two 3 (CTI: -500 ms, 0 ms, and 500 ms) x 2 (cue degradation: non-degraded vs. degraded) x 2 (target degradation: non-degraded vs. degraded) x 3 (transition: cue repetition, task repetition, and task alternation) were conducted, one for accuracy and the other on RT. There was no evidence of speed accuracy tradeoff so subsequent analysis focused on RT.

### RT and CTI effects

Table 1 presents the accuracy and average RT for each CTI condition. RT depended on CTI. The average RT was 1164ms for 500 ms CTI, 1188 ms for -500 ms CTI, and 1552 for 0 ms CTI. The main effect of CTI was significant, $F(2,62) = 193.71$, $p < 0.01$, $MSE = 90795.68$. The RT difference between the 0 ms CTI and the -500 ms and 500 ms CTI suggests that some of the stimulus processing was absorbed in the slack created by the CTI. Because this interval of time that was not present in the 0 ms CTI condition, the processing of stimuli contributed more to RT than it did at the -500 ms and 500 ms CTI conditions.

Cue degradation increased RT by 181 ms, irrespective of target degradation. The main effect of cue degradation was significant, $F(1,31) = 106.89$, $p < 0.01$, $MSE$ = 89483.93. Target degradation increased RT by 292 ms, regardless of the cue degradation. The main effect of target degradation was significant, $F(1,31) = 265.16$, $p < 0.01$, $MSE$ = 89106.98. The significant main effect of cue and target degradation illustrates that the character substitution manipulation successfully prolonged cue encoding and target processing.

Figure 6 plots the interaction between cue degradation and target degradation averaged over the CTI conditions. Cue degradation increased RT by 175 ms on trials when the target was non-degraded and increased RT by 187 when the target was degraded. Target degradation increased RT by 286 ms when the cue was non-degraded and 298 ms when the cue was degraded. The absence of a reduction in the degradation effects of the second stimulus when the first stimulus was degraded indicates that the joint effects of cue degradation and target degradation were additive. This was confirmed statistically: the interaction between cue degradation and target degradation was not significant, $F(1,31) = 1.13$, $p = 0.30$, $MSE$ = 37095.32. We interpret this as evidence for serial processing of cues and targets.

The three way interaction between CTI, cue degradation, and target degradation was not significant, $F(2,62) = 0.33$, $p = 0.72$, $MSE$ = 39692.96. We conducted planned comparisons to evaluate the interaction between cue degradation and target degradation for each CTI condition. The joint effects of cue and target degradation were additive for each CTI conditions. None of the interaction contrasts were significant: for -500 ms CTI condition, $F(1,62) = 0.15$, $p = 0.89$, $MSE$ = 39692.96; for the 0 ms CTI condition, $F(1,62)$

= 0.12, $p = 0.89$, $MSE = 39692.96$; and for the 500 ms CTI condition, $F(1,62) = 0.92$, $p = 0.34$, $MSE = 39692.96$. From these results, we conclude serial processing of cues and targets when degraded by character substitution. We also conclude that character substitution affected central or post-central processes for the following reason: a central or post-central manipulation would cause the degradation of the first stimulus (cue for -500 ms CTI and target for 500 ms CTI) to be absorbed in the CTI so that there would be no significant difference between non-degraded and degraded trials and only a linear increase in RT caused by the degradation of the second stimulus. This would lead to the additive interaction we observed for character substitution at each CTI condition.

The effect of cue degradation varied with CTI. Regardless of target degradation, cue degradation increased RT by 129 ms at 500 ms CTI, 264 at 0 ms CTI, and 150 ms at -500 ms CTI. The interaction between CTI and cue degradation was significant, $F(2,62) = 10.44$, $p < 0.01$, $MSE = 45323.28$. For the 500 ms CTI condition, we expected cue degradation to have the least effect because cue degradation effects could be absorbed during the CTI. However, for the 0 ms CTI condition and the -500 ms CTI condition, CTI would not absorb the cue degradation effect, so we observed larger cue degradation effects. We conducted pair-wise comparisons of the cue degradation effects for each CTI condition. The cue degradation effects at the -500 ms and 0 ms CTI conditions were significantly different, $t = -3.40$, $p = 0.00$. The cue degradation effects at the -500 ms and 500 ms CTI conditions were not significantly different, $t = 0.89$, $p = 0.38$. The cue degradation effects at the 500 ms and 0 ms CTI conditions were significantly different, $t = 3.78$, $p = 0.00$. We expected for the cue degradation effects at the -500 ms and 0 ms

CTI conditions to be the same and for the cue degradation effects at the -500 ms and 500 ms CTI conditions to be different; we have not explanation for the results we observed.

The effect of target degradation also varied with CTI. Regardless of cue degradation, target degradation increased RT by 251 ms at -500 ms CTI, 294 ms at 500 ms CTI, and 332 ms at 0 ms CTI. The interaction between CTI and target degradation approached significance, $F(2,62) = 2.90$, $p = 0.06$, $MSE = 30636.88$. Although the interaction is only marginally significant, the pattern of results supported our predictions. We expected target degradation to have the least effect when target encoding and resolution could take place during the CTI (-500 ms CTI condition) because the CTI could absorb the degradation effects. There was no slack to absorb target degradation for the 0 ms and 500 ms CTI which resulted in larger target degradation effects. We also conducted pair-wise comparisons of the target degradation effects for each CTI condition. The target degradation effects at the -500 ms and 0 ms CTI conditions were significantly different, $t = -2.91$, $p = 0.00$. The target degradation effects at the -500 ms and 500 ms CTI conditions were not significantly different, $t = -1.90$, $p = 0.07$. The target degradation effects at the 500 ms and 0 ms CTI conditions were not significantly different, $t = 1.62$, $p = 0.12$.

Cue degradation and CTI contrasts

*Cue degradation and the 0 ms vs. -500 ms CTI*

We conducted two contrasts between CTI (0ms and -500 ms; 0 ms and 500 ms) and cue degradation. Figure 7 plots the interaction between CTI (0 ms and -500 ms) and cue degradation. The contrast between CTI (0 ms and -500 ms) and cue degradation provides diagnostic information about how cues and targets are processed because the predictions for pre-central and central loci of effects are different. At the 0 ms CTI, cue degradation increased RT by 263 ms; at the -500 ms CTI, cue degradation increased RT by 149 ms. The larger degradation effects at the 0 ms CTI condition compared to the -500 ms CTI condition indicates over-additive joint effects of CTI and cue degradation. The interaction between CTI and cue degradation was significant, $F(1,62) = 13.76$, $p < 0.01$, $MSE = 45323.28$; however, because the interaction was not significantly under-additive, we conclude that the over-additive joint effects of CTI (0 ms and -500 ms) and cue degradation provide evidence against parallel processing of cues and targets and evidence for serial processing of cues and targets.

*Cue degradation and the 0 ms vs. 500 ms CTI*

Figure 8 plots the interaction between CTI (0 ms and 500 ms) and cue degradation. The interaction between CTI and cue degradation was significant, $F(1,62) = 19.29$, $p < 0.01$, $MSE = 45323.28$. The observed over-additive joint effects of CTI (0 ms and -500 ms) and target degradation provide no information to address our question of serial or parallel processing of cues and targets; our prediction for this contrast was the same for both pre-central and central manipulation. Of greater importance to our investigation of serial or parallel processing of cues and targets is the contrast between CTI (0 ms and -500 ms) and cue degradation of which provided evidence of serial processing of cues and targets due to the lack of under-additive significance of the interaction.

Target degradation and CTI contrasts

*Target degradation and the 0 ms vs. 500 ms CTI*

We conducted the same contrasts for CTI and target degradation. Figure 9 plots the interaction between CTI (0 ms and 500 ms) and target degradation. Of the two contrasts conducted between CTI and target degradation, this contrast provides information to diagnose serial and parallel processing. Target degradation increased RT by 332 ms at the 0 ms CTI and 293 ms at the 500 ms CTI. The interaction was not significant, $F(1,62) = 2.29$, $p = 0.14$, $MSE = 30636.88$. The additive joint effects of CTI (0 ms and 500 ms) and target degradation provide evidence for serial processing of cues and targets.

*Target degradation and the 0 ms vs. -500 ms CTI*

Figure 10 plots the interaction between CTI (0 ms and -500 ms) and target degradation. Target degradation increased RT by 332 ms at the 0 ms CTI and 293 ms at the -500 ms CTI. The interaction was significant, $F(1,62) = 10.15$, $p < 0.01$, $MSE = 30636.88$. The over-additive joint effects of CTI (0 ms and -500 ms) and target degradation do not provide information that bears upon our question of serial or parallel processing of cues and targets because our predictions were the same for both kinds of processing. Consequently, we focus on the contrast between CTI (0 ms and 500 ms) and target degradation which provided evidence of serial processing of cues and targets and a manipulation of central processing.

RT and Transition effects

Mean RT varied with transition. Table 2 presents the accuracy and average RT for each transition. The average RT was 1189 ms for cue repetitions, 1319 ms for task repetitions, and 1351 ms for task alternations. The main effect of transition was significant, $F(2,62) = 31.69$, $p < 0.01$, $MSE = 88741.21$. We again interpret the difference between transitions as residual activation from the previous trial facilitating cue encoding. This interpretation was supported by a 130 ms repeated cue encoding benefit and a 32 ms switch cost, both of which are predicted by the priming theory of explicit task cuing (Arrington & Logan, 2004; Logan & Bundesen, 2003, 2004; Schneider & Logan, 2005; for alternative interpretation of switch costs, see Mayr & Keele, 2000; Mayr & Kliegl, 2000; Monsell et al., 2000).

Table 3 presents the accuracy and average RT for each transition and CTI condition. The effect of transition varied with CTI. For each CTI condition, cue repetition was consistently faster than both task repetition and task alternation. For the -500 ms CTI condition, cue repetitions were 103 ms faster than task repetitions and 149 ms faster than task alternations. For the 500 ms CTI condition, cue repetitions were 114 ms faster than task repetitions and 128 ms faster than task alternations. For the 0 ms CTI condition, cue repetitions were 172 ms faster than task repetitions and 207 ms faster than task alternations. The pattern of results was not confirmed statistically; the interaction between transition and CTI was not significant, $F(4,124) = 1.56$, $p = 0.19$, $MSE = 45388.82$. The interaction between transition and cue degradation was not significant, $F(2,62) = 0.14$, $p = 0.87$, $MSE = 34081.18$, and neither was the interaction between transition and target degradation, $F(2,62) = 1.45$, $p = 0.24$, $MSE = 35059.19$.

The three way interaction between transition, cue degradation, and target degradation was not significant, $F(2,62) = 1.34$, $p = 0.27$, $MSE = 26653.94$. To evaluate the interaction between cue and target degradation at each transition, we conducted planned comparisons. All of the planned comparisons were not significant: for cue repetitions, $F(1,124) = 1.74$, $p = 0.19$, $MSE = 26653.94$; for task repetitions, $F(1,124) = 0.3$, $p = 0.54$, $MSE = 26653.94$; for task alternations, $F(1,124) = 2.14$, $p = 0.15$, $MSE = 26653.94$. We interpret the additive joint effects of cue and target degradation at each transition as evidence for serial processing of cues and targets. The three-way interaction between transition, CTI, and cue degradation was not significant, $F(4,124) = 0.87$, $p = 0.46$, $MSE = 33664.69$ and neither was the interaction between transition, CTI, and target degradation, $F(4,124) = 0.87$, $p = 0.49$, $MSE = 38268.39$. The four-way interaction between transition, CTI, cue degradation, and target degradation was also not significant, $F(4,124) = .79$, $p = 0.54$, $MSE = 35427.93$.

## Conclusions

This experiment tested the validity of the serial processing assumption by independently degrading the stimuli through character substitution at three CTI conditions. We analyzed three interaction contrasts that provided diagnostic information for serial and parallel processing: the interaction between cue and target degradation, the interaction between CTI (0 ms and -500 ms) and cue degradation, and the interaction between CTI (0 ms and 500 ms) and target degradation. We observed additive joint effects of cue and target degradation, which we interpret as evidence of serial processing of cues and targets. We observed over-additive joint effects between CTI (0 ms and -500 ms) and cue degradation which suggest serial processing of cues and targets.  We observed additive joint effects between CTI (0 ms and 500 ms) and target degradation which suggest serial processing of cues and targets.  Based upon the results of these three critical interactions, we conclude that stages of processing of cues and targets that is prolonged by character substitution occurs in series.

# CHAPTER IV

# GENERAL DISCUSSION

The current experiments tested the validity of the serial processing assumption through the use of stimulus degradation—reduced brightness and contrast (Exp. 1) and character substitution (Exp. 2)—and three CTI conditions—0ms, 500 ms, and -500ms. For each experiment, we evaluated three critical interactions that provided diagnostic information of serial and parallel processing: the interaction between cue and target degradation, the interaction between CTI (0 ms and -500 ms) and cue degradation, and the interaction between CTI (0 ms and 500 ms) and target degradation. Experiment 1 provided evidence of that cues and targets are processed in parallel when degraded by reducing brightness and contrast based upon the under-additive pattern of results observed for each of the three critical interactions. Experiment 2 provided evidence for serial processing of cues and targets when degraded through character substitution based upon the additive pattern of results observed for each of the three critical interactions.

We attribute the differences across the two experiments to different stages of processing—pre-central stage, or central or post-central stage—that each degradation manipulation prolonged. As past and current results have confirmed, the reduced brightness and contrast manipulation in Experiment 1 affects perceptual processing which occurs during the pre-central stage (Oriet & Jolicoeur, 2003; Pashler & Johnston, 1989; Sternberg, 1969). Because reduced brightness and contrast affects a pre-central process, we observe evidence of parallel processing of cues and targets. Unlike reduced brightness and contrast, the character substitution manipulation used in our Experiment 2 affects memory retrieval which occurs during the central stage of processing (Broadbent & Broadbent, 1975; Carrier & Pashler, 1995). Consequently, we observe evidence of serial processing of cues and targets because the locus of effect for character substitution is a stage of processing that operates in series.

Oriet & Jolicoeur (2003) adapted locus of slack logic to their experiments that investigated whether early perceptual processing could occur in parallel with task-set reconfiguration. They reported results from three experiments. Two experiments produced additive joint effects between contrast manipulation and SOA that were interpreted as evidence that early perceptual processing could not occur in parallel with task-set reconfiguration; the other experiment produced under-additive joint effects between contrast manipulation and SOA. The mixed results of the interaction between SOA and stimulus intensity manipulation observed by Oriet & Jolicoeur (2003) are consistent with the mixed results observed in the current Experiment 1. Although we concluded that cues and targets were processed in parallel based upon the under-additive pattern of results for the CTI and stimulus degradation contrasts, we failed to obtain strong statistical confirmation for the under-additivity suggested in the data.

Even though Oriet & Jolicoeur (2003) and the current research both observed mixed results for CTI and intensity manipulation, we propose a different interpretation of our results. Based upon diagnostic information provided by the under-additive interaction between cue and target degradation, we conclude that cues and targets are processed in parallel when a manipulation affects pre-central processing. Additionally, we do not assume that task-set reconfiguration is necessarily involved, contrary Oriet & Jolicoeur

(2003), because of the large cue encoding benefits and small switch costs we observed. Consequently, we conclude that perceptual processing of cues and targets takes place in parallel because there is no task switching to impose a bottleneck upon early stimulus processing.

Our conclusion of parallel processing of cues and targets in our Experiment 1 is consistent with Besner and Risko (2005) but inconsistent with Besner and Care (2003). Besner and Risko (2005) manipulated the brightness and contrast of digits to study if functional encoding of the stimulus during a localization task and an identification task can begin while the task cue is being processed. Through a significant main effect of contrast as well as significant interactions among task, contrast, and SOA, they demonstrate that contrast manipulation increases RT and that processing of target and encoding of cue can occur in parallel However, their findings and the current findings differ from the results observed by Besner and Care (2003) in their investigation of whether functional target processing could be voluntarily delayed. Their manipulation of brightness and contrast and varying SOA resulted in additive joint effects between SOA and contrast; these results were interpreted as the inability for subjects to resolve the degradation of the target and encode the cue in parallel.

We do not observe the same results for Experiment 2 because the character substitution does not affect a pre-central process but instead affects memory retrieval, which occurs during a central or post-central stage (Carrier & Pashler, 1995; for alternate account, see Hommel, 1998; Logan & Delheimer, 2001; Logan & Schulkind, 2000). Because the character manipulation affects a central or post-central stage instead of a pre-central stage as in Experiment 1, we observe evidence of serial processing of cues and targets in Experiment 2.

Logan & Bundesen (2003) observed an under-additive interaction between SOA and cue degradation by character substitution. This is consistent with the current finding of under-additivity for the interaction between CTI and cue degradation observed for Experiment 2. One explanation for the consistency in the current results and those of Logan & Bundesen (2003) are based upon procedural similarities between the two studies. As does the current study, Logan & Bundesen (2003) used the explicit cuing procedure and used CTIs that span similar interval of times (0ms to 500ms in the current study vs, 0 ms to 950 ms). The under-additive interaction they observed between SOA and cue character substitution was probably the result of a significant difference between short SOAs (e.g. 0 ms SOA) when some degradation effects were more likely to be absorbed and long SOAs (e.g. 950 ms) when degradation effects were less likely to be absorbed. Our under-additive interaction in Experiment 2 was produced similarly – the absorption of cue degradation effects at the 0 ms CTI and 500 ms CTI condition and the lack of absorption of cue degradation effects at the -500 ms CTI.

The findings of the current study could indicate that the serial processing assumption can hold only when manipulations affect central or post-central stages, such as character substitution in Experiment 2, but not when manipulations affect pre-bottleneck stages, such as reduced brightness and contrast in Experiment 1. Further research must be conducted to substantiate this claim. One way of testing this idea would be to replicate the current study but use different stimulus degradation, one that affects a pre-central process such as perceptual processing (e.g. reducing the size of the cues and targets) and another that affects a central or post-central process such as memory retrieval (e.g. character deletion). If a pattern of results is observed that is similar to the current findings, we can gain a better understanding of the potential locus of effect limitations of the serial processing assumption and come closer to determining its place within models of executive control.

# CHAPTER IV

# CONCLUSIONS

The current series of experiments used stimulus degradation and different CTI conditions to test the validity of the serial processing assumption common to models of executive control. With reduced brightness and contrast (Exp. 1), we observed evidence of parallel processing which suggests that the reduced brightness and contrast affects pre-central processing. We conclude that the pre-central process that is affected by this manipulation is perceptual processing. With character substitution (Exp. 2) we observed evidence of serial processing which suggests that character substitution affects central processing. We conclude that the central process that is affected by this manipulation is memory retrieval. The evidence of parallel processing of cues and targets with reduced brightness and contrast and the evidence of serial processing of cues and targets with character substitution lead us to conclude that the serial processing assumption common to models of executive control is reliable when manipulations affect central processes but not reliable when manipulations affect pre-central processes.

Appendix A

Table 1

Mean Response Time in milliseconds and Accuracy (Percentage of Correct Responses) for each CTI and each trial type in Experiment 1 and Experiment 2

| | Target Non-Degraded | | Target Degraded | |
|---|---|---|---|---|
| | Cue Non-Degraded | Cue Degraded | Cue Non-Degraded | Cue Degraded |
| Experiment 1: Reduced Brightness and Contrast | | | | |
| CTI condition | | | | |
| -500 ms | 880 (97) | 950 (97) | 968 (97) | 938 (98) |
| 0 ms | 980 (97) | 1057 (98) | 1043 (96) | 1067 (98) |
| 500 ms | 1011 (98) | 1048 (96) | 1039 (96) | 1061 (96) |
| Experiment 2: Character Substitution | | | | |
| -500 ms | 880 (97) | 950 (97) | 968 (97) | 938 (98) |
| 0 ms | 980 (97) | 1057 (98) | 1043 (96) | 1067 (98) |
| 500 ms | 1011 (98) | 1048 (96) | 1039 (96) | 1061 (96) |

Appendix B

Table 2

Mean Response Time in milliseconds and Accuracy (Percentage of Correct Responses) for each transition and each trial type for Experiment 1 and Experiment 2

| | Target Non-Degraded | | Target Degraded | |
|---|---|---|---|---|
| | Cue Non-Degraded | Cue Degraded | Cue Non-Degraded | Cue Degraded |
| Experiment 1: Reduced Brightness and Contrast | | | | |
| Transition | | | | |
| Cue Repetition | 880 (97) | 950 (97) | 968 (97) | 938 (98) |
| Task Repetition | 980 (97) | 1057 (98) | 1043 (96) | 1067 (98) |
| Task Alternation | 1011 (98) | 1048 (96) | 1039 (96) | 1061 (96) |
| Experiment 2: Character Substitution | | | | |
| Cue Repetition | 958(98) | 1230 (97) | 1126 (97) | 1443 (96) |
| Task Repetition | 1111 (98) | 1347 (97) | 1267 (97) | 1586 (97) |
| Task Alternation | 1105 (9) | 1419 (96) | 1292 (96) | 1586 (95) |

Appendix C

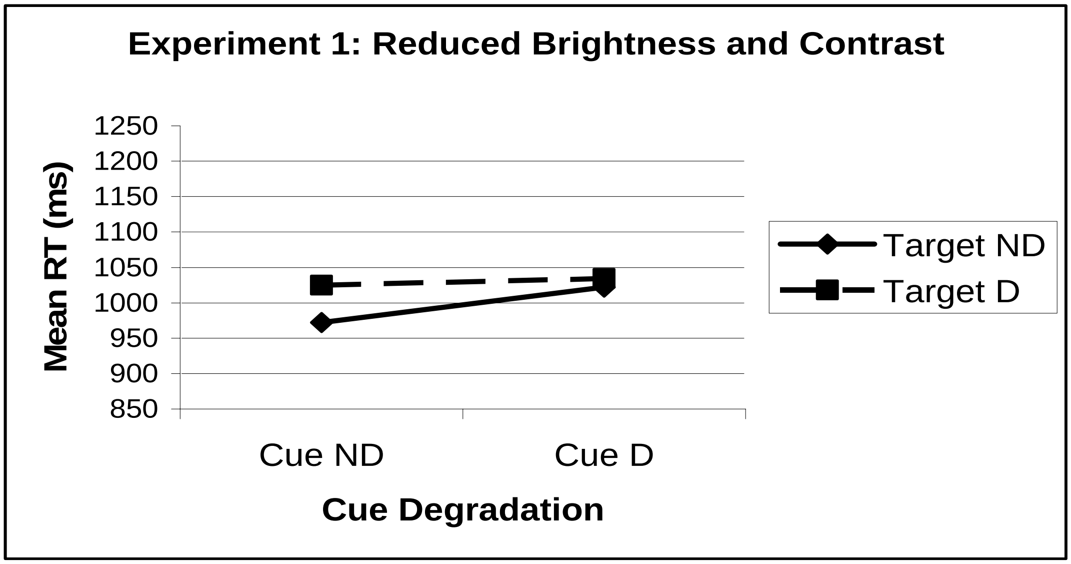
Table 3

Mean Response Time in milliseconds and Accuracy (Percentage of Correct Responses) for each transition per CTI condition in Experiment 1 and Experiment 2

| Experiment 1: Reduced Brightness and Contrast | | | |
|---|---|---|---|
| | CTI condition | | |
| | -500 ms | 0 ms | 500 ms |
| Transition | | | |
| Cue Repetition | 858 (97) | 1097 (97) | 846 (97) |
| Task Repetition | 965 (97) | 1222 (98) | 923 (96) |
| Task Alternation | 949 (98) | 1231 (96) | 939 (96) |
| Experiment 2: Character Substitution | | | |
| Cue Repetition | 1089 (98) | 1407 (96) | 1072 (97) |
| Task Repetition | 1192 (96) | 1579 (95) | 1186 (96) |
| Task Alternation | 1238 (97) | 1614 (98) | 1200 (97) |

Appendix D

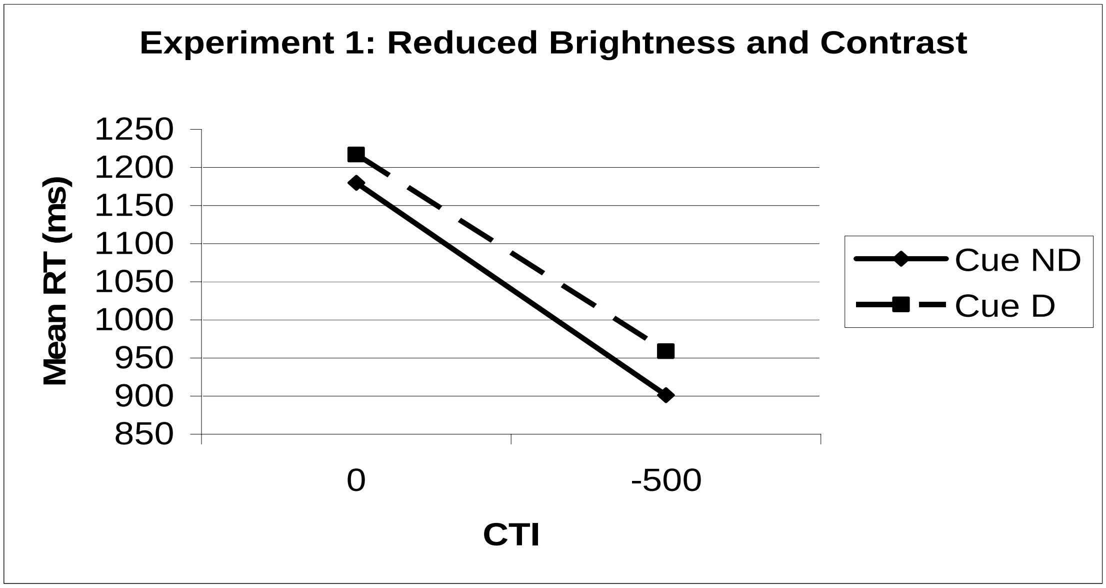
Figure 1




Mean reaction times in ms for cue and target degradation combinations for Experiment 1.
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli

Appendix E

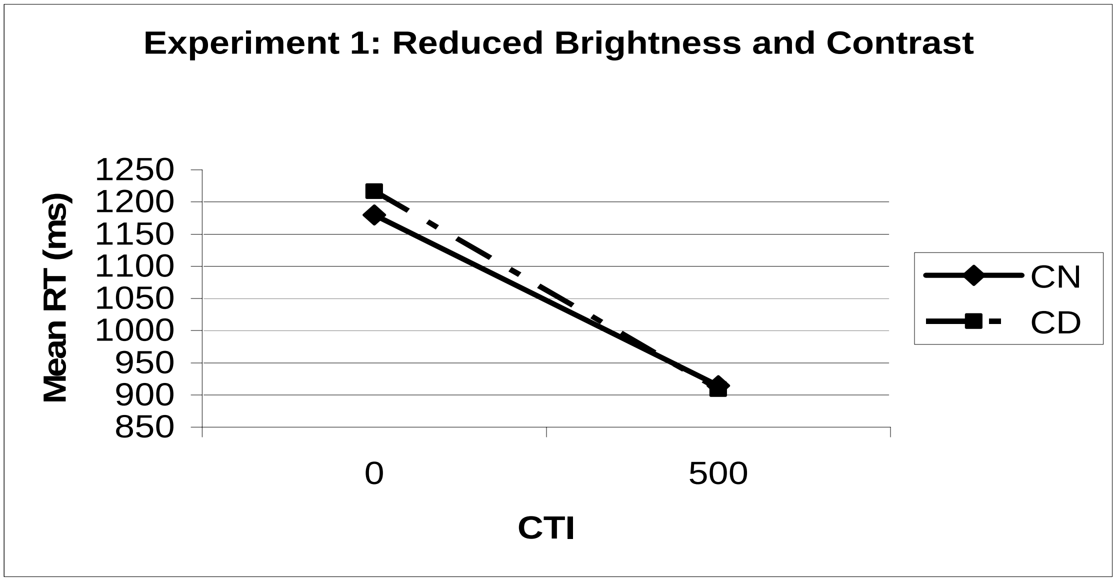
Figure 2




Mean reaction time in ms for cue degradation and CTI for Experiment 1.
Graph of the interaction between CTI (0 ms and -500 ms) and cue degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI cue-target interval.

Appendix F

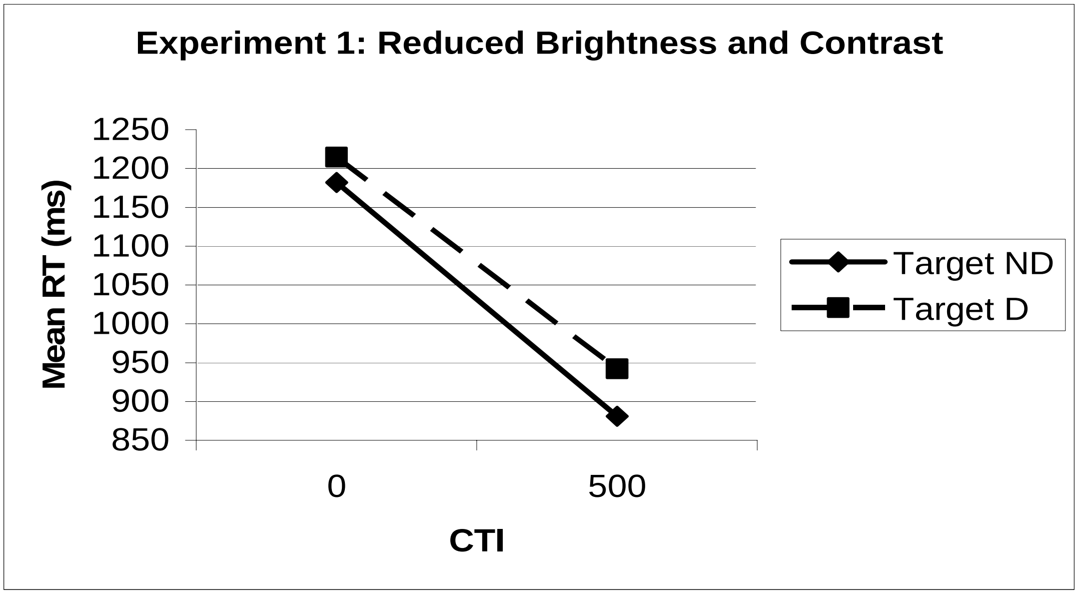
Figure 3




Mean reaction time in ms for cue degradation and CTI for Experiment 1.
Graph of the interaction between CTI (0 ms and 500 ms) and cue degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix G

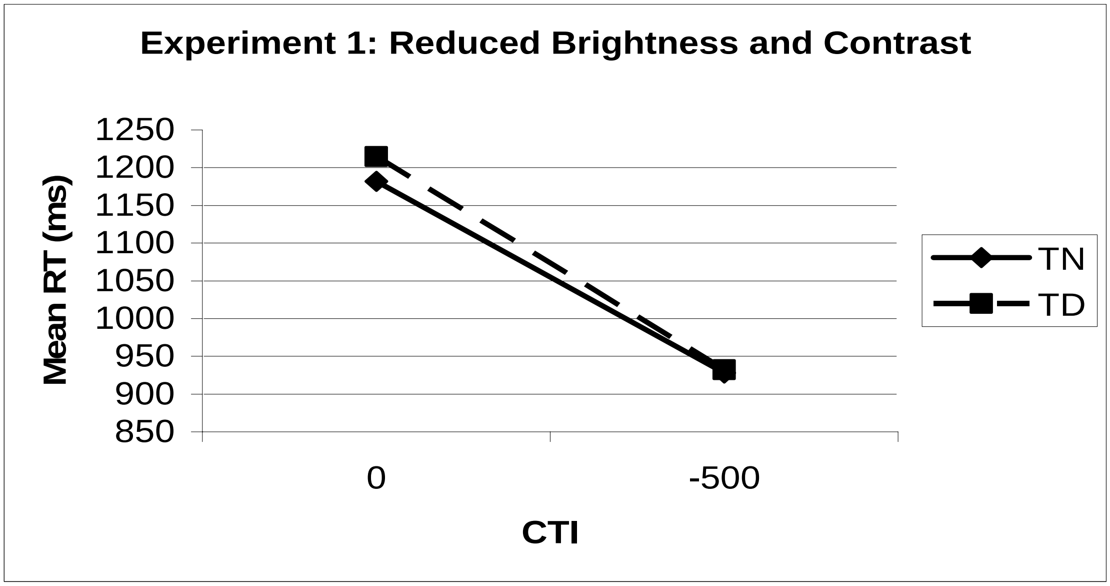
Figure 4




Mean reaction time in ms for target degradation and CTI for Experiment 1.
Graph of the interaction between CTI (0 ms and 500 ms) and target degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix H

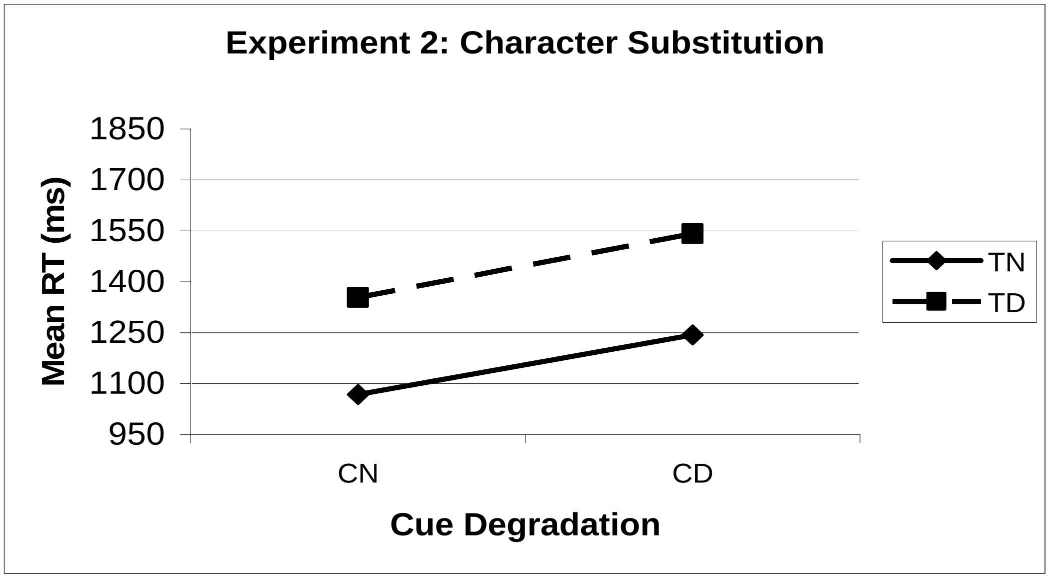
Figure 5




Mean reaction time in ms for target degradation and CTI for Experiment 1.
Graph of the interaction between CTI (0 ms and -500 ms) and target degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix I

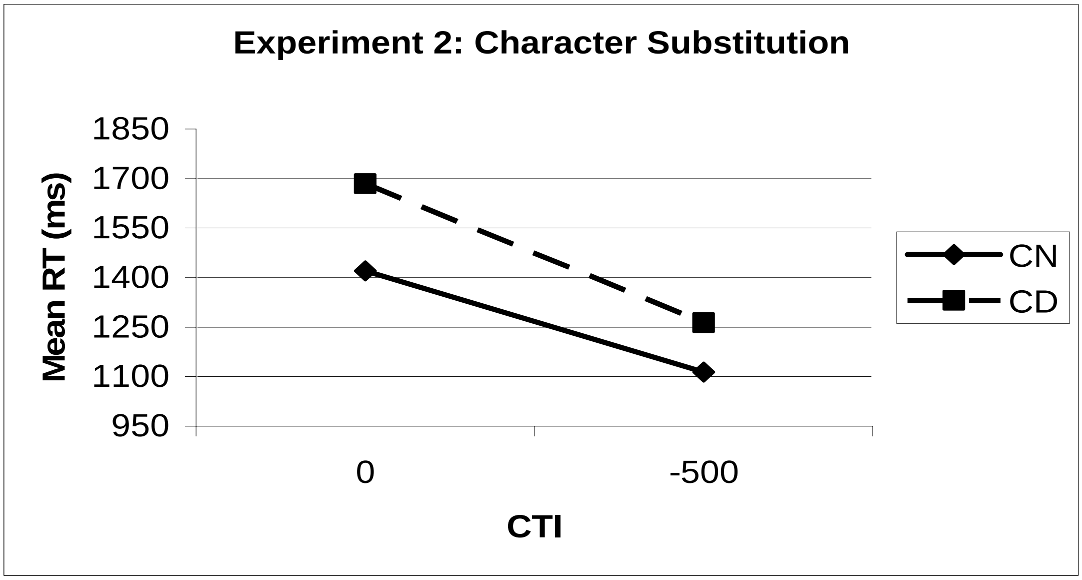
Figure 6




Mean reaction times in ms for cue and target degradation combinations for Experiment 2.
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli

Appendix J

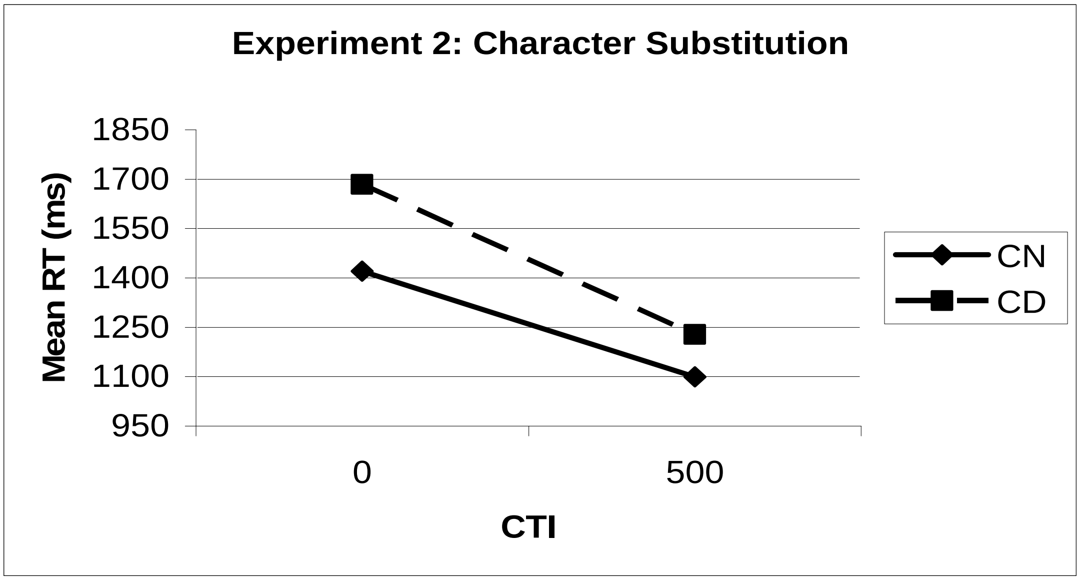
Figure 7




Mean reaction time in ms for cue degradation and CTI for Experiment 2.
Graph of the interaction between CTI (0 ms and -500 ms) and cue degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix K

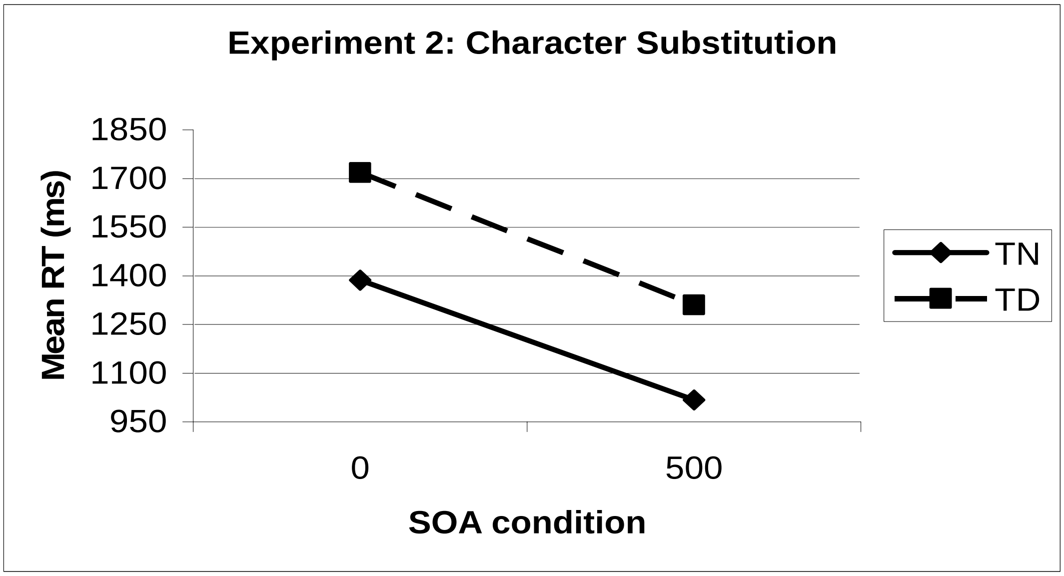
Figure 8




Mean reaction time in ms for cue degradation and CTI for Experiment 2.
Graph of the interaction between CTI (0 ms and 500 ms) and cue degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix L

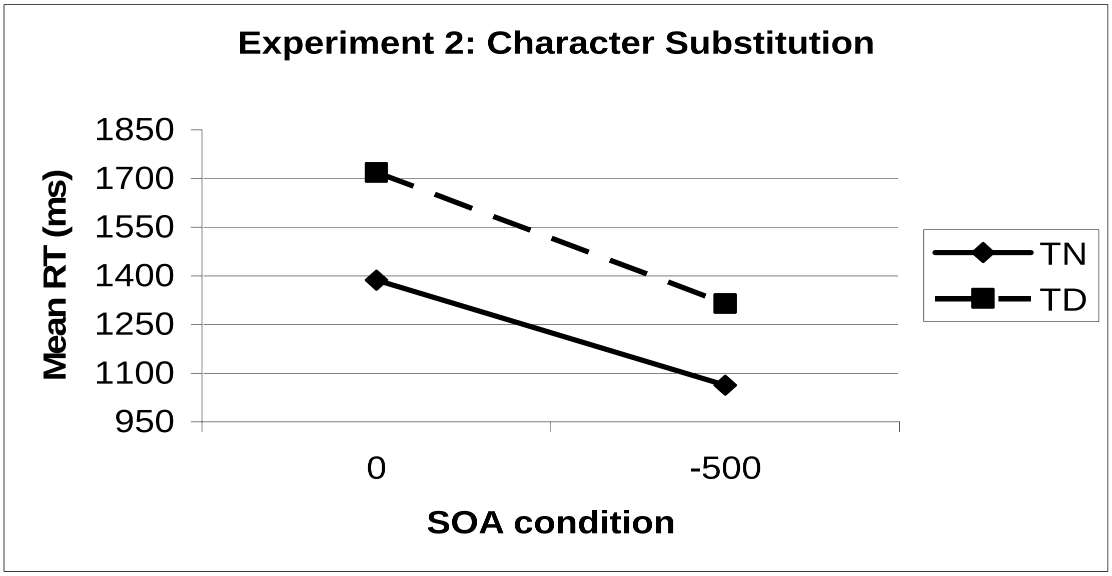
Figure 9




Mean reaction time in ms for target degradation and CTI for Experiment 2.
Graph of the interaction between CTI (0 ms and 500 ms) and target degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

Appendix M

Figure 10




Mean reaction time in ms for target degradation and CTI for Experiment 2.
Graph of the interaction between CTI (0 ms and -500 ms) and target degradation
Note: ND denotes non-degraded stimuli; D denotes degraded stimuli; and CTI denotes cue-target interval.

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