A Stimulus-Response Account of Stroop and Reverse Stroop Effects

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Psychology

Waterloo, Ontario, Canada, 2006

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis concerns selective attention in the context of the Stroop task (identify the colour) and Reverse Stroop task (identify the word). When a person is asked to select and identify one dimension of a bidimensional stimulus (e.g., the word RED printed in green) the typical finding is that the word influences colour identification (i.e., the Stroop effect) but the colour does not influence word identification (i.e., no Reverse Stroop effect). A major account of performance in these tasks posits that one dimension interferes with the other only when a translation occurs (e.g., Roelofs, *Psychological Review,* 2003; Sugg & McDonald, *Journal of Experimental Psychology: Human Perception & Performance,* 1994; Virzi & Egeth, *Memory & Cognition,* 1985). This translation assumption is implicit in virtually all work in the field.

The first part of this thesis completely undermines the translation assumption. In a series of four experiments (two unique paradigms), I demonstrate that interference from the colour in a Reverse Stroop task occurs in the absence of a translation.

The second part of this thesis contains two additional experiments designed to discriminate between translation effects and response conflict effects. The results of these experiments confirm that a translation was not required because no stimulus conflict effect, the most likely locus of a translation effect, was observed. However, response conflict effects were observed.

The third part of this thesis implements a computational model based on the principle that the strength of association (Cohen, Dunbar, & McClelland,

Psychological Review, 1990) between a specific stimulus and its response (Logan, *Psychological Review,* 1988) is important in determining the influence of the irrelevant dimension. This model has no translation mechanism. A final experiment was conducted to test this model; the model accounted for over 98% of the variance in RTs and 92% of the variance in interference and facilitation scores in both the Stroop and Reverse Stroop tasks independent of whether a translation was required.

Acknowledgments

First, extra-special thanks to my wife, Laura, who put up with me for the last several years as I abandoned her, striving to make her proud. I also thank my daughter, Lily, who is too young to understand why daddy is always busy. I pray that when she is old enough she doesn't resent me for it. Many thanks also need to be extended to my other family and friends. Without their support, this thesis would never have been finished.

Second, additional thanks must be extended to the numerous research assistants who volunteered their time to collect the vast majority of the data from these experiments. I also thank Ilona Medvedovsky and Serje Robidoux for their assistance in implementing the simulation.

Last, but certainly not least, I thank my advisor, Derek Besner. His commitment to excellence and genuine excitement in research inspires his students to excel. Derek always has the best intentions of his students at heart. I could not imagine a better advisor for me.

Dedication

For the two women in my life, Laura and Lily

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Chapter 1: Reverse Stroop Effects with Untranslated Responses

1.1 Selective attention

Philosophers and psychologists have sought to understand how attention operates for over a century:

> "Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*, and *Zerstreutheit* in German."
>
> James (1890, pp 403-404)

It has long been known that some things are easier to attend to than others. For example, it is easy to attend to a single red tulip in a field of green grass but more difficult to attend to a specific red tulip in a field of red tulips. That is, some objects are much more effective at capturing attention than are others. When a single red tulip is in a field of green grass, the tulip is very distinct from its background, almost "popping out" (e.g., Treisman & Gelade, 1980). However, when attempting to focus on a specific red tulip in a field of red tulips, this task is very difficult because there are many other similar objects in the environment (see Duncan & Humphreys, 1989).

In the laboratory, the Stroop task has long been the "gold standard" of attention research (MacLeod, 1992). In this task and its many variants, individuals are presented with colour words printed in various colours and asked either to read the word or, much more commonly, to identify the colour of the print. It is easy to set up a situation where the colour word and the print colour conflict. The basic Stroop effect shows an asymmetry in the observed difference between colour-word reading and colour naming. Specifically, when reading the word aloud, the ink colour is relatively easy to ignore. However, when identifying the colour, the meaning of the word has a strong influence on how quickly its colour is responded to. For example, the ink colour red is responded to more quickly when the word is RED than when the word is GREEN. In the latter case, the word GREEN interferes with the process of identifying the red ink. Thus, as in the red tulip anecdote, the Stroop effect illustrates an important aspect of selective attention: Some features of the environment are easier to ignore than others.

The Stroop effect represents a situation that the mind regularly encounters, selecting some aspects of the environment while ignoring others. It further demonstrates that some aspects of the environment are selected more easily than others, as is evident from the fact that the word influences colour processing much more than the colour influences word processing. Thus, understanding Stroop and Stroop-like effects is important because it illuminates how features are selected and why some are selected more easily than others. It is therefore important to closely scrutinize theories which seek to provide an explanation for such effects.

This thesis focuses on two classes of theories purporting to explain Stroop-like effects: translation accounts and strength of association accounts. The empirical work with university-level readers shows that the translation account is insufficient to account for both colour naming data (arguably, as was known) and word reading data (a new finding). The thesis ends with a discussion of a strength of association account which explains why a Reverse Stroop effect occurs in some contexts but not others. What follows is a more formal discussion of these issues.

1.1.1 The Stroop task and the Stroop effect

Stroop (1935) was the first to demonstrate that the time required to identify the ink colour (relevant information) of stimuli in a list was slowed by incongruent colour words (distractor information). In the prototypical modern variant of this task, a single item is displayed and a response to that stimulus is measured. The robust finding is that words displayed in an incongruent colour (e.g., the word RED displayed in blue) interfere with identifying the colour relative to a neutral trial (e.g., the word TABLE displayed in red; see MacLeod's 1991 review). This finding is referred to as the Stroop effect. Few argue that the Stroop effect is not genuine (but see Dishon-Berkovits & Algom, 2000; Melara & Algom, 2003, for some boundary conditions). There is considerably less agreement over the mechanisms responsible for the Stroop effect (e.g., Cohen, Dunbar, & McClelland, 1990; vs. Klopfer, 1996; vs. Sugg & McDonald, 1994).

1.1.2 The reverse Stroop task and the reverse Stroop effect

In the Reverse Stroop task, subjects identify the word and ignore the colour. Stroop (1935, Experiments 1 and 3) was the first to investigate whether there is a Reverse Stroop Effect (RSE; colour interfering with word responses). Using a vocal response, Stroop reported that the RSE was observed only after considerable practice identifying the print colour of colour words across several blocks of trials, and then quickly dissipated after a single block of reading words aloud.

Although there are literally hundreds of experiments exploring the Stroop effect (see the review by MacLeod, 1991), there is considerably less work (approximately twenty papers) that explores the Reverse Stroop effect. The purpose of this thesis is to reconsider elements of this body of work. More specifically, the focus is on when an RSE should be present and when it should be absent according to a major account in the field. Six experiments are reported in which an RSE is observed. The observation of an RSE is inconsistent with one major account of Reverse Stroop performance in which a translation mechanism is important, but consistent with an account in which the strength of association between the stimulus and a *specific* response is important.

1.2 How are Stroop and reverse Stroop effects explained?: Translation accounts

A major account of Stroop performance posits that an irrelevant dimension affects performance whenever a *translation* is needed to correctly respond to the target (Glaser & Glaser, 1989; Roelofs, 2003; Sugg & McDonald, 1994; Virzi & Egeth, 1985). That is, colours and words are held to be processed in separate systems, each of which operates in its own code. To make a vocal response in the context of the Stroop task, the colour code must engage a translation module so as to be converted into a verbal code. Engaging the translation module causes interference.[1] Thus, when *naming the colour,* the irrelevant word interferes. The translation account appeals to this same process to explain results from the Reverse Stroop Task in which there is no RSE when *reading aloud the word.* The irrelevant colour does *not* interfere because the word is already in the verbal code required to say it aloud.

Variants of the standard Stroop paradigm which manipulate the type of response (e.g., a button press response versus a vocal response) are relevant to translation theories. As it turns out, *how* the response-buttons are labeled is likely critical to whether interference from the irrelevant dimension is observed. According to translation accounts, if the buttons are labeled with words, interference occurs when responding to the colour (Stroop Task) but not when responding to the word (Reverse Stroop Task). Conversely, if the buttons are labeled with colour patches, interference occurs when responding to the word (Reverse Stroop Task) but not when responding to the colour (Stroop Task; see Virzi & Egeth, 1995).

One potential difficulty with a translation account is the common observation of a Stroop effect when the response is manual and the buttons are labeled with colour patches (e.g., Bauer & Besner, 1997; Besner & Stolz, 1999; Besner, Stolz, & Boutilier, 1997; Blais & Besner, 2005; Roberts & Besner, 2005 among many others). In Sugg and McDonald's (1994) terminology, this is an "untranslated colour-response" (*p*. 648). To respond to the colour using a colour-labeled button, a translation need not occur because both relevant aspects of the task – the to-be-identified colour and its colour response – are in the same code. According to Sugg and McDonald's account, only responses that require a translation should produce interference. How are such data to be explained?

Proponents of translation accounts propose that the presence of a Stroop effect in this context arises because such responses are verbally mediated:

> "…it is possible that inhibition is obtained in the untranslated colour-response task – a result contrary to the translation models – only when the subjects are encouraged by task characteristics either to attach verbal labels to the colored response buttons or to translate the relevant colour stimulus into a word."
>
> Sugg and McDonald (1994, *p*. 653)

> Morton (1969), Dalrymple-Alford and Azkoul (1972), La Heij (1988), and others have suggested … that in manual Stroop tasks the stimulus colour code is not directly associated with the manual response but … is mediated by a verbal code.
>
> Hommel (1998, *p*. 1374)

> According to WEAVER++, Stroop interference lies within the language production system. Interference should remain if lexical entries are needed to mediate a button-press response."
>
> Roelofs (2003, *p*. 115)

According to these accounts then, *whenever verbal mediation occurs,* an effect observed using a vocal response should also be observed when using a non-vocal response and *vice versa* (but see Sharma & McKenna, 1998; cf. Brown & Besner, 2001). Here I reassess whether this verbal mediation explanation provides a sufficient account of the data in the context of the *Reverse Stroop Task.*

The results of all the RSE experiments that I have been able to locate with intact participants using an untranslated (shown in bold) or ambiguous (shown in italics) manual response are summarized in Table 1. In addition, a few RSE experiments using translated or vocal responses are shown in Table 1 to provide a more complete picture.

1.2.1 Contexts that reliably produce an RSE

There are at least three contexts in which an RSE is readily obtained despite using a *vocal* response. First, if a lot of practice in colour naming is given prior to the Reverse Stroop task, an RSE is observed (but note that it disappears soon thereafter; see, Stroop 1935, Experiment 3). Second, an RSE is obtained if the word is rendered difficult to read by printing the words upside down and backwards and there are many other non-response-set items in the experiment (Dunbar & MacLeod, 1984, Experiment 4), or by making the word so small that it is hard to identify (e.g., Melara & Mounts, 1993). Third, an RSE occurs in a task switching paradigm when subjects switch between colour and word identification, typically performing two colour naming trials followed by two word reading trials over the course of several hundred trials (e.g., Wylie & Allport, 2000).

All of these contexts have a common underlying theme; they disrupt attention by making the word harder to *select*. With a lot of practice in colour naming,

Table 1: Summary of Reverse Stroop studies using vocal and manual responses. B=blocked, M=intermixed; $_{C,\ N}$, and $_I$ subscripts refer to congruent, neutral, and incongruent respectively (e.g., B $50_N:50_I$ represents 50% neutral trials and 50% incongruent trials which were blocked).

Source	Experiment	Response	Word response type	Set Size	Baseline	Composition	Size of RSE[a]
Stroop (1935)	3	vocal	reading, day 2	5	neutral (black)	B $50_N:50_I$	0.3 s [b]
		vocal	reading, day 13	5	neutral (black)	B $50_N:50_I$	15.7 s [b]*
		vocal	reading, day 14	5	neutral (black)	B $50_N:50_I$	2.9 s [b]*
Pritchatt (1968)	2	card pointing	translated	6	neutral (black)	B $33_C:33_N:33_I$	4.0 s [b]*
		card pointing	**untranslated**	**6**	**neutral (black)**	**B $33_C:33_N:33_I$**	**2.7 s [b]**
Dunbar & MacLeod (1984)	1A	vocal	reading	5	neutral (white)	M $33_C:33_N:33_I$	7 ms
	1B	vocal	reading	5	neutral (white)	M $33_C:33_N:33_I$	5 ms
Virzi & Egeth (1985)	1	card sorting	translated	4	congruent	B $33_C:33_N:33_I$	8.1 s [c]*
		card sorting	**untranslated**	**4**	**congruent**	**B $33_C:33_N:33_I$**	**1.0 s [c]**
Simon & Berbaum (1990)	*1*	*button press*	*ambiguous*	*2*	*congruent*	*M $50_C:50_I$*	*15 ms* *
Melara & Mounts (1993)	*1w*	*mouse button*	*ambiguous*	*2*	*congruent*	*M $50_C:50_I$*	*9 ms* *
	2w	*mouse button*	*ambiguous*	*2*	*congruent*	*M $50_C:50_I$*	*22 ms* *
Sugg & McDonald (1994)	1	touch screen	translated	2	neutral (grey)	M $33_C:33_N:33_I$	124 ms [d]*
		touch screen	**untranslated**	**2**	**neutral (grey)**	**M $33_C:33_N:33_I$**	**17 ms [d]**
Durgin (2000)	1	pointing	translated	4	neutral (grey)	B $50_N:50_I$	69 ms *
Lu & Proctor (2001)	*1*	*button press*	*ambiguous*	*2*	*congruent*	*M $50_C:50_I$*	*19 ms [d]**
	2	*button press*	*ambiguous*	*2*	*congruent*	*M $50_C:50_I$*	*12 ms [d]*
Ruff, Woodward, Laurens, & Liddle (2001)	*1*	*button press*	*ambiguous*	*4*	*neutral*	*M $50_N:50_I$*	*26 ms* *
Durgin (2003)	1	pointing	translated	4	out-of-set incongruent	*M $50_I:50_I$*	30 ms [e]*
	2	pointing	translated	4	out-of-set incongruent	*M $50_I:50_I$*	29 ms [e]*

Experiments using untranslated responses are in **bold** and those using ambiguous responses are in *italics*.

[a] Incongruent minus baseline.

[b] These effect sizes reflect the reaction time to read an entire list. Because participants were told to "leave no error uncorrected", dividing by the number of items on the list would likely overestimate the true mean difference in reaction time for correct responses.

[c] These effects sizes reflect the reaction time to sort an entire deck of cards. Errors were not corrected and thus dividing by the number of cards in the deck may not represent a true mean difference in reaction time for correct responses.

[d] Interference at SOA = 0.

[e] This is likely a low-ball estimate of the RSE since it is the difference between in-set and out-of-set incongruent trials.

participants are biased to process the colour, making it difficult to selectively attend to the word (Stroop, 1935). When the word is rendered difficult to read, more time (and arguably attention) is required to process the word thus affording the colour an opportunity to interfere (Melara & Mounts, 1993). Last, in the context of task switching, participants perform two colour naming trials followed by two word reading trials. Remembering which task to do on the current trial arguably consumes resources which could be put toward filtering colour processes. In short, there is no experiment which shows an RSE with a vocal response in the absence of a translation or some "capacity demanding" manipulation.

1.2.2 Ambiguous results

There are several reports of an RSE using a non-vocal response which at first blush would seem to undermine a translation account. These experiments are ambiguous, however, in that it is unclear whether the response required participants to engage the translation module or not. If engaged, then an RSE should be present according to the translation account. If *not* engaged, then no RSE should be seen according to the translation account.

Simon and Berbaum (1990) labeled their response buttons with words printed in the colour which they index (e.g., RED printed in red). With the response buttons labeled in this manner, participants can successfully perform this task using (1) only the verbal information on the button (an untranslated response), (2) only the colour information on the button (a translated response) or (3) both (a translated response).

This experiment yielded an RSE but is not considered further because it is impossible to discriminate between these possibilities.

Melara and Mounts (1993) also reported an RSE when participants responded via a button press. However, they did not specify how the response buttons were labeled. Without this information it is difficult to determine whether this result is consistent or inconsistent with a translation account.

Lu and Proctor (2001) also reported an RSE when participants responded via a button press. However, it is unclear as to whether the response required a translation. Lu and Proctor state "[the experimenter] also indicated which key was to be pressed for each stimulus alternative (for example, respond to the word RED by pressing the 'z' key and to the word GREEN by pressing the '/' key)." (*p*. 105). One can only speculate as to whether the participant's interpretation of the instructions involves a translation.

Lastly, Ruff, Woodward, Laurens, and Liddle (2001) also reported an RSE when participants responded via a button press. However, they too did not specify how the buttons were labeled. They stated that "[*p*]rior to entering the scanning room, subjects were trained to read colour words using a manual response" (*p*. 1151). Without specifying how subjects learned this association, it is difficult to determine how subjects are making their response.

In conclusion, these experiments are, arguably, all ambiguous with respect to the issue of whether a translation was involved or not. The fact that these experiments produced an RSE is therefore not easy to interpret with respect to the question of why.

1.2.3 Null results using untranslated responses

Translation accounts are consistent with the results from Table 1 in which the *failure* to see an RSE occurred when the stimulus-response mapping is untranslated because it is performed in the context of a non-vocal response (see the bolded experiments in Table 1). However, there was a trend for an RSE in each of these three experiments. Caution is necessary when the results of an experiment fail to reject the null hypothesis. Further, all of these experiments use experimental designs that, for one reason or another, may be problematic.

Pritchatt (1968) had participants point to a card with word labels, and Virzi and Egeth (1985) had participants sort a deck of cards into bins. In neither of these experiments were reaction times collected on a trial-by-trial basis (as has become standard in more recent investigations). As seen in Table 1, both of these experiments yielded a trend toward an RSE. It may be that these failures to observe an RSE are Type II errors.

Sugg and McDonald's (1994) experiments were unique in that their participants responded by pressing one of three "virtual" buttons on a touch screen and the verbal labels on these virtual buttons varied randomly from trial to trial. Thus, participants needed to search the display for the location of the correct response button. It may be that a small RSE was absorbed into the cognitive slack associated with this visual search component (see Pashler, 1994, for a discussion of cognitive slack in the context of the Psychological Refractory Period paradigm; see also Durgin, 2000, in which the magnitude of reverse Stroop interference is smaller [albeit not statistically different] in a similar condition compared to one in which the location of the label is constant). However, using a similar procedure, I obtain an RSE (see Experiment 3).

In short, I am unaware of a published Reverse Stroop experiment in which there is a (1) a discrete trial procedure, (2) a key press response, (3) and words are mapped to word labeled keys.

1.3 Testing the verbal mediation hypothesis

If the presence of a Stroop effect when the response keys are coded with colour patches is caused by verbal mediation, then the obvious argument by analogy is that no RSE should be observed when the response keys are labeled with words because the participant is responding to the word using a word-labeled key (an untranslated response). Given our facility with language, the assumption that subjects use verbal mediation as a strategy to remember the key labels seems natural. It is difficult to argue that the Reverse Stroop task is different from the Stroop task such that a different strategy would be applied to learning the key mappings.

Experiments 1 and 2 were therefore conducted such that (a) the participant had to identify the word and ignore the colour, (b) a discrete trial procedure was used and, (c) the stimulus-response mapping consisted of word-to-vocal responses for one group of participants (Experiment 1 only), and word-to-word-labeled response buttons for another group of participants. The proportion of congruent to incongruent trials was 50:50 in Experiment 1. The initial experiment used this ratio because Stroop experiments using a four-choice manual response standardly use this proportion. The a priori prediction is that an RSE will be observed in both experiments because of my hypothesis that, although "translation" modulates the *size* of the Stroop and Reverse Stroop effects, it is not the principle factor in driving the effect. Rather, as I elaborate in Chapters 2 and 3, the primary determinant of these Stroop and Reverse Stroop effects is the result of the strength of association between a particular stimulus and a particular response.

1.3.1 Experiment 1

1.3.1.1 Method

1.3.1.1.1 Participants

Fifty-four undergraduates from the University of Waterloo were tested individually and paid $4.00 each for their participation.

1.3.1.1.2 Stimuli

The stimulus set consisted of four colour words displayed in lower case letters in MEL's "system72" font (0.6° tall and 1.2°-2.7° wide when viewed at approximately 60 cm). On half of the trials, the stimuli were congruent (the colour and the word referred to the same colour), and on the remaining trials they were incongruent (the colour and the word referred to different colours; all possible incongruent pairings were used). For the congruent condition, each word appeared in the colour to which it referred 24 times for each of the four colour words (96 trials). For the incongruent condition, each word appeared in one of the three colours to which it did not refer, 8 times for each of the four colour words (96 trials). This trial configuration yielded a 50:50 congruency ratio.

1.3.1.1.3 Apparatus

The experiment was programmed in MEL (Schneider, 1988) running on a Pentium computer with a colour monitor. The four colours used (and their corresponding MEL codes) were red (RGB 42, 0, 0), blue (RGB 0, 0, 42), green (RGB 0, 42, 0), and yellow (RGB 63, 63, 21).

1.3.1.1.4 Procedure

On each trial, a single word was presented in the middle of the screen. The participants were randomly assigned to one level of response type (vocal vs. manual). Half of the participants were told to read the word aloud and ignore the colour (word-naming condition). The remaining participants were told to read the word and respond by pressing one of four buttons labeled with words. These participants responded by pressing the appropriate button on the keyboard: the "z," "x," ">," and "?" keys, which were covered, respectively, by stickers with the words "red", "blue", "yellow", and "green" printed on them in black ink.

Each participant saw a different random order of 192 test trials. These were preceded by 24 practice trials whose composition mirrored the test trials. During the first 10 or so practice trials, the experimenter called out the correct response (a) to encourage participants to attach verbal labels to the response buttons and (b) to ensure that participants were responding to the correct dimension.

1.3.1.2 Results and discussion

Trials on which the microphone was not triggered (mistrials) were excluded from the analysis, resulting in the elimination of 5.5% of the data. Correct RT data for each participant in each condition were then subjected to a recursive outlier analysis (see Van Selst & Jolicoeur, 1994) eliminating 1.5% of the RT data for the vocal condition and 3.1% of the RT data in the manual condition. Visual inspection of Figure 1 confirms the standard report of no RSE in the vocal condition. Visual inspection of the left-hand side of Figure 2 shows a 35 ms RSE in the context of a manual response.

The two-way interaction between Response Type and Congruency was significant in both the RT data, $F(1, 26) = 15.5$, $MSe = 561$, $p < .001$, and the error data, $F(1, 26) = 3.95$, $MSe = 1.3$, $p < .053$. For vocal responses, there was no difference between incongruent and congruent trials in RT (474 ms vs. 472 ms), $F(1, 26) = 2.86$, $MSe = 23$, $p > .10$, nor in errors ($F < 1$). In contrast, for manual responses, there was a difference between incongruent and congruent trials in both the RT data (672 ms vs. 637 ms), $F(1, 26) = 23.1$, $MSe = 744$, $p < .001$, and the error data (3.2% vs. 2.2%), $F(1, 26) = 4.86$, $MSe = 2.6$, $p < .05$. Twenty-two of 27 subjects showed this direction of difference in RT (sign test $p < .05$) for manual responding.

In summary, Experiment 1 yielded the standard null effect in the vocal condition but a 35 ms RSE in the manual condition. This latter result is contrary to the translation account's prediction of a null effect. The fact that there is no RSE in the vocal condition may be because subjects are too fast. When subjects are slowed down by making the words difficult to read, for example, an RSE is typically observed (see Dunbar & MacLeod, 1984).

Figure 1: Mean RTs (and mean percent errors) for the vocal condition in Experiment 1. Error bars represent 95% confidence intervals.

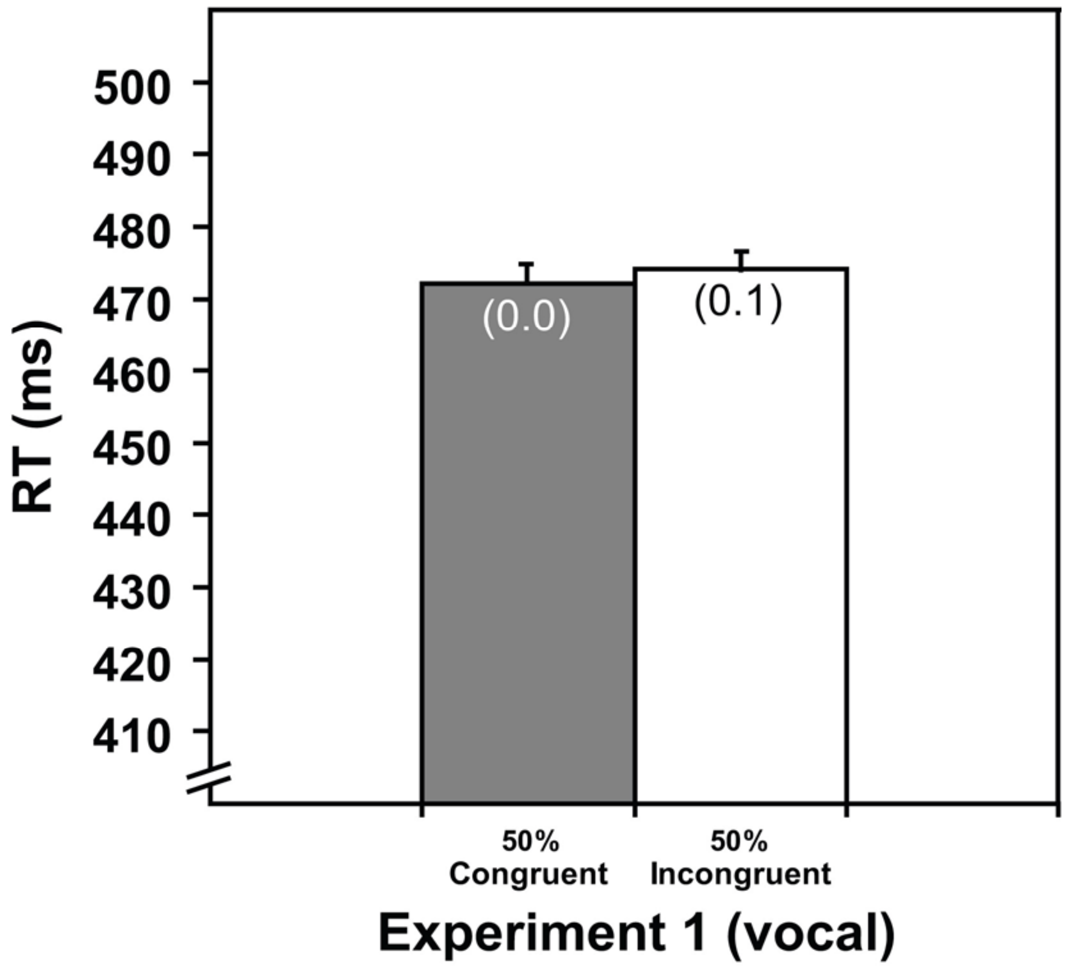
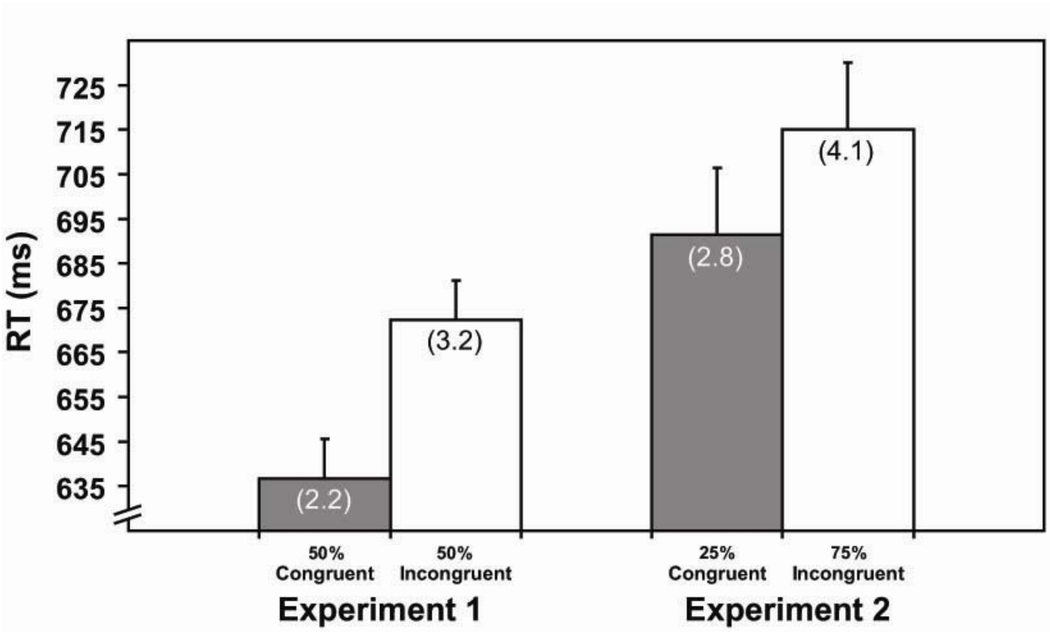


Figure 2: Mean RTs (and mean percent errors) for the manual condition in Experiment 1 and Experiment 2. Error bars represent 95% confidence intervals.



1.3.2 Experiment 2: The effect of congruency ratio

The Stroop effect is typically modulated by the ratio of congruent to incongruent trials such that its size increases as the proportion of congruent trials increases (e.g., Cheesman & Merikle, 1985). The general account of this result is that as the proportion of congruent trials increases, participants are more likely to attend to the contingency between the colour and the word because the word is predictive of the colour (e.g., Dishon-Berkovits & Algom, 2000). In Experiment 1, therefore, there is the potential problem that because the colour is predictive of the word, participants are translating the colour into a verbal code and it is this that causes an RSE to emerge. Experiment 2 therefore uses a 25:75 congruency ratio because the colour no longer predicts the word (see Section 1.3.2.1.3).

1.3.2.1 Method

1.3.2.1.1 Participants

Thirty undergraduates from the University of Waterloo were tested individually and paid $4.00 each for their participation.

1.3.2.1.2 Stimuli and apparatus

These were the same as in Experiment 1.

1.3.2.1.3 Procedure

The procedure was identical to Experiment 1 except for the following. First, there was no vocal condition. Second, the congruency proportion was changed from 50:50 congruent:incongruent to 25:75 congruent:incongruent by removing two-thirds of the congruent trials. Each word now appeared equally in all of the four colours. Each of the 16 colour-word combinations was presented 12 times. This resulted in 192 experimental trials; 48 congruent trials and 144 incongruent trials. The experimental trials were preceded by 16 practice trials; 4 congruent trials and 12 incongruent trials.

1.3.2.2 Results

Correct RT data were subjected to the same recursive outlier analysis described earlier. This eliminated 3.0% of the RT data. The remaining RT data and associated error data can be seen in the right-hand side of Figure 2. There was a significant 24 ms RSE in RT, (715 ms vs. 691 ms), $F(1, 29) = 5.22$, $MSe = 1619$, $p < .05$. Twenty-two of 30 subjects showed the effect (sign test $p < .05$). There was also an RSE in the error data (4.1% vs. 2.8%), $F(1, 29) = 2.86$, $MSe = 8.4$, $p < .05$, one-tailed. A mixed ANOVA comparing the the size of the RSE in RT between Experiments 1 and 2 (35 ms vs. 24 ms) was not significant ($F < 1$).

1.3.2.3 Discussion

The novel empirical result from Experiments 1 and 2 is the presence of an RSE in the context of a manual *untranslated* response. Nonetheless, a reviewer suggested that there is a potential problem with these two experiments: Because the button labels were covered by the participant's fingers, button names are not necessarily represented verbally. In reply, I note that the experimenter verbally stated the names of the buttons during practice, and that the vast majority of participants could be heard reciting the names of the buttons (i.e., looking down at the buttons and saying "blue, red, yellow, green, blue, red, ….") while the experimenter was present in the room during the practice trials.[2] Nonetheless, an experiment in which the response label was always visible was conducted and yielded the same results (see below).

1.3.3 Experiment 3

The purpose of Experiment 3 was to address the criticism that one cannot be certain of the code used to store the button label information because the button labels were covered by the participant's fingers. To rectify this, a third experiment was conducted in which the button labels were always visible on the computer screen. Neutral trials were also included to allow calculation of both facilitation and interference components.

1.3.3.1 Method

1.3.3.1.1 Participants

Twenty-four undergraduates from the University of Waterloo were tested individually and paid $4.00 each for their participation.

1.3.3.1.2 Stimuli

These were the same as in Experiment 1 with the exception that neutral trials were also included (the word presented in grey).

1.3.3.1.3 Apparatus

The experiment was programmed in e-Prime running on a Pentium 4 computer with a colour monitor. The five colours used (and their corresponding red, green, blue [RGB] values) were red (255, 0, 0), blue (0, 0, 255), green (0, 255, 0), yellow (255, 255, 0), and grey (170, 170, 170). White (255, 255, 255) was used to indicate the response labels that appeared near the bottom of the display.

1.3.3.1.4 Procedure

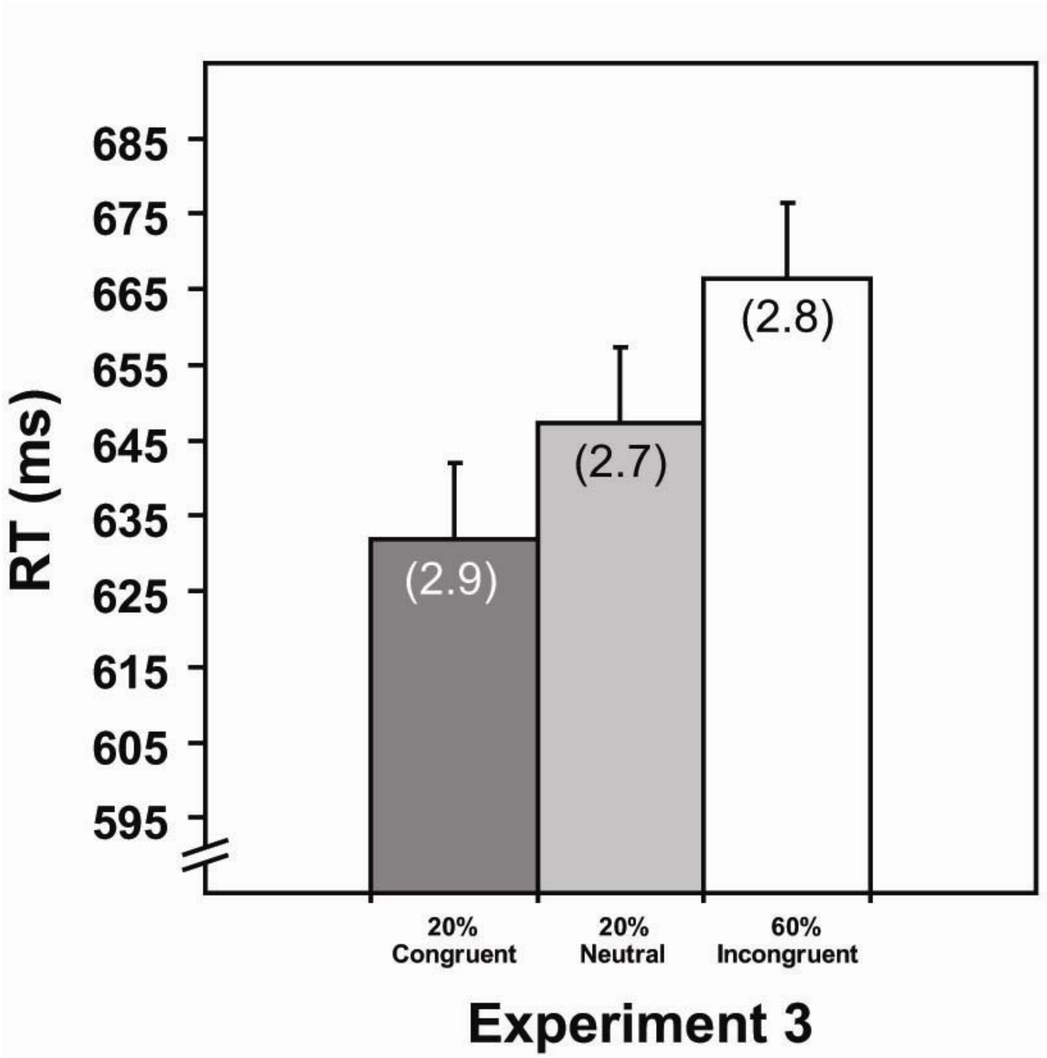
The procedure was identical to Experiment 2 except for the following. Each participant was randomly assigned one of the 4! = 4 x 3 x 2 x 1 = 24 possible key mappings such that each mapping was used once. Second, the congruency proportion was changed from 25:75 congruent:incongruent to 20:20:60 congruent:neutral:incongruent. The result was that each of the four words appeared equally in all of the five colours; each of the 20 colour-word combinations was presented 8 times. This resulted in 160 experimental trials. The experimental trials were preceded by 40 practice trials.

1.3.3.2 Results

The subject's mean RT in each condition served as their measure of central tendency. Mean RTs and mean percentage errors can be seen in Figure 3. Incongruent trials were 19 ms slower than neutral trials, $t(23) = 3.58$, $p < .005$. Twenty of 24 participants showed this effect. Congruent trials were marginally faster than neutral trials, $t(23) = 1.99$, $p < .06$. Fifteen of 24 participants showed this effect.

None of these effects were observed in the error data (*p*s > .50).

Figure 3: **Mean RTs (and mean percent errors) for Experiment 3. Error bars represent 95% confidence intervals.**



1.3.3.3 Discussion

Replicated in Experiment 3 is the demonstration of an RSE in the context of an untranslated response. However, a strong proponent of the translation account could still argue that the interference (and facilitation) seen here is the result of a translation between the (unvarying) *location* of the response button and a verbal code. If this does result from a translation, it is difficult to conceive of *how* the interference occurs given that a button's location has no bearing on the particular response. To discount this seemingly preposterous defense of a translation account, a fourth experiment was conducting which employed a novel method which allowed for "button" location to vary randomly from trial to trial.

1.3.4 Experiment 4

Experiment 4 provides the strongest test to date of the verbal mediation hypothesis. According to translation accounts, if the response labels are words rather than colour patches, then no RSE should be observed because a translation is not required. Experiments 1 and 2 reported an RSE under these conditions, but that demonstration may be open to the objection that a translation (e.g., a visual image of the colour associated with the key) was used when participants responded by pressing word-labeled keys that were covered by the subject's fingers (although subjects denied using this strategy when asked). In Experiment 3, given that the button mappings were constant, one may claim that a translation occurred between the memory codes used to store location information and the code used to store verbal information

Experiment 4 therefore used a variant of Durgin's (2000) procedure in which subjects identify the coloured word at fixation by *pointing* to a printed response word in one of the four corners of the display. This procedure has the advantage that the target word and the response word are always visible. The observation of an RSE in this context is unlikely to be understood in terms of translation.

It is important to note that both retinal resolution and cortical representation decline rapidly as stimuli are presented outside the fovea. This is especially problematic when the response locations vary on a trial by trial basis because the response words may not easily be read without an eye movement. Given that any RSE independent of a translation is likely small in magnitude, visual "search" for the response label may obscure its detection. In visual search tasks, reaction time increases with retinal eccentricity (Carrasco, Evert, Chang, & Katz, 1995). It has been shown that cortically magnifying items in the search display neutralizes this eccentricity effect (Carrasco & Frieder, 1997). The central target word and response words were therefore equated in size using the cortical magnification factor described by Findlay and Gilchrist (2004, p. 14).

1.3.4.1 Method

1.3.4.1.1 Participants

Thirty undergraduates from the University of Waterloo were tested individually and paid for their participation.

1.3.4.1.2 Words at fixation

The stimulus set consisted of four colour words displayed at fixation in upper case letters in 10 pt Courier New font (approximately 0.4° tall and 1.1°-2.3° wide when viewed at 60 cm). All possible word-colour pairings occurred equally often. Each of the 20 possible stimuli (the words red, blue, yellow, and green presented in each of those colours in addition to white for neutral trials) were presented 12 times yielding 48 congruent, 48 neutral, and 144 incongruent trials for a congruent: neutral: incongruent ratio of 20:20:60. The colours and the words are therefore not correlated.[2] All trial types were randomly intermixed.

1.3.4.1.3 Words at response locations

The response word locations were 2.7° diagonally from fixation, and the words were presented in grey, lower case 20 pt Courier New font (approximately 0.8° tall and 2.3°-4.6° wide when viewed at approximately 60 cm). The words in the periphery were sized according to the cortical magnification factor noted earlier (Findlay & Gilchrist, 2004, p. 14). Most importantly, the location of the response words varied randomly from trial to trial to rule out the possibility that subjects were making a translation between the word at fixation and a learned location.

1.3.4.1.4 Apparatus

The apparatus was identical to Experiment 3.

1.3.4.1.5 Procedure

On each trial, a single colour word was presented in the middle of the screen against a black background. The participants identified the word by moving the mouse approximately 2.9° diagonally from fixation to its corresponding response word location displayed in one of the four corners of the screen. Reaching the response location required less than 25 mm of mouse movement across the surface of the table. The position of the mouse cursor was reset to 0.4° below fixation (to prevent occlusion of the stimulus) at the beginning of each trial. RT was measured as the time that had elapsed from the onset of the target word until the mouse cursor passed over the boundary of the invisible box defining each response location.

Each participant saw a different random order of 240 test trials. The experimental trials were preceded by 48 practice trials whose composition mirrored the test trials.

1.3.4.2 Results

The subject's mean RT in each condition served as their measure of central tendency. Mean RTs and mean percentage errors can be seen in Figure 4. Incongruent trials were 18 ms slower than neutral trials, $t(29) = 2.97$, $p < .01$. Twenty of 30 participants showed this effect. There was no reliable difference between neutral trials and congruent trials ($t < 1$).

There was a trend toward more errors on incongruent trials than neutral trials, $t(29) = 1.50$, $p < .15$. Nineteen of 30 participants showed this error pattern. There was no reliable difference between neutral and congruent trials ($t < 1$).

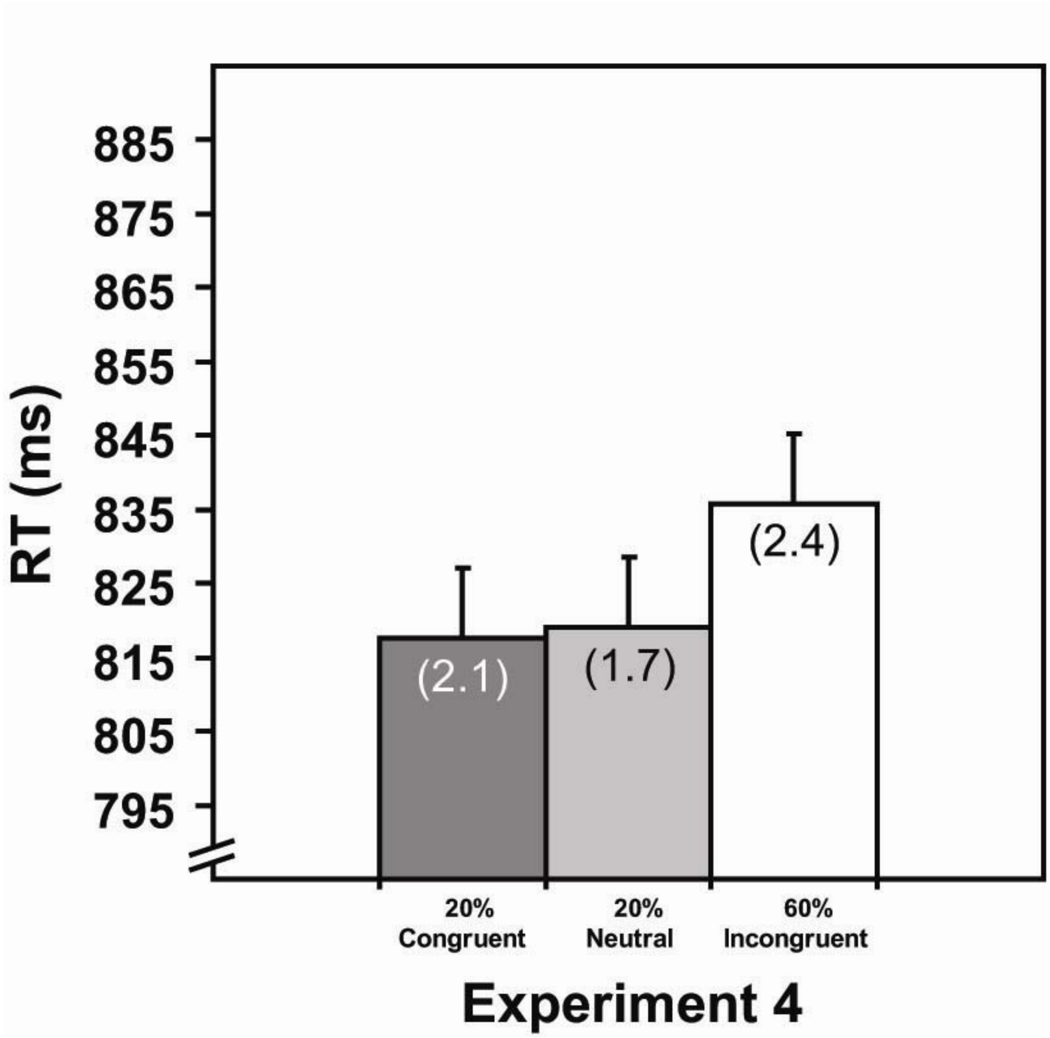
1.3.4.3 Discussion

An RSE was observed in Experiment 4 in which it is difficult to make a convincing argument that a translation occurred. Furthermore, it appears as though the RSE results entirely from interference from the irrelevant colour; no facilitation effect is seen.

Proponents of translation accounts assume that the *presence* of a Stroop effect in the context of a manual response with coloured keys is the result of verbally mediating the response. Thus, *a fortiori*, it follows that the key labels in the present experiments were also verbally mediated.

Relatedly, given that the size of the RSE reported in Experiments 1-4 is quite similar in magnitude to the “ambiguous” experiments in Table 1, it seems likely that the response keys were verbally mediated in each of those experiments as well.

Figure 4: Mean RTs (and mean percent errors) from Experiment 4. Error bars represent 95% confidence intervals.



Chapter 2: What Determines the RSE?

2.1 Introduction

If a translation is not responsible for the RSE observed in Experiments 1-4, then what is responsible for producing this effect? Let me begin by noting that I do not assume that the colour is processed automatically and free from attentional resources. Rather, I assume that pressing a button does not require all attentional resources and these residual resources are allocated to processing the colour in accordance with Lavie and colleagues' (Lavie, Hirst, Fockert, & Viding, 2004) load theory of selective attention and cognitive control.

According Lavie et al. (2004), there are two selective attention mechanisms. There is a *perceptual selection* mechanism which reduces the perception of distractors in situations of high perceptual load that exhaust perceptual capacity in processing relevant stimuli. There is also a *cognitive control* mechanism that reduces interference from perceived distractors as long as cognitive control functions are available to maintain current priorities (low cognitive load).

Given that only one stimulus is presented on the screen, clearly the *perceptual* load is low. My proposal is that stimulus-response mappings can either demand low or high amounts of cognitive load. When the stimulus-response mapping is consistent (i.e., the mapping is in the same code as the dimension you need to respond to), few cognitive resources are utilized by the mapping, leaving plenty to filter out the (in this case) irrelevant colour, resulting in a small Reverse Stroop effect. When the stimulus-response mapping is inconsistent (i.e., the mapping is in a different code from the dimension you need to respond to), many cognitive resources are utilized by the mapping leaving little to filter out the irrelevant colour, resulting in a large Reverse Stroop effect. When viewed in this light, the results of Stroop and Stroop-like experiments that are traditionally explained in terms of a "translation" fit better into this framework because there is always a trend for the presence of an interference effect even if that particular experiment lacks the power to detect it. This point of view seems to imply that the effect observed in Experiments 1-4 occurs at the level of response competition.

2.1.1 Experiment 5

The late processing hypothesis is tested in Experiment 5 using a old paradigm (see Sanders, 1970) recently resurrected by de Houwer (2003) in which multiple responses are assigned to an individual button (e.g., if the colour is BLUE or GREEN, subjects are told to press the 'c' key; if the colour is RED or YELLOW, subjects are told to press the 'm' key). In this paradigm, there are three types of trials: *identity* trials in which the colour and word are the same (e.g., RED in red; these are traditionally called congruent trials); *stimulus* conflict trials which the colour and word are different, but the response is the same (e.g., RED in yellow); and lastly, *response* conflict trials in which the colour and word are different and *map to different responses* (e.g., RED in blue).

In the context of this paradigm, the Stroop effect is defined as the difference between identity trials and response conflict trials. Using de Houwer's analysis, the Stroop effect can be decomposed into a relatively early stimulus conflict component (the difference between identity trials and stimulus conflict trials) and a relatively late response conflict component (the difference between stimulus conflict trials and response conflict trials)[3]. de Houwer (2003) reported that the Stroop effect is comprised of roughly half stimulus conflict and half response conflict.

Converging evidence is always useful. Schmidt and Cheesman (2005) used de Houwer's paradigm to investigate the locus (loci) of interference for colour *associates*. They had participants respond to the print colour of colour associated words (e.g., frog and sky). In this context, when asked to identify the print colour, the names of the words are never viable responses. Thus, an effect with colour associates in the context of de Houwer's paradigm should be entirely a stimulus conflict effect. No response conflict should be seen. This is exactly what Schmidt and Cheesman reported: They reported only a stimulus conflict effect. This result is important because it shows that, in the context of this paradigm, one aspect of the Stroop effect (stimulus conflict) can occur in the absence of another aspect of the Stroop effect (response conflict).

To return to the RSE, the present hypothesis is that during the extra time it takes to *select* a manual response, the colour is processed and produces interference in responding to the word. If the RSE observed in Experiments 1-3 represents such a late effect, then in the context of applying de Houwer's analysis to the Reverse Stroop Task, a response conflict effect should be observed, but no stimulus conflict effect.

2.1.1.1 Method

2.1.1.1.1 Participants

Thirty-six undergraduates from the University of Waterloo were tested individually and paid $4.00 each for their participation.

2.1.1.1.2 Stimuli

The stimulus set consisted of four colour words displayed in upper case letters in Arial 18 pt font (0.9° tall and 2.6°-5.7° wide when viewed at approximately 60 cm). There were 15 trials for each of the sixteen colour-word pairings. Identity trials were the 60 trials in which the word and colour were the same (congruent trials). Stimulus conflict trials were the 60 trials in which the word appeared in the colour which was assigned to *the same button as the word*. For example, if the button mapping is to press 'c' if the word is blue or green and to press 'm' if the word is yellow or red, a stimulus conflict trial would be either green in BLUE, blue in GREEN, red in YELLOW, or yellow in RED. Response conflict trials were the 120 remaining trials in which the word and the colour referred to different buttons (e.g., using the above button map, blue in RED).

2.1.1.1.3 Apparatus

The experiment was programmed in E-Prime running on a Pentium computer with a colour monitor. The same four words and colours as in Experiments 1 and 2 were used.

2.1.1.1.4 Procedure

On each trial, a single word was presented in the middle of the screen. Participants were instructed to respond to the word and to ignore the colour by pressing either the ‘c’ or the ‘m’ key on the keyboard. Two words were assigned to the ‘c’ key and the other two words were assigned to the ‘m’ key. Button assignment was counterbalanced across participants.

Each participant saw a different random order of 240 test trials which were preceded by 48 practice trials whose composition mirrored the test trials.

2.1.1.2 Results

Correct RT data were subjected to the same recursive outlier analysis described earlier. This eliminated 3.0% of the data. The remaining RT data and associated errors can be seen in Figure 5. A one-way repeated measures ANOVA confirms the obvious main effect of condition for RT, $F(1.434, 50.198)$[4] = 9.28, MSe = 894, $p < .001$. The main effect of condition was marginal in the error data, $F(2, 70) = 2.54$, MSe = 4.7, $p < .05$ (one-tailed).

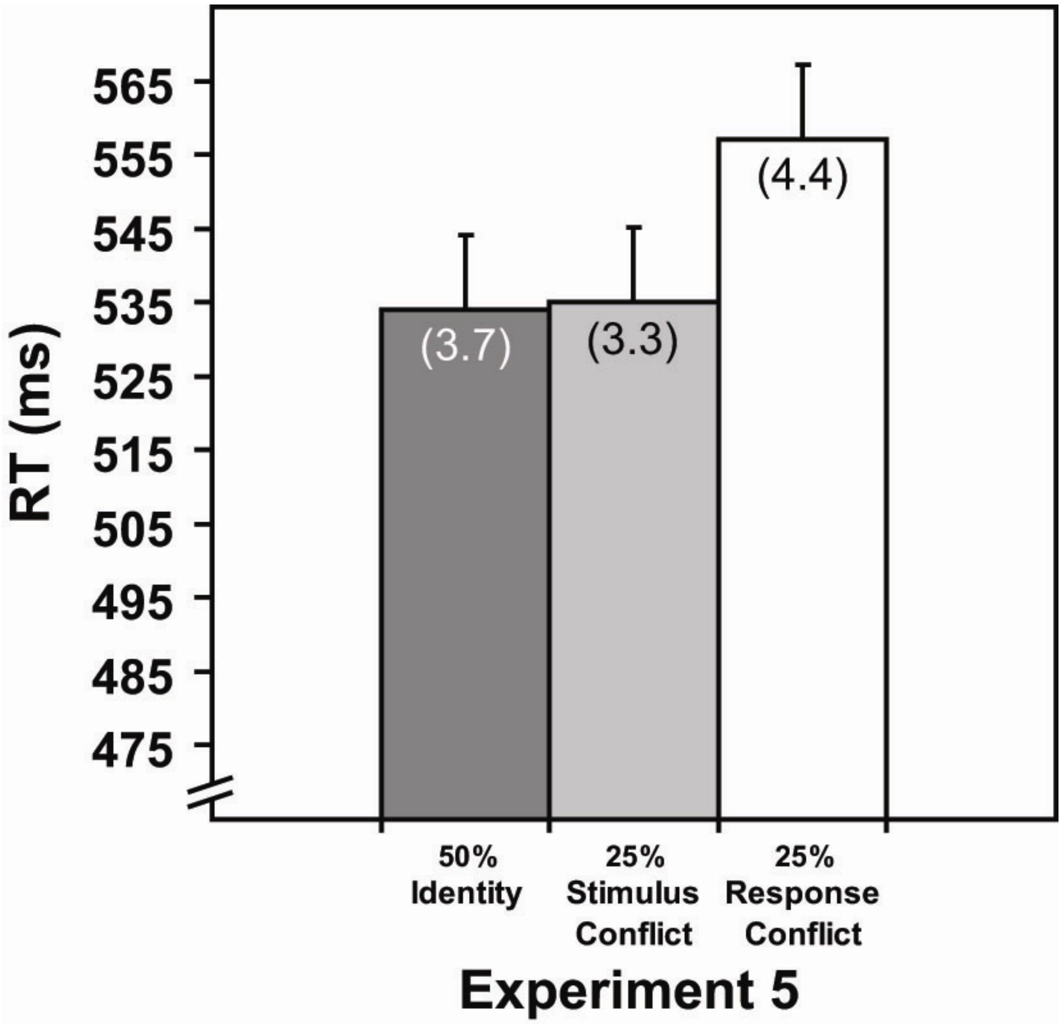
Planned *t*-tests reveal a significant RSE in RT such that response conflict trials (557 ms) were slower than identity trials (534 ms), $t(35) = 3.51$, $p < .001$; 30 of 36 subjects showed the effect, sign test $p < .05$. The error data did not produce a significant RSE, $t(35) = 1.34$, $p > .15$, but the trend was in the same direction such that response conflict trials (4.4%) were more error prone than identity trials (3.7%). Response conflict trials (557 ms) were also slower than stimulus conflict trials (535 ms), $t(31) = 5.82$, $p < .001$. Thirty-one of 36 subjects showed this effect, sign test $p <$

.05. This effect was also observed in the error data. Response conflict trials (4.4%) were more error prone than stimulus conflict trials (3.3%), $t(31) = 2.06$, $p < .05$. Finally, there was no stimulus conflict effect in RT ($t < 1$); stimulus conflict trials (535 ms) were as fast as identity trials (534 ms). Stimulus conflict trials were faster than identity trials for only 19 of 36 subjects, sign test $p > .50$. There was also no stimulus conflict effect in the error data ($t < 1$); stimulus conflict trials (3.3%) were as prone to errors as identity trials (3.7%).

2.1.1.3 Discussion

Experiment 5 investigated the RSE in the context of the de Houwer paradigm. An RSE was observed that is entirely attributable to response conflict. This is consistent with the hypothesis that because the absolute time to respond to the word is slowed by using a manual response, the colour has time to compete as a potential response. This argument is also consistent with data reported by Dunbar and MacLeod (1984) in which they slowed down word reading by printing the word backwards or backwards and rotated and observed an RSE in the context of reading aloud.

Figure 5: **Mean RTs (and mean percent errors) for Experiment 5. Error bars represent 95% confidence intervals.**



2.1.2 Experiment 6

Experiments 1-5 show that it is possible to obtain an RSE in the context of an untranslated response when the experiment contains congruent trials. Although Experiments 3 and 4 showed that there was no facilitation component, the interference component may somehow result from the fact that there were congruent trials present in the experiment. Despite the fact that there was no statistical basis for attending to the colour (i.e., the colour did not aid in predicting the word), participants may have done so nevertheless (see Risko & Stolz, *in preparation*).

Experiment 6 addresses this rather improbable concern by repeating Experiment 5 with the exception that congruent trials were replaced by neutral trials. If an RSE is obtained, it can only be the result of interference from the irrelevant colour. Further, if the RSE is a response conflict effect, then the same pattern of results should be observed as in Experiment 5. That is, a response conflict effect should appear but there should be no significant stimulus conflict effect.

2.1.2.1 Method

2.1.2.1.1 Participants

Thirty-six undergraduates from the University of Waterloo were tested individually and paid for their participation.

2.1.2.1.2 Stimuli

The stimuli were identical to Experiment 5 except that congruent trials were replaced by neutral trials in which the word was displayed in white (255,255,255).

2.1.2.1.3 Apparatus

The apparatus was identical to Experiment 5.

2.1.2.1.4 Procedure

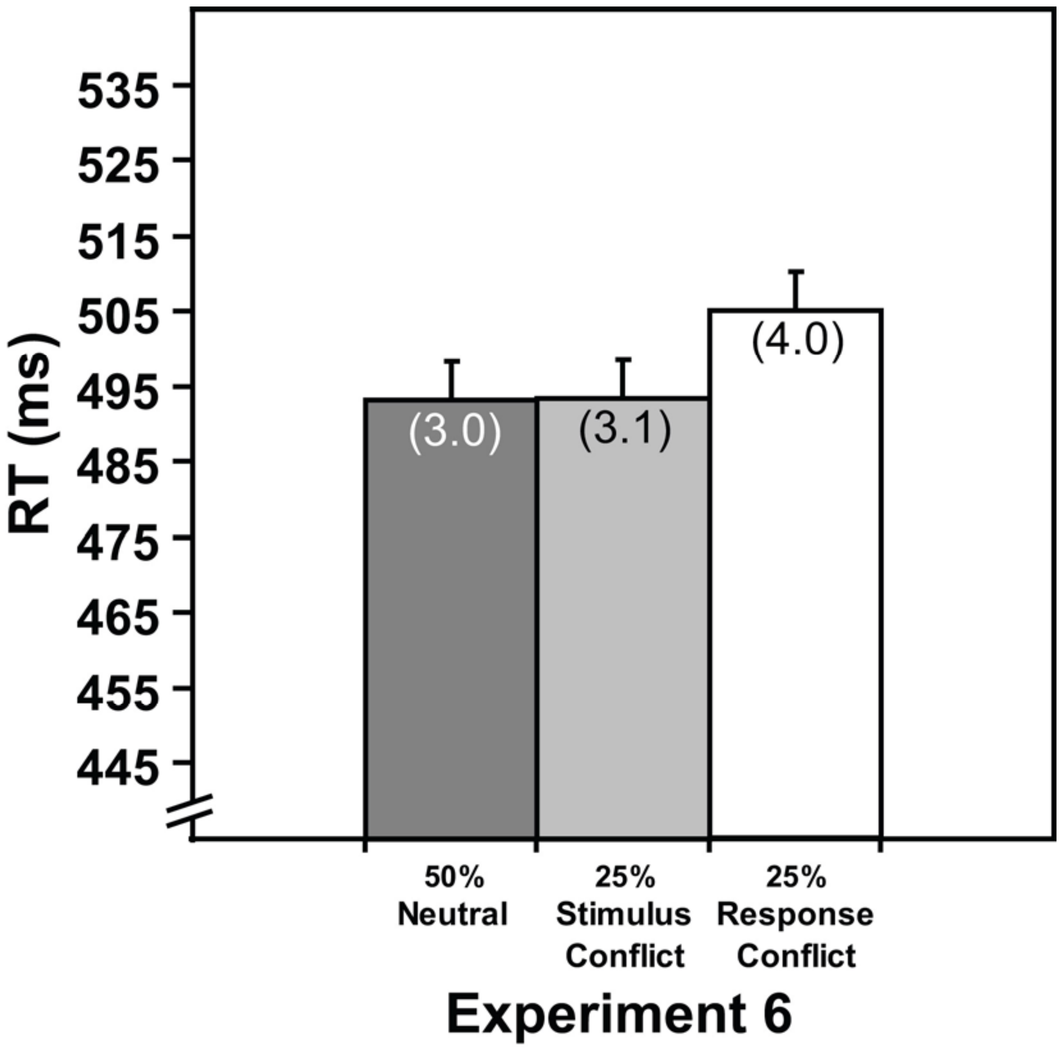
The procedure was identical to Experiment 5.

2.1.2.2 Results

Correct RT data were subjected to the same recursive outlier analysis described above. This eliminated 3.2% of the data. The remaining RT data and associated error data can be seen in Figure 6. A one-way repeated measures ANOVA confirmed the main effect of condition for RT, $F(2,70) = 6.91$, $MSe = 242$, $p < .002$, as well as for errors, $F(2,70) = 3.11$, $MSe = 3.7$, $p < .051$.

Planned *t*-tests yielded a significant RSE in RT such that response conflict trials (505 ms) were slower than neutral trials (493 ms), $t(35) = 3.89$, $p < .001$; 25 of 36 subjects showed the effect (sign test $p < .05$). There was also an RSE in errors such that response conflict trials (4.0%) were more error prone that neutral trials (3.0%), $t(31) = 2.27$, $p < .05$. Importantly, a significant response conflict effect was observed for RT such that response conflict trials (505 ms) were slower than stimulus conflict trials (493 ms),

Figure 6: **Mean RTs (and mean percent errors) for Experiment 6. Error bars represent 95% confidence intervals.**



$t(35) = 2.86$, $p < .05$; 24 of 36 subjects showed the effect (sign test $p < .07$). The effect was also significant in errors. Response conflict trials (4.0%) were more error prone than stimulus conflict trials (3.1%), $t(35) = 2.25$, $p < .05$. However, no stimulus conflict effect was observed either in RT ($t < 1$), in which only 15 of 36 subjects showed the effect, or in errors ($t < 1$).

Post hoc analyses on Experiments 5 and 6 which compared the size of (a) the RSE (22 ms vs. 12 ms), (b) the response conflict component (23 ms vs. 12 ms), and (c) the stimulus conflict component (1 ms vs. 0 ms) show that only the response conflict component was smaller in Experiment 6, $F(1, 70) = 3.20$, $p < .078$; other *p*s > .13. That said, such cross-experiment comparisons typically have low power to detect an effect. Although the effect does not appear to be facilitatory given the results of Experiments 3 and 4, it appears as though excluding congruent trials does reduce the magnitude of response conflict if only by introducing a contingency between the word and the colour such that the word only appears in one of the three colors it does not reference.

2.1.2.3 Discussion

Experiment 6 showed that at least a portion of the RSE observed in Experiment 5 is the result of interference from the irrelevant colour. It also replicates and extends the results of Experiment 5 in showing that a response conflict effect but no stimulus conflict effect is observed in the context of de Houwer's (2003) analysis as applied to the Reverse Stroop task. This is consistent with the hypothesis that, because the absolute time to respond to the word is slowed by using a manual response, the colour has time to compete as a potential response. Moreover, a significant RSE was observed in a context in which there is no incentive to attend to the colour because congruent trials were replaced with neutral trials.

2.2 General discussion

An RSE was obtained in all six experiments (overall, 75% of participants showed an effect). These findings cannot be explained by current accounts of the RSE in which the mechanism producing interference involves a translation between memory codes for colour and word. In none of these experiments is there any strong reason to assume that a strategy other than verbally mediating the buttons occurred. Given our facility with language, a natural assumption is that subjects use verbal mediation as a strategy to remember the key labels. It is difficult to argue that the Reverse Stroop Task is different from the Stroop Task such that a different strategy would be applied to learning the key mappings. A translation is therefore not needed to respond to the word.

2.2.1 A strength of association account

The present findings are consistent with an account of the Reverse Stroop (and Stroop effect) which relies on the principle of the *strength of association* between the stimulus and the response (e.g., Cohen, Dunbar, & McClelland, 1990; Logan, 1988; MacLeod & Dunbar, 1988; but see Durgin, 2003). These accounts[5] assume that reading words aloud is more skilled than colour naming because people are more practiced at the former than the latter. In these accounts, the outcome of skilled processes interferes with the outcome of less skilled processes. Thus, the RSE occurs when the response is a button press because the strength of association between the to-be-identified word and the button is not as strong as the association between the to-be-identified word and its pronunciation (see Cohen *et al.,* 1990, particularly early in training when interference occurs in responses to both dimensions).

These accounts also explain the fact that words interfere with colours but not *vice versa* in the context of a vocal response (i.e., the Stroop Effect) because responding to the word is an overlearned response. Importantly, Logan (1988) stands apart from Cohen *et al.* (1990) in his proposal that the *specific* response made to the stimulus is important:

> "each encounter with a stimulus is encoded, stored, and retrieved separately. Each encounter with a stimulus is assumed to be represented as a processing episode, which consists of the goal the participant was trying to attain, the stimulus encountered in pursuit of the goal, the interpretation given to the stimulus with respect to that goal, *and the response made to the stimulus.* When the stimulus is encountered again in the context of the same goal, some proportion of the processing episodes it participated in are retrieved."
>
> (Logan, 1988, *p*. 495, *italics mine*)

Thus, the stimulus-response mapping for a word and its verbal code is relatively strong because a large number of instances exist.[6] If the stimulus-response mappings for the word are made relatively unfamiliar, as is the case when using a button-press, a smaller proportion of those previously existing instances can be recruited because fewer are sufficiently similar to the nature of the current task. The result is that the irrelevant dimension now interferes. Simply put, resistance to interference is a function of practice. As stimulus-response expertise increases, it becomes less likely that an irrelevant task feature has the ability to interfere.

2.2.2 Implications for translation accounts of the Stroop effect

The present results constrain a translation account of performance in the Reverse Stroop Task. That said, they carry no necessary implications for a translation account of performance in the *Stroop* task other than an argument by association.

2.2.3 Conclusions

Whether translation models can be modified to explain the data reported here remains to be seen. McDonald (personal communication, August 15, 2003) has noted that:

> "…the Translation model does not preclude other mechanisms that might produce such an effect such as changes in 'capacity-demand' due to 'unfamiliar mappings'".

In agreement with McDonald's caveat, it is obvious from Table 1 that the magnitude of the RSE when a translation is involved is larger than the magnitude of the RSE when a translation is not involved. Thus, the concept of a translation is clearly important. However, it is entirely insufficient to explain the data.

Chapter 3: A Formal Model

3.1 How could a translation be operationalized?

There is no disputing that when the response requires a translation both the Stroop and Reverse Stroop effects are considerably larger than when no translation is required (e.g., Sugg & McDonald, 1994; Virzi & Egeth, 1985). However, there has been little elaboration beyond the notion that a translation is required when the to-be-elicited response is different than the original code used to process that information. More specifically, what does it mean when 'the output of the colour process(es) must be translated into a verbal code in order to be vocalized'? *How* might this be operationalized in the context of a computational model?

The general idea that habit and will compete for the control of action is centuries old. Modern psychologists use words like "automatic" or "unconditional" to refer to habit and words like "intentional" or "conditional" to refer to will. The outcome of a translation will interfere with desired performance when it activates a habitual response that is inconsistent with the goal state.

> If the outcome of this translation is in agreement with…the intended action goal, only minimal effort (or will power) needs to be applied, and execution is facilitated. If an existing habit activates a counterproductive tendency, however, this needs to be overcome by an increase in effort deployed.
>
> (Hommel, 2000, p. 258)

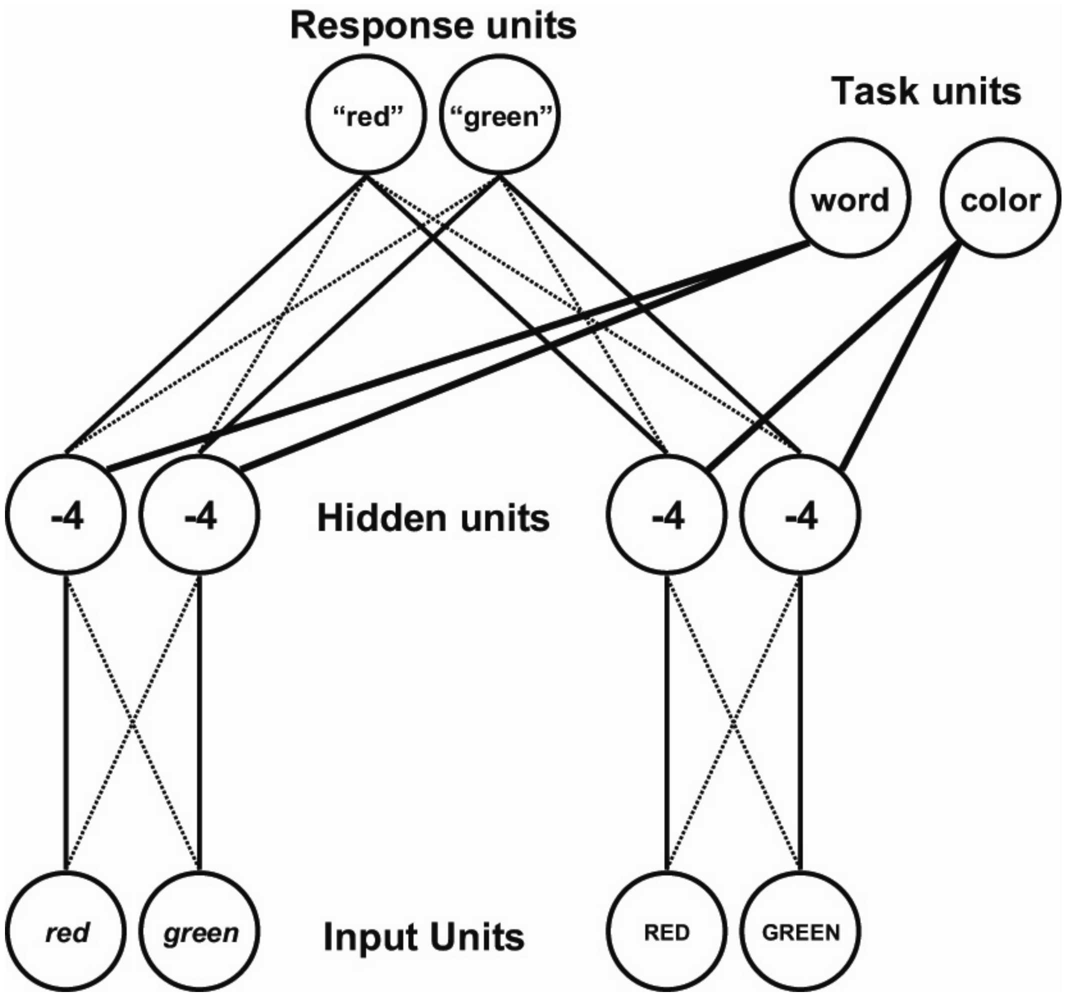
In the context of a vocal Stroop task, the colour name must be translated into a vocal code. The word is always translated into a vocal code, because people habitually read words, where the word competes with the colour for selection. According to Hommel (2000), the fact that the word is unconditionally translated into a vocal code causes an increase in the amount of effort that is deployed. More formally, my claim is that this increase in effort leads to a reduction in the amount of resources that would otherwise be used for goal maintenance. This important issue will be discussed further when I detail the specifications of the simulation (see p. 59).

3.2 A formal model of the strength of association account

I now briefly sketch an alternative account[7] in which *the strength of association* between the target and the *specific* response is central. Unlike a translation account, which assumes that the response is only important in terms of whether it requires a translation or not, this strength of association account assumes that the response is important in terms of the amount of practice subjects have making a *specific* response.

Like virtually all accounts of Stroop and Reverse Stroop performance, I assume a "word pathway" and a "colour pathway" which process words and colours respectively. For purposes of illustration, I utilize Cohen, Dunbar, and McClelland's (1990) model, which is depicted in Figure 7. This model contains a layer of input units for colours and a layer of input units for words, a layer of response units, and a layer of hidden units that are modulated by a set of task units. The task units allow the model to respond to the appropriate dimension (word or colour). To simulate word reading as

Figure 7: Cohen, Dunbar, and McClelland's (1990) strength of association model of Stroop performance.



more practiced than colour naming, the word pathway in Cohen et al.'s model receives more training cycles than the colour pathway. Consequently, the word pathway has stronger connections between the input and response units than does the colour pathway. The trained model successfully simulates the *presence* of a Stroop effect and the *absence* of a reverse Stroop effect (the standard effects when the response is vocal).

This model is combined here with an arguably important (but generally neglected) element of Logan's (1988) *instance* theory: the *specific* response to the target. The word pathway and the colour pathway in Cohen et al.'s (1990) model are meant to reflect S-R learning that has occurred over a person's lifetime. The information contained in these "*instances"* is specified by Logan (1988):

> "the goal the participant was trying to attain, the stimulus encountered in pursuit of the goal, the interpretation given to the stimulus with respect to that goal, *and the response made to the stimulus.*"
>
> Logan (1988, p. 495, *italics mine*).

Importantly, if the stimulus is encountered again in the context of the same goal, some proportion of the processing episodes it participated in will be retrieved. Moreover, the number of instances *retrieved* on any given trial is directly proportional to how similar the current context is to the context in which the episode was created.

As noted earlier, Cohen et al. (1990) have shown that when the response is vocal, their model simulates results from both Stroop and Reverse Stroop tasks. What happens when the response is non-vocal, as in the case of pointing to a word?

3.2.1 When the response consists of pointing

The contention here is that there are two consequences when the response consists of pointing. First, according to Logan's instance theory, both the colour and word "pathways" (instances) will be less influential given their dissimilarity to the current task. That is, there will be fewer instances within each pathway that are "similar enough" to the task afforded by the experiment. Computationally, a reduction in the connection weights across both the colour and word pathways approximates this notion. More realistically, the reduction in connection weights should be larger for the word pathway because words, particularly colour *words* like "yellow" and "blue" for example, are less often used to point to an object whereas colours themselves are pointed at regularly (e.g., look at the blue house). That is, we are more likely to point to a referent colour than the referent (colour) *word*. In this limited sense, pointing to colours is more practiced than pointing to colour words. In any case, the specific response called for here – using a mouse to point – is no more practiced for these words than for these colours. Hence, the standard asymmetry in which reading a word aloud is more practiced than naming a colour is absent, allowing the colour an opportunity to interfere with selecting a response to the word.

One assumption that underlies virtually all theories of Stroop performance is the notion that responding to words is more practiced than responding to colours. This is certainly true when the response is vocal. However, in the current context – responding with a highly novel response – that asymmetry is essentially neutralized. Because both words and colours are essentially equal in terms of response strength, virtually symmetric interference is observed. This is evident in Durgin (2000) where he obtained 11 ms of Stroop interference when matching the colour of the Stroop stimulus to a colour patch that varied in location from trial to trial compared to the 18 ms of reverse Stroop interference obtained in the present Experiment 3.

For the purpose of modeling, I replicated Durgin (2000) in one of the three conditions from Experiment 7 and obtained 23 ms of interference and 6 ms (*n.s.*) of facilitation when participants made an "untranslated" colour-response (i.e., a Stroop task where the participant matched the colour of the Stroop word to a colour patch whose location varied from trial to trial). I also used two additional conditions to provide an adequate test of the computational model that follows. These two other conditions *required* a translation (i.e., respond to the colour by pointing to a word; respond to the word by pointing to a colour).

3.3 Experiment 7

3.3.1.1 Method

3.3.1.1.1 Participants

Sixty undergraduates from the University of Waterloo were tested individually and paid for their participation. Twenty participants served in each condition.

3.3.1.1.2 Condition 1: Responding to the colour with a word response

The stimuli and procedure were identical to Experiment 3 except that (a) participants were told to respond to the display colour of the stimulus rather than the word and (b) neutral trials consisted of the word TABLE displayed in one of the four colours.

3.3.1.1.3 Conditions 2 and 3: Colours at the response locations

The response colour locations were 2.7° from fixation but a response was not registered until the mouse cursor moved 2.9° diagonally from fixation to be consistent with the word response conditions. The four 100 px^2 colour squares serving as response colours appeared in blue, green, red, and yellow (approximately 4.6° square when viewed at approximately 60 cm). The location of these response colours varied randomly from trial to trial. The only difference between Conditions 2 and 3 was that one group of participants was told to respond to the display colour of the stimulus (neutral trials as in Condition 1) whereas the other group responded to the word itself (neutral trials as in Experiment 3). All other details were identical to Experiment 3.

3.3.2 Results

The subject's mean RT in each condition served as their measure of central tendency. Mean RTs and mean percentage errors can be seen in Table 2. The results of Experiment 4 were also included in the ANOVA which consisted of a 2 (Task: Stroop vs. Reverse Stroop) x 2 (Translation: translated vs. untranslated) x 3 (Condition: congruent, neutral, incongruent) analysis with Task and Translation as between-subjects factors and condition as a within-subjects factor. In RTs, all of the main effects and two-way interactions were highly significant (*p*s < .001; the ANOVA table

Table 2: Mean RTs and mean percent errors for the manual condition in Experiments 4 and 7. Standard deviations are shown in parentheses.

		Incongruent		Neutral		Congruent		Interference		Facilitation	
RTs	Reverse Stroop Translated	776	(88)	724	(87)	671	(83)	53	(35)	52	(33)
	Reverse Stroop Untranslated	836	(95)	818	(93)	819	(100)	18	(33)	-1	(41)
	Stroop Translated	1146	(170)	1037	(192)	994	(168)	109	(65)	43	(53)
	Stroop Untranslated	624	(62)	593	(60)	583	(46)	31	(38)	10	(30)
Errors	Reverse Stroop Translated	4.7	(3.1)	2.1	(2.1)	1.3	(2.1)	2.6	(2.2)	0.8	(1.9)
	Reverse Stroop Untranslated	2.4	(2.4)	1.7	(2.5)	2.1	(2.4)	0.7	(2.6)	-0.3	(2.2)
	Stroop Translated	6.3	(4.3)	2.4	(2.5)	3.1	(2.1)	3.9	(3.8)	-0.7	(2.8)
	Stroop Untranslated	2.5	(2.1)	0.9	(1.6)	0.5	(1.2)	1.6	(2.8)	0.4	(1.9)

is shown in Appendix H). The three-way interaction was marginal, $F(2, 172) = 2.80$, $MSe = 924$, $p < .07$. Nonetheless, planned t-tests measuring interference and facilitation within each of the conditions were conduced. In the Reverse Stroop/Translated condition, there was a 53 ms interference effect, $t(19) = 6.94$, $p < .001$, and a 52 ms facilitation effect, $t(19) = 7.23$, $p < .001$. In the Reverse Stroop/Untranslated condition, there was a 18 ms interference effect, $t(29) = 2.97$, p < .01; the -1 ms facilition effect was not reliable (t < 1). In the Stroop/Translated condition, there was a 109 ms interference effect, $t(19) = 7.75$, $p < .001$ and a 43 ms facilitation effect $t(19) = 3.76$, $p < .001$. Finally, in the Stroop/Untranslated condition, there was a 31 ms interference effect, $t(19) = 3.74$, $p < .001$; the 10 ms facilitation effect did not reach conventional significance levels, $t(19) = 1.59$, $p = .129$.

3.3.2.1 Comparison of interference and facilitation effects

Follow-up Neuman-Keuls contrasts comparing the sizes of the interference and facilitation effects across each of the 4 conditions were conducted. The results of this analysis are shown in Table 3. To summarize, all of the interference effects were statistically different from each other; all of the facilitation effects were statistically different from each other except in the untranslated conditions (i.e., 1 ms does not differ from 10 ms) and the translated conditions (i.e., 43 ms does not differ from 52 ms).

Table 3: The difference in the sizes of the interference and facilitation effects (in ms) across conditions in Experiments 4 and 7.

Interference	RS.U	S.U	RS.T	S.T	Critical Value
RS.U (18)	-	13*	35*	91*	
S.U (31)		-	22*	78*	16.5
RS.T (53)			-	56*	15.1
S.T (109)				-	12.6
Facilitation	**RS.U**	**S.U**	**S.T**	**RS.T**	**Critical Value**
RS.U (1)	-	9	42*	51*	
S.U (10)		-	33*	42*	15.4
S.T (43)			-	9	14.0
RS.T (52)				-	11.7

* $p < .05$

RS.U = Reverse Stroop untranslated

S.U = Stroop untranslated

RS.T = Reverse Stroop translated

S.T = Stroop translated

Critical values are based on a Neuman-Keuls analysis where $MS_{E\mathit{interference}}$ is 1795 and $MS_{E\mathit{facilitation}}$ is 1558 and *df* is 86.

3.4 Model details

As an existence proof of the theory described in Section 3.1, I implemented a four-response version of the network described in Cohen et al. (1990) which is shown in Figure 8. The operation of this model is relatively transparent. As in virtually all cognitive models, units within the network update their activations on the basis of a weighted sum of the input they receive from units at lower levels in the network. Mathematically, the net input at time t $(t > 0 \in \mathrm{I})$ for unit_j (at level_n) equals:

$$\text{net}_j(t) = \sum_i a_i(t) w_{ij} \tag{1}$$

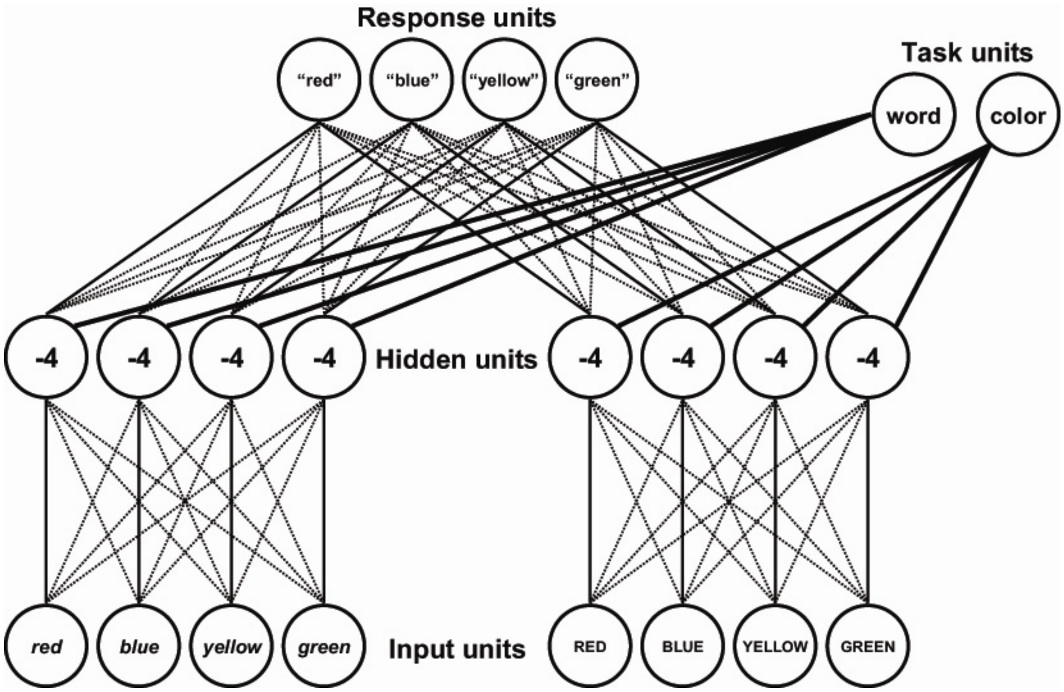
where $a_i(t)$ is the activation of each unit_i (at $\text{level}_{n\text{-}1}$) from which unit_j received input and w_{ij} is the strength of the connection weight between each unit_i through unit_j. Processing in the system is cascaded. That is, the activation of a unit is a running average of its net input over time:

$$a_j(t) = \overline{\text{net}}_j(t) = \tau \cdot \text{net}_j(t) - (\tau - 1)\overline{\text{net}}_j(t-1) \tag{2}$$

where $\overline{\text{net}}_j(t)$ is the average of the net input to unit_j over time, $\text{net}_j(t)$ is the net input to unit_j at time t, and τ is the cascade rate $(0 < \tau \leq 1)$. When τ is small, activation within the unit will change slowly; when τ is large, it will change more quickly.

One problem with having this network cascade is that activation in the model is linear: The activation of a unit is a weighted sum of the inputs in receives. Such networks suffer from fundamental computational limits (see Rumelhart, Hinton, &

Figure 8: The four-choice response network utilized in the simulation.



McClelland, 1986, for a discussion). This is easily overcome by introducing nonlinearity into processing. Typically, this is done using a sigmoid function (see Figure 9) to calculate the activation of a unit based on its instantaneous net input:

$$a_j(t) = \text{logistic}[\text{net}_\text{j}(t)] = \frac{1}{1 + e^{-\text{net}_\text{j}(t)}} \tag{3}$$

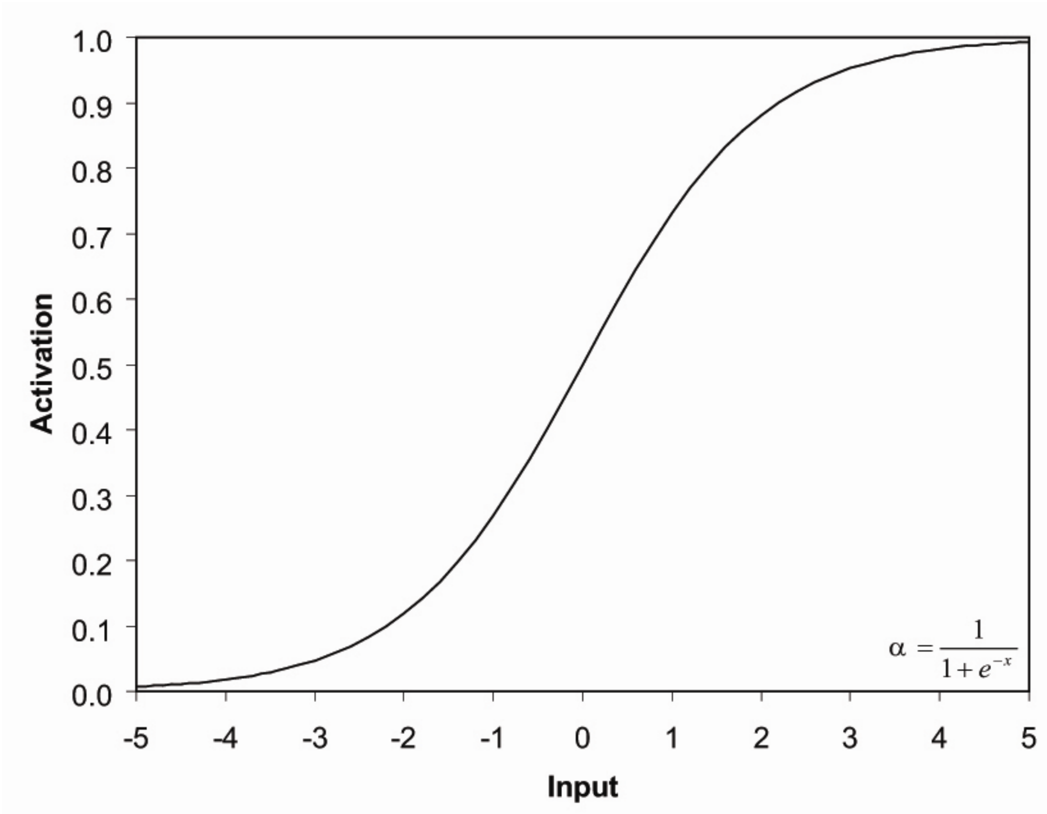
where $\text{net}_j(t)$ is given by Equation 1. This function constrains activation values between 0 and 1 (see Figure 9). This nonlinearity provides important behaviors such as tuning the nodes to be relatively sensitive at intermediate input values (e.g., −1.2 to +1.2) but insensitive at more extreme inputs (e.g., <−1.2 and >+1.2). However, it does not exhibit a gradual buildup of activation over time. The dynamic properties of the cascade model can be introduced if we assume, as the cascade model did, that the net input to a unit is averaged over time before the activation value is calculated. This gives us the following activation rule:

$$a_j(t) = \text{logistic}[\overline{\text{net}}_\text{j}(t)] \tag{4}$$

where $\overline{\text{net}}_j(t)$ is defined by Equation 2.

Now, activation builds up slowly over time (as controlled by the cascade rate, τ) and is constrained to a value between 0 and 1. The only thing the model cannot do is determine a response.

Figure 9: The sigmoid function. Note that inputs ranging between -1.2 and 1.2 produce nearly linear changes in activation.



3.4.1 Response selection

The model uses principles from a random walk (Link, 1975) and a diffusion process (Ratcliff, 1978) to select its ultimate response. Specifically, each potential response is paired with an evidence accumulator that takes its input from the output units of the network. At the beginning of each trial, the evidence accumulators are set to 0, and at each time-step of processing (a cycle), evidence accumulates as a function of the activation in the relevant output node. The amount of evidence accumulated for response *i* is given by the formula:

$$\text{evidence}_i = \alpha \cdot [act_i - \max(act_{i \neq j})] \tag{5}$$

where α determines the rate of evidence accumulation, act_i is the activation in output unit *i*, and $\max(\text{act}_{i \neq j})$ is the maximum activation of the other output units. Taking the difference between activation in the output unit of interest and in the other output unit with the strongest activation allows evidence in the response nodes to separate more quickly as the activation in the output nodes begins to more clearly differentiate between potential responses. A response is generated when one of the accumulators reaches a fixed threshold. For all of the present simulations, the value of α varied (see Section 3.5.1), and the value of the threshold was 1.0.

3.5 Simulation details

Given that we simply do not know how to accurately introduce noise into these PDP models (e.g., Mewhort, Braun, & Heathcoate, 1992), no source of noise was included; performance was entirely deterministic. Thus, a single simulation was run for each of the four conditions in Experiments 4 and 7. The only differences between the parameter sets were those to account for translation components and visual search components as discussed in Sections 3.5.1 and 3.5.2 below.

For the purposes of this thesis, I was not concerned with how the model learns to identify the word and colour. Thus, rather than obtain the connection weights through a training algorithm, I handset them to the values reported by Cohen et al. (1990; Figure 3). Importantly, despite the increase in the number of response nodes, my implementation exactly reproduces the data seen in Cohen et al. Figure 5b. Next, to approximate the idea that pointing to (colour) words has less in common with reading them aloud than pointing to colours has to do with naming them, I reduced the connection weights in the word pathway to 60% of their original values and the connection weights in the colour pathway to 85% of their original values. This change was sufficient to produce reverse Stroop interference of the magnitude observed in Experiment 3 reported here, but also to maintain the (albeit reduced) asymmetry in interference and facilitation between the two tasks when the response consists of pointing rather than verbalizing aloud.

Two additional assumptions are required to explain all of the data. First, "translation" clearly affects performance; the model must be adjusted to accommodate this. Second, the model does not take into consideration that determining *what* the response is may be different from determining *where* to make the response. This is important because the response locations varied on a trial-to-trial basis in Experiments 4 and 7.

3.5.1 Accounting for a translation

As discussed in the introduction of this chapter (p. 44), a translation can be conceptualized as a difficulty in maintaining a goal. In the context of the model, this is accomplished by adjusting two parameters. Thus, in the model, translation affects (a) the cognitive control mechanism involved in maintaining the goal set and (b) how fast evidence for a particular response is accumulated (which is likely indirectly linked to aspects of goal representation). First, when a translation is required, it affects the system's ability to maintain the current task set. In the context of the model, this is controlled by the task input. For example, if in the context of an untranslated response the task input is 1.0, I propose that in the context of a translated response the task input is a value less than 1.0. For these simulations, the task input was set to .825.

Second, I claim that this loss of a vivid representation of the goal makes it difficult to accumulate evidence for a particular response. In the context of the model, this is controlled via the α parameter in Equation 5. In the context of an untranslated response, $\alpha = .100$; in the context of a translated response, $\alpha = .065$.

3.5.2 The visual search component

In Experiments 4 and 7, there clearly is a visual search component. That is, after (or during) computing *what* the correct response is, participants must then locate *where* that response option is located on the screen given that the response locations varied randomly from trial to trial. However, it is well documented that visual search times are highly dependent upon (a) what the target stimulus is (e.g., Treisman & Gelade, 1980) and (b) how similar the target is to the distracter items in the display (e.g., Duncan & Humphreys, 1989). In the context of these experiments, the search consisted of either finding a colour patch among several colour patch distracters (i.e., responding to the colour or the word by pointing to a colour patch) or finding a word among several word distracters (i.e., responding to the colour or the word by pointing to a word).

A small sampling of the visual search literature is enough to show that finding a colour (e.g., RED) among multiple colour distractors (e.g., GREEN, YELLOW, BLUE) is easy; RT is nearly independent of set size (i.e., shallow search slope; see D'Zmura, 1991). In contrast, finding a word (e.g., *red*) among multiple word distractors (e.g., *green, yellow, blue*) is difficult; RT rapidly increases as a function of set size (i.e., steep search slope; see Flowers & Lohr, 1985). For the purpose of simplicity, I assume that the visual search process(es) do not interact with what the correct response is. Thus, overall cycle time in the model is given by the equation:

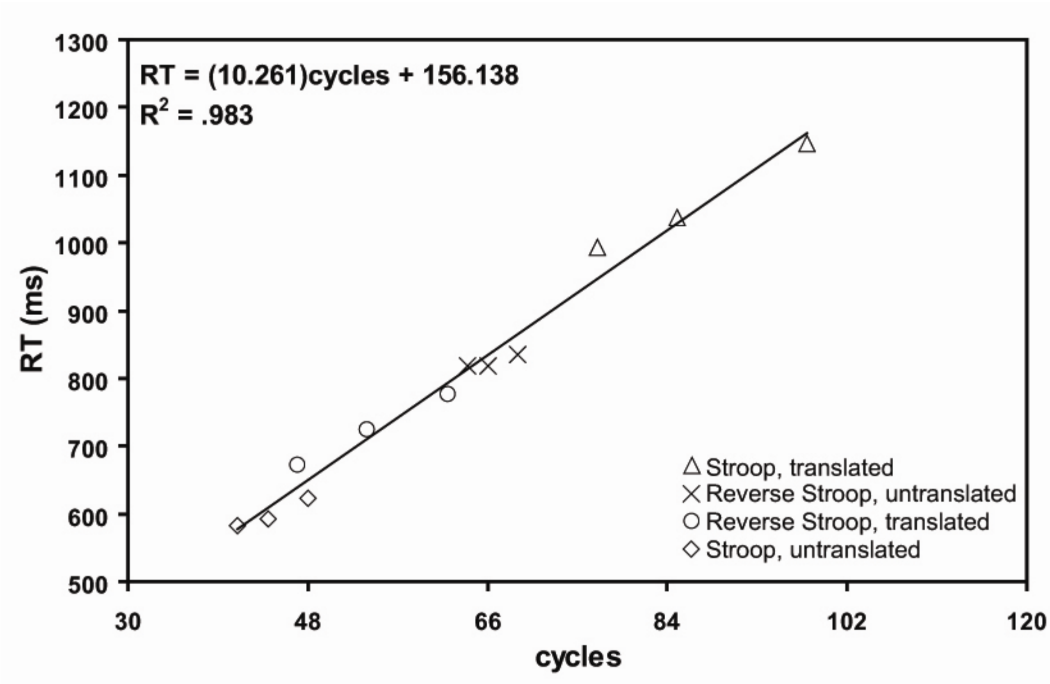
$$cycles = output + c_{searchtime} \quad (6)$$

where *output* is the number of cycles produced by the model and $c_{searchtime}$ is a constant representing how long the visual search process takes. When searching for a colour (i.e., making a response by pointing to a colour patch), $c_{searchtime}$ was 0; when searching for a word (i.e., making a response by pointing to a word), $c_{searchtime}$ was 28.

3.5.3 Simulation results

Figure 10 shows a regression plotting the RTs in Experiments 4 and 7 against the number of cycles until response in the model. The fit of the model across all twelve

Figure 10: A regression analysis plotting the number of cycles in each condition against the RT observed in Experiments 4 and 7.



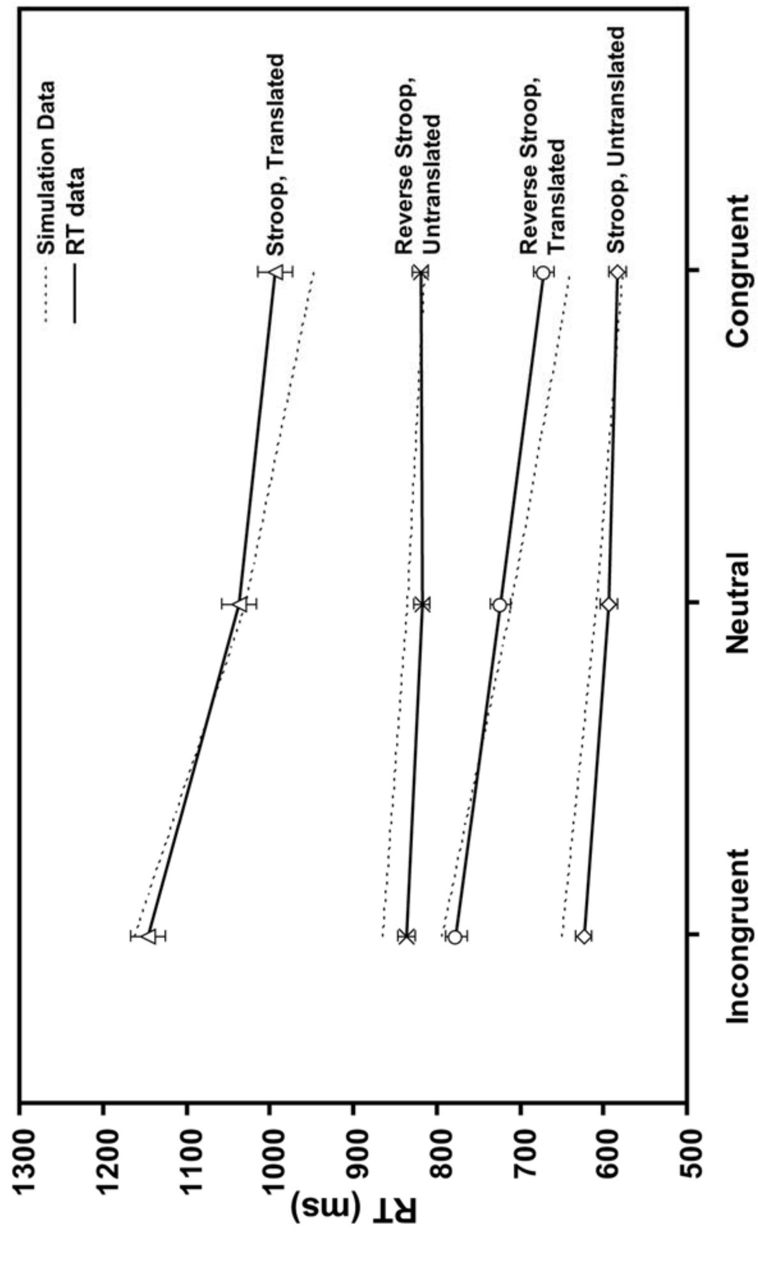
points is quite good and explains 98.3% of the variance. Importantly, both the slope (10.261) and intercept (156.138) are positive.

Figure 11 plots the data slighting differently. Here, the solid line represent the RTs observed in Experiments 4 and 7 and the dotted line represents a linear transformation of the number of cycles in condition. Not noted on the graph is that the simulation accounts for 94.9% of the variance in the size of the facilitation and interference effects. The exact parameter set used to obtain these results is shown in Appendices K and L.

3.5.4 Discussion

Translation is a central issue in that it stresses the importance of the nature of the internal representation, an issue which is all too often overlooked (e.g., for ease of implementation as in Cohen et al.'s, 1990, computational model). Here, I provide a plausible mechanism for how a translation might affect performance. Specifically, I claim that a translation hinders the systems' ability to maintain an adequate representation of the task goal. Although this claim is not by any means novel (e.g., Ach, 1910), this is the first time it has been implemented in a computational model of Stroop performance. I modeled the idea by (a) reducing the amount of resources available to the mechanism which maintains the task set and (b) as a result, reducing the rate at which evidence for a specific response accumulates. Whether this account of the Reverse Stroop and Stroop tasks prevails, a comprehensive account of these

Figure 11: Simulation results which highlight the interference and faciliation effects in each of the four conditions (Stroop/translated, Stroop/untranslated, Reverse Stroop/translated, and Reverse Stroop/untranslated) from Experiments 4 and 7. Solid lines represent RTs and dotted lines represent the simulation.



tasks should encompass both (a) the key principle of strength of association between a stimulus and its *specific* response and (b) the *specifics* of the code used to represent each dimension internally.

3.5.5 Conclusion

In summary, this thesis reports three major findings. First, it demonstrates that a Reverse Stroop effect (Experiments 1-6) and a Stroop effect (Experiment 7) can occur in the absence of a translation. This is important because the implicit, and often explicit, assumption is that Stroop effects occur only when a translation occurs. Second, it shows that, in the context of the Reverse Stroop task, the effect observed is entirely the result of response conflict (Experiments 5 & 6). Last, the simulation provides a coherent account for (a) how a Stroop and Reverse Stroop effects arise in the absence of a translation and (b) how a translation affects the size of the Stroop and Reverse Stroop effects.

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Footnotes

[1] Strictly speaking, Roelofs (2003) is not a translation model per se. However, the way that manual responses are modeled is consistent with a translation model in that only if the responses are verbally mediated is a Stroop effect observed.

[2] There is other evidence that the keys are verbally mediated in the context of an untranslated colour-response. For example, Chmiel (1984) showed a reduced Stroop effect under concurrent articulation (but see Besner, Davies, & Daniels, 1981). In addition, if the need to verbally mediate the keys is removed, there is no *Stroop* effect. For example, Hommel (2004) trained subjects to colour-code the response buttons and eliminated the Stroop effect.

[3] Traditionally, semantic effects are viewed as affecting an early component and response effects as affecting a relatively late (e.g., response selection) component.

[4] Mauchley's test indicated that the assumption of sphericity was violated. Here I report the Greenhouse-Geisser correction. The difference was still significant using a lower-bound correction ($p < .01$).

[5] Logan's (1988) model is not a model of the Stroop effect *per se* but a general model of automaticity.

[6] Logan (1988) assumes that the retrieval of instances from memory is automatic.

[7] One can explain the present data in the context of a translation account if the colour is assumed to have unconditional access to the lexicon even when a translation is not

required (see Sugg & McDonald, 1994, p. 660 and their Figure 4) in the same way that Sugg and McDonald assume that responding to the colour by pressing a colour-labeled button (an untranslated response) produces interference because the word is processed and has unconditional access to semantics. The problem with this approach is that classifying a response as translated or not becomes meaningless in the context of the very theory which claims that whether a response is translated or not is central to explaining performance.

[8] The model still produces a small (but significant) facilitation effect that I did not observe in the human data.

Appendix A

Experiment 1 subject data

Table 1: Participant data from Experiment 1: Manual Condition

	RT			%E		
SJ	C	I	RSE	C	I	RSE
1	729	776	47	0.0	3.1	3.1
2	574	616	42	4.2	5.2	1.0
3	706	695	-10	0.0	2.1	2.1
4	618	725	107	2.1	5.2	3.1
5	576	615	40	2.1	1.0	-1.0
6	627	615	-12	0.0	3.1	3.1
7	584	617	33	1.0	2.1	1.0
8	509	565	55	3.1	4.2	1.0
9	747	788	41	1.0	3.1	2.1
10	668	678	10	4.2	5.2	1.0
11	579	605	26	2.1	5.2	3.1
12	510	618	108	6.3	3.1	-3.1
13	515	544	29	1.0	0.0	-1.0
14	534	557	23	3.1	4.2	1.0
15	566	600	33	2.1	7.3	5.2
16	749	730	-20	3.1	1.0	-2.1
17	534	588	54	1.0	3.1	2.1
18	525	534	9	0.0	1.0	1.0
19	605	630	25	1.0	4.2	3.1
20	575	609	34	1.0	3.1	2.1
21	605	719	114	3.1	6.3	3.1
22	650	713	63	2.1	1.0	-1.0
23	695	648	-47	5.2	1.0	-4.2
24	578	606	27	3.1	4.2	1.0
25	1078	1169	91	2.1	4.2	2.1
26	789	788	0	4.2	1.0	-3.1
27	767	805	38	1.0	1.0	0.0
Mean	**637**	**672**	**36**	**2.2**	**3.2**	**1.0**
SD	122	127	39	1.6	1.9	2.3
			t= 4.80			*t*= 2.20
			***p*= .000**			***p*= .037**
			SE= 7.4			*SE*= 0.4

C = congruent, I = incongruent, RSE = I – C

Table 2: Participant data from Experiment 1: Vocal Condition

	RT			%E		
SJ	C	I	RSE	C	I	RSE
1	416	420	4	0.0	1.1	1.1
2	485	484	-1	0.0	0.0	0.0
3	453	454	1	1.1	0.0	-1.1
4	472	473	1	0.0	0.0	0.0
5	497	500	4	0.0	0.0	0.0
6	409	416	7	0.0	0.0	0.0
7	464	464	0	0.0	0.0	0.0
8	484	483	-1	0.0	0.0	0.0
9	444	459	15	0.0	0.0	0.0
10	426	419	-7	0.0	0.0	0.0
11	356	357	1	0.0	0.0	0.0
12	506	514	8	0.0	0.0	0.0
13	542	549	7	0.0	1.1	1.1
14	520	521	1	0.0	0.0	0.0
15	607	623	16	0.0	0.0	0.0
16	476	483	7	0.0	0.0	0.0
17	499	499	0	0.0	0.0	0.0
18	491	497	6	0.0	0.0	0.0
19	535	533	-2	0.0	0.0	0.0
20	511	505	-6	0.0	0.0	0.0
21	491	483	-8	0.0	1.1	1.1
22	423	429	6	0.0	0.0	0.0
23	491	490	-1	0.0	0.0	0.0
24	395	395	0	0.0	0.0	0.0
25	471	473	2	0.0	0.0	0.0
26	419	413	-5	0.0	0.0	0.0
27	456	458	2	0.0	0.0	0.0
Mean	**472**	**474**	**2**	**0.0**	**0.1**	**0.1**
SD	52	54	6	0.2	0.4	0.4
			t= 1.69			*t*= 0.97
			***p*= .103**			***p*= .339**
			SE= 1.2			*SE*= 0.1

C = congruent, I = incongruent, RSE = I – C

Appendix B

Experiment 2 subject data

Table 3: Participant data from Experiment 2

	RT			%E		
SJ	C	I	RSE	C	I	RSE
1	525	563	38	0.0	9.0	9.0
2	598	623	26	2.0	13.0	11.0
3	509	534	25	2.0	1.0	-1.0
4	632	687	56	2.0	3.0	1.0
5	772	693	-79	0.0	1.0	1.0
6	924	1057	133	0.0	0.0	0.0
7	562	576	14	0.0	3.0	3.0
8	650	654	4	6.0	4.0	-2.0
9	684	702	18	4.0	1.0	-3.0
10	511	503	-8	6.0	5.0	-1.0
11	666	684	18	2.0	2.0	0.0
12	674	845	171	4.0	9.0	5.0
13	674	653	-21	2.0	2.0	0.0
14	688	668	-20	2.0	5.0	3.0
15	558	621	63	13.0	9.0	-4.0
16	659	661	2	4.0	3.0	-1.0
17	814	751	-63	4.0	3.0	-1.0
18	735	653	-82	2.0	10.0	8.0
19	902	947	44	0.0	0.0	0.0
20	919	1069	150	0.0	0.0	0.0
21	878	887	8	4.0	3.0	-1.0
22	860	908	47	0.0	1.0	1.0
23	653	642	-11	13.0	6.0	-7.0
24	955	990	35	0.0	1.0	1.0
25	729	715	-14	0.0	11.0	11.0
26	668	734	66	2.0	3.0	1.0
27	561	587	26	2.0	4.0	2.0
28	582	590	8	4.0	5.0	1.0
29	669	707	38	0.0	3.0	3.0
30	530	552	22	4.0	2.0	-2.0
Mean	**691**	**715**	**24**	**2.8**	**4.1**	**1.3**
SD	133	153	57	3.3	3.5	4.1
			t= 2.29			*t*= 1.69
			***p*= .030**			***p*= .101**
			SE= 10.4			*SE*= 0.7

C = congruent, I = incongruent, RSE = I – C

Appendix C

Experiment 3 subject data

Table 4: Participant data from Experiment 3 (RTs)

SJ	C	N	I		Interference	Facilitation	RSE
1	612	601	586		-15	-11	-26
2	446	470	473		4	24	28
3	571	567	598		30	-4	26
4	846	826	788		-38	-20	-58
5	644	635	699		64	-9	55
6	537	523	547		24	-14	11
7	540	561	602		41	21	62
8	538	561	594		33	23	56
9	532	556	570		14	24	38
10	571	611	598		-12	40	27
11	600	628	645		18	27	45
12	741	685	719		35	-56	-22
13	710	681	713		32	-28	4
14	754	762	777		16	8	24
15	803	799	832		32	-4	28
16	640	666	703		37	26	62
17	768	882	910		28	113	141
18	609	695	658		-36	86	50
19	691	703	709		6	11	18
20	771	776	843		67	5	73
21	646	732	748		16	86	102
22	480	503	509		6	23	29
23	523	523	539		16	0	16
24	594	589	630		41	-4	37
Mean	**632**	**647**	**666**		**19**	**15**	**34**
SD	108	109	112		26	38	41
				t=	3.58	1.99	4.15
				***p*=**	**.002**	**.059**	**.000**
				SE=	5.3	7.7	8.3

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 5: Participant data from Experiment 3 (percent errors)

SJ	C	N	I		Interference	Facilitation	RSE
1	4.2	6.3	4.9		-1.4	2.1	0.7
2	6.3	6.3	2.1		-4.2	0.0	-4.2
3	2.1	2.1	2.1		0.0	0.0	0.0
4	0.0	0.0	0.7		0.7	0.0	0.7
5	0.0	2.1	2.1		0.0	2.1	2.1
6	0.0	0.0	1.4		1.4	0.0	1.4
7	0.0	2.1	2.8		0.7	2.1	2.8
8	0.0	0.0	1.4		1.4	0.0	1.4
9	0.0	0.0	2.8		2.8	0.0	2.8
10	4.2	6.3	3.5		-2.8	2.1	-0.7
11	10.4	10.4	4.9		-5.6	0.0	-5.6
12	4.2	2.1	3.5		1.4	-2.1	-0.7
13	4.2	2.1	2.1		0.0	-2.1	-2.1
14	6.3	8.3	6.3		-2.1	2.1	0.0
15	2.1	2.1	2.8		0.7	0.0	0.7
16	8.3	2.1	7.6		5.6	-6.3	-0.7
17	2.1	0.0	0.7		0.7	-2.1	-1.4
18	2.1	2.1	1.4		-0.7	0.0	-0.7
19	2.1	2.1	2.1		0.0	0.0	0.0
20	0.0	0.0	0.7		0.7	0.0	0.7
21	2.1	6.3	2.8		-3.5	4.2	0.7
22	0.0	2.1	5.6		3.5	2.1	5.6
23	8.3	0.0	3.5		3.5	-8.3	-4.9
24	0.0	0.0	0.7		0.7	0.0	0.7
Mean	**2.9**	**2.7**	**2.8**		**0.1**	**-0.2**	**0.0**
SD	3.1	3.0	1.9		2.5	2.7	2.4
				t=	0.28	0.32	0.06
				***p*=**	**.781**	**.753**	**.954**
				SE=	0.5	0.5	0.5

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Appendix D

Experiment 4 subject data

Table 6: Participant data from Experiment 4 (RTs)

SJ	C	N	I		Interference	Facilitation	RSE
1	982	1013	1006		-7	32	24
2	813	848	859		11	35	46
3	818	804	832		28	-13	14
4	801	792	825		32	-9	24
5	776	749	789		40	-27	12
6	721	743	750		7	21	29
7	923	988	963		-25	65	40
8	685	682	708		26	-3	23
9	891	888	891		3	-3	0
10	712	691	695		4	-21	-17
11	763	733	699		-35	-29	-64
12	732	739	816		77	7	84
13	815	817	843		26	2	28
14	586	672	655		-17	86	69
15	774	835	808		-27	61	34
16	893	911	881		-30	18	-12
17	803	870	845		-25	67	42
18	857	784	821		37	-73	-36
19	916	870	863		-7	-46	-52
20	753	711	750		39	-41	-3
21	843	855	906		50	12	63
22	909	841	902		61	-68	-7
23	970	920	1015		95	-51	44
24	892	889	906		17	-3	15
25	832	872	902		30	40	70
26	682	688	752		63	7	70
27	1029	978	1009		32	-51	-20
28	749	721	763		42	-28	14
29	953	935	930		-5	-18	-23
30	701	691	688		-3	-10	-13
Mean	**819**	**818**	**836**		**18**	**-1**	**17**
SD	103	99	99		33	40	37
				t=	2.98	0.19	2.45
				***p*=**	**.006**	**.851**	**.021**
				SE=	6.0	7.4	6.8

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 7: Participant data from Experiment 4 (percent errors)

SJ	C	N	I		Interference	Facilitation	RSE
1	0.0	0.0	2.1		2.1	0.0	2.1
2	0.0	2.1	1.4		-0.7	2.1	1.4
3	2.1	4.2	9.0		4.9	2.1	6.9
4	0.0	0.0	0.7		0.7	0.0	0.7
5	4.2	6.3	6.3		0.0	2.1	2.1
6	0.0	0.0	0.7		0.7	0.0	0.7
7	0.0	2.1	0.7		-1.4	2.1	0.7
8	4.2	0.0	1.4		1.4	-4.2	-2.8
9	4.2	0.0	2.1		2.1	-4.2	-2.1
10	2.1	0.0	0.0		0.0	-2.1	-2.1
11	2.1	2.1	0.7		-1.4	0.0	-1.4
12	0.0	0.0	2.1		2.1	0.0	2.1
13	0.0	4.2	1.4		-2.8	4.2	1.4
14	4.2	0.0	1.4		1.4	-4.2	-2.8
15	0.0	0.0	2.1		2.1	0.0	2.1
16	2.1	0.0	3.5		3.5	-2.1	1.4
17	4.2	2.1	3.5		1.4	-2.1	-0.7
18	2.1	4.2	4.9		0.7	2.1	2.8
19	4.2	4.2	0.7		-3.5	0.0	-3.5
20	0.0	0.0	0.7		0.7	0.0	0.7
21	2.1	2.1	1.4		-0.7	0.0	-0.7
22	0.0	2.1	1.4		-0.7	2.1	1.4
23	8.3	10.4	5.6		-4.9	2.1	-2.8
24	0.0	0.0	0.7		0.7	0.0	0.7
25	2.1	0.0	9.0		9.0	-2.1	6.9
26	4.2	2.1	3.5		1.4	-2.1	-0.7
27	8.3	4.2	2.8		-1.4	-4.2	-5.6
28	2.1	0.0	0.7		0.7	-2.1	-1.4
29	0.0	0.0	0.7		0.7	0.0	0.7
30	0.0	0.0	2.1		2.1	0.0	2.1
Mean	**2.1**	**1.7**	**2.4**		**0.7**	**-0.3**	**0.3**
SD	2.4	2.5	2.4		2.5	2.2	2.7
				t=	1.50	0.87	0.70
				***p*=**	**.144**	**.393**	**.488**
				SE=	0.5	0.4	0.5

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Appendix E
Experiment 5 subject data

Table 8: Participant data from Experiment 5 (RTs)

SJ	ID	SC	RC		RC − ID	RC − SC	SC − ID
1	417	433	426		9	-7	16
2	496	521	530		34	9	25
3	456	476	508		52	32	20
4	405	403	430		25	27	-2
5	483	513	517		34	4	30
6	447	429	448		1	19	-18
7	878	907	886		8	-21	29
8	679	650	683		4	33	-29
9	567	570	588		21	18	3
10	461	464	458		-3	-6	3
11	590	593	640		50	47	3
12	495	511	523		28	12	16
13	448	448	469		21	21	0
14	460	452	485		25	33	-8
15	520	542	549		29	7	22
16	474	466	522		48	56	-8
17	660	647	659		-1	12	-13
18	577	557	592		15	35	-20
19	485	505	523		38	18	20
20	513	527	569		56	42	14
21	425	450	443		18	-7	25
22	457	452	465		8	13	-5
23	609	666	743		134	77	57
24	492	514	557		65	43	22
25	524	509	532		8	23	-15
26	516	530	542		26	12	14
27	497	504	523		26	19	7
28	599	539	552		-47	13	-60
29	809	669	729		-80	60	-140
30	470	472	484		14	12	2
31	470	466	477		7	11	-4
32	607	762	741		134	-21	155
33	764	696	728		-36	32	-68
34	397	387	394		-3	7	-10
35	595	573	636		41	63	-22
36	467	455	483		16	28	-12
Mean	**534**	**535**	**557**		**23**	**22**	**1**
SD	112	108	110		39	22	43
				t=	3.51	5.82	0.19
				***p*=**	**.001**	**.000**	**.849**
				SE=	6.5	3.7	7.1

ID = identity, SC = stimulus competition, RC = response competition

Table 9: Participant data from Experiment 5 (percent errors)

SJ	ID	SC	RC		RC − ID	RC − SC	SC − ID
1	1.7	3.3	2.5		0.8	-0.8	1.7
2	11.7	11.7	10.8		-0.8	-0.8	0.0
3	10.0	8.3	11.7		1.7	3.3	-1.7
4	3.3	0.0	5.8		2.5	5.8	-3.3
5	1.7	6.7	2.5		0.8	-4.2	5.0
6	1.7	0.0	9.2		7.5	9.2	-1.7
7	0.0	1.7	0.8		0.8	-0.8	1.7
8	3.3	3.3	4.2		0.8	0.8	0.0
9	1.7	0.0	0.8		-0.8	0.8	-1.7
10	6.7	3.3	0.8		-5.8	-2.5	-3.3
11	1.7	1.7	0.8		-0.8	-0.8	0.0
12	6.7	5.0	4.2		-2.5	-0.8	-1.7
13	0.0	3.3	0.0		0.0	-3.3	3.3
14	5.0	5.0	10.8		5.8	5.8	0.0
15	11.7	8.3	15.8		4.2	7.5	-3.3
16	3.3	5.0	1.7		-1.7	-3.3	1.7
17	0.0	0.0	0.8		0.8	0.8	0.0
18	5.0	6.7	3.3		-1.7	-3.3	1.7
19	1.7	1.7	4.2		2.5	2.5	0.0
20	1.7	3.3	9.2		7.5	5.8	1.7
21	5.0	1.7	4.2		-0.8	2.5	-3.3
22	5.0	0.0	5.0		0.0	5.0	-5.0
23	5.0	3.3	3.3		-1.7	0.0	-1.7
24	0.0	3.3	2.5		2.5	-0.8	3.3
25	0.0	0.0	0.0		0.0	0.0	0.0
26	0.0	5.0	9.2		9.2	4.2	5.0
27	0.0	1.7	0.8		0.8	-0.8	1.7
28	3.3	3.3	4.2		0.8	0.8	0.0
29	0.0	1.7	0.8		0.8	-0.8	1.7
30	3.3	3.3	2.5		-0.8	-0.8	0.0
31	3.3	1.7	2.5		-0.8	0.8	-1.7
32	8.3	3.3	2.5		-5.8	-0.8	-5.0
33	5.0	1.7	1.7		-3.3	0.0	-3.3
34	3.3	3.3	4.2		0.8	0.8	0.0
35	6.7	5.0	7.5		0.8	2.5	-1.7
36	6.7	1.7	8.3		1.7	6.7	-5.0
Mean	**3.7**	**3.3**	**4.4**		**0.7**	**1.1**	**-0.4**
SD	3.3	2.7	3.9		3.2	3.3	2.6
				t=	1.34	2.06	0.97
				***p*=**	**.188**	**.047**	**.341**
				SE=	0.5	0.5	0.4

ID = identity, SC = stimulus competition, RC = response competition

Appendix F
Experiment 6 subject data

Table 10: Participant data from Experiment 6 (RTs)

SJ	N	SC	RC		RC − N	RC − SC	SC − N
1	552	517	582		30	65	-35
2	372	378	398		26	20	6
3	569	531	565		-4	34	-38
4	500	510	541		41	31	10
5	491	481	487		-4	6	-10
6	433	449	447		14	-2	16
7	568	562	555		-13	-7	-6
8	518	498	539		21	41	-20
9	662	620	690		28	70	-42
10	438	437	455		17	18	-1
11	476	459	468		-8	9	-17
12	500	522	537		37	15	22
13	439	453	440		1	-13	14
14	526	522	544		18	22	-4
15	457	435	470		13	35	-22
16	480	488	512		32	24	8
17	487	484	519		32	35	-3
18	469	449	457		-12	8	-20
19	401	400	420		19	20	-1
20	400	415	408		8	-7	15
21	474	471	479		5	8	-3
22	451	447	451		0	4	-4
23	472	481	470		-2	-11	9
24	575	549	563		-12	14	-26
25	504	483	509		5	26	-21
26	486	498	500		14	2	12
27	486	520	509		23	-11	34
28	530	574	567		37	-7	44
29	515	548	526		11	-22	33
30	548	603	549		1	-54	55
31	500	527	549		49	22	27
32	474	470	478		4	8	-4
33	558	573	548		-10	-25	15
34	528	522	566		38	44	-6
35	470	470	469		-1	-1	0
36	438	409	409		-29	0	-29
Mean	**493**	**493**	**505**		**12**	**12**	**0**
SD	57	56	60		18	25	23
				t=	3.89	2.86	0.06
				***p*=**	**.000**	**.007**	**.953**
				SE=	3.1	4.1	3.8

N = neutral, SC = stimulus competition, RC = response competition

Table 11: Participant data from Experiment 6 (percent errors)

SJ	N	SC	RC		RC − N	RC − SC	SC − N
1	3.3	3.3	3.3		0.0	0.0	0.0
2	1.7	0.0	1.7		0.0	1.7	-1.7
3	0.0	0.0	0.8		0.8	0.8	0.0
4	1.7	0.0	2.5		0.8	2.5	-1.7
5	0.0	0.0	5.0		5.0	5.0	0.0
6	0.0	1.7	0.8		0.8	-0.8	1.7
7	1.7	0.0	0.8		-0.8	0.8	-1.7
8	8.3	6.7	5.8		-2.5	-0.8	-1.7
9	6.7	1.7	4.2		-2.5	2.5	-5.0
10	5.0	3.3	6.7		1.7	3.3	-1.7
11	1.7	10.0	2.5		0.8	-7.5	8.3
12	1.7	1.7	0.0		-1.7	-1.7	0.0
13	1.7	10.0	9.2		7.5	-0.8	8.3
14	1.7	0.0	5.0		3.3	5.0	-1.7
15	6.7	6.7	5.8		-0.8	-0.8	0.0
16	5.0	1.7	4.2		-0.8	2.5	-3.3
17	5.0	5.0	7.5		2.5	2.5	0.0
18	3.3	1.7	5.0		1.7	3.3	-1.7
19	3.3	6.7	6.7		3.3	0.0	3.3
20	3.3	1.7	1.7		-1.7	0.0	-1.7
21	5.0	5.0	7.5		2.5	2.5	0.0
22	1.7	0.0	1.7		0.0	1.7	-1.7
23	0.0	1.7	6.7		6.7	5.0	1.7
24	5.0	1.7	6.7		1.7	5.0	-3.3
25	1.7	3.3	3.3		1.7	0.0	1.7
26	1.7	5.0	3.3		1.7	-1.7	3.3
27	1.7	0.0	1.7		0.0	1.7	-1.7
28	8.3	3.3	2.5		-5.8	-0.8	-5.0
29	0.0	0.0	1.7		1.7	1.7	0.0
30	1.7	5.0	3.3		1.7	-1.7	3.3
31	6.7	5.0	4.2		-2.5	-0.8	-1.7
32	3.3	3.3	3.3		0.0	0.0	0.0
33	0.0	3.3	5.8		5.8	2.5	3.3
34	1.7	3.3	3.3		1.7	0.0	1.7
35	5.0	5.0	4.2		-0.8	-0.8	0.0
36	3.3	5.0	6.7		3.4	1.7	1.7
Mean	**3.0**	**3.1**	**4.0**		**1.0**	**0.9**	**0.1**
SD	2.4	2.7	2.3		2.7	2.5	2.9
				t=	2.27	2.25	0.19
				***p*=**	**.030**	**.031**	**.849**
				SE=	0.4	0.4	0.5

N = neutral, SC = stimulus competition, RC = response competition

Appendix G

Experiment 7 subject data

Table 12: Participant data from Experiment 7: Respond to the word by pointing to a colour patch (RTs)

SJ	C	N	I		Interference	Facilitation	RSE
1	710	749	814		65	39	104
2	597	611	690		78	15	93
3	558	618	739		122	59	181
4	793	877	894		17	84	101
5	607	664	676		12	57	69
6	682	749	801		52	67	119
7	697	697	813		117	0	117
8	658	670	666		-4	12	8
9	708	796	810		14	88	102
10	637	701	784		83	64	147
11	704	818	896		79	113	192
12	596	638	678		40	42	81
13	607	715	788		73	108	181
14	780	829	878		49	49	97
15	716	721	770		50	4	54
16	724	775	830		55	50	106
17	864	882	925		43	18	60
18	558	596	616		20	38	58
19	614	680	700		20	66	86
20	613	687	759		72	74	146
Mean	**671**	**724**	**776**		**53**	**52**	**105**
SD	82	85	86		34	32	47
				t=	6.94	7.23	10.07
				***p*=**	**.000**	**.000**	**.000**
				SE=	7.6	7.2	10.4

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 13: Participant data from Experiment 7: Respond to the word by pointing to a colour patch (percent errors)

SJ	C	N	I		Interference	Facilitation	RSE
1	0.0	0.0	2.8		2.8	0.0	2.8
2	6.3	4.2	7.6		3.5	-2.1	1.4
3	0.0	2.1	2.1		0.0	2.1	2.1
4	0.0	0.0	0.7		0.7	0.0	0.7
5	2.1	2.1	6.9		4.9	0.0	4.9
6	0.0	0.0	5.6		5.6	0.0	5.6
7	0.0	0.0	2.1		2.1	0.0	2.1
8	2.1	4.2	7.6		3.5	2.1	5.6
9	0.0	4.2	6.3		2.1	4.2	6.3
10	0.0	0.0	4.2		4.2	0.0	4.2
11	2.1	2.1	6.3		4.2	0.0	4.2
12	4.2	2.1	0.0		-2.1	-2.1	-4.2
13	2.1	0.0	1.4		1.4	-2.1	-0.7
14	0.0	2.1	8.3		6.3	2.1	8.3
15	0.0	2.1	2.8		0.7	2.1	2.8
16	0.0	0.0	4.2		4.2	0.0	4.2
17	0.0	2.1	5.6		3.5	2.1	5.6
18	0.0	2.1	1.4		-0.7	2.1	1.4
19	6.3	8.3	11.8		3.5	2.1	5.6
20	0.0	4.2	5.6		1.4	4.2	5.6
Mean	**1.3**	**2.1**	**4.7**		**2.6**	**0.8**	**3.4**
SD	2.1	2.1	3.0		2.2	1.8	2.8
				t=	5.34	2.03	5.36
				***p*=**	**.000**	**.057**	**.000**
				SE=	0.5	0.4	0.6

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 14: Participant data from Experiment 7: Respond to the colour by pointing to a colour patch (RTs)

SJ	C	N	I		Interference	Facilitation	RSE
1	561	563	601		38	2	39
2	662	739	764		24	77	101
3	544	550	608		58	6	64
4	521	516	523		7	-5	2
5	621	624	658		34	3	37
6	542	539	600		62	-4	58
7	614	620	649		30	6	35
8	608	595	665		70	-13	58
9	607	620	661		40	13	54
10	606	694	632		-61	87	26
11	630	591	693		102	-39	62
12	596	615	629		14	19	33
13	534	559	549		-11	25	15
14	631	651	668		18	19	37
15	527	532	598		66	5	71
16	575	549	591		42	-27	16
17	642	647	688		40	5	46
18	572	563	623		60	-9	51
19	549	567	549		-18	17	-1
20	511	529	526		-2	18	16
Mean	**583**	**593**	**624**		**31**	**10**	**41**
SD	45	58	60		37	29	25
				t=	3.74	1.59	7.30
				***p*=**	**.001**	**.129**	**.000**
				SE=	8.2	6.5	5.6

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 15: Participant data from Experiment 7: Respond to the colour by pointing to a colour patch (percent errors)

SJ	C	N	I		Interference	Facilitation	RSE
1	0.0	0.0	0.0		0.0	0.0	0.0
2	0.0	4.2	1.4		-2.8	4.2	1.4
3	2.1	0.0	1.4		1.4	-2.1	-0.7
4	0.0	0.0	0.0		0.0	0.0	0.0
5	0.0	0.0	5.6		5.6	0.0	5.6
6	0.0	4.2	0.7		-3.5	4.2	0.7
7	0.0	0.0	3.5		3.5	0.0	3.5
8	0.0	0.0	2.1		2.1	0.0	2.1
9	0.0	4.2	3.5		-0.7	4.2	3.5
10	0.0	0.0	4.9		4.9	0.0	4.9
11	0.0	0.0	5.6		5.6	0.0	5.6
12	0.0	0.0	0.0		0.0	0.0	0.0
13	4.2	2.1	6.3		4.2	-2.1	2.1
14	0.0	0.0	0.0		0.0	0.0	0.0
15	0.0	0.0	3.5		3.5	0.0	3.5
16	0.0	0.0	5.6		5.6	0.0	5.6
17	2.1	0.0	0.7		0.7	-2.1	-1.4
18	0.0	2.1	1.4		-0.7	2.1	1.4
19	0.0	0.0	2.1		2.1	0.0	2.1
20	2.1	2.1	2.1		0.0	0.0	0.0
Mean	**0.5**	**0.9**	**2.5**		**1.6**	**0.4**	**2.0**
SD	1.1	1.6	2.1		2.7	1.9	2.2
				t=	2.57	1.00	3.98
				***p*=**	**.019**	**.330**	**.001**
				SE=	0.6	0.4	0.5

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Table 16: Participant data from Experiment 7: Respond to the colour by pointing to a word (RTs)

SJ	C	N	I		Interference	Facilitation	RSE
1	1055	1079	1183		104	24	128
2	994	1011	1075		64	17	81
3	1137	1187	1245		59	49	108
4	960	1077	1228		151	117	268
5	771	755	966		211	-15	196
6	989	973	1042		69	-15	53
7	852	942	936		-6	90	83
8	811	875	958		83	64	147
9	1107	1146	1183		37	39	76
10	1230	1308	1383		75	78	152
11	849	936	1106		170	87	257
12	886	893	1002		109	7	116
13	999	932	1057		124	-67	58
14	782	853	976		123	71	194
15	894	886	1087		201	-9	193
16	1338	1493	1558		65	155	219
17	940	1000	1205		205	59	264
18	1321	1389	1427		38	68	107
19	996	1008	1107		99	12	111
20	969	1005	1200		195	36	231
Mean	**994**	**1037**	**1146**		**109**	**43**	**152**
SD	164	187	166		63	51	71
				t=	7.75	3.76	9.63
				***p*=**	**.000**	**.001**	**.000**
				SE=	14.0	11.5	15.8

C = congruent, N = neutral, I = incongruent
Interference = I – N, Facilitation = N – C, RSE = I – C

Table 17: Participant data from Experiment 7: Respond ot the colour by pointing to a word (percent errors)

SJ	C	N	I		Interference	Facilitation	RSE
1	0.0	0.0	0.0		0.0	0.0	0.0
2	0.0	2.1	2.8		0.7	2.1	2.8
3	4.2	8.3	22.2		13.9	4.2	18.1
4	6.3	6.3	3.5		-2.8	0.0	-2.8
5	4.2	2.1	8.3		6.3	-2.1	4.2
6	2.1	0.0	3.5		3.5	-2.1	1.4
7	4.2	4.2	5.6		1.4	0.0	1.4
8	4.2	0.0	6.9		6.9	-4.2	2.8
9	4.2	0.0	9.0		9.0	-4.2	4.9
10	2.1	2.1	4.2		2.1	0.0	2.1
11	6.3	2.1	6.9		4.9	-4.2	0.7
12	2.1	2.1	3.5		1.4	0.0	1.4
13	4.2	4.2	4.2		0.0	0.0	0.0
14	2.1	2.1	5.6		3.5	0.0	3.5
15	0.0	0.0	6.9		6.9	0.0	6.9
16	6.3	0.0	6.9		6.9	-6.3	0.7
17	2.1	6.3	9.7		3.5	4.2	7.6
18	2.1	0.0	6.3		6.3	-2.1	4.2
19	0.0	2.1	2.8		0.7	2.1	2.8
20	6.3	4.2	7.6		3.5	-2.1	1.4
Mean	**3.1**	**2.4**	**6.3**		**3.9**	**-0.7**	**3.2**
SD	2.2	2.5	4.5		3.8	2.7	4.2
				t=	4.59	1.20	3.36
				***p*=**	**.000**	**.246**	**.003**
				SE=	0.9	0.6	0.9

C = congruent, N = neutral, I = incongruent

Interference = I – N, Facilitation = N – C, RSE = I – C

Appendix H

ANOVA for Experiments 4 and 7

Table 18: ANOVA tables for Experiments 4 and 7.

	Source	*SS*	*df*†	*MS*	*F*	*p*
	Condition	280853	2	140426	151.97	.000
	Condition × Task	17875	2	8937	9.67	.000
RT	Condition × Translation?	109377	2	54688	59.18	.000
	Condition × Task × Translation?	5178	2	2589	2.80	.063
	Error(Condition)	158937	172	924		
	Condition	284.0	1.77	160.6	38.32	.000
	Condition × Task	13.8	1.77	7.8	1.86	.165
Errors	Condition × Translation?	64.7	1.77	36.6	8.73	.000
	Condition × Task × Translation?	16.8	1.77	9.5	2.26	.114
	Error(Condition)	637.3	152.11	4.2		

† Mauchley's test for sphericity was violated in the error data ($p < .01$). The Greenhouse-Geisser correction was applied.

Appendix I

model.cc

```
/*==========================================
Usage:
./model param.txt input.txt output.txt
==========================================*/
#include <stdio.h>
#include <iostream>
#include <iomanip>
#include <fstream>
#include "node.h"
#include <math.h>
#include <dirent.h>
#include <float.h>
using namespace std;
static int numColors;
static const  int maxNumColors = 9;
enum colors {red, green,blue, yellow, pink, orange, white, black};
static ofstream out;
static ofstream detail;
static Node * inkColor[maxNumColors];
static Node * word[maxNumColors];
static Node * innerColor[maxNumColors];
static Node * innerWord[maxNumColors];
static Node * response[maxNumColors];
static double output[maxNumColors];
static double color_weight[maxNumColors][maxNumColors];
static double word_weight[maxNumColors][maxNumColors];
static double taskdemand_weight[maxNumColors];
static double inner_color_weight[maxNumColors][maxNumColors];
static double inner_word_weight[maxNumColors][maxNumColors];

/*==========================================================================
get double and number of digits and round to the specified # of digits
==========================================================================*/
double round(double num, int d){
  int temp = num * pow(10.0,d);
  double k = temp/ pow(10.0,d);
  return k;
}

/*==========================================================================
takes t (tau) as a parameter and initialized all the nodes in the network
==========================================================================*/
void InitNetwork(double t) {
  for (int i =0; i<numColors; i++) {
    response[i] = new Node(i, t, numColors);
    innerWord[i] =  new Node(i, response, inner_word_weight[i],  -
taskdemand_weight[i], t, numColors);
    innerColor[i] = new Node(i, response, inner_color_weight[i], -
taskdemand_weight[i], t, numColors);
  }
```

```
  for (int i =0; i<=numColors; i++) {
    if (i == numColors) {
         inkColor[i] = new Node(i, innerColor, taskdemand_weight, 0.0, t,
           numColors);
         word[i] =     new Node(i, innerWord,  taskdemand_weight, 0.0, t,
          numColors);
    }
    else {
         inkColor[i] = new Node(i, innerColor, response, color_weight[i], 0.0, t,
           numColors);
         word[i] =     new Node(i, innerWord,  response, word_weight[i],  0.0, t,
           numColors);
    }
  }
}

/*=============================================================================
finds the maximum out of all the reponse nodes, excluding the specified node
==============================================================================*/
double maxAct(int exclude) {
    double max=0.0;
    for(int i =0; i<numColors; i++) {
        if (i != exclude)
        if (response[i]->activation > max)
            max = response[i]->activation;
    }
   return max;
}

int maxResponse() {
    double max = 0.0;
    int val = -1;
    for(int i = 0; i< numColors; i++) {
        if (output[i]> max) {
            max = output[i];
            val = i;
        }
    }
    return val;
}

double setResponse(double alpha) {
  double max=0.0;
  for(int i =0; i< numColors; i++) {
      output[i] += (alpha*(response[i]->activation-maxAct(i)));
          if (output[i] > max)
              max = output[i];
  }
  return max;
}
```

```
/*===========================================================
OUTPUT OF THE SYSTEM
===========================================================*/
void getResults( int col, int word, int com, int cycle) {
    int cong;
    if (col == word)
        cong = 2;
    else if(col == -1 || word == -1)
        cong = 1;
    else
        cong = 0;
    out<< col << "\t" << word << "\t" << com << "\t" << maxResponse() <<
     "\t" << cong << "\t" << cycle << "\n";
}

/*============================================================
DETAILED OUTPUT OF THE SYSTEM
============================================================*/
void getResultsDetailed( int col, int word, int com, int cycle) {
    detail << col << "\t" << word << "\t" << com << "\t";
    for (int i =0; i <numColors; i++)
        detail << round(innerColor[i]->activation,5) << "\t";
    for (int i =0; i <numColors; i++)
        detail << round(innerWord[i]->activation,5) << "\t";
    for (int i =0; i <numColors; i++)
        detail << round(response[i]->activation,5)<<"\t";
    for (int i =0; i <numColors; i++)
        detail << round(output[i],4)<<"\t";
    detail << cycle<<"\n";
}

/*=============================================================
resets the network beween trials
=============================================================*/
void reset(double d) {
    for (int i =0; i<numColors; i++) {
        innerWord[i]->old = innerWord[i]->old*d;
        innerWord[i]->activation = innerWord[i]->activation*d;
        innerColor[i]->old = innerColor[i]->old*d;
        innerColor[i]->activation = innerColor[i]->activation*d;
        response[i]->old = response[i]->old*d;
        response[i]->activation = response[i]->activation*d;
        output[i] = output[i]*d;
    }
}

/*===========================================================
resets the network within the same  trials
===========================================================*/
void resetWithinTrial() {
    for (int i =0; i<numColors; i++) {
        innerWord[i]->old  =  innerWord[i]->activation;
        innerWord[i]->activation = 0.0;
        innerColor[i]->old  = innerColor[i]->activation ;
        innerColor[i]->activation = 0.0;
        response[i]->old  =   response[i]->activation;
        response[i]->activation = 0.0;
    }
}
```

```
/*==========================================================
Begin main routine
==========================================================*/
int main(int argc, char * argv[]) {

    double maxResponse;
    fstream  in;
    double a;
    fstream param;
    int col;
    int wrd;
    int com;
    double t;
    string temp;
    string filename;

/*=====Read in the parameters=====*/
    param.open(argv[1]);
    while(true) {
        if(param.eof()) break;
        param>>temp;
        if (temp == "tau")
            param>>t;
        else if (temp == "alpha")
            param>>a;
        else if (temp == "numColors")
            param>>numColors;
        else if (temp == "colorWeight")
            for (int i = 0; i< numColors; i++)
                for(int j = 0; j < numColors; j++)
                    param>>color_weight[i][j];
        else if (temp == "wordWeight")
            for (int i = 0; i< numColors; i++)
                for(int j = 0; j < numColors; j++)
                    param>>word_weight[i][j];
        else if (temp == "innerWordWeight")
            for (int i = 0; i< numColors; i++)
                for(int j = 0; j < numColors; j++)
                    param>>inner_word_weight[i][j];
        else if (temp == "innerColorWeight")
            for (int i = 0; i< numColors; i++)
                for(int j = 0; j < numColors; j++)
                    param>>inner_color_weight[i][j];
        else if (temp == "taskDemand")
            for (int i = 0; i< numColors; i++)
                    param>>taskdemand_weight[i];
           else if (temp == "#")
           getline(param, temp);
    }
/*=====finished reading in parameters=====*/
```

```
for (int i = 0; i< numColors; i++)
    cout<<taskdemand_weight[i];
    cout << "t"<<t;
    cout <<"alpha"<<a;
    cout << "numColors"<<numColors;

    InitNetwork(t);
    in.open(argv[2]);

    out.open("output");
    detail.open("output_detailed");
    out<<"col\tword\ttask\toutput\tcong\tcycles\n";

    while(true) {
        double threshold = 1.0;
        if (in.eof()) break;
        in >> col;
        in >> wrd;
        in >> com;
        int cycle =0;
        do {
            cycle++;
           //activate the input nodes (with 0.0 and 1.0)
            for(int i = 0; i<numColors;i++){
                if(col == i)
                    inkColor[i]->activate(1.0,i);
                else
                    inkColor[i]->activate(0.0,i);
                if(wrd == i)
                    word[i]->activate(1.0, i);
                else
                    word[i]->activate(0.0,i);
            }
           //activate the task demand nodes
           //0 means read word 1 means name color
                if(com == 0) {
                    inkColor[numColors]->activate(0.0, numColors);
                    word[numColors]->activate(1.0, numColors);
                }
                else {
                    inkColor[numColors]->activate(1.0, numColors);
                    word[numColors]->activate(0.0, numColors);
                }

          //activation of outer nodes
                for (int j = 0; j<numColors ;j++) {
                   innerWord[j]->calculate(t);
                   innerColor[j]->calculate(t);
                }
                for (int j = 0; j<numColors ;j++) {
                   response[j]->calculate_response();
                }
                maxResponse = setResponse(a);
                getResultsDetailed( col, wrd, com, cycle);
                resetWithinTrial();
        }
        while(threshold > maxResponse && cycle < 1000);
```

```
      //output
        if (in.eof()) break;
        getResults( col, wrd, com, cycle);
        reset(0.0);
    }
    in.close();
    out.close();
    param.close();
}
```

Appendix J

node.h

```
#include <math.h>
#include <iostream>
#include <iomanip>
#include <fstream>
using namespace std;

class Node{
public:
   int numColors;

/*constructor for the response nodes*/
Node(int d, double k , int nColors)  {
   next = NULL;
   desc = d;
   t =k;
   old = 0.0;
   numColors = nColors;
}

/*constructor for inner and input nodes.*/
Node(int d, Node * nodes[], double w[], double n, double k , int nColors)
{
      t = k;
      bias = n;
    //id of the color
      desc = d;
    //array with the nodes that the the current node is connected to
      next = nodes;
    //array of weights on the connections
      weight  = w;
      numColors = nColors;
}

Node(int d, Node * nodes[], Node * respNodes[], double w[], double n,
double k , int nColors) {
      t = k;
      bias = n;
    //id of the color
      desc = d;
    //array with the nodes that the the current node is connected to
      next = nodes;
      nextResp = respNodes;
    //array of weights on the connections
      weight  = w;
      numColors = nColors;
}
```

```
/*activation of the input nodes
  Takes the activation multiplies it by the corresponding weight
  and passes it on by activating  the inner node
*/
void activate(double act, int col){
    for(int i =0; i < numColors; i++) {
        next[i]->activate_inner(act*weight[i],i);
    }
}

/*calculates the activation of the inner node*/
void activate_inner(double act, int num) {
     this->activation+=act;
}

void calculate(double t) {
    activation += bias;
    activation = t/(1+ exp(0.0-activation))+(1-t)*old;
    for (int i =0; i < numColors; i++){
        if (next != NULL) {
          //actually activates the response
            next[i]->activate_inner(activation*weight[i],i);
        }
    }
}

void calculate_response() {
    activation = t/(1+ exp(0.0-activation))+(1-t)*old;
}

double old;
double activation;
double value;
Node ** next;
Node ** nextResp;

private:
double t;
double bias;
double *weight  ;
int desc;
};
```

Appendix K

params.untranslated

```
#response selection parameters
alpha 0.100

#cascade rate
tau 0.1

#sets the number of response alternatives
#must adjust weight arrays to match this
numColors 4

#Long-term "static" weight parameters
taskDemand  4.0 4.0 4.0 4.0

colorWeight       1.87 -1.87 -1.87 -1.87
                 -1.87  1.87 -1.87 -1.87
                 -1.87 -1.87  1.87 -1.87
                 -1.87 -1.87 -1.87  1.87

wordWeight        1.56 -1.56 -1.56 -1.56
                 -1.56  1.56 -1.56 -1.56
                 -1.56 -1.56  1.56 -1.56
                 -1.56 -1.56 -1.56  1.56

innerColorWeight  1.105 -1.105 -1.105 -1.105
                 -1.105  1.105 -1.105 -1.105
                 -1.105 -1.105  1.105 -1.105
                 -1.105 -1.105 -1.105  1.105

innerWordWeight   1.5 -1.5 -1.5 -1.5
                 -1.5  1.5 -1.5 -1.5
                 -1.5 -1.5  1.5 -1.5
                 -1.5 -1.5 -1.5  1.5
```

Appendix L

params.translated

```
#response selection parameters
alpha 0.065

#cascade rate
tau 0.1

#sets the number of response alternatives
#must adjust weight arrays to match this
numColors 4

#Long-term "static" weight parameters
taskDemand  3.3 3.3 3.3 3.3

colorWeight       1.87 -1.87 -1.87 -1.87
                 -1.87  1.87 -1.87 -1.87
                 -1.87 -1.87  1.87 -1.87
                 -1.87 -1.87 -1.87  1.87

wordWeight        1.56 -1.56 -1.56 -1.56
                 -1.56  1.56 -1.56 -1.56
                 -1.56 -1.56  1.56 -1.56
                 -1.56 -1.56 -1.56  1.56

innerColorWeight  1.105 -1.105 -1.105 -1.105
                 -1.105  1.105 -1.105 -1.105
                 -1.105 -1.105  1.105 -1.105
                 -1.105 -1.105 -1.105  1.105

innerWordWeight   1.5 -1.5 -1.5 -1.5
                 -1.5  1.5 -1.5 -1.5
                 -1.5 -1.5  1.5 -1.5
                 -1.5 -1.5 -1.5  1.5
```