

Cognitive Control Operations Involved in Switching Tasks,
and Deficits Associated with Aging and Parkinson's Disease

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ABSTRACT

The purpose of this investigation was to identify the cognitive control operations involved in task switching, and to apply this understanding to a theoretical account of the qualitatively different task-switching deficits associated with aging versus Parkinson's disease (PD). Participants in young ($N=33$), elderly ($N=34$) and PD ($N=34$) samples switched between color naming and word reading in response to incongruent, neutral, or congruent Stroop stimuli, and vocal response time (RT) was recorded. The results suggested that executive processes involved in switching selective attention between object attributes determined a substantial portion of task-switching RT costs. More specifically, these component control processes were identified as: (a) shifting selective attention from the stimulus dimension just attended to on the previous response to the now-relevant stimulus dimension (SHIFT), and (b) a preventative operation characterized by the partial inhibition of selective attention to the now-relevant stimulus dimension, carried out when the probability is high that the now-relevant dimension must be ignored on a future response (MODERATE). A multilayer, linear, parallel distributed processing (PDP) model was presented to demonstrate how these cognitive processes may be implemented by the cognitive system, and how these findings relate to the executive function concepts of the Supervisory Attentional System (SAS) and Contention Scheduling (CS). In addition, a cost associated with responding to the first member of a stimulus pair or triplet was also identified (FIRST); however, this operation appeared to function independently from the executive control operations involved in switching tasks (i.e., FIRST was also present for task repetition trials). Finally, a number of two-way interactions between these three main effects (SHIFT, MODERATE and FIRST) accounted for unique variance in task-switching RTs, such that RT was increased when these effects co-occurred. In the neuropsychological investigation it was demonstrated that the SHIFT and MODERATE effects were significantly greater for an elderly sample compared to a young sample, resulting in an increase in task-switching RT. This deficit was attributed to an inefficient shifts of selective attention. Conversely, PD did not necessarily affect the SHIFT and MODERATE operations, when compared to age-

matched controls; however, the disease was associated with difficulty overcoming Stroop interference while switching tasks. This deficit was interpreted as affecting the SHIFT operation under the most taxing conditions, attributable to a central resource deficit in PD. In contrast, no between-group differences on the effect FIRST were observed.

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INTRODUCTION

The founding of the Cognitive Neuroscience Society in 1994 reflects the recent trend towards multidisciplinary cooperation on scientific problems that were traditionally the subject area of psychology. Diverse disciplines such as cognitive psychology, neuropsychology, neurology, biology, physics, chemistry, mathematics, statistics, computer science, linguistics and philosophy now appear to be forging mutually beneficial relationships for the purpose of confronting a longstanding mystery of science: the psychological, computational, and neuroscientific bases of perception and cognition. Because advances in the field of cognitive neuroscience are yoked to advances in precise measurement of cognitive abilities, psychological research may now find itself increasingly at centre stage in the scientific community.

These high expectations arrive at a fertile period in our discipline's development. We now enjoy a relatively solid knowledge base, the quality of which is increasingly recognized on an international and interdisciplinary scale. As an example, over the past 10 years, advances in the understanding of important aspects of cognition such as attention (Posner, Petersen, Fox, & Raichle, 1988), memory (Baddeley, 1992; Gabrieli, Brewer, Desmond, & Glover, 1997; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Tulving & Schacter, 1990), language (Pinker, 1991; Seidenberg, 1997), and imagery (Kosslyn, 1988) have been recognized as important scientific contributions by publication in the multidisciplinary journal *Science*.

These aspects of cognition that have been best understood by psychology are generally considered the more basic components. Like the instrumental sections of an orchestra, their combined activity will not be adaptable to unique arrangements unless coordinated by a conductor. While our field has developed a reasonable understanding of these basic cognitive mechanisms responsible for functions such as perception, memory and attention, we remain more ignorant of higher level control processes that lend these systems the flexibility that is characteristic of the human operator (Monsell, 1996). These coordinating mechanisms, labelled the "executive functions" or "control processes" of the brain, are now receiving substantial interest within the field of cognitive psychology and

neuropsychology (Baddeley, 1996; Baddeley & Della Sala, 1996; Robbins, 1996; Shallice & Burgess, 1996).

This particular aspect of cognition would seem to be of great importance to the advancement of cognitive neuroscience, due to the central role taken by these higher level cognitive functions in characteristically human behaviours such as decision making, appropriate social behaviour, and planning for future events. The most influential theoretical account put forward to date is that of Norman and Shallice (1986), which was based on the distinction between automatic and controlled actions (Shiffrin & Schneider, 1977). Norman and Shallice attributed automatic, bottom-up operations to cognitive processes termed action schemas and contention scheduling (CS), and controlled, top down, executive operations to cognitive processes labelled the supervisory attentional system (SAS). According to this theory, action schemas, described as lower level, basic units underlying cognitive activity, are organized by hard-wired weights (the CS mechanism), which have been (presumably) programmed over time and experience. Thus, CS weighting patterns determine coordinated, automatic responses to specific stimuli, carried out by action schemas. The SAS influences cognitive activity by overriding CS weighting patterns, allowing nonautomatic coordination of action schemas when necessary.

Norman and Shallice (1986) suggested that the SAS controls cognitive activity when an automatic response would produce an error. They listed five such situations: (a) planning and decision making, (b) troubleshooting, (c) novel sequences of actions, (d) dangerous or technically difficult situations, and (e) overcoming habitual or tempting responses. Similarly, Logan (1980; Logan, 1985) wrote that executive functions would be necessary when (a) developing alternative strategies, (b) executing the strategy in real time, and (c) disabling the strategy if it becomes inappropriate.

The complexity of the cognitive operations underlying the executive functions, and the difficulties with controlling them experimentally, have almost certainly contributed to psychology's slow progress in this domain. The first step towards advancement, as for any scientific problem, is the division of this complex phenomenon into more manageable, isolable sub-operations, and specification of when these sub-operations are active.

Previous theories addressing the structure of the executive system (Logan, 1980; Logan, 1985; Norman & Shallice, 1986) did not specify whether this system could be fractionated into more specific operations that may function independently (although this possibility was later endorsed; Shallice & Burgess, 1993). As Monsell (1996) wrote, “the heart of the mystery of control is how to deconstruct the SAS” (p. 105). The notion that the SAS can be fractionated is now widely accepted (Baddeley, 1996; Baddeley, 1998; Parkin, 1998; Roberts & Pennington, 1996), and some initial progress towards this end has been made (Roberts & Pennington, 1996; Shallice & Burgess, 1996).

Perhaps one of the simplest aspects of cognitive control is the optimization of performance when switching between two tasks. The investigation that follows was designed to foster an understanding of the cognitive operations involved in switching tasks, as they relate to the executive system. Towards this end, a series of nine task-switching experiments carried out on young, unimpaired samples is presented. The implications of these findings in relation to the identification of sub-operations of the SAS, and the nature of its influence on CS, is then discussed, and a parallel distributed processing (PDP) model presented to demonstrate how these processes may be implemented by the cognitive system. Following this, one of these nine experiments was administered to a sample of people with Parkinson’s disease (PD), and to a normal, age-matched control group. This understanding of the executive processes involved in task-switching is then extended to explain the task-switching deficits associated with aging and PD.

TASK SWITCHING

The earliest investigation into task switching was carried out by Jersild (Jersild, 1927), who demonstrated that when response cues were ambiguous (i.e., cued both of two prepotent responses), execution of a pair of tasks in sequential blocks (AAAAAABBBBBB) was more efficient than in alternation (ABABABABAB). Importantly, Jersild also demonstrated that when response cues were unambiguous (i.e., cued only one response), this so called “shift cost” or “switch cost” was absent, or greatly reduced. These findings were replicated by Spector and Biederman (1976), who

concluded that “when the stimulus did not cue which of the two interfering operations was required, a large shift loss was obtained” (p. 678).

Over the past decade, a number of studies relevant to the subject have surfaced (Allport, Styles, & Hsieh, 1994; Duncan, 1995; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Giesbrecht & Kingstone, 1998; Gopher, 1996; Meiran, 1996; Meyer et al., 1998; Potter, Chun, Banks, & Muckenhoupt, 1998; Rogers & Monsell, 1995; Rogers et al., 1998; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). Shallice (1994), in a review of this burgeoning research area, confirmed that costs associated with switching tasks arose only when stimuli were ambiguously cued, in the sense of eliciting both of two possible prepotent responses (e.g., Stroop stimuli).

Two major theoretical accounts have been put forward in an attempt to understand the cognitive control operations contributing to task switching costs. The first, put forward by Allport et al. (1994), stated that switch costs are attributable to competition between stimulus-response (S-R) mappings, an effect termed *task-set inertia* (TSI). In the TSI hypothesis, Allport et al. suggested that S-R mappings consolidated on previous trials interfere with performance on the present trial. Put another way, “the inertial effects of task set” (p. 442) from previous list conditions, and/or from the immediately preceding trial, were held to be responsible for switch costs when responding to incongruent Stroop stimuli (due to “competing ... S-R mappings”, p. 442). Moreover, and importantly for the ensuing discussion, the strength of the imposition of these S-R mappings, and their effect on the present trial, were purported to vary with task dominance.

The second major approach was introduced by Rogers and Monsell (1995). They claimed that when a subject has been trained to respond with two types of tasks to one stimulus type, these two tasks temporarily form a dual task set. Both tasks are activated (perhaps loaded into a temporary buffer) when the ambiguous stimulus is viewed, an effect termed *task-cueing* (TC). Thus, task cueing is automatically (i.e., exogenously) elicited by the stimulus, and control mechanisms (endogenous or executive processes) must be implemented to determine which of these two tasks to execute. The time taken by the process which overcomes the TC effect was proposed to be responsible for the costs

associated with switching tasks, an effect termed *task-set reconfiguration* (TSR; Monsell, 1996).

Notice that these two theoretical accounts are actually quite similar, in that they both suppose that switch costs are present only when subjects have previously experienced responding with both tasks to ambiguously cued stimuli. In other words, a dual task set (resulting in TC), and S-R conflicts (resulting in TSI), should arise only when the subject has previously experienced responding in this fashion, and therefore expects to do so on future trials.

As will be demonstrated below, the similarity of these theories is of great importance to understanding the mechanisms responsible for switch costs. However, before approaching this larger issue, we have found it helpful to focus, at least in the initial stages of analysis, on a seemingly minor issue that confronted Allport et al. (1994). This is the finding of asymmetrical word-reading and color-naming switch costs. When comparing switch to repetition trials, they found a cost only when shifting *to* the dominant task (this issue did not confront the other theorists, due to their use of equidominant tasks). Thus, central to Allport et al.'s interpretation of switch costs was an interaction between stimulus type and presence of a switch, whereby a large switch cost was associated with word reading responses, but no switch cost was present for color naming responses.

Allport et al. (1994) explained this asymmetry by regarding the word-reading switch cost as a by-product of the incongruency of Stroop color naming and word reading. They suggested that the word-reading switch cost may be due to suppression of the dominant S-R mappings, a process deemed necessary for execution of the non-dominant task on the previous response. This argument implies that, because it is not necessary to suppress competing S-R mappings when carrying out the dominant task, no switch cost should result when switching to the non-dominant task. This theoretical account will be referred to as the Dominant Task Suppression (DTS) hypothesis.

This word reading switch cost reported by Allport et al. (1994) was exceedingly large (≈ 150 ms). Could DTS be sufficient to account for this entire effect? Evidence from other task switching studies suggests that this is probably not the case. Most notably, many other researchers reported the presence of costs when switching between

equidominant tasks (Duncan, 1995; Duncan et al., 1996; Giesbrecht & Kingstone, 1998; Gopher, 1996; Meiran, 1996; Meyer et al., 1998; Potter et al., 1998; Rogers & Monsell, 1995; Rogers et al., 1998; Salthouse et al., 1998). Therefore, the relevant question is: What *proportion* of the task-switching costs reported by Allport et al. can be attributed to DTS?

On closer inspection of Allport et al.'s (1994) result, it becomes clear that it is not possible to determine the magnitude of DTS with this experimental design. This is because the use of blocked task repetition as a control condition introduces a number of confounds that cloud interpretation. For example, for task repetition, only one task must be kept “on-line”, possibly affording an advantage over task switching (Rogers & Monsell, 1995). Similarly, task repetition may allow an accumulation of repetition benefits, again imparting an advantage to task repetition over task switching. In the next section, we explore more fully the type of comparison that would allow a less obscured view of the components of a simple switching mechanism. These comparisons involve conceptualizing types of switches in a hierarchy of complexity, and postulated that theoretically meaningful comparisons can be made only across adjacent levels of complexity. However, in order to render the discussion more expedient, a notation system designed to facilitate reference to the various switching conditions is introduced.

Notation

The following notation will be used for the remainder of this manuscript:

1. Ci - color naming in response to incongruent Stroop stimuli,
2. Wi - word reading in response to incongruent Stroop stimuli,
3. Cn - color naming in response to neutral Stroop stimuli,
4. Wn - word reading in response to neutral Stroop stimuli,
5. Cc - color naming in response to congruent Stroop stimuli
6. Wc - word reading in response to congruent Stroop stimuli,
7. Ci/n - color naming in response to incongruent or neutral Stroop stimuli,
8. Wi/n - word reading in response to incongruent or neutral Stroop stimuli.

Combinations of these symbols will be used to represent trials of sequentially presented stimulus pairs or triplets. For example, the notation CiWi will refer to trials characterized

by color naming in position one, and word reading in position two, in response to sequentially presented incongruent Stroop stimuli (i.e., stimuli consisting of color words for which the color of the ink is incongruous with the meaning of the word). Similarly, the notation CnWn will refer to trials characterized by color naming then word reading in response to sequentially presented neutral Stroop stimuli (e.g., naming the ink color of a display of XXXX, and reading black words). As a final example, the notation CnWi will refer to trials characterized by color naming in response to XXXX, and then word reading in response to an incongruent Stroop stimulus.

Before returning to the theoretical issues, one final aspect of the notational system must be specified. When one particular response type from a trial is being discussed, that symbol will be underlined and written in bold font. For example, the notation Ci**Wi** will refer to the word reading response of CiWi trials (i.e., a trial characterized by color naming then word reading in response to sequentially presented incongruent Stroop stimuli). Similarly, **Ci**Wi will refer to the color naming response of the same trial type. In the experiments presented below, the number of trials that constituted a block will be specified on an experiment-wise basis.

Analysis and Remedy of Possible Confounds in Measuring the Cost of a Switch

This section begins with a discussion of the DTS effect that confronted Allport et al. (1994). Allport et al. stated that DTS was a special case of TSI, but did not specify the importance of DTS relative to other aspects of TSI, and did not specify when these other aspects of switch costs are active and when they are not. Recall that Allport et al. (1994) compared task switching to task repetition to assess the magnitude of switch costs. Due to the nature of the control condition (*viz.*, task repetition), RT comparisons of a task-switching condition to a task repetition condition cannot isolate the effect of DTS. Three potential confounds are listed here.

First, task repetition benefits may accumulate over a list of repeated trials, increasing repeated trial RTs relative to switching trial RTs. Second, as pointed out by Rogers and Monsell (1995), only one task must be loaded into “task working memory” in the task repetition condition, whereas two are present for task switching. Because two tasks must be “on-line” for the switching condition, this may also benefit the non-switch

condition. This potential cost for task switching will be termed the *dual task-set cost*. Finally, other switch costs that may be active over and above the DTS effect also contrast across this comparison. Therefore, although the DTS effect does contrast across task switching and task repetition conditions, this effect cannot be studied in isolation due to confounds associated with the use of this experimental design. Table 1 lists the three confounding effects that affect interpretation of the second position word-reading RT comparison of the control (Wi**Wi**) and experimental (Ci**Wi**) conditions of Allport et al.'s (1994) Experiment 5.

These difficulties appear insurmountable as long as task repetition is used as the experimental control condition. This difficulty can be overcome by reconsidering the conclusion reached by Shallice (1994), whereby costs associated with switching tasks arise only when stimuli are ambiguously cued, in the sense of eliciting both of two possible prepotent responses. Translating this finding into classical Stroop terms, if only neutral Stroop stimuli are used, the time to complete two lists of 35 CnWn trials (for a total of 70 task switching trials) should not differ significantly from the time to complete a block of 35 CnCn trials followed by a block of 35 WnWn (for a total of 70 task repetition trials). Thus, under the conditions of concern here, task repetition is not quantitatively different from task switching. This provides preliminary justification for using *task switching* in response to neutral stimuli as the control condition, in place of the problematic *task repetition*.

However, simply using neutral Stroop stimuli as an all-purpose control condition still does not allow isolation of the DTS effect. Although the comparison of Ci**Wi** to Cn**Wn** appears valid, due to the fact that word-reading processes are suppressed on CiWi, but not on CnWn, interpretational confounds persist. Namely, RT to an incongruent Stroop stimulus (Ci**Wi**) is being compared to that of a neutral Stroop stimulus (Cn**Wn**). Although the so-called Reverse Stroop effect (Wi-Wn) is notoriously difficult to detect under normal experimental conditions, it appears to be readily observable within the context of task switching (Allport et al., 1994, Experiment 5). The appropriate comparison, therefore, for isolation of the DTS effect, is not Ci**Wi** to Cn**Wn**, but Ci**Wi** to Cn**Wi** (or Ci**Wn** to Cn**Wn**), where the now-relevant stimulus type remains constant.

Thus, in order to cancel the confounds listed in Table 1, thereby isolating the effects of interest, comparison of task-switching *contexts* must be carried out, as opposed to comparison of task-switching trials to task-repetition trials. More specifically, the comparison condition must be changed from task repetition to an appropriate task switching condition, by combining neutral and incongruent Stroop stimuli. Table 2 demonstrates how this methodology allows the cancellation of confounds, facilitating isolation of the DTS effect. For **CnWi** responses, DTS cannot have an effect on RT, as no suppression takes place on **CnWi**.

This method of combining neutral and incongruent Stroop stimuli can be extended in order to observe effects other than DTS. As mentioned above, using switching in response to unambiguously cued stimulus blocks (e.g., neutral Stroop stimuli) solves some of the difficulties associated with using task repetition as a baseline. However, a more interesting tactic is to superimpose effects caused by responding to ambiguous stimuli on the neutral switch condition, allowing creation of a hierarchy of control conditions that would allow isolation of a number of effects in various experimental conditions.

What exactly are these effects beyond the notion of DTS that could be superimposed on the neutral switch conditions? For precise explanation of these effects, the term *extra-dimensional shift* (EDS) is introduced. An EDS refers to a response for which the stimulus dimension processed on the previous trial must be ignored (Downes et al., 1989; Robbins et al., 1998). Thus, an EDS is present for all switching trials on which an incongruent Stroop stimulus is presented. Extra-dimensional shifts are known to increase response time, and are thought to involve shifting selective attention between stimulus attributes (Downes et al., 1989; Robbins et al., 1998). In Allport et al.'s (1994), paradigm, an EDS is carried out whenever an incongruent stimulus is responded to.

Another possible contributor to task switching costs was hinted at when it was noted that both TC and TSI assume that switch costs are present only when subjects have previously experienced executing both tasks in response to ambiguously cued stimuli (and therefore expect to do so on future trials). Since switching between two tasks in response to ambiguously cued stimuli involves EDSs, this anticipation of an EDS is also present for all trials. Put another way, for trials where an EDS has been experienced recently,

expectation that it may occur again is produced, even when this is probabilistic. In this way, anticipation of an EDS may affect responses to incongruent *or* neutral (or congruent) Stroop stimuli within switching contexts necessitating EDSs.

In summary, the pure neutral switch condition, and the neutral switch condition with the EDS influences superimposed, can be used as a variety of baseline conditions that can be utilized to allow observation of effects of interest (e.g., DTS, EDS, or anticipation of an EDS) in an experimental condition. Precise combinations of neutral and incongruent Stroop stimuli, and their effects on switching RT, will be explained in detail below as the following series of eight experiments unfolds.

The present paper begins with the introduction of experimental methodology which will be used throughout this manuscript. Following this, an attempted replication of Allport et al.'s (1994) Experiment 5 is reported (Experiments 1a and 1b). Although the major findings of Allport et al. were confirmed, some inconsistencies were also observed (e.g., the presence of a switch cost for color naming). From these inconsistencies, a number of questions emerged which were investigated by way of seven subsequent experiments, all of which were designed by superimposing specific effects upon a neutral switching baseline.

The first of these seven experiments, Experiments 2a and 2b, were designed to investigate the influence of DTS over and above other costs associated with switching tasks. These investigations demonstrated that, as predicted by Allport et al.'s (1994) TSI theory, DTS was present, and affected the dominant task only. However, its influence was much smaller than would be expected based on these previous theoretical accounts. Therefore, Experiment 3 was designed to quantify the influence of task-switching mechanisms active over and above the influence of DTS. A parallel processing model is then introduced which specifies how these components of task switching may be implemented by the cognitive system. Experiments 4, 5, 6, and 7 were designed to clarify interpretation of the major effects identified and modelled in Experiment 3.

General Experimental Methodology

The following series of experiments share some aspect of their experimental design; therefore, a general methodology that is applicable to all experiments is presented

first. The stimuli used were incongruent, neutral or congruent Stroop stimuli. Incongruent Stroop stimuli are color words printed such that the ink color in which each word is printed does not agree with the meaning of the word (e.g., GREEN printed in red ink). Congruent Stroop stimuli are color words printed such that the color ink in which each word is printed agrees with the meaning of the word (e.g., GREEN printed in green ink). The neutral color condition was XXXX printed in colored letters (no word dimension), and the neutral word condition was the color word written in black ink (no color dimension). Stroop stimuli are frequently employed in cognitive psychology for the study of the “Stroop effect”, whereby word reading interferes with color naming due to the relative dominance of the word-reading task (MacLeod, 1991; Stroop, 1935).

All experiments were presented using a Macintosh powerbook computer controlled by Psychlab software (Bub & Gum, 1990). For all experiments, a trial consisted of a pair, or a triplet of Stroop stimuli. A box, divided into upper and lower halves, preceded the arrival of the experimental trial by 15 ms. Each participant was instructed by the experimenter to name the color when the stimulus appeared in the bottom half of the box, and read the word when it appeared in the top half of the box, or vice versa. Participants were randomly assigned to the color top/word bottom or color bottom/word top conditions.

With five colors used in all experiments, 20 incongruent Stroop stimulus exemplars were possible. Therefore, 400 sets of incongruent stimulus pairs, and 8000 sets of incongruent stimulus triplets were possible. Because the maximum number of trials presented in any one experimental block was 40, the set of stimuli presented to any given subject was randomly chosen from all possible combinations (with replacement). Thus, new sets of randomly chosen pairs or triplets were created for every participant (i.e., no two participants received the same set of stimuli).

The first stimulus of the trial disappeared from the screen once a vocal reaction time was recorded. After a response-stimulus interval of 500 ms, during which time the box remained on the screen, the second member of the pair or triplet was presented, and RT recorded. For the experiments where triplets were presented, a third stimulus was presented in the same manner as the second. After the completion of a trial (two or three

responses, depending on whether a pair or triplet was presented), the experimenter recorded any errors manually, and initiated advancement to the next trial with a key press.

Two types of errors were recorded: (a) *incongruent*, where the correct response for the now-irrelevant task was given, and (b) *unrelated*, where an incorrect color name was produced which was not correct for the now-relevant or now-irrelevant task. Invalid trials were recorded as those where the voice-key picked up extraneous noise, or did not record a response. Any responses longer than 3000 ms, or shorter than 300 ms, which were not coded as voice-key errors in the experimental session, were coded as such *post hoc*. The first trial of every block was dropped.

Experiment 1a

Experiment 1a was designed primarily as a replication of a portion of Allport et al.'s (1994) Experiment 5 (results displayed in their Figure 17.6a), for which a trial consisted of sequential pairs of neutral or incongruent Stroop stimuli. In Allport et al.'s study, subjects either switched from color naming to word reading (CiWi and CnWn conditions), or from word reading to color naming (WiCi and WnCn conditions). The control conditions were repeated word reading (WiWi and WnWn) and color naming (CiCi and CnCn) trials. Allport et al.'s participants completed a list of five trials (i.e., five pairs) in each condition before changing to another condition. The presentation order of the conditions was randomly assigned. Prior to each list, the participants were instructed as to which task to carry out in response to the first and second members of the to-be-viewed pairs. The following two experiments from the present investigation focussed on Allport et al.'s incongruent trial results only (in a later section neutral trials will be considered).

The reaction times of interest to Allport et al. (1994) were the *second reaction time of each pair* (i.e., $Wi\mathbf{Wi}$, $Ci\mathbf{Ci}$, $Wi\mathbf{Ci}$, $Ci\mathbf{Wi}$). When comparing the switch to repetition trials, they found a cost only when shifting *to* the dominant task ($Ci\mathbf{Wi}$ – $Wi\mathbf{Wi}$, and not for $Wi\mathbf{Ci}$ – $Ci\mathbf{Ci}$). Thus, central to their interpretation of these switch costs was an interaction between stimulus type and presence of a switch, where a large switch cost was associated with word reading, but no switch cost was present for color naming. Replication of this finding, among others, was tested in the present experiment.

Method

Participants

Participants were eight students enrolled in an introductory psychology course at the University of Victoria.

Procedure

All stimuli presented were incongruent Stroop stimuli. Stimulus pairs were one of the following four types: (a) repeated color naming (CiCi), (b) repeated word reading (WiWi), (c) color naming in response to the first member of the pair, and word reading in response to the second member (CiWi), and (d) word reading in response to the first member of the pair, and color naming in response to the second member (WiCi). Each participant received 40 trials of each pair type (160 trials in total). These 160 stimulus pairs were presented in a random order. Breaks were taken after the 40th, 80th and 120th trials. The colors and color words used for all stimuli were blue, yellow, red, green, and brown.

Results

For more direct comparison to Allport et al. (1994), initially only the second-position RTs (WiCi, CiCi, CiWi, WiWi) were analyzed. A repeated measures ANOVA resulted in a significant main effect of Presence of a Switch, $F(1,7) = 21.87$, $p < .005$, $\eta^2 = .76$, and Response Type, $F(1,7) = 11.27$, $p < .02$, $\eta^2 = .62$. Importantly, the interaction between Response Type and Presence of a Switch was significant, $F(1,7) = 12.35$, $p < .02$, $\eta^2 = .75$. However, while Allport et al. (1994) reported a large (≈ 150 ms) switch cost for word reading, and no switch cost for color naming, these data show significant switch costs for both response types, $t(7) = 4.51$, $p < .002$, one tailed, $\eta^2 = .74$, $t(7) = 2.92$, $p < .02$, one tailed, $\eta^2 = .55$, respectively. The size of this switch cost was asymmetrical, being larger for word reading (137 ms) than for color naming (38 ms) (see Figure 1). Incongruent and unrelated errors accounted for 0.6% of responses combined, and 2.5% of the responses were invalid.

Discussion

In general, the results of Allport et al. (1994) were replicated. A large switch cost for word reading was found, as was an asymmetrical switch cost for word reading and color naming. However, the presence of a significant switch cost for color naming was not anticipated, given Allport et al.'s results.

On Allport et al.'s (1994) inability to find a switch cost for color naming, Monsell wrote that this may be accounted for by unusually slow color naming trials (Monsell, 1996, p. 142-143), perhaps due to the use of non-focal color samples. However, this explanation does not apply directly to the present set of results, as the color naming RTs from the present investigation (≈ 1000 ms) were longer than those of Allport et al. (≈ 800 ms).

The relatively slow response latencies found in the present investigation were probably due to methodological differences between Allport et al.'s (1994) investigation and the present one. In particular, for each condition in Allport et al.'s study (CiCi, WiCi, WiWi, CiWi), a list of five pairs was presented to the participant. Prior to each list, the participant was instructed as to which task to carry out in response to the first and second members of the pair for the following list. In contrast, pair types in Experiment 1a were presently randomly – location of the stimulus determined the response. This methodological difference may account for the significant color naming switch cost, as previous investigators have reported increased switch costs with decreased opportunity for preparation (Gopher, 1996; Meiran, 1996; Rogers & Monsell, 1995). To explore this possibility, Experiment 1b was designed to increase the opportunity for participants to prepare for stimulus arrival.

Experiment 1b

Method

To assess the impact of stimulus predictability, the same pairs types (CiCi, WiCi, WiWi, CiWi) were presented to the participants from the previous experiment; however, instead of randomly presenting pair types, each pair type was presented in blocks of 40 trials. Block presentation order was randomly determined for each participant.

Results

A repeated measures ANOVA comparing second-position RTs (WiCi, CiCi, CiWi, WiWi) resulted in a significant main effect of Presence of a Switch, $F(1,7) = 17.16$, $p < .005$, $\eta^2 = .71$, and Response Type, $F(1,7) = 30.21$, $p < .005$, $\eta^2 = .81$. However, the interaction between Response Type and Presence of a Switch reported by Allport et al. (1994) (and found in Experiment 1a), was not significant, $F(1,7) = 1.31$, $p = .17$. On the contrary, significant and substantial switch costs were present for both color naming and word reading, $t(7) = 3.10$, $p < .01$, one tailed, $\eta^2 = .59$, $t(7) = 3.82$, $p < .005$, one tailed, $\eta^2 = .68$, respectively. A trend towards agreement with Allport et al. was present, with a larger switch cost for word reading (230 ms) than for color naming (108 ms) (see Figure 2). Incongruent and unrelated errors accounted for 1.3% of responses combined, and 3.7% of the responses were invalid.

Discussion

Given that the switch cost for color naming remained despite a decrease in response latency (compared to random presentation), neither Monsell's (1996) hypothesis of slow color naming trials, nor the aforementioned hypothesis of pair predictability, explains Allport et al.'s (1994) finding of no switch cost for colors. The ensuing experiments and discussion will focus on the interpretation of the robust color naming switch cost that was found in Experiments 1a and 1b, and more detailed interpretation of the word reading switch cost.

Additional Results and Discussion of Experiments 1a and 1b

The results presented so far suggest the presence of a large switch costs for word reading, and a (perhaps smaller) switch cost for color naming. The presence of this apparently robust color-naming switch cost casts doubt on Allport et al.'s (1994) interpretation of their results, which are valid only if no color-naming switch cost is present. Allport et al. regarded the word-reading switch cost to be a by-product of the task-dominance incongruency of Stroop color naming and word reading. However, their description of the effect was rather vague. They suggested that the word-reading switch cost may be due to suppression of the dominant S-R mappings, deemed necessary to perform the non-dominant task. This suppression effect would slow execution of the

dominant task on the subsequent response (p. 442). This argument implies that, because it is not necessary to suppress competing S-R mappings when carrying out the dominant task, no switch cost should result when switching to the non-dominant task. This theoretical account will be referred to as the Dominant Task Suppression (DTS) hypothesis.

Clearly, the presence of the color-naming switch cost in the present investigation presents some difficulties for Allport et al.'s (1994) DTS hypothesis. This finding indicates that, although DTS may contribute to asymmetries in word-reading and color-naming switch costs, it cannot be held solely responsible for all switch costs. An experiment that addresses this issue will be returned to below.

Other aspects of the data collected for Experiments 1a and 1b, not reported by Allport et al. (1994) are (a) an increased RT for position one responses, and (b) switch costs in position one. A repeated measures ANOVA on the repeated trial RTs (CiCi, CiCi, WiWi, WiWi), blocked pair presentation condition, revealed significant main effects for Order (first versus second), $F(1,7) = 13.46$, $p < .01$, $\eta^2 = .66$, and Response Type (word vs. color), $F(1,7) = 36.06$, $p < .001$, $\eta^2 = .84$, and no significant interaction, $F(1,7) = 1.31$, $p = .17$. As can be observed in Figure 3, the order effect is characterized by a faster response when the stimulus arrived second, compared to when it arrived first in the pair.

Essentially identical results were observed in the random pair presentation condition, with significant main effects for Order (first versus second), $F(1,7) = 26.43$, $p < .005$, $\eta^2 = .79$, and Response Type (word vs. color), $F(1,7) = 15.07$, $p < .01$, $\eta^2 = .68$, and no significant interaction, $F(1,7) = 2.84$, $p = .14$ (see Figure 4).

Order effects were present not only for the repeated response trials, but also for the switching trials. A repeated measures ANOVA on the switching trial RTs (CiWi, WiCi, WiCi, CiWi), blocked pair presentation condition, revealed significant main effects for Order (first versus second), $F(1,7) = 23.7$, $p < .005$, $\eta^2 = .77$, and Response Type (word reading vs. color naming), $F(1,7) = 28.97$, $p < .005$, $\eta^2 = .81$, but no significant interaction, $F(1,7) = 1.29$, $p = .29$. As can be observed in Figure 5, the order effect is characterized by faster responses when the stimulus arrived second, compared to first.

Very similar results were observed in the random pair presentation condition, with significant main effects for Order (first versus second), $F(1,7) = 6.62$, $p < .05$, $\eta^2 = .49$, and Response Type (word vs. color), $F(1,7) = 10.12$, $p < .02$, $\eta^2 = .59$, but no significant interaction, $F(1,7) = 1.67$, $p = .24$ (see Figure 6).

To complete the description of the results, the presence of first position switch costs are reported. A repeated measures ANOVA on the first-position RTs from Experiment 1b (**WiCi**, **CiCi**, **CiWi**, **WiWi**) was carried out. This resulted in a significant main effect of Presence of a Switch, $F(1,7) = 19.11$, $p < .005$, $\eta^2 = .73$, and Response Type, $F(1,7) = 37.6$, $p < .001$, $\eta^2 = .84$. As was the case for the second position RTs, the interaction between Response Type and Presence of a Switch was not significant, $F(1,7) = 1.47$, $p = .26$. Significant and substantial switch costs were present for both color naming (233 ms) and word reading ($M = 238$ ms), $t(7) = 3.45$, $p < .01$, one tailed, $\eta^2 = .62$, $t(7) = 6.9$, $p < .001$, one tailed, $\eta^2 = .87$, respectively (see Figure 7).

The presence of switch costs in the first position for the randomly presented pairs was not investigated, because the nature of the preceding pair was not coded for these data. However, given the symmetry of the Order effect over Response Type, for switching and non-switching trials, the switch costs observed in the second position would also be present in the first position.

Returning to the experimental results, recall that Allport et al.'s (1994) TSI interpretation was developed without considering a switch cost for color naming, and without reporting first position effects. The fact that switch costs, for color naming and word reading, were present at both the first and second positions in Experiments 1a and 1b, must be accounted for in any theoretical account of switch costs, and was not considered by Allport et al. For example, although the switch cost in the first position may result (at least partially) from a DTS effect imposed by position two of the previous trial, another possibility is the presence of a cost associated with anticipation of an EDS. These incompatible positions will be considered in the next experiment, as will the source of the color-naming switch cost.

Experiment 2a

Experiment 2a was designed to investigate further switch costs associated with word reading (color naming will be addressed separately). In particular, as was suggested by the results of Experiments 1a and 1b, the DTS interpretation cannot account for all task-switching costs. This is because whereas DTS can affect only word-reading, color-naming switch costs were present. However, the DTS hypothesis may provide a partial explanation of word-reading switch costs, and may account for the apparent asymmetry of color-naming and word-reading switch costs. Allport et al. (1994) did not specify the importance of DTS relative to other aspects of TSI, and they did not specify when other aspects of switch costs are active and when they are not. These questions will be investigated in the present experiment.

Recall that Allport et al. (1994) compared task switching to task repetition to assess the magnitude of switch costs. As was suggested by Rogers and Monsell (1995), due to the nature of the control condition chosen by Allport et al. (1994) (*viz.*, task repetition), the proportion of the switch cost on the second position attributable to DTS cannot be determined. That is to say, comparing second members of a pair, RT comparisons of a task-switching condition to a task repetition condition cannot isolate the effect of DTS. A number of reasons for this interpretational difficulty can be listed. First, repetition may benefit the second position repeated RT (*position-wise* benefit), and repetition benefits may accumulate over a list of repeated trials, affecting both the first and second position repeated trial pairs (*list-wise* benefit).

Second, as pointed out by Rogers and Monsell (1995), only one task must be loaded into “task working memory” in the task repetition condition. Because two tasks must be “on-line” for the switching condition, this may also benefit the non-switch condition. This potential cost for task switching will be termed the *dual task-set cost*. Finally, the presence of a switch cost for color naming in Experiments 1a and 1b suggests that some costs attributable to switching tasks cannot be explained by the DTS hypothesis. Thus, any switch costs over and above the DTS effect also contrast across this comparison. Therefore, although the DTS effect does contrast across task switching and task repetition conditions, this effect cannot be studied in isolation due to confounds

associated with using this experimental design. Table 1 lists the three confounding effects that affect interpretation of the second position word-reading RT comparison of the control (**WiWi**) and experimental (**CiWi**) conditions of Experiments 1a and 1b.

What changes must be made to Table 1 to compare effects that contrasted across the control and experimental conditions of Experiments 1a and 1b in *position one* (as opposed to position two, which Table 1 is based on)? As mentioned above, a cost associated with the anticipation of an impending EDS must be added, as must a cost associated with arrival in position one. Table 3 lists the four confounding effects that cloud interpretation of the first position word-reading RT comparison of the control (**WiWi**) and experimental (**WiCi**) conditions of Experiments 1a and 1b.

In order to exclude the confounds listed in Tables 1 and 3, allowing isolation of the effects of interest, comparison of task-switching *contexts* must be made, as opposed to comparison of task-switching trials to task-repetition trials. More specifically, the control condition must be changed from task repetition to task switching. This objective can be met by forming a control condition by combining neutral and incongruent Stroop stimuli. As will be demonstrated below, this methodology allows confounds to be discounted, facilitating isolation of effects.

Experiment 2a was designed to determine the magnitude of the DTS effect, and the influence of anticipation of an EDS, by removing confounds attributable to using task repetition as the control condition. Comparisons of task-switching contexts were made, as opposed to comparison of task-switching trials to task-repetition trials. Moreover, in order to discount confounding variables uniquely affecting the first position word-reading RT (see Table 3), Experiment 2a was designed using triplets instead of pairs. This methodology ensured that costs on the first stimulus of a trial could not be attributed to a carry-over DTS effect.

For example, the RT to **WiCiWi** may be affected by anticipation of an EDS (an EDS will occur on the **WiCiWi** trial), or it may be affected by occurring first in the triplet. In previous experiments involving pairs, **WiCi** could have been affected by a carry-over DTS effect from the **WiCi** response of the previous trial, by the anticipation of an EDS (which will occur on the **WiCi** of the present trial), or by occurring first in the pair. Using

triplets, because **WiCiWi** of the previous trial is the same type of task, the confound of a carry-over DTS effect can be disregarded (although **WiCiWi** is susceptible to a carry-over position-wise task-repetition benefit - this complication will be considered below).

Table 4 and Table 5 list how this improved design allows isolation of the word-reading effects of interest. In Table 4 it is demonstrated that, because color naming in response to incongruent Stroop stimuli necessitates DTS, while color naming in response to neutral Stroop stimuli does not, isolation of the DTS effect is possible by comparing the mean **WiCiWi** RT to the mean **WiCnWi** RT. Similarly, the isolation of a cost associated with anticipation of an EDS is demonstrated in Table 5 (on the assumption that DTS lasts for only one response – evidence to support this assumption is presented in Experiment 3).

As a further attempt to decouple anticipation effects from carry-over effects, the predictability of the color-naming stimulus type (**WiCiWi** or **WiCnWi**) was manipulated, which should affect only effects depending upon expectation (*viz.*, anticipation of an EDS). In the blocked condition, all trials were of one triplet type. In the random condition, triplet types were presented in a random order. With this design, any effect due to anticipation of an EDS should be stronger in the blocked **WiCiWi** condition than in (a) the random conditions (either **WiCiWi** or **WiCnWi**), or (b) the blocked **WiCnWi** condition. This is because an EDS is expected on 100% of the trials in the **WiCiWi** blocked condition, 50% of the trials in the random condition, and 0% of the trials in the **WiCnWi** blocked condition.

Method

Participants

Participants were 13 University of Victoria students who were enrolled in an introductory psychology course.

Procedure

Trials consisted of a triplet of Stroop stimuli, presented sequentially, where participants read a word, named a color, then read a word. Triplets were of two types: (a) all incongruent Stroop stimuli (**WiCiWi**), or (b) one neutral Stroop stimulus interleaved between two incongruent Stroop stimuli (**WiCnWi**).

One hundred and sixty triplets were generated for each participant, from which two stimulus sets of 40 blocked trials, and one set of 80 randomly presented trials were created. In the blocked presentation condition, each participant received 40 trials of each triplet type (WiCiWi and WiCnWi). In the random presentation condition, the participants again received 40 trials of each pair type, but with a randomly assigned presentation order (WiCiWi and WiCnWi intermixed). Breaks were taken after every 40 trials. The order of presentation for these three stimulus sets (two blocked and one random) was randomly determined. The colors and color words used for all stimuli were blue, yellow, red, green, and brown.

Results

The RT data were analyzed with a 2 x 2 x 3 (Predictability x Triplet Type x Stimulus Position) repeated measures ANOVA. The two levels of the Predictability factor were blocked triplet types and randomly presented triplet types. The two levels of the Triplet Type factor were the WiCiWi and WiCnWi triplet types. The three levels of the Stimulus Position factor were positions one, two and three in the triplet.

A significant interaction was found between Triplet Type and Stimulus Position, $F(2, 24) = 57.31$, $p < .001$, $\eta^2 = .83$. To simplify interpretation of how the effect of Stimulus Position depended upon Triplet Type, the linear and quadratic effects were investigated separately.

No significant linear effect of Stimulus Position (i.e., a difference between WiCi/nWi and WiCi/nWi, averaged over Predictability, where Ci/n denotes Ci or Cn) was found at either level of Triplet Type. However, comparison of Figure 8 and Figure 9 demonstrates that the quadratic effect was larger for the WiCiWi triplet type, $F(1, 12) = 76.38$, $p < .001$, $\eta^2 = .86$, than for the WiCnWi triplet type, $F(1, 12) = 29.61$, $p < .001$, $\eta^2 = .71$. This interaction of the Stimulus Position quadratic effect and Triplet Type provided a very large effect, $F(1, 12) = 64.80$, $p < .001$, $\eta^2 = .84$, and is due to the mean RT for Cn ($M = 662$) being faster than that of Ci ($M = 806$), $t(12) = 8.02$, $p < .001$, $\eta^2 = .84$ (the Stroop effect, when word reading interferes with color naming).

A marginally significant two-way interaction between Predictability and Triplet Type was investigated further, $F(1, 12) = 4.46$, $p = .06$, $\eta^2 = .27$. Comparison of Figure 8

and Figure 9 demonstrates that this interaction reflects a difference between blocked ($M = 592$ ms) and random ($M = 638$ ms) RTs for the WiCnWi triplet type, $F(1, 12) = 10.44$, $p < .01$, $\eta^2 = .47$, but not for the WiCiWi triplet type, $F(1, 12) = 0.38$, $p = .55$. From this result, it can be concluded that RT can be reduced if the triplet type is completely predictable, but only for the WiCnWi triplet type. Moreover, this RT decrease was not exclusive to one response type (word reading or color naming), or position in the triplet (position one, two, or three). Thus, a cost due to anticipation of an EDS was present, but not unique to the WiCiWi - WiCnWi comparison. It appeared to affect response time in all positions.

To directly test the DTS hypothesis of Allport et al. (1994), a comparison of WiCiWi and WiCnWi RTs was carried out. Due to previously reported Predictability X Triplet Type interaction (whereby all RTs were speeded in the blocked WiCnWi condition, confounding the WiCiWi - WiCnWi comparison), the comparison was made within the random condition only. A small significant effect was found, $t(12) = 2.76$, $p < .01$, one tailed, $\eta^2 = .39$, where WiCiWi ($M = 640.7$) was slower than WiCnWi ($M = 619.7$; see Figure 10).

Discussion

Allport et al. (1994) suggested that the RT discrepancy between CiWi and WiWi may be due to DTS generated on the CiWi response. In the present experiment, this hypothesis was tested by comparing WiCiWi to WiCnWi (when pair type was randomly presented). A discrepancy of 21 ms was found between these reaction times, giving some support to the DTS hypothesis. However, this small effect appears insufficient to account for the entire 150 ms switch cost (CiWi - WiWi) reported by Allport et al. (1994), the 137 ms switch cost found in Experiment 1a, or the 230 ms switch cost found in Experiment 1b. A theoretical account to explain the remainder of this switch cost reported by Allport et al. will be preceded by additional experimentation.

It was also demonstrated that color-naming and word-reading RT can be reduced when the triplet type is completely predictable, but only for the WiCnWi triplet type. The fact that this effect was not present for the blocked WiCiWi RTs may provide an important clue. For example, the WiCiWi RT in the blocked condition is the same speed

as the **WiCiWi** RT in the random condition (as was the case for **WiCiWi** and **WiCiWi**, see Figure 8). One may expect the **WiCiWi** in the random condition to be faster than that in the blocked condition, because any cost due to anticipation of an EDS should be diluted in the random condition (because either Ci or Cn was expected). On the contrary, it appears that experiencing an EDS on 50% of trials (or more) produces as much anticipation of an EDS as experiencing an EDS on 100% of trials. Furthermore, given that a cost due to anticipation of an EDS was present in all positions, it seems unlikely that it contributed to the Order effect observed for switching trials in Experiments 1a and 1b. A general order effect for repeated and switch trials seems a more likely explanation.

Experiment 2b

Experiment 2b was designed to investigate further the cause of the previously reported color-naming switch cost. As mentioned above, the DTS interpretation explains only a fraction of the word-reading switch cost, and should explain none of the color-naming switch cost, according to Allport et al. (1994) (DTS should affect only the dominant task).

This experiment was designed to explore the possibility that a color-naming counterpart to DTS does, in fact, affect color naming on switch trials. If a color-naming counterpart to DTS does exist, this may help explain the presence of the color-naming switch cost reported in Experiments 1a and 1b. However, according to Allport et al. (1994), and given the understanding of DTS gained in Experiment 2a, a color-naming counterpart to DTS was expected to not be observed.

The four confounding effects that result from using task repetition as the control condition, as outlined in reference to word reading in the introduction to Experiment 2a, also apply to color naming. In light of the unexpected result reported Experiment 2a (*viz.*, that expectation of an EDS switch can affect not only the first member of a trial, but all members), anticipation of an EDS is listed as additional confound not present for task repetition, for positions one *and* two (see Table 6 and Table 7).

As in Experiment 2a, the control condition was changed from task repetition to task switching, triplets were used instead of pairs, and the predictability of the triplet type (**CiWiCi** or **CiWnCi**) was manipulated. Table 8 and Table 9 list how this improved design

allows isolation of the effects of interest. In Table 8, a check that a color-naming counterpart to DTS does not exist can be made by comparing the mean $CiWiCi$ RT to the mean $CiWnCi$ RT in the random condition (not the blocked condition, which is expected to be confounded by the anticipation of an EDS effect). Similar methodology is demonstrated in Table 9, where a cost due to anticipation of an EDS cost is isolated in the blocked condition (although this cost must now be expected on all three positions, given the results of Experiment 2a).

Method

Participants

Participants were 11 students enrolled in an introductory psychology course at the University of Victoria.

Procedure

The procedure for this experiment was the same as for Experiment 2a, except that all participants named a color, read a word, and then named a color. Thus, triplets were of two new types: (a) all incongruent Stroop stimuli ($CiWiCi$), or (b) one neutral Stroop stimulus interleaved between two incongruent Stroop stimuli ($CiWnCi$).

Results

The RT data were analyzed with a $2 \times 2 \times 3$ (Predictability \times Triplet Type \times Stimulus Position) repeated measures analysis of variance. The two levels of the Predictability factor were blocked triplet types and random triplet types. The two levels of the Triplet Type factor were the $CiWiCi$ and $CiWnCi$ triplet types. The three levels of the Stimulus Position factor were positions one, two and three in the triplet.

A significant two-way interaction was found between Triplet Type and Stimulus Position, $F(2, 20) = 28.564$, $p < .001$, $\eta^2 = .75$. To simplify interpretation of effects involving Stimulus Position, the linear and quadratic effects were investigated separately.

A significant linear trend, which did not interact with Triplet Type, was found, $F(1,20) = 29.05$, $p < .001$, $\eta^2 = .59$. This trend was characterized by shorter latencies for color naming responses to stimuli in position three ($M = 847$) compared to color naming

responses to stimuli in position one ($\underline{M} = 922$). This effect was independent of Triplet Type and Predictability (see Figures 11 and 12).

The quadratic trend, on the other hand, did interact with Triplet Type $\underline{F}(1,20) = 45.56$, $p < .001$, $\eta^2 = .69$. The quadratic trend was more dominant for the CiWnCi triplets, $\underline{F}(20) = 118.16$, $p < .001$, $\eta^2 = .86$, than for the CiWiCi triplets, $\underline{F}(20) = 34.22$, $p < .001$, $\eta^2 = .63$, condition (see Figures 11 and 12). This interaction was due to the word-reading RT in response to Wn ($\underline{M} = 670$ ms) being faster than that to Wi ($\underline{M} = 763$ ms), $\underline{t}(10) = 4.87$, $p < .005$, $\eta^2 = .70$, averaged over Predictability (the Reverse Stroop effect, when color naming interferes with word reading).

The second significant two way interaction was between Predictability and Triplet Type, $\underline{F}(1, 10) = 6.693$, $p < .05$, $\eta^2 = .57$. This interaction reflects speeded RTs (averaged over Stimulus Position) in the blocked condition ($\underline{M} = 782$ ms) compared to the random condition ($\underline{M} = 824$ ms), for the CiWnCi triplet type, $\underline{t}(10) = 2.32$, $p < .05$, $\eta^2 = .35$, but not the CiWiCi triplet type, $\underline{t}(10) = -.33$, $p = .75$ (see Figures 11 and 12). As was observed in Experiment 2a, RT can be reduced if the triplet type is completely predictable, but only for the triplet type with a neutral stimulus at position two. Note that this RT decrease did not depend upon response type (word or color), or position in the triplet (positions one, two or three).

To check that a color-naming counterpart of the DTS effect was absent, CiWiCi was compared to CiWnCi in the random condition. This comparison was not significant, $\underline{t}(10) = 1.12$, $p = .10$, confirming the absence of a color-naming counterpart to DTS (see Figure 13).

Discussion

As expected, a color-naming counterpart to DTS did not influence color naming. The absence of the DTS on color naming, and its presence for word reading, is in agreement with the asymmetry of switch costs hypothesis put forward by Allport et al. (1994), but does not contribute to an explanation of the existence of the switch cost for color naming reported in Experiments 1a and 1b.

The results of Experiment 2a relating to predictability were replicated, in that both color-naming and word-reading RT were reduced when the triplet type was completely

predictable, but only for the CiWnCi triplet type. This provides additional evidence for the postulation put forward in Experiment 2a that experiencing an EDS on 50% of trials produces as much anticipation cost as experiencing an EDS on 100% of the trials (see Figure 11). As was the case for Experiment 2a, this effect was not restricted to the first triplet member, so is probably not responsible for the order reported in Experiments 1a and 1b. It is more likely that there is a general cost for responses to stimuli arriving first in the trial, for color naming and word reading.

Discussion of Experiments 2a and 2b

Three effects were consistent across Experiments 2a and 2b: (a) response latency to incongruent stimuli was longer than to neutral stimuli, (b) anticipation of an EDS in position two on 100% of trials increased RT latency to stimuli in all positions, and (c), presentation of an incongruent stimulus on only 50% (as opposed to 100%) of the trials was sufficient to produce this EDS anticipation effect.

Regarding finding (a), the presence of a Stroop effect ($C_i - C_n = 137$ ms, random condition) was expected. The presence of a Reverse Stroop effect (RS; color naming interfering with word reading) was unexpected, although Allport et al. (1994) had previously reported a RS effect when comparing word-reading response latency from C_iW_i to that from C_nW_n . However, it is clear that this effect ($C_iW_iC_i - C_iW_nC_i = 82$ ms for the random condition) was not caused entirely by DTS, as this effect was found to be small in Experiment 2a (≈ 20 ms). In subsequent experiments, other combinations of incongruent and neutral stimuli will be used to clarify interpretation of this robust RS effect.

Regarding findings (b) and (c), the fact that anticipation of an EDS appeared to affect all responses suggests that anticipation had influenced the color naming and word reading switch costs observed in Experiment 1b. Despite the fact that the pair types in Experiment 1a were randomly presented, anticipation of an EDS remains a viable explanation of the switch costs reported in this experiment as well. This is because anticipation of an EDS is present even when an EDS is anticipated on only 50% of the trials, which was the expected frequency of EDSs in Experiment 1a. Thus, the anticipation

of an EDS cannot be implicated in order effects, but appears to influence RT at all positions when switching tasks.

Unexpectedly, order effects were present for color naming in Experiment 2b, but not for word reading in Experiment 2a. The cost associated with CiWi/nCi compared to CiWi/nCi found in Experiment 2b agrees with the findings of Experiments 1a and 1b, in that a cost for any response occurring first in the series was found. The results of Experiment 2a, however, are somewhat of a curiosity, in that a first-position RT cost was not found. One possibility for this discrepancy is that a strong repetition effect on WiCi/nWi from WiCi/nWi may mask the order effect that was observed in Experiments 1a and 1b. Other possibilities will be considered below subsequent to further experimentation.

DTS was present (but small), for word reading responses, and the absence of a color-naming counterpart to DTS was confirmed. As mentioned above, this DTS effect is insufficient to explain the large word-reading switch costs found by (a) Allport et al. (1994, 150 ms), (b) the present Experiment 1a (137 ms), and (c) the present Experiment 1b (230 ms). Any of the confounding variables listed in Table 1 could be implicated in an explanation of these word-reading switch costs. Another candidate is anticipation of an EDS. Although not listed in Table 1, it was discovered in Experiments 2a and 2b that EDS would also contrast across the CiWi – WiWi comparison. These possibilities will be reconsidered subsequent to further experimentation. Nonetheless, as was previously mentioned, DTS remains a viable explanation of the asymmetry of switch costs found by Allport et al., and observed in Experiments 1a and 1b. This possibility will be considered in the following experiment.

Experiment 3

Introduction

In Experiments 2a and 2b, it was demonstrated that (a) suppression of the dominant task set (DTS) does occur, but is a relatively small effect (b) costs due to anticipation of an EDS increase pre- *and* post-switch response latencies, and are present when only 50% of the trials involve EDS, and (c) large Stroop and RS effects are detectable within the context of task switching.

This new understanding of influences on response latency while switching tasks in triplets promotes a clearer interpretation of the switch costs previously found using stimulus pairs. For example, although Allport et al. (1994) implied that the DTS may account for up to the entire 150 ms word-reading switch costs observed in their experiment, the present investigation found that this effect slowed RT by only about 20 ms. Anticipation of an EDS may also account for some of the switch costs observed previously.

Experiment 3 reverted to pairs methodology to address the following questions, among others: (a) What cognitive mechanisms account for the effect of anticipation of an EDS on attentional switching? (b) What other variables affect switch costs? (c) What is the source of the color-naming switch cost? (d) Can the minor influence of DTS be replicated? (e) exactly which cognitive processes contribute to the DTS effect? To provide answers to these questions, task switching contexts were again compared, using sequentially presented stimulus pairs.

Method

Participants

Participants were 33 students enrolled in an introductory psychology course at the University of Victoria.

Procedure

For 19 of the 33 participants, testing began with administration of a “baseline” condition to demonstrate that a Stroop effect was present and a RS effect not present out of the context of task switching. W_i/n stimuli were presented in advance of C_i/n stimuli to avoid the between-list TSI effect (as reported by Allport et al., 1994), but block order (incongruent vs. neutral) was randomized within response type. Thirty-five trials of W_n , W_i , C_n and C_i responses were administered for each block. The stimulus disappeared from the screen once a response was recorded. The experimenter recorded any errors manually, and advanced to the next trial by a key press.

A switching trial consisted of either (a) a pair of incongruent Stroop stimuli, where the participant was instructed to respond either word-color (W_iC_i) or color-word (C_iW_i); (b) a pair of neutral Stroop stimuli, where the participant was instructed to respond either

word-color (WnCn) or color-word (CnWn); (c) a pair consisting of one incongruent and one neutral stimulus, where the participant was instructed to respond word-color (WnCi or WiCn) or color-word (CnWi or CiWn). Thus, in total, eight pair types were presented (WiCi, CiWi, WiCn, WnCi, CnWi, CiWn, WnCn, CnWn). The colors and color words used for all stimuli were blue, yellow, red, green, and purple. Each participant received 35 blocked trials of each pair type. The order of presentation for these eight stimulus blocks was randomly determined.

Results

Word Reading

In Experiments 1a, 1b, 2a and 2b, a number of effects that acted upon word reading, within the context of task switching, were identified (the DTS effect, the EDS anticipation effect, and an order effect). These effects will be studied in more detail below, beginning with an investigation of how they may contribute to the RS effect. Table 10 displays the mean RTs and error types for word reading.

Reverse Stroop Effect

While the Stroop effect is one of the most robust (and most studied) phenomena in the field of cognitive psychology, its counterpart, the RS effect is considered transient and fragile. Contrary to this expectation, Allport et al. (Allport et al., 1994) found a large and robust RS effect within the context of task-switching. In their experiment, subjects switched from color naming to word reading in response to incongruent (CiWi) or neutral (CnWn) Stroop stimuli. The reaction times (RTs) of interest were the *second RT of each pair* (CiWi, CnWn). An unexpected and very large (≈ 150 ms) RS effect was found for the CiWi - CnWn comparison.

Allport et al. (1994) attributed the existence of the RS effect to competition between S-R mappings, or TSI (task-set inertia). They proposed that, when alternating tasks, “incongruent color word stimuli evoke color naming and word reading responses with nearly equal strength” (p. 442), while neutral stimuli evoke only one response, and do not demand switching between instructions sets. Similarly, Rogers and Monsell (1995) proposed the TC (task-cueing) effect, whereby two tasks are loaded into task working

memory in response to an ambiguous stimulus, resulting in a cost associated with activating the now-appropriate task is incurred (TSR, or task-set reconfiguration; p. 216, 228).

A literal interpretation of the TSI and TC/TSR hypotheses gives rise to two predicted results which are directly challenged by the results of the previously reported experiments, casting doubt on the generalizability of these hypotheses:

1. Responses to neutral stimuli should never be subjected to the S-R conflict, even when paired with incongruent stimuli. This is because a neutral stimulus cannot evoke color naming *and* word reading responses. Therefore, the following equality should hold: $(C_iW_i - C_iW_n) = (C_iW_i - C_nW_n)$ (i.e., $C_iW_n = C_nW_n$). In contradiction to this extension of the TSI and TC/TSR theory, from the result of Experiment 2b it would be expected that the following inequality would hold $(C_iW_i - C_iW_n) < (C_iW_i - C_nW_n)$ (i.e., $C_iW_n > C_nW_n$), due to the anticipation of an EDS cost on C_iW_n associated with expecting C_iW_n on 100% of the trials (anticipation of an EDS is not present for C_nW_n).

2. Responses to incongruent stimuli should not be affected unless paired with *another incongruent stimulus*. The conflicting S-R mappings that affect the now-relevant response had to have been generated on the now-irrelevant response. Therefore, the following equality should hold: $(C_nW_i - C_nW_n = 0)$ (i.e., $C_nW_i = C_nW_n$). This is because neither the C_nW_i pair, nor the C_nW_n pair, demand switching between instructions sets for one stimulus type (*viz.*, incongruent Stroop stimuli). However, results of Experiment 2a (*viz.*, that the RS effect cannot be fully explained by the DTS effect), suggest that the RS effect may be present even outside the context of C_i . In other words, whatever effect produces the RS effect ($C_iW_iC_i > C_iW_nC_i$) over and above DTS may also affect the $C_nW_i - C_nW_n$ comparison.

Some of the results of Experiment 3 also contradict these extensions of the TSI and TC/TSR hypotheses for *position one* RTs (see Figure 14):

1. The results of Allport et al. (1994) were replicated, in that a large RS effect (130 ms) was found for the $W_iC_i - W_nC_n$ RT difference score, $t(32) = 7.11$, $p < .001$, $\eta^2 = .61$.

2. For the **WiCi** – **WnCi** RT difference score, a significant RS effect (94 ms) was found, $t(32) = 5.37$, $p < .001$, $\eta^2 = .47$, as predicted by the TSI and TC/TSR hypotheses. However, contrary to predictions implied by the TSI and TC/TSR hypotheses, taken in isolation, this effect was significantly smaller than that from the **WiCi** – **WnCn** comparison, $t(32) = 3.37$, $p < .01$, $\eta^2 = .26$.

3. Also contrary to the predictions of the TSI and TC/TSR hypotheses, a significant RS effect (50 ms) was found for the **WiCn** – **WnCn** RT difference score, $t(32) = 4.29$, $p < .001$, $\eta^2 = .37$. This effect, though substantial, was significantly smaller than that from Allport et al.'s (1994) comparison method, $t(32) = 5.16$, $p < .001$, $\eta^2 = .45$. and significantly smaller than the previously reported **WiCi** – **WnCi** comparison, $t(32) = 2.55$, $p < .02$, $\eta^2 = .17$.

The same set of results for *position two* follow (see Figure 15):

1. The results of Allport et al. (Allport et al., 1994) were replicated, in that a large RS effect (135 ms) was found for the **CiWi** – **CnWn** RT difference score, $t(32) = 10.11$, $p < .001$, $\eta^2 = .76$.

2. For the **CiWi** – **CiWn** RT difference score, a significant RS effect (85 ms) was found, $t(32) = 6.03$, $p < .001$, $\eta^2 = .53$, as predicted. However, contrary to predictions implied by the TSI and TC/TSR hypotheses, this effect was significantly smaller than that from the **CiWi** – **CnWn** comparison, $t(32) = 2.52$, $p < .02$, $\eta^2 = .17$.

3. Also contrary to the predictions of the TSI and TC/TSR hypotheses, a significant RS effect (45 ms) was found for the **CnWi** – **CnWn** RT difference score, $t(32) = 6.09$, $p < .001$, $\eta^2 = .54$. This effect was significantly smaller than that from Allport et al.'s (1994) comparison method, $t(32) = 7.14$, $p < .001$, $\eta^2 = .61$. and significantly smaller than the previously reported **CiWi** – **CiWn** comparison, $t(32) = 2.80$, $p < .01$, $\eta^2 = .20$.

Discussion – Reverse Stroop

The results of Allport et al. (1994) have been confirmed, as an RS effect was present under these conditions. However, the TSI and TC/TSR hypotheses, taken literally, imply that the RS effect will exist only in the presence of a conflicting set of instructions to

process, and respond to, the color dimension of incongruent Stroop stimuli. Contrary to implications of the TSI and TC/TSR hypotheses, it was also shown that:

1. The RS effect reduces when the control condition $Ci\mathbf{Wn}$ is used in place of $Cn\mathbf{Wn}$ (or $\mathbf{Wn}Ci$ in place of $\mathbf{Wn}Cn$).
2. The RS effect is present (but reduced) when $Cn\mathbf{Wi}$ is used as the experimental condition in place of $Ci\mathbf{Wi}$ (or when $\mathbf{Wi}Cn$ is used in place of $\mathbf{Wi}Ci$).

This set of results is the first step in the fractionation of switch costs into identifiable sub-components. Why, for example, is response latency to $Cn\mathbf{Wi}$ slower than that to $Cn\mathbf{Wn}$? It may have been expected that they would be equal, as S-R competition is present for neither. The reason must be related to the fact that $Cn\mathbf{Wi}$ is colored, while $Cn\mathbf{Wn}$ is not. One interpretation, which would presumably be adopted by Allport et al. (1994), is that TSI from responding Ci on previous stimulus *blocks* (e.g., $Ci\mathbf{Wi}$) produces proactive interference on $Cn\mathbf{Wi}$ due to between-block carry-over competing S-R mappings. This hypothesis has been tested, and in Experiment 4 it will be reported that this can be discounted as a full explanation.

An alternative hypothesis, which draws upon costs associated with switching attention between object dimensions, is that shifting attention away from the previously attended, now-irrelevant stimulus dimension, to the now-relevant dimension, produces a cost. This attention based effect will be referred to as SHIFT. Notice that this effect is active independently of any suppression of a dominant task, and is active only when incongruent stimuli are presented.

Along related lines, why is the response latency to $Ci\mathbf{Wn}$ slower than that to $Cn\mathbf{Wn}$? On first glance, it may appear that DTS could be held responsible for this difference. However, Allport et al. (1994) do not directly state whether or not TSI and DTS can act upon neutral stimuli. Indirectly, they state that TSI involves proactive interference from “competing S-R mappings with the same stimuli” (p. 436). Since the stimulus for $Ci\mathbf{Wn}$ (a neutral Stroop stimulus) is not the same as that for $Ci\mathbf{Wn}$ (an incongruent Stroop stimulus), it could be argued that TSI should not be applicable to $Ci\mathbf{Wn}$. In a statement characterizing DTS as a special type of TSI, they state that “the more strongly imposed the S-R set is for a given task feature, the greater is the TSI” (p.

442). Again, since TSI is supposed to be present only for incongruent Stroop stimuli, this increased TSI (*viz.*, DTS) should not act upon a neutral Stroop stimulus.

Despite this apparent inconsistency, the DTS explanation could quite easily be extended to neutral stimuli, implicating a general suppression of the word-reading task-set. However, even if DTS does, in fact, act upon W_n stimuli, we would expect only about a 20 ms effect, whereas the RT difference in question is 51 ms. Thus, the DTS aspect of the TSI hypothesis cannot easily explain the magnitude of the $C_iW_n - C_nW_n$ difference, EDS anticipation is a likely candidate to explain this discrepancy.

Recall that in Experiment 2b, a cost associated with anticipation of an EDS (i.e., anticipation of a switch to C_i) slowed W_n RT. Why would expectation of C_i affect W_n ? In accordance with the attention switching theory, the system may optimally configure by inhibiting attention to the word dimension, due to the necessity of averting attention from this dimension on a future trial. Evidence that attention can be strategically divided between stimulus dimensions is relevant to this argument (Logan, 1979; Logan, Zbrodoff, & Williamson, 1984). However, this “strategy” appears to be automatically imposed by the cognitive system. This automatically instantiated optimizing operation, which facilitates future attentional shifts, involving the moderation of attentional shifts, will be referred to as MODERATE.

Additional complications arise when the *size* of the RS effects are compared. For example, the following inequality holds: $(C_iW_i - C_iW_n = 85 \text{ ms}) > (C_nW_i - C_nW_n = 45 \text{ ms})$. If both RS effects are attributed to the SHIFT effect (the MODERATE effect is cancelled out; see Appendix A, method of computing SHFxMOD), this size discrepancy remains unexplained. This inequality also holds for position one RTs: $(W_iC_i - W_nC_i = 94 \text{ ms}) > (W_iC_n - W_nC_n = 50 \text{ ms})$. This discrepancy can be explained by asserting that simultaneous execution of SHIFT and MODERATE produces an interaction cost, perhaps due to sharing resources. This interaction effect will be referred to as SHFxMOD. Table 11 displays the presence of these effects for any given stimulus pair, and Tables 12 and 13 demonstrate how these effects may contrast across task-switching conditions, and the corresponding RS effect sizes.

PDP Model

Before continuing with the results of Experiment 3, it would be helpful at this point to present a model demonstrating how the SHIFT, MODERATE and SHFxMOD effects may be implemented by the cognitive system (see Figure 16). The proposed working model is a multilayer, linear parallel distributed processing (PDP) system (Jordan, 1986). It is not a non-linear, self-organizing system (e.g., Plaut & Shallice, 1994), nor is it a static box-and-arrow model (e.g., Baddeley, 1992; Howard & Franklin, 1988; Norman & Shallice, 1986). Development of this working model was influenced by previous theorists utilizing three types of modelling practice: (a) non-linear self-organizing networks (Cohen, Dunbar, & McClelland, 1990; Cohen & Huston, 1994; Cohen, Servan-Schreiber, & McClelland, 1992), (b) mathematical models (Logan, 1980; Strayer & Kramer, 1994a; Trainham, Lindsay, & Jacoby, 1997), and (c) box-and-arrow models (Norman & Shallice, 1986), to represent the distinction between automatic and controlled processing. It is an attempt to meet the challenge posed by Allport (1989), who called for presentation of “computational mechanisms by which attentional engagement is established, coordinated, maintained, interrupted, and redirected, both in spatial and nonspatial terms, in the preparation and control of action” (p. 663).

Most of these investigators used attentional weighting models to investigate costs associated with directing selective attention (Cohen et al., 1990; Cohen & Huston, 1994; Cohen et al., 1992; Logan, 1980). Following this lead, the model presented here simulates task switching costs by “computing and assigning weights to each dimension through an act of attention” (Logan, 1979, p. 167). This act of attention can be considered the “continued amplification of the signal of a relevant stimulus” (Milliken, Joordens, Merikle, & Seiffert, 1998, p. 204).

A method for building real time into the model to simulate RT (Kim & Myung, 1995), was inspired by the work of theorists proposing counter models (Cohen et al., 1990; Cohen & Huston, 1994; Cohen et al., 1992; Logan, 1980; Strayer & Kramer, 1994a; Strayer & Kramer, 1994b; Trainham et al., 1997). RT can be simulated as the number of iterations (i.e., counts) before a response node reaches threshold. Network iterations were of two types: (a) *information-gathering passes* (IGPs), for which a heavily weighted pathway will send more activation to response nodes per pass, allowing the

response nodes to reach threshold in fewer iterations, and (b) *attentional adjustment passes* (AAP), for which attentional weights are adjusted, but information is not gathered. Both IGPs and AAPs invoke time-consuming processes, and contribute to simulated RT length.

The resulting model was based on four types of processing nodes. When possible, aspects of the model are linked to familiar concepts originating in the automatic versus controlled processing literature:

1. Perceptual Nodes (PNs), which code (with dichotomous values 0 or 1) the presence or absence of color and word dimensions in the viewed stimulus. Thus, PNs are units that represent different object dimensions and compete for attention (Cohen & Huston, 1994, p. 459).

2. Response Nodes (RNs), which trigger (by taking continuous values between 0 and 1.0) the color-naming or word-reading schemas when their activation passes threshold (at 1.0) (Cohen et al., 1990, p. 338; Norman & Shallice, 1986, p. 4). The PNs, the RNs, and their connecting pathways represent the task schemas of Norman and Shallice (1986), defined as a “simple, self-contained, well-learned action sequence” (p. 3).

3. Task Demand Nodes (TDNs) code the demand for color naming and word reading with dichotomous values of 0 or 1. This control mechanism influences the activation of the task schemas in a top-down fashion, and thus can be considered an instance of supervisory attentional system (SAS) activity (Norman & Shallice, 1986). The SAS is defined as a mechanism which “operates entirely through the application of extra activation and inhibition to schemas” (Norman & Shallice, 1986, p. 6), thereby allowing a “less automatic process to direct a more automatic process” (Cohen & Huston, 1994, p. 465).

4. Connection Nodes (CNs), which serve to pass information from PNs to RNs, and to transfer task-demand information from TDNs to the PN attentional weights. This, this relay station carries out the inhibition and activation of task schemas, such that task demands can be met by the system. Thus, their influence on the schemas is analogous to contention scheduling (CS) activity (Norman & Shallice, 1986, pp. 5-6).

These four node types are interconnected by four path types:

1. PN → CN pathways are weighted corresponding to the allocation of attention, and send PN activation to CNs. Although the *initial values* for these weights are “hard-wired” in correspondence with the automaticity of attentional capture for the stimulus dimension in question (Cohen et al., 1990, pp. 356-7; MacLeod & Dunbar, 1988; Zbrodoff & Logan, 1986), they are adjustable. These pathways are affected both by top-down attentional influences of the TDNs (Cohen & Huston, 1994, p. 465; Norman & Shallice, 1986, p. 6-7), and the bottom-up influence of attentional capture (Cohen & Huston, 1994, p. 456-7). Prior environmental influences affect which attributes capture attention most effectively on initial contact with the stimulus (in accordance with the “continuum of automaticity” theory; Cohen et al., 1990, pp. 356-7; MacLeod & Dunbar, 1988; Zbrodoff & Logan, 1986).

2. CN → RN pathways are excitatory, with fixed weights. These pathways simply transfer activation to RNs.

3. TDN → CN activation weights are excitatory, with adjustable weights, representing excitatory top-down influences on attentional weighting (PN → CN pathway weights).

4. TDN --| CN inhibition weights are inhibitory, with adjustable weights, representing inhibitory top-down influences on attentional weighting (PN → CN pathway weights).

The set of effects proposed to account for variations in RS effect size in Experiment 3 can be incorporated into this PDP model as follows:

1. SHIFT: a cost associated with the additional iterations (AAPs) necessary for top-down inhibition of the just-activated attentional weights, and top-down activation of the attentional weights for the now-relevant dimension, carried out by the SAS (TDNs and the associated pathways) on CS (CN and PN → CN pathway weights), affecting activation of word-reading and color-naming task schemas, and IGP effectiveness.

2. MODERATE: for optimal task switching performance, the system must prepare for an EDS. This involves activation of the TDN the *now-irrelevant task* (thereby setting into motion the TDN --| CN inhibition weights and the TDN → CN activation weights). This operation has three effects: a) additional IGPs are needed for the now-

relevant task, due to the inhibition of the now-relevant task schema, (b) additional AAPs are necessary to reduce the attentional weight to the now-relevant task, producing the MODERATE cost, and c) fewer IGPs and AAPs are necessary when SHIFT is implemented on the immediately following trial, due to the “head start” provided by decreased activity on the PN → CN pathways (due to MODERATE). In other words, the MODERATE effect serves to reduce the cost of the SHIFT effect on a subsequent EDS. Moreover, the overall influence of this effect should depend upon the degree of difficulty in averting attention from that dimension on the subsequent SHIFT operation.

3. SHFxMOD: a cost attributable to the necessity of sharing the limited resources of the SAS between SHIFT and MODERATE, resulting in less efficient AAPs, and additional IGPs for RNs to reach threshold.

This model will be referred to throughout this manuscript for conceptualization of these effects, and will be returned to in a later section to describe additional effects and interactions.

Context Effects

The presence of the aforementioned effects (SHIFT, MODERATE, and SHFxMOD) can be confirmed through comparison of response latencies when stimulus types remain constant, but switching contexts vary. For example, in the previous section, it was noted that the response latency for $C_i\mathbf{W}_n$ was longer than that for $C_n\mathbf{W}_n$, due to the effect of the neighbouring stimulus (*viz.*, C_i vs. C_n). In this section, this and other context effects are considered, and the effects influencing these differences are specified.

The word-reading costs listed in Table 11 are translated into context effects for position one in Table 14, and the corresponding RT differences listed. Mean differences are displayed in Figure 21. The MODERATE and SHFxMOD effects combined to produce an 80 ms RT difference for the $\mathbf{W}_iC_i - \mathbf{W}_iC_n$ comparison, $t(32) = 5.16$, $p < .001$, $\eta^2 = .45$. For the $\mathbf{W}_nC_i - \mathbf{W}_nC_n$ RT difference score, a significant MODERATE effect (36 ms) was found, $t(32) = 3.37$, $p < .003$, $\eta^2 = .26$.

The word-reading costs listed in Table 11 are translated into context effects for the second position in Table 15, and the corresponding RT differences listed. Mean

differences are displayed in Figure 22. The MODERATE and SHFxMOD effects combined to produce a 91 ms RT difference for the $Ci\mathbf{Wi} - Cn\mathbf{Wi}$ comparison, $t(32) = 7.14$, $p < .001$, $\eta^2 = .61$. For the $Ci\mathbf{Wn} - Cn\mathbf{Wn}$ RT difference score, a significant MODERATE effect (51 ms) was found, $t(32) = 6.69$, $p < .001$, $\eta^2 = .58$.

Order Effects

The results of Experiments 1a and 1b suggest that order effects should be expected, whereby responses are slower in position one. This effect will be referred to as FIRST. It can be incorporated into the previously presented PDP model by postulating a very general cost associated with pre-trial pathway inhibition, manifesting as a temporary suppression of activity in all pathways, which is overcome when the first stimulus is encountered. Thus, additional iterations would be necessary to bring all pathways to resting state for the first response of a trial. Note that the FIRST effect appears to be a general effect not specific to task switching, as it was also present for task repetition (see Experiments 1a and 1b).

Table 16 displays the magnitude of order effects for word reading. There were significant order effects for $WiCi$, $WiCn$, $WnCi$, and $WnCn$ pair types, $t(32) = 2.76$, $p < .02$, $\eta^2 = .19$; $t(32) = 4.87$, $p < .001$, $\eta^2 = .43$; $t(32) = 2.88$, $p < .01$, $\eta^2 = .21$; $t(32) = 5.21$, $p < .001$, $\eta^2 = .46$, respectively. The replication of a word-reading order effect in this experiment provides evidence for the theory that the position one RT in Experiment 2a ($\mathbf{Wi}Ci/n\mathbf{Wi}$) was influenced by a repetition effect from the position three RT ($WiCi/n\mathbf{Wi}$) of the previous trial, a situation that appears to be unique to the triplets methodology.

Position one costs have been observed previously by Pashler (1994), when studying task repetition. Pashler reported that the first RT of a trial was slowest, particularly when the imperative stimuli had been previewed. He attributed this unexpected cost to “setting in motion the processes required to coordinate these various activities” (p. 186), or a “warm-up effect” (p. 175). The fact that some order effects were larger than others suggests the presence of interactions between these cognitive operations. That is to say, the previously mentioned effects (SHIFT and MODERATE)

appear to interact with position. This possibility will be explored in the following section entitled Manual Partialling.

Manual Partialling

Although the effects already mentioned explained the data fairly well, is there anything to be learned from the *between-table* variation in the sizes of effects? For example, the within-table variation in RT differences listed in the Tables 14 and 15 are explained by the presence or absence of the SHFxMOD effect. That is to say, when this effect contrasts, RT differences are larger. However, the between-table RT differences have not yet been explained. Why is the additive cost of MODERATE and SHFxMOD in Table 14 eleven ms smaller than the same additive cost in Table 15? Preliminary answers to these questions can be established by more specific between-table comparisons for word-reading RTs.

For example, the only difference between MODERATE & SHFxMOD in Table 14 and MODERATE & SHFxMOD in Table 15 is the pair positioning, whereby the contrast is larger in position two. Thus, a cost associated with either MODERATE or SHFxMOD in the second position could account for this discrepancy. RT comparisons to test if the MODERATE + SHFxMOD sum is larger in position two than in position one follow.

In order to assign the position two cost to either MODERATE or SHFxMOD, these effects should be individually isolated in the first and second positions, and their size compared. For example, SHFxMOD and SHIFT (not MODERATE) are isolated in the first position by the difference $\mathbf{W_iC_i} - \mathbf{W_nC_i}$, and in the second position by the difference $\mathbf{C_iW_i} - \mathbf{C_iW_n}$ (see Table 11).

The combined effect of SHFxMOD + SHIFT would be expected to be greater in the second position than the first if there were a second position cost associated with SHFxMOD. However, the reverse is true – the first position RT difference ($\mathbf{W_iC_i} - \mathbf{W_nC_i} = 94$ ms) is larger than the second position difference ($\mathbf{C_iW_i} - \mathbf{C_iW_n} = 85$ ms) (see Table 12 and Table 13). Thus, SHFxMOD is not a good candidate for a position two cost (unless, of course, a cost associated with SHIFT in the first position is at least twice the size of one associated with SHFxMOD in the second position – a scenario that will be discounted in future analyses).

The possibility that the position two cost can be attributed to MODERATE can be tested using similar methods as were used to discount a position two cost for SHFxMOD. The effect MODERATE can be isolated in the first position by the difference $\underline{\mathbf{WnCi}} - \underline{\mathbf{WnCn}}$, and in the second position by the difference $\mathbf{Ci}\underline{\mathbf{Wn}} - \mathbf{Cn}\underline{\mathbf{Wn}}$ (see Table 11). In accordance with the hypothesis that there is a cost associated with MODERATE in the second position, the $\mathbf{Ci}\underline{\mathbf{Wn}} - \mathbf{Cn}\underline{\mathbf{Wn}}$ response latency difference is larger than that of $\underline{\mathbf{WnCi}} - \underline{\mathbf{WnCn}}$ ($\underline{\mathbf{M}} = 51$ and $\underline{\mathbf{M}} = 36$ ms, respectively, see Table 14 and Table 15). Thus, a position two cost can be attributed to MODERATE. In other words, an interaction between MODERATE and position is present.

This test involved the four pairs $\mathbf{Ci}\underline{\mathbf{Wn}}$, $\mathbf{Cn}\underline{\mathbf{Wn}}$, $\underline{\mathbf{WnCi}}$ and $\underline{\mathbf{WnCn}}$. Can this finding be replicated using a different set of pairs? In fact it can, using the other four word-reading RTs $\mathbf{Ci}\underline{\mathbf{Wi}}$, $\mathbf{Cn}\underline{\mathbf{Wi}}$, $\underline{\mathbf{WiCi}}$ and $\underline{\mathbf{WiCn}}$. For the difference $\mathbf{Ci}\underline{\mathbf{Wi}} - \mathbf{Cn}\underline{\mathbf{Wi}}$, the effects SHFxMOD and MODERATE contrast in the second position, while for the difference $\underline{\mathbf{WiCi}} - \underline{\mathbf{WiCn}}$, the same effects contrast in the first position. And, in accordance with the hypothesis that there is a cost associated with MODERATE in the second position, the RT was slower in the second position than the first ($\underline{\mathbf{M}} = 91$ ms and $\underline{\mathbf{M}} = 80$ ms, respectively).

This analysis leads to the following question: Why would MODERATE produce a larger cost in the second position, compared to the first? In more descriptive terms, whenever Ci is the first position stimulus, word reading in response to any stimulus type is slowed in position two. This appears to be a manifestation of the familiar DTS effect introduced by Allport et al. (1994), which evidently acts locally (immediately following a Ci response) upon neutral and incongruent stimuli. DTS appears to be active only in the second position, and cannot carry over between trials. The test using the pairs $\mathbf{Ci}\underline{\mathbf{Wn}}$, $\mathbf{Cn}\underline{\mathbf{Wn}}$, $\underline{\mathbf{WnCi}}$ and $\underline{\mathbf{WnCn}}$ indicated that the DTS was about 15 ms, while that using the pairs $\mathbf{Ci}\underline{\mathbf{Wi}}$, $\mathbf{Cn}\underline{\mathbf{Wi}}$, $\underline{\mathbf{WiCi}}$ and $\underline{\mathbf{WiCn}}$ indicated that DTS cost was about 11 ms. The small size of these costs is in agreement with the small size of the DTS effect found in Experiment 2a (21 ms). Thus, what appeared at first to be a position interaction involving the MODERATE effect, which involves top-down preventative operations, is actually a manifestation of the DTS effect, a bottom-up, local suppression effect.

The manual partialling method outlined in this section is presented in full detail in Appendix A. The goal of manual partialling was to study the influence of particular effects on RT when other effects were not confounding interpretation. Use of this methodology confirmed the presence of the three main effects on word-reading already mentioned (MODERATE, SHIFT, and FIRST), and all combinations of two-way interactions between these effects. The presence and absence of these six hypothetical effects for all word-reading latencies are listed in Table 17, and all possible methods of computation by manual partialling are listed in Appendix A.

Regression Method

Unfortunately, using manual partialling, the aforementioned effects are often impossible to study in isolation due to more than one effect contrasting across conditions. For example, the MODERATE effect that determined a portion of the $\mathbf{W_nC_i}$ response latency can be isolated by only one differencing operation (*viz.*, $\mathbf{W_nC_i} - \mathbf{W_nC_n}$). However, MODERATE also determines a portion of the $\mathbf{W_iC_i}$, $\mathbf{C_iW_i}$, and $\mathbf{C_iW_n}$ response latencies (see Table 17), but cannot be isolated using these RT measures, because no other RT measure can be used to partial out only the to-be-ignored effects.

A solution to this problem can be arrived at using multiple regression, which allows *mathematical* partialling of effects (Lorch & Myers, 1990). Using this methodology, the impact of each main effect and interaction could be assessed over and above any other effect. For example, the influence of MODERATE on the overall pattern of RT variance could be tested, whereas with the manual partialling procedure, MODERATE could be observed on one RT comparison (*viz.*, $\mathbf{W_nC_i} - \mathbf{W_nC_n}$).

This multiple regression methodology involved four steps:

1. The data set was transposed, so that “subjects” constituted the columns of the data matrix, and “condition” (e.g., $\mathbf{W_nC_n}$, $\mathbf{C_iW_i}$, etc.) the rows.
2. Columns representing the presence and absence of effects (effect contrasts) were added alongside subject columns, whereby each RT condition (i.e., each row) was assigned a 1 if the effect is expected to be present, and a 0 if the effect was expected to not be present (see Table 17).

3. RT means were regressed on the contrast vectors (that code the presence or absence of effects) for each participant separately. The method of contrast vector selection for a given regression analysis is presented below.

4. A beta weight was computed for each *participant*, that represented the influence of each effect (over and above other contrast vectors in the regression equation), on that participant's pattern of RT variance.

5. These beta weights were then used as dependent variables for within- and between-groups RT cost comparisons. For example, for within-group comparisons, the significance of RT costs was assessed by testing whether mean betas for the effects were significantly different from zero by way of one-sample t-tests. For between-group comparisons, between group differences in RT costs were assessed by testing between-group mean beta differences way of independent-groups t-tests.

The contrast codes were constructed such that 1 coded the presence of a given effect, and 0 coded its absence. The full matrix of contrast vectors can be created by translating the "Yes" entries to 1, and the "No" entries to 2 in Table 17 for word reading, and in Table 27 for color naming. Using this type of coding allows the beta weights to be interpreted as the response latency added (in milliseconds) by the effect in question, over and above the other effects in the model.

Regression Analysis

Using ANOVA terminology, the SHIFT, MODERATE, and FIRST contrast codes were considered main effects. In accordance with recommended regression procedures (Pedhazur, 1982, p. 375-376), the highest order interaction term (the three way interaction) was tested first, and was found to be non-significant, $t(32) = 0.21$, $p = .84$.

When the interaction effects involving FIRST (MODx1st and SHFx1st) were tested, with the main effects and remaining two way interactions partialled out, the mean beta sizes were not significantly different from zero, $t(32) = -1.07$, $p = .29$, $t(32) = 0.73$, $p = .73$, respectively. This indicates that although these effects were detectable through manual partialling, they did not exert enough overall influence to reach significance. Therefore, the effect FIRST was interpreted independently, and was significantly different

from zero, $t(32) = 6.08$, $p < .001$, $\eta^2 = .54$. The FIRST effect was characterized by increased response latencies in position one ($M = 43$ ms).

The two-way interaction term SHFxMOD ($M = 42$ ms) was significantly different from zero, $t(32) = 3.42$, $p < .003$, $\eta^2 = .27$. This indicates that when the SHIFT and MODERATE effects co-occurred, response latencies were 42 ms longer. A regression including the SHIFT, MODERATE and SHFxMOD contrast codes demonstrated that the SHIFT effect was significantly different from zero when MODERATE was not present ($M = 47$ ms), and MODERATE was significantly different from zero when SHIFT was not present ($M = 43$ ms), $t(32) = 5.74$, $p < .001$, $\eta^2 = .51$, $t(32) = 6.69$, $p < .001$, $\eta^2 = .58$, respectively. Figure 23 displays all word-reading effects and their observed RT costs, with 95% confidence intervals. Table 18 lists effects that were partialled out for each effect displayed in Figure 23. Table 19 displays correlations between contrast vectors.

Discussion (Word Reading)

Four effects on word reading RT, within the context of task switching, accounted for significant overall variance: (a) FIRST, a cost associated with responding to the first member of the pair, (b) SHIFT, a cost associated with switching attention from the previously attended, now-irrelevant dimension, to the now-relevant dimension, when both dimensions are present in the stimulus, (c) MODERATE, a cost associated with inhibiting the allocation of attention to a stimulus dimension that has a high probability of being irrelevant on a future trial, and (d) the interaction effect SHFxMOD, a cost present when SHIFT and MODERATE co-occur, proposed to be due to a sharing of SAS resources. Two interaction effects identified through manual partialling (DTS, which was tested by MODx1st, and SHFx1st) did not account for significant variance over and above these effects.

Relationship to Previous Results

Translation of these new effects into those found using triplets methodology (Experiments 2a and 2b) presented some difficulties, due to differences in experimental design. This difficulty is pronounced for the FIRST effect for word reading, which was robust and replicable in pairs experiments (e.g., Experiments 1a, 1b, and 3), but not

present in Experiment 2a, which used triplets. Previously, it was suggested that this may be due to the influence of task-repetition on WiCi/nWi from WiCi/nWi of the previous trial. However, another possibility arises from the knowledge gained in Experiment 3 that SHIFT may influence WiCi/nWi not WiCi/nWi, due to the fact that only WiCi/nWi directly follows a color naming response. This cost on WiCi/nWi may counteract a FIRST cost on WiCi/nWi, preventing the observation of either effect. Perhaps a combination of task repetition benefit on WiCi/nWi and SHIFT on WiCi/nWi combined to cancel an effect of FIRST on WiCi/nWi in Experiment 2a.

The minimal influence of the DTS effect, however, was consistent across methodologies. In Experiment 2a it was demonstrated that DTS was a small effect, and this was confirmed in the present experiment. Although manual partialling suggested that DTS acted upon Wn and Wi responses in the second position, this effect did not explain significant variance over and above the other effects (tested by MODx1st). Therefore, although apparently present, DTS has relatively little impact on the overall switch costs. In summary, although DTS is present, and acts independently of the SHIFT and MODERATE effects, its overall influence must be considered minor when compared to these effects.

In Experiment 2b, response latency to neutral word-reading stimuli (CiWnCi) was contrasted with response latency to incongruent word-reading stimuli (CiWiCi), producing a large RS effect ($M = 93$ ms, averaged over Predictability). Experiment 3 demonstrated clearly that this effect cannot be attributed to DTS, as DTS acts upon both Wi and Wn responses. This effect also cannot be attributed to MODERATE, as this effect does not contrast across this comparison (i.e., both the Wn and Wi responses are affected by MODERATE, as Ci is expected on 100% of the trials, and MODERATE affects both neutral and incongruent stimuli). However, the SHIFT and SHFxMOD effects do contrast, and probably combine to produce the major portion of the RS effects observed in Experiment 2b.

Also of interest in Experiment 2b is the slowing of the CiWnCi RT in the random condition, compared to the blocked condition. This cost may be attributable to diluted versions of SHIFT and SHFxMOD. In the random condition, even the black color of the

neutral stimulus may draw attention (when that dimension has just been attended). This is because on 50% of the trials a colored stimulus was encountered ($Ci\mathbf{Wi}Ci$), evoking the SHIFT effect. Thus, since colored stimuli are expected for 50% of the $Ci\mathbf{Wi/n}Ci$ random trials, the black color of the neutral stimulus is more likely to draw attention in this situation than in the $Ci\mathbf{Wn}Ci$ blocked trials, perhaps evoking a weak version of the SHIFT effect (and therefore a weak SHFxMOD effect). Thus, while the $Ci\mathbf{Wn}Ci$ and $Ci\mathbf{Wn}Ci$ costs in the random condition (compared to the blocked condition) were attributed to the MODERATE effect (previously called anticipation of an EDS), the $Ci\mathbf{Wn}Ci$ cost (compared to the blocked condition) can be attributed to the presence of a diluted SHIFT effect.

In Experiment 2a, increases in some word reading response latencies were attributed to anticipation of an EDS ($\mathbf{Wi}CiWi$ and $WiCi\mathbf{Wi}$ in the random and blocked conditions, and $\mathbf{Wi}CnWi$ and $WiCn\mathbf{Wi}$ in the random condition). In Experiment 3, it was demonstrated that this increased response latency may be attributable to the MODERATE effect. In other words, in Experiment 2a, the word-reading costs were correctly associated with a high probability of an EDS to the color dimension on a future trial. In summary, EDS can be explained in more detail as top-down partial inhibition of attention to the word dimension in preparation for an upcoming EDS to the color dimension (i.e., MODERATE).

The source of the RS effect found by Allport et al. (1994) has previously been identified as a combination of SHIFT + MODERATE + SHFxMOD (see Table 13). Presumably, a significant portion of the word-reading switch cost ($Ci\mathbf{Wi} - Wi\mathbf{Wi}$) reported in Allport et al.'s Experiment 5 (displayed in their Figure 17.6a), and in Experiments 1a and 1b of the present investigation, can also be attributed to these three effects. None of these effects would be expected to be present in task repetition.

To summarize, in this section, (a) the minor importance of DTS was confirmed, (b) anticipation of an EDS was reformulated into the more specific MODERATE effect (which is a cost associated with top-down partial inhibition of attention to the word dimension in preparation for an upcoming EDS, for the purpose of optimizing task-switching performance), (c) the influence of a cost associated with switching attention

between stimulus dimensions was introduced (SHIFT), and (d) a cost associated with a general pre-trial decreased activation in the neural network was proposed (FIRST). Finally, it was recognized that response latency was longer when the SHIFT and MODERATE effects co-occurred (SHFxMOD), an effect proposed to be due to sharing of SAS resources.

Color Naming

For the sake of comparison, the discourse presented for word reading is now repeated for color naming, but in less detail. In Experiments 2a and 2b, a number of effects were identified that act upon color naming response latency within the context of task switching (e.g., anticipation of an EDS, and an order effect). These effects will be studied in more detail below, using pairs methodology, beginning with a detailed investigation into the Stroop effect. Table 20 displays the mean RTs and error types for color naming.

Stroop Effect

Tests of the Stroop effect involve comparing Ci RT to Cn RT. An in-depth analysis of the Stroop effect under different switching conditions lead to the identification of a number of switching costs that appeared to affect other response latencies.

Allport et al. (1994) found a large and robust Stroop effect within the context of task-switching. In their experiment, participants switched from word reading to color naming in response to incongruent (WiCi) or neutral (WnCn) Stroop stimuli. The reaction times (RTs) of interest were the *second RT of each pair* (WiCi, WnCn). An expected and large (≈ 150 ms) Stroop effect was found for the WiCi - WnCn comparison. This effect will be investigated in more detail in the first and second positions.

The results for *position one* were as follows (see Figure 24):

1. The results of Allport et al. (1994) were replicated, in that a large Stroop effect (238 ms) was found for the CiWi – CnWn RT difference score, $t(32) = 16.88$, $p < .001$, $\eta^2 = .61$.

2. For the CiWi – CnWi RT difference score, a significant Stroop effect (209 ms) was found, $t(32) = 13.76$, $p < .001$, $\eta^2 = .86$, as predicted. This effect was significantly smaller than that from the CiWi – CnWn comparison, $t(32) = 3.39$, $p < .005$, $\eta^2 = .26$.

3. For the **CiWn** – **CnWn** RT difference score, a significant Stroop effect (182 ms) was found, $t(32) = 12.13$, $p < .001$, $\eta^2 = .82$. This effect was significantly smaller than that from Allport et al.'s (1994) comparison method, $t(32) = 3.75$, $p < .001$, $\eta^2 = .31$, but not significantly smaller than the previously reported **CiWi** – **CnWi** comparison, $t(32) = 1.51$, $p = .14$.

These previously unreported effects confirm (as expected) that Stroop effects are also present in the first position. However, as was observed for the RS effect, previously uninvestigated effects include a reduction in the Stroop effect when **CnWi** was used as the control condition, and a reduction when **CiWn** was used as the experimental condition.

The results for *position two* were as follows (see Figure 25):

1. The results of Allport et al. (1994) were replicated, in that a large Stroop effect (175 ms) was found for the **WiCi** – **WnCn** RT difference score, $t(32) = 13.73$, $p < .001$, $\eta^2 = .85$.

2. For the **WiCi** – **WiCn** RT difference score, a significant Stroop effect (167 ms) was found, $t(32) = 11.83$, $p < .001$, $\eta^2 = .81$, as predicted. As was the case for position one, this effect was not significantly smaller than that from the **WiCi** – **WnCn** comparison, $t(32) = 1.02$, $p = .31$.

3. For the **WnCi** – **WnCn** RT difference score, significant Stroop effect ($M = 138$ ms) was found, $t(32) = 13.53$, $p < .001$, $\eta^2 = .85$. As for position one, this effect was significantly smaller than that from Allport et al.'s (1994) comparison method, $t(32) = 3.70$, $p < .002$, $\eta^2 = .30$. Unlike for position one, this effect was significantly smaller than the previously reported **WiCi** – **WiCn** comparison, $t(32) = 2.26$, $p < .05$, $\eta^2 = .14$.

The results of Allport et al. (1994) were replicated, confirming the existence of a Stroop effect for the **WiCi** – **WnCn** comparison. However, a previously unreported result was also discovered: the Stroop effect was reduced when **WnCi** was used as the experimental condition. These findings replicated in position one.

Discussion – Stroop Effect

These size variations of the Stroop effect afford the opportunity to observe analogues of the word reading effects acting upon color naming, within the context of

task-switching. Using the manual partialling method developed for the word reading analysis, the color naming RTs were assessed. The resultant effects for color naming were similar to those for word reading: (a) moving attention from the previously attended, now-irrelevant dimension to the now-relevant dimension (e.g., W_nC_i ; SHIFT), (b) the partial inhibition of attention to the now-relevant dimension, due to a high probability of shifting attention off this dimension in the future (e.g., W_iC_n ; MODERATE), and (c) a cost due to simultaneous execution of SHIFT and MODERATE (SHFxMOD; e.g., W_iC_i). Table 21 displays the presence of these effects for any given stimulus pair, and Tables 22 and 23 show how these effects may contrast across task-switching conditions.

For color naming there exists a confound that cannot be discounted using this experimental design. This confound is that SHIFT cannot be measured independently of the traditional Stroop effect. Evidence suggesting that the SHIFT effect does, in fact, exist independently of the Stroop effect includes: (a) the presence of interaction effects involving SHIFT, which appear to correspond to those observed for word reading, and (b) the presence of color naming switch costs in Experiments 1a and 1b, for which the Stroop effect is not a confound. However, as reminder of this confound, for color naming the SHIFT effect will be referred to as the SHIFT/Stroop effect. Note that although this appears to be a confound, the Stroop operation can also be conceptualized as a special case of SHIFT, involving a difficult switch of selective attention from a highly activated, dominant word dimension, to the nondominant color dimension (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992).

Context Effects

As was the case for word reading, the existence of the effects acting on color naming can be confirmed through comparison of response latencies to the same stimulus types in different switching contexts. In this section similar direct comparisons are made and quantified, and the effects influencing these differences specified.

Using the color-naming costs listed in Table 21, Table 24 shows how these effects contrast across task-switching contexts, and the corresponding RT differences, in position one. These mean differences are displayed in Figure 26. The MODERATE and SHFxMOD effects combined to produce a 56 ms RT difference for the $C_iW_i - C_iW_n$

comparison, $t(32) = 3.75$, $p < .002$, $\eta^2 = .30$. For the CnWi – CnWn RT difference score, a significant MODERATE effect (29 ms) was found, $t(32) = 3.39$, $p < .005$, $\eta^2 = .26$.

Using the color-naming costs listed in Table 21, Table 25 shows context effects and the corresponding RT differences in position two. These mean differences are displayed in Figure 27. The MODERATE and SHFxMOD effects combined to produce a 37 ms cost for the WiCi – WnCi RT difference score, $t(32) = 3.69$, $p < .002$, $\eta^2 = .30$. For the WiCn – WnCn RT difference score, a non-significant MODERATE effect (8 ms) was found, $t(32) = 1.02$, $p = .31$.

Order Effects

The results of Experiments 1a and 1b suggest that order effect should be expected, as do the results of Experiment 2b. Table 26 shows the size of order effects for color naming. There were significant order effects for CiWi ($M = 87$), CnWi ($M = 45$), CiWn ($M = 67$), and CnWn ($M = 26$), $t(32) = 6.15$, $p < .001$, $\eta^2 = .54$, $t(32) = 4.24$, $p < .001$, $\eta^2 = .36$, $t(32) = 5.71$, $p < .001$, $\eta^2 = .67$, $t(32) = 2.71$, $p < .02$, $\eta^2 = .19$, respectively.

As was the case for word reading, the fact that some color naming order effects were larger suggests the presence of interactions between FIRST, and MODERATE and SHIFT. The differing sizes of the effects suggest that some of the previously mentioned effects (MODERATE and SHIFT/Stroop) may interact with position. That is to say, some effects may have been larger when they occurred first in the pair compared to second. These possibilities will be explored by manual partialling.

Manual Partialling

The manual partialling methods used for word-reading effects (listed in Appendix A) were applied to color naming RTs (see Appendix B). This led to the isolation of three color naming analogues to word-reading main effects: (SHIFT/Stroop, MODERATE, and FIRST), and their two-way interactions (SHFxMOD, SHFx1st and MODx1st). The presence and absence of these six effects in all color-naming latencies are listed in Table 27, and all possible methods of computation are listed in Appendix B.

Regression Analysis

The regression method used for word reading (Lorch & Myers, 1990) was employed to test if the main effects and interactions identified through manual partialling accounted for significant, independent portions of overall color-naming RT variance. The three way interaction term of the main effects (MODERATE X SHIFT X FIRST) was tested first, and was found to be non-significant (over and above all main effects and two-way interactions), $t(32) = -0.10$, $p = .92$.

The subsequent tests of the two-way interactions (with main effects and other two-way interactions partialled out) resulted in significant interactions for MODx1st ($M = 20$ ms), $t(32) = 2.36$, $p < .03$, $\eta^2 = .15$, SHFx1st ($M = 43$ ms), $t(32) = 4.27$, $p < .001$, $\eta^2 = .36$, and SHFxMOD ($M = 28$ ms), $t(32) = 2.45$, $p < .03$, $\eta^2 = .16$. Therefore, the simple main effects were interpreted taking these interactions into account.

For color naming, the MODERATE effect did not account for significant variance over and above the other effects, $t(32) = 1.17$, $p = .25$ (although the significant MODx1st indicates that this effect was important in position one). SHIFT/Stroop was highly significant ($M = 138$ ms), $t(32) = 12.64$, $p < .001$, $\eta^2 = .83$. The effect FIRST was significantly different from zero ($M = 24$ ms), over and above the other effects $t(32) = 2.61$, $p < .02$, $\eta^2 = .18$. Figure 28 displays all color-naming effects and their associated RT costs, with 95% confidence intervals. Table 28 lists effects that were partialled out for each effect of interest.

Discussion (Color Naming)

Two main effects and three two-way interaction effects accounted for significant portions of unique variance in color naming RT, within the context of task switching. They were: (a) FIRST (a cost associated with responding to the first member of the pair), (b) SHIFT/Stroop (a cost associated with ignoring the stimulus dimension that was attended on the previous response, plus a Stroop effect), (c) MODx1st (a cost associated with MODERATE in the first position), (d) SHFx1st (a cost associated with SHIFT in the first position), and (e) SHFxMOD (a cost present when SHIFT and MODERATE coincided).

The fact that the MODERATE effect on color naming did not reach significance outside the influence of FIRST and SHIFT may be related to the relative dominance of the word reading dimension. In other words, the overall influence of MODERATE on color naming responses may be reduced because it is not difficult to avert attention from that dimension on future trials (i.e., the bottom-up attentional capture invoked by the color dimension is relatively weak, whereas it is strong for the word dimension).

Relationship to Previous Results

The translation of these effects into those found in the experiments using triplets (Experiments 2a and 2b), as mentioned above, presented some difficulties. For example, A general slowing of color naming RT (for CiWiCi and CiWiCi in the random and blocked condition, and for CiWnCi and CiWnCi in the random condition) found in Experiment 2b was attributed to anticipation of an EDS, but can now be understood as a manifestation of the MODERATE effect. However, the MODERATE effect alone did not account for significant RT variance in Experiment 3, although it did in position one, and when SHIFT was present. Thus, MODERATE may have been more effective in Experiment 2b because it always coincided with the triplets version of FIRST and SHIFT. Alternatively, it may have more influence when Ci responses are more frequent.

Also of interest in Experiment 2a is the slowing of the WiCnWi RT in the random condition compared to the blocked condition. This cost may be attributable to diluted versions of SHIFT and SHFxMOD. In the random condition, the linguistic nature of the XXXX display may draw attention (when that dimension is primed). This is because on 50% of the trials an incongruent Stroop stimulus was encountered (WiCiWi), evoking the SHIFT effect. Attention is more likely to be drawn to the primed word dimension when it is expected to be present in the stimulus. Thus, since word stimuli are expected for WiCi/nWi random trials, the linguistic nature of the neutral stimulus is more likely to draw attention than in the WiCnWi blocked trials, perhaps evoking a weak SHIFT effect (and therefore a weak SHFxMOD effect).

An important issue brought to light by Experiments 1a and 1b was the source of the color-naming switch cost. The results of Experiment 3 suggest that the color-naming switch cost from Experiments 1a and 1b may be attributed to the following color-naming

effects that are substantial in position two, unique to task switching, and thus not present for repeated trials: SHFxMOD and SHIFT. Note that for the situation presented in Experiments 1a and 1b, the influence of SHIFT can be observed out of the presence of the Stroop effect. Thus, it may be that, because the SHFxMOD effect is of moderate size (20 ms), the SHIFT effect accounts for much of the remaining 108 ms. The precise amount, however, cannot be determined due to the confounds associated with using task repetition as the control condition.

The reason as to why Allport et al. (1994) did not find a switch cost for color naming (their Experiment 5, displayed in their Figure 17.6a), remains a mystery. There is no reason to suspect that SHIFT and SHFxMOD were not present for the WiCi response in Allport et al.'s Experiment 5. A more likely scenario is that the SHIFT and SHFxMOD effects were present for the repeated condition. This possibility becomes more plausible when methodological differences between Allport et al.'s study and Experiment 1a are considered.

For each of the eight conditions in Allport et al.'s (1994) study (including CiCi and WiCi), a list of only five pairs was presented to the participant (list order was randomly determined for each eight condition block, and three blocks were presented). Prior to each list, the participant was instructed as to which task to carry out in response to the first and second members of the pair. In contrast, for each condition in Experiment 1b, 40 pairs were presented. Therefore, in Allport et al.'s study, many subjects in the CiCi condition were recently word reading in response to incongruent Stroop stimuli (in the WiWi, CiWi, or WiCi conditions), sometimes on the immediately preceding list of five pairs.

Under these conditions, the previously active word-reading response may influence CiCi responses. Thus, slowing of CiCi RT could conceivably be due to the MODERATE effect, active due to expectation of an EDS on a future response. In addition, the SHIFT effect influences CiCi, since the Stroop effect can be considered a special case of the SHIFT operation (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992). If the SHIFT and MODERATE effects are simultaneously present, the SFTxMOD interaction would also effect RT, thereby increasing CiCi RT to that of WiCi in Allport et al.'s (1994) experiment 5.

General Discussion (Asymmetry of Switch Costs)

The asymmetry of word reading and color naming switch costs reported by Allport et al. (1994), and in Experiments 1a and 1b, has not yet been explained. The following inequality was reported in all three experiments: $(C_iW_i - W_iW_i) > (W_iC_i - C_iC_i)$. It has already been determined that the DTS effect makes a minor contribution to this asymmetry in position two; however, DTS does not explain a similar inequality found on position one. The following are possible explanation of this asymmetry: (a) the relatively minor influence of MODERATE on W_iC_i trials reported in Experiment 3, and (b) the SHIFT effect is present in both C_iC_i , and W_iC_i , and the magnitude of SHIFT on W_iC_i trials is does not add much to RT above the influence of SHIFT on C_iC_i . These possibilities must be assessed through further experimentation; however, the more important finding of the present investigation was that significant color-naming switch costs exist, and the MODERATE, SHIFT and FIRST affects can be applied to color naming to in some capacity.

Extension of the PDP Model

In Experiment 3, it was demonstrated that the major color-naming and word-reading switch costs can be attributed to either *shifting* attention during an EDS (SHIFT), and/or *moderating* these attentional shifts to allow optimal task switching on a future EDS (MODERATE). More specifically, switch costs may be due to (a) top-down shifting of attention from the previously attended stimulus dimension to the now-relevant dimension (SHIFT), (b) top-down partial inhibition of attention to a stimulus dimension from which attention must be averted on a future trial (MODERATE), (c) a general, pre-stimulus network deactivation was present (FIRST), and (d) interactions between these main effects.

As a working example, a series of figures are presented demonstrating how the previously presented model can be used to simulate the C_nW_i response. The example begins with Figure 29, which displays the state of this model in mid-trial, subsequent to the C_nW_i response, but prior to presentation of the C_nW_i stimulus. In this situation, both RNs have a value of 0 (all activation subsided), both PNs have a value of 0 (neither dimension present), both TDNs have a value of 0 (no task demand activity until stimulus

presented, but see Meiran, 1996; Rogers & Monsell, 1995, regarding preparation for a switch), and the activated state of the color dimension attentional weight (PN → CN color pathway) is carried over from the previous response (.5 is activated for the color dimension, which rests at .25). The attentional weight to the word dimension (PN → CN color pathway) has the resting value (.5 is resting activation for the word dimension), as no word dimension was present on the previous response, and activation has subsided.

Figure 30 displays the state of the model for the initial reaction to the **CnWi** stimulus (i.e., IGP one). In this situation, both RNs have a values slightly above 0 (initial accumulation of evidence collected at each IGP that will eventually bias the system towards a response), and both PNs have a value of 1 (both dimensions are present in the object). For IGPs, the CN activation value is determined by $PN * PN \rightarrow CN$ weight.

Figure 31 displays the state of the model for the **CnWi** response on AAP one, where attentional weights (PN → CN pathways) are being adjusted according to state of task demand nodes. The attentional weight to the color dimension (PN → CN color pathway) is in the process of being reduced due to the influence of the TDN --| CN inhibition weights (top-down influences on attention). Simultaneously, the attentional weight to the word dimension (PN → CN word pathway) is in the process of being increased, due to the influence of the TDN → CN activation weights (top-down influences on attention). The CN value is determined by (TDN value) * (TDN --| CN pathway weight) for AAPs. The amount of top-down induced increment or decrement for the attentional weights is determined by (TDN value) * (TDN --| or → CN pathway weight) * (PN → CN pathway weight).

Figure 32 displays the state of the model on IGP two. The system now accumulates evidence using the newly adjusted attentional weights. Another AAP will follow this IGP, which in turn will be followed by another IGP. The response will be determined when the word-reading task schema reaches threshold (1.0) before the color naming task schema threshold, over a series of IGP and AAP iterations.

In this example, the SHIFT effect was instantiated by the AAPs taken to adjust the attentional weights to reduce the influence of the color dimension, and increase the influence of the word dimension, along with the IGPs. The MODERATE effect (not

present in this example) would be represented by activation of the inhibitory TDN --| CN pathway, producing a preventative decrease of the PN → CN attentional word-dimension weight (in preparation for diverting attention from this dimension on a future trial involving an EDS).

The Stroop Effect can be incorporated into the PDP model as a special case of the SHIFT operation. When Stroop stimuli are viewed, the more frequently processed dimension (word) immediately captures attention. Translated into the terms of the PDP model, the PN → CN word-dimension weight is increased rapidly on contact with the stimulus. The TDNs must then be implemented to switch attention to the color dimension, producing a cost. Thus, the cost observed in the traditional Stroop color/word paradigm can be considered a special case of the SHIFT effect, involving the same cognitive mechanisms (the impact of TDN on PN → CN pathways).

Color-Word Asymmetry of MODERATE and SHIFT effects

Two word-reading/color naming asymmetries warrant more detailed explanation, within the context of the PDP model: (a) the MODERATE effect is smaller for color-naming ($\underline{M} = 32$ ms) than word-reading ($\underline{M} = 64$ ms), $t(32) = 8.23$, $p < .001$, $\eta^2 = .68$, and (b) the SHIFT/Stroop effect is large for color naming ($\underline{M} = 174$ ms), compared to the SHIFT effect for word reading ($\underline{M} = 68$ ms), $t(32) = -4.05$, $p < .001$, $\eta^2 = .34$ (these mean estimates were averaged over the levels of the other effects). Specific rules were incorporated into the PDP model to account for these asymmetries, and the RTs pattern from Experiment 3 were simulated fairly precisely. Figure 33 compares the pattern of selected word-reading RTs to that simulated by the PDP model. Figure 34 displays a similar comparison for color-naming RTs. The model rules and weight settings that achieved this match are outlined in the following section.

Regarding the MODERATE effect, as mentioned in the discussion of the color naming results, the influence of MODERATE on color naming responses may be smaller than on word-reading responses, because it is less difficult to avert attention from that dimension on future trials. That is to say, because the bottom-up attentional capture invoked by the color dimension is relatively weak compared to the word dimension, the SHIFT operation is less taxing, and the need for the MODERATE operation is reduced.

This asymmetrical MODERATE effect was incorporated into the PDP model by permitting a greater commitment of attention to the now-relevant dimension for color naming compared to word reading. More specifically, for color naming, the MODERATE operation was activated (by activation of the word TDN inhibition pathway, and subsequent reduction of the color dimension attentional weight) when the color dimension attentional weight surpassed .95 (the maximum weight was 1.0). On the other hand, for word reading, the MODERATE operation was activated (by activation of the color naming TDN inhibition pathway) when the word dimension attentional weight surpassed .80 (maximum weight was 1.0). In other words, the system acted earlier, more frequently, and allocated more resources to MODERATE for word reading compared to color naming. The net result was a simulation of a larger MODERATE effect for word reading trials compared to color naming trials.

As for the SHIFT/Stroop effect, consider the $Wn\mathbf{C}_i$ task-switching response. Under these conditions, on contact with the stimulus, the attentional weight to the word dimension would become highly activated. This is due to two sources of activation: (a) the strong attentional capture of the frequently processed word dimension, and (b) priming of the word dimensions, due having been activated on the previous response. The cognitive operations involved in the SHIFT effect will now dominate RT, as the shift of attention from the word-reading back to the color-naming dimension would be difficult under these conditions.

As a comparison, consider the $Cn\mathbf{W}_i$ response. On contact with the stimulus, the color dimension weight would be activated, due to fact that the color dimension was activated (or primed) on the previous response. However, unlike for word reading, additional activation due to strong attentional capture would not be present, because the color dimensions is the less dominant dimension. To reflect this asymmetry in the model, on contact with an incongruent stimulus, the attentional weight to the word dimension was increased to .8, while the attentional weight to the color dimension increased to .5. Thus, this asymmetry in the attentional weights resulted partly from priming of the word dimension due to the EDS, and partly from the attentional capture produced by the more

active resting state of the attentional weight to the word dimension (i.e., the dominance of the word over the color dimension).

As a final point, these asymmetric effects may affect the SHFxMOD interaction, which appeared to differ between color naming ($M = 28$ ms) and word reading ($M = 42$ ms). Although this RT difference was not significant, $t(32) = -1.33$, $p = .19$, this asymmetry was incorporated into the model as an asymmetry in the way resources are shared between SHIFT and MODERATE. Because the MODERATE effect demanded less resources for color naming than for word reading, resource sharing was not reflected in the model to a large degree for color naming. However, for word reading, both the MODERATE and SHIFT operations demanded resources; therefore, SAS resource sharing took on increased importance, reducing the effectiveness of both operations more substantially.

Singles Results

According to previous research (Jersild, 1927; Spector & Biederman, 1976; Umiltá, Nicoletti, Simion, Tagliabue, & Bagnara, 1992a), no switching cost should be present if the stimuli unambiguously cue the response. Therefore, for neutral Stroop stimuli, the mean RT for the Cn and Wn lists (summed and averaged) should equal the mean RT for the CnWn and WnCb lists (summed and averaged). This hypothesis was tested using the single trials administered to 19 participants at the beginning of Experiment 3. Also reported is the presence/absence of Stroop and RS effects.

As expected, no significant difference between the mean single ($\underline{M} = 591$ ms; $(Cn + Wn)/2$) and switching ($\underline{M} = 602$ ms; $(CnWn + WnCb)/2$) trials was present for neutral stimuli, $t(18) = 1.23$, $p = .23$. This can be compared to the difference between the mean single ($\underline{M} = 664$ ms; $(Ci + Wi)/2$) and switching ($\underline{M} = 782$ ms; $(CiWi + WiCi)/2$) trials for incongruent stimuli, which was highly significant, $t(18) = 6.00$, $p < .001$, $\eta^2 = .67$. As expected, the Stroop effect was significant ($\underline{M} = 135$ ms; Ci-Cn), $t(18) = 9.92$, $p < .001$, $\eta^2 = .84$, and the RS effect was not ($\underline{M} = 11$ ms; Wi-Wn), $t(18) = 1.38$, $p = .19$.

Experiment 4

This experiment was designed to discount a confound affecting interpretation of the SHIFT effect in Experiment 3. Allport et al. (1994) reported that TSI can exert proactive interference from previous response lists, not only from previous responses. This effect was used by Allport et al. as a possible explanation for a small RS effect found when comparing W_iW_i to W_nW_n (≈ 30 ms; their Experiment 5, Figure 17.7a, Reverse Stroop). This theoretical account could also be held responsible for the previously reported $C_nW_i - C_nW_n$ and the $W_iC_n - W_nC_n$ RS effects (≈ 50 ms) reported in Experiment 3, affecting interpretation of the SHIFT effect. To test the plausibility of this argument, an experiment was run where the order of block presentation was controlled, to observe the effect of SHIFT in subjects who had not previously responded color to incongruent Stroop stimuli. If this RS effect is formed from proactive interference from a previous list, the RS effect should not be present in this situation. On the other hand, if the SHIFT effect can be produced by attention switching on an EDS trial, the RS effect should be observed.

Method

Participants

Participants were nine students enrolled in an introductory psychology course at the University of Victoria.

Procedure

Participants first responded by color naming, then word reading, to a block of 25 C_nW_n stimuli, and subsequently to a block of 25 C_nW_i stimuli, thus never responding color to an incongruent Stroop stimulus.

Results

A significant RS effect (47ms; $C_nW_i - C_nW_n$) was observed, $t(8) = 2.60$, $p < .03$, one tailed, $\eta^2 = .46$.

Discussion

The RS effect observed in this experiment was comparable in size to the RS effect observed when stimulus blocks were presented in a random order. Thus, although TSI (proactive interference) from previous lists may be present in Experiment 3, it cannot be

held responsible for the entire $Cn\mathbf{Wi} - Cn\mathbf{Wn}$ and $\mathbf{Wi}Cn - \mathbf{Wn}Cn$ RS effects. This result confirms the conclusions of Experiment 3, that the effect SHIFT produces a cost of approximately 50 ms, independent of any proactive interference from previous lists.

Experiment 5

The preventative operation MODERATE was proposed to optimize task switching by reducing the impact of the SHIFT cost on EDSs. In other words, when the probability is low (or zero) that an EDS will be necessary, performance should suffer if the EDS, counter to expectation, does arrive. Increased word-color interference with decreased expectation of incongruent trials has previously been observed for single trials (Henik, Singh, Beckley, & Rafal, 1993; Lindsay & Jacoby, 1994; Tzelgov, Henik, & Berger, 1992). This result has been interpreted as an increase in the influence of the word dimension on IGPs (information gathering passes) (Lindsay & Jacoby, 1994; Trainham et al., 1997). Stated in terms of the proposed MODERATE effect, when a high proportion of incongruent trials are expected, an automatic “strategy” is assembled, which involves inhibiting attention to the word dimension, therefore facilitating color-naming responses on incongruent trials. The notion that spontaneous strategy generation in the absence of explicit problem solving can cause CS to affect task schemas has already been proposed (Shallice & Burgess, 1996), as has the notion that spontaneous, nonexplicit strategy generation can adjust attentional weighting to stimulus dimensions (Robertson, Lamb, & Knight, 1988).

Because MODERATE is an optimizing operation supposed to reduce the effect of SHIFT, in the absence of the MODERATE effect, the SHIFT effect should be magnified. In the present experiment, the percentage of incongruent pairs was manipulated, with the expectation that as the percentage of incongruent trials decreased, the strategic, top-down influence of the MODERATE effect would decrease, and an unchecked SHIFT effect would reduce switching efficiency.

Method

Participants

Participants were 14 students enrolled in an introductory psychology course at the University of Victoria.

Procedure

All participants received (a) a blocked 25 trial CiWi condition (100% incongruent trials), (b) a condition where 25 CiWi and 25 CnWn trials were randomly interspersed (50% incongruent trials), and (c) a condition where 25 CiWi trials were randomly interspersed among 75 CnWn trials (25% incongruent trials). Thus, this experiment was designed such that percentage incongruent context effects could be assessed for CiWi and CiWi response latencies.

Results

For both the CiWi and CiWi RTs, there was no significant difference between response latency in the 50% ($M = 1017$ ms, $M = 717$ ms, respectively) and 100% ($M = 983$ and 728 ms, respectively) ambiguous pair conditions, $t(13) = 1.92$, $p = .08$, $t(13) = 0.36$, $p = .72$, respectively. However, the contrast comparing CiWi and CiWi RTs from the 25% ambiguous condition ($M = 1115$ and 776 ms, respectively) to the collapsed 50% and 100% conditions ($M = 1000$ and 722 ms, respectively), was highly significant for the CiWi RTs, $F(1,13) = 24.03$, $p < .001$, $\eta^2 = .65$, and significant for the CiWi RTs, $F(1,13) = 5.31$, $p < .04$, $\eta^2 = .29$ (see Figure 35 and Figure 36).

Discussion

In this experiment it was demonstrated that when the probability of EDS occurrence decreased, switching efficiency on EDS trials decreased. The absence of the MODERATE effect, due to decreased expectation of an EDS increased both CiWi and CiWi responses. Moreover, the findings of Experiments 2a and 2b were replicated, as 50% incongruent trials elicited as much EDS preparation as 100% incongruent trials (i.e., no significant difference was found between response latencies in the 50% incongruent and 100% incongruent conditions).

The color naming increase in the 25% incongruent condition was very large (\underline{M} = 115 ms). This result provides evidence for a decrease in MODERATE on the word reading trials, resulting in an increase in the taxing SHIFT/Stroop effect for unexpected CiWi responses. The implication is that attention is too easily drawn to the word dimension on CiWi responses, increasing the difficulty in switching attention from the word dimension to the color dimension on that EDS (i.e., increasing the SHIFT cost for color naming).

The word-reading increase in the 75% neutral condition (CiWi) was smaller, but still substantial (\underline{M} = 54 ms). This smaller effect is in agreement with the relatively minor role played by MODERATE for color naming responses in Experiment 3 (due to the relative nondominance of the color dimension). In summary, implementation of MODERATE, although cost producing, allows the mechanisms involved in SHIFT to operate more efficiently.

Experiment 6

Rogers and Monsell (1995) reported that within the context of task switching, response latency to stimuli for which both dimensions elicited the same response (congruent stimuli) was almost equal to that for incongruent stimuli, and appreciably longer than response latency to neutral stimuli (p. 215, Figure 2, Congruent Switch condition). To explain this result, Rogers and Monsell hypothesized that the now-irrelevant stimulus dimensions of incongruent *and* congruent stimuli elicit the “whole package of S-R associations”, which includes competing S-R mappings, producing conflict with the now-relevant S-R mapping, and slowing response latency.

This result seems counterintuitive – most investigators report a facilitation effect for responses to congruent Stroop stimuli (MacLeod, 1991, p. 174-175). Moreover, the present interpretation of switch costs hinges on the presence of *conflicting* information on an EDS. Within this theoretical framework, it should not be possible for CiWc (Wc symbolizes word reading in response to congruent Stroop stimuli) to elicit SHIFT, because, as is the case for CiWn, selective attention is not necessary to complete the task. Thus, the SHIFT cost should not be present, but the MODERATE cost should be (as is the case for CiWn).

Method

Participants

Participants were 12 students enrolled in an introductory psychology course at the University of Victoria.

Procedure

Participants received 35 trials of either CiWi, CiWc, or CiWn pairs. The order of block presentation was randomly determined.

Results

For word reading, the difference between the CiWc and CiWn RT means was not significant, $t(11) = 0.65$, $p = .53$. However, the contrast comparing CiWi ($M = 677$ ms) to the average of these two conditions (CiWc and CiWn, $M = 554$ ms) was significant, $F(1,11) = 10.07$, $p < .01$, $\eta^2 = .49$ (see Figure 37).

The results were similar for color naming responses. There was no significant difference between the CiWc and CiWn RT means, $t(11) = 0.41$, $p = .69$. However, the contrast comparing CiWi ($M = 1021$ ms) to the average of these two conditions (CiWc and CiWn, $M = 921$ ms) was again significant, $F(1,11) = 12.04$, $p < .01$, $\eta^2 = .52$ (see Figure 38).

Discussion

From the results of this experiment, it can be concluded that the congruent stimuli are affecting task-switching RT in the same way as neutral stimuli, with no SHIFT but a MODERATE effect being present. No facilitation effect was present, and no switch cost over and above neutral stimuli was present. Contrary to the findings of Rogers and Monsell (1995), congruent stimuli were not affected by the switch costs that would be expected from incongruent stimuli. As predicted, an attentional conflict did not arise because the task did not necessitate selective attention to one dimension.

Rogers and Monsell (1995) reported a switch cost for congruent stimuli that approached the magnitude of that found for incongruent stimuli. This conflicting result can be attributed to methodological differences between their study and the present experiment. First, Rogers and Monsell used stimuli that may not be processed the same

way as objects with multiple stimulus dimensions. Each stimulus was actually two stimuli placed adjacent to each other on the screen (e.g., G7). The task was to decide whether the stimulus is a consonant or a vowel, or an odd or even number, depending upon task demands (consonant/odd = left index response, vowel/even = right index response, or vice-versa). Subjects switched between the consonant/vowel task and the odd/even task on switch trials, and repeated these tasks on repetition trials.

For this experimental design, the stimulus G7 would be a congruent stimulus (consonant/odd > left index), and the stimulus G6 an incongruent stimulus (consonant > left index, even > right index). Obviously the way these stimuli are processed will be different from incongruent and congruent Stroop stimuli. As both dimensions of the G7 and G6 stimuli draw attention, and responses do not differ in automaticity, selective attention will be necessary in both congruent and incongruent conditions. In the present paradigm, as was the case for neutral stimuli, the absence of a conflicting color resulted in an absence of a necessity of shifting of attention away from it.

Experiment 7

This experiment tested the hypothesis that the switch costs observed in Experiment 3 would be present even when the stimuli were not traditional Stroop stimuli, but were neutral words. If the SHIFT and MODERATE effects are indeed attentional, and do not depend upon semantic conflict for processing or response, a change in the stimuli away from color words should not affect the presence of the effects. However, as the traditional Stroop conflict is supposed to depend upon the priming of an associative semantic category (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992), the SHIFT/Stroop effect should be reduced (but not SHIFT and MODERATE), as the attentional capture of the word dimension should be reduced due to the absence of color words. In other words, although the reduced Stroop effect can still be interpreted as a special case of the SHIFT operation, the necessary attentional adjustments are expected to be less extreme than in Experiment 3 (due to the reduced attentional capture of the word dimension), resulting in a reduced SHIFT/Stroop effect.

Method

Participants

Participants were 13 students enrolled in an introductory psychology course at the University of Victoria.

Procedure

A trial consisted of either (a) a pair of incongruent Stroop stimuli, where the participant was instructed to respond either word-color (WiCi) or color-word (CiWi); (b) a pair of neutral Stroop stimuli, where the participant was instructed to respond either word-color (WnCn) or color-word (CnWn); (c) a pair consisting of one incongruent and one neutral stimulus, where the participant was instructed to respond word-color (WnCi or WiCn) or color-word (CnWi or CiWn). Thus, in total, eight pair types were presented (WiCi, CiWi, WiCn, WnCi, CnWi, CiWn, WnCn, CnWn). The colors used for all stimuli were blue, yellow, red, green, and purple. The words used were waist, idea, luck, hop, and friend. Each participant received 35 blocked trials of each pair type. The order of presentation for these eight stimulus blocks was randomly determined.

Results

The regression method used previously (Lorch & Myers, 1990) was employed to test for the main effects and interactions identified in Experiment 3.

Word Reading

Table 29 displays the mean RTs and error types for word reading. Using ANOVA terminology, SHIFT, MODERATE, and FIRST were the main effects for this experiment. The three way interaction was tested first, and was found to be non-significant (with all main effects and two-way interactions partialled out), $t(12) = -0.84$, $p = .42$.

When the two-way interaction effects involving FIRST (MODx1st and SHFx1st) were tested separately, with the main effects and remaining two way interactions partialled out, the mean beta sizes were not significantly different from zero, $t(12) = 1.88$, $p = .08$, $t(12) = 1.41$, $p = .18$, respectively. Therefore, the effect FIRST can be interpreted independently, and was significant, $t(12) = 5.39$, $p < .001$, $\eta^2 = .71$. Response latencies were increased in position one ($M = 81$ ms).

Unlike in Experiment 3, the two-way interaction term SHFxMOD was not significant, $t(12) = 0.99$, $p = .32$. Therefore, the SHIFT and MODERATE effects were interpreted independently. The SHIFT effect was significantly different from zero ($M = 60$ ms), and MODERATE was significantly different from zero ($M = 61$ ms), $t(12) = 5.88$, $p < .001$, $\eta^2 = .74$, $t(12) = 5.20$, $p < .001$, $\eta^2 = .69$, respectively. Figure 39 displays all word-reading effects and their associated RT costs, with 95% confidence intervals. Table 30 lists effects that were partialled out for each effect of interest.

Color Naming

Table 31 displays the mean RTs and error types for color naming. The highest order interaction term (the three way interaction) was tested first, and was found to be non-significant (with all main effects and two-way interactions partialled out), $t(12) = 1.96$, $p = .07$. The subsequent tests of the two-way interactions (with main effects and other two ways partialled out) resulted in a non significant interaction for MODx1st, $t(12) = 1.08$, $p = .30$, and a marginally significant interaction for SHFx1st, $t(12) = 2.23$, $p < .05$. The interaction effect SHFxMOD was significant, $t(12) = 3.00$, $p < .02$, $\eta^2 = .43$.

Regarding the effect of SHIFT/Stroop and MODERATE, when both effects were present, response latencies were multiplicatively longer ($M = 36$ ms added). As was the case in Experiment 3, MODERATE ($M = -2$ ms) did not account for significant variance out of the presence of FIRST and SHIFT/Stroop, $t(12) = -0.17$, $p = .87$. However, SHIFT/Stroop was highly significant ($M = 63$ ms) out of the presence of FIRST and MODERATE, $t(12) = 3.48$, $p < .005$, $\eta^2 = .50$. The effect FIRST was not significantly different from zero ($M = 16$ ms), over and above the other effects $t(12) = 0.96$, $p = .35$. Figure 40 displays all color-naming effects and their associated RT costs, with 95% confidence intervals. Table 32 lists effects that were partialled out for each effect of interest.

Discussion

As hypothesized, the SHIFT and MODERATE effects present for word reading in Experiment 3 replicated, as did the SHIFT/Stroop effect for color naming. Moreover, as

predicted the size of the SHIFT/Stroop effect reduced, as was expected with a reduction in Stroop interference (MacLeod, 1991, p. 16).

The analysis of unhypothesized differences between this experiment and Experiment 3 should be made with discretion, due to the small sample size in the present experiment, combined with regression partialling procedures. For example, the word-reading interaction effect SHFxMOD was not significant, but did produce an increase in RT when present ($\underline{M} = 31$ ms, compared to $\underline{M} = 42$ ms in Experiment 3). With more subjects, this effect may become significant.

Singles Analysis

According to previous research (Jersild, 1927; Spector & Biederman, 1976; Umiltá et al., 1992a), no switch cost should be present if the stimuli unambiguously cue the response. Therefore, for the neutral Stroop stimuli, the mean RT for the Cn and Wn lists (summed and averaged) should equal the mean RT for the CnWn and WnCn lists (summed and averaged). This hypothesis was tested using the single trials administered at the beginning of Experiment 7. Also reported is the presence/absence of Stroop and RS effects.

As expected, no significant difference between the mean single ($\underline{M} = 665$ ms; $(Cn + Wn)/2$) and switching ($\underline{M} = 681$ ms; $(CnWn + WnCn)/2$) trials was present for neutral stimuli, $t(12) = 0.93$, $p = .37$. This can be compared to the difference between the mean single ($\underline{M} = 707$ ms; $(Ci + Wi)/2$) and switching ($\underline{M} = 804$ ms; $(CiWi + WiCi)/2$) trials for incongruent stimuli, which was highly significant, $t(12) = 4.24$, $p < .002$, $\eta^2 = .60$. As expected, the Stroop effect was significant, but reduced ($\underline{M} = 51$ ms; Ci-Cn), $t(12) = 4.38$, $p < .002$, $\eta^2 = .62$, and the RS effect was not ($\underline{M} = 32$ ms; Wi-Wn), $t(12) = 1.15$, $p = .27$.

General Discussion of Experimental Results

The above experimental evidence has led to the postulation that the major color-naming and word-reading switch costs can be attributed to either *shifting* attention during an EDS (SHIFT), and/or *moderating* these attentional shifts in anticipation of a future EDS (MODERATE). More specifically, switch costs may be due to (a) switching

attention from the previously attended stimulus dimension to the now-relevant dimension (SHIFT), (b) partial inhibition of attention to a stimulus dimension from which attention must be averted on a future trial (MODERATE), (c) initiating response to the first member of the pair (FIRST), or (d) interactions between these main effects.

This focus on the influence of attentional processes in task switching is a rather abrupt shift from the TSI and TC/TSR hypotheses, which focus on competition at the post-attentional stages of processing. These theories employed language such as the measurement of “duration of a process of enabling and disabling connections between processing modules” (Monsell, 1996, p. 135), “competing ... S-R mappings” (Allport et al., 1994, p. 442), or of an operation which “modulates the relative gain of the two sets of S-R connections” (Monsell, 1996, p. 127).

From a historical perspective, these aforementioned explanations of switch costs appear to have been influenced by previous, related research on the psychological refractory period (PRP). PRP theorists commonly referred to competition between cognitive processes. For example, reference to “cognitive processes subject to postponement” (Pashler, 1992b, p. 254) and to “executive cognitive processes that coordinate concurrent tasks” (Meyer & Kieras, 1997) implied conflict at post-attentional stages of processing: stimulus identification, response selection, and/or response production. The task-switching theorists previously mentioned also focussed on post-attentional management of conflicting S-R mappings.

This is somewhat surprising in light of the fact that although PRP researchers demonstrated a response selection conflict even for task repetition (Pashler, 1994), the earliest investigators of task-switching noted that there are no costs associated with task switching when responses are unambiguously cued (Jersild, 1927; Spector & Biederman, 1976). Thus, because stimulus perception, response selection and response production for task one are *not* interrupted by switching to task two (provided the inter-stimulus interval is longer than the PRP), the probability that switch costs are attributable to PRP limitations (Pashler, 1992a; Pashler, 1992b), or to co-ordination of locking and unlocking cognitive processes (Meyer & Kieras, 1997), is negligible.

Thus, switching between two tasks as such does not necessarily pose a problem for the cognitive system. Switch costs are observed only when ambiguous stimuli are processed. Therefore, the pivotal question is: At what stage of cognitive processing does this variable (*viz.*, stimulus type) impact? Perhaps because the contribution of visual attention to PRP costs was effectively quashed by PRP theorists (e.g., Pashler, 1992b, p. 254), the major investigators of switch costs have also neglected to consider costs associated with switching attention (but see Visser, Bischof, & Di Lollo, in press). Despite this neglect, a theory proposing difficulties shifting selective attention between object attributes is readily adaptable to switch costs.

The SHIFT operation can be conceptualized as the alternation of attention between competing dimensions of a two-dimensional stimulus. Thus, the slowing effect of ambiguous stimuli on task switching may arise (at least in part) from conflict at the level of selective attention to object attributes, not exclusively from conflict at the level of post attentional “S-R mappings”. In other words, the challenge presented to the cognitive system is not as much selectively processing information that has passed attentional filters as it is selectively amplifying of the signal of the relevant aspect of the stimulus (Milliken et al., 1998, p. 204). This view of switch costs implicates the involvement of a nonspatial attentional control mechanism of “selection-for-action among competing stimulus dimensions” (Allport, 1993, p. 203). The prevailing neglect of investigation into this type of selective attention has been recognized previously (e.g. , Allport et al., 1994; Visser et al., in press).

Relation to Stroop Literature

A particular theoretical approach to investigation of the traditional Stroop effect provides a starting point for the transition from discussion of post-attentional S-R conflict to discussion of costs due to nonspatial attentional control. In his thorough review of the theoretical approaches to investigation of the Stroop effect, MacLeod (1991) listed 18 empirical results that must be explained by any successful account of the Stroop effect. In the process of testing the existing theoretical positions with regard to their ability to account for this set of results, two emerged as (arguably) the most constraining: (a) Stroop interference is decreased when color and word attributes are not integrated into

one object, and (b) manipulations affecting available attentional resources affect the degree of Stroop interference. These findings implicate the contribution of *attention* to the processing of *integrated object attributes* when responding to Stroop stimuli.

Specific experimental evidence for these constraints includes: (a) a conflicting word written on an unattended object produces much less color-naming interference than the same word written on an attended object (Kahneman & Henik, 1981), (b) diluting attention reduces interference (Kahneman & Chajczyk, 1983), and (c) increased Stroop interference is present when color and word attributes are integrated into one object, compared to when they are spatially separated (Kahneman & Henik, 1981; MacLeod, 1998). Thus, the influence of attention on the processing of integrated object attributes must be accounted for by a successful account of the Stroop phenomenon.

Kahneman and Treisman (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992) provided a theoretical account of the Stroop effect which incorporated these two results. The Stroop effect, according to their account, is not a failure of selective attention in general, but evidence for a difficulty in filtering out the irrelevant attributes of an object, once the object has captured the attentional spotlight.

The postulation that selective attention is effective for object selection, and that attentional capture is strong for objects, is well documented. It has been demonstrated that selective attention is less effective for poor examples of objects (Ward & Goodrich, 1996), that elements are better detected when embedded in objects (Treisman, 1986), and that an object-centered spatial reference frame exists (Behrmann & Tipper, 1994; Tipper & Behrmann, 1996). Kahneman and Treisman's interpretation of the Stroop effect rests on the assumption that, under the circumstances for which the system was designed, all dimensions of an object are processed simultaneously, presumably for the purpose of efficiently converging on the correct point in semantic space, thereby accessing meaning (Arguin, Bub, & Dudek, 1996).

Kahneman and Treisman (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992) proposed that the subject's knowledge that they will be producing color names acts as a category prime (Kahneman & Henik, 1981) (*viz.*, the associative semantic category of color names is primed; Woodward, Dixon, Mullen, Christensen, & Bub, 1999), facilitating

attention to written color words. This account also makes the assumption that the more frequently processed dimension of the stimulus (the word dimension) captures attention more effectively than the less frequently processed dimension (the color dimension). The mutual dependence of attention allocation and semantics was echoed by Allport (1989). He favoured a *compatible information* account of the Stroop effect, whereby attention is captured by the information source most compatible with the task in question.

In summary, according to this account of the Stroop effect, a major source of *conflict*, when processing incongruent Stroop stimuli, arises at the early stage of selective attention for object attributes (pre-response selection-for-action; Allport, 1993, p. 203). Although the later stages of semantic processing or response selection are probably involved in driving the type of selective attentional selection, and certainly run up against their own sources of conflict in other situations (e.g., PRP conflicts and negative priming), the major source of conflict for the present situation is proposed to occur at the stage of information gathering. Increased response latency for color naming, in this situation, may be attributable to difficulty overcoming the attentional capture produced by the more frequently processed stimulus dimension.

This theoretical account does not appear to conflict with MacLeod's (1991) 18 empirical results that should be explained by any successful account of the Stroop effect. This theoretical account also accommodates a recently reported phenomenon, whereby the Stroop effect is eliminated if only one letter is colored (Besner, Stolz, & Boutilier, 1997). This result casts doubt on the theory that Stroop *conflict* necessarily arises in associative semantic space, as any semantic color/word conflict should arise in this situation. We stress that this point is unrelated to the postulation that priming of the color word category in associative semantic space increases attentional capture for color words (Kahneman & Henik, 1981). However, this result fits well with the theory that conflict arises at the level of selective attention.

Besner et al.'s (1997) result can be explained using Kahneman and Treisman's (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992) attentional conflict theory by noting that color is an attribute of the letter object only, not the word object. Selective attention should effectively select the "word object" when reading, and the "letter object"

when color naming. Therefore, letter-color name conflicts should not produce strong interference. It should be noted that although the effect of attribute integration has a major influence on the Stroop effect, when it is overcome by extensive practice, a small effect due to “managing conflicting information sources” persists (MacLeod, 1998, p. 201).

Some support for the transfer of this theoretical explanation from the Stroop literature to the task-switching literature is presently available. For example, switch costs have been observed when one task had vocal responses, and one manual (Monsell, 1996, p. 135), when vocal responses for the two tasks were semantically unrelated (Stablum, Leonardi, Mazzoldi, Umiltá, & Morra, 1994; Umiltá, Nicoletti, Simion, Tagliabue, & Bagnara, 1992b), and when the two tasks were of equal dominance (Giesbrecht & Kingstone, 1998; Meiran, 1996; Meyer et al., 1998; Potter et al., 1998; Rogers & Monsell, 1995). Thus, because switch costs do not appear to be dependent upon response modality, semantic competition between responses, or differences in task dominance, both the traditional Stroop effect, the SHIFT operations, and the MODERATE operation, may be manifestations of a difficulty selectively attending to integrated object attributes.

Generalizability

As an overview, the present theoretical account conceptualized RT costs as attributable to time consuming, bottom-up information gathering passes (IGPs), and time consuming, top-down adjustments to the attentional weighting system (AAPs). Costs were attributed to added iterations associated with IGPs and AAPs in an optimizing network. A model was presented specifying the active operations necessary for implementing task switching, whereby inhibition and activation of attention to stimulus dimensions interacted to optimize performance. The overall purpose of this information gathering is to bias the neural architecture towards the response demanded by the environment. Simply put, the greater the complexity of the network adjustments, the more IGPs and AAPs, and the greater the RT cost.

It was also demonstrated that:

1. SHIFT costs could affect RT to *neutral* stimuli if an incongruent stimulus was expected for that trial (Experiment 2a and 2b).

2. When the probability of EDS trials increased, the impact of the SHIFT operation on task switching RT was reduced, presumably due to an increase in the MODERATE effect (Experiment 5).

3. Congruent stimuli were processed in the same way as neutral stimuli, because neither necessitates selective attention for conflicting object dimensions (Experiment 6).

4. The MODERATE and SHIFT effects did not appear to depend upon semantically conflicting responses (Experiment 7).

Despite the fact that MODERATE and SHIFT effects were conceptualized to depend upon one system, their interpretations differ substantially at a general level. While MODERATE activates a preventative strategy, SHIFT actually carries out the shift of attention. This interpretation of the MODERATE effect assumes that some strategies do not require conscious adaptation, or explicit problem solving attempts, but may be instantiated spontaneously and/or reflexively (Logan, 1985; Schneider & Shiffrin, 1977; Shallice & Burgess, 1996).

Strategy implementation such as the strategic adjustment of response criteria (Strayer & Kramer, 1994a; Strayer & Kramer, 1994b; Treisman & Williams, 1984) are usually implied to be under the conscious control of the subject, but the present author finds it difficult to accept that all top-down, optimizing adjustments of cognitive operations would be consciously initiated. Therefore, the supposition that strategies can be spontaneously or reflexively instantiated by the SAS on CS to temporarily adjust the task-schema activity, outside of the awareness of the responder, seems a reasonable assumption to make. Working memory would surely be overloaded if awareness was imparted to every optimizing strategy instantiated by the cognitive system.

The SHIFT operation appears to result not from implementation of a strategy, but from difficulty shifting attention between object attributes. Presumably the system has evolved in an environment, where attending to multiple object attributes is helpful for the system to converge on the correct area of semantic space (e.g., Arguin et al., 1996). Experiment 7 provides evidence that the conflict to be overcome by the operations involved in SHIFT are not at the level of semantics, or response selection, but at the stage of selective attention. A situation where one dimension of an object must be selectively

attended to is unnatural; thus, when cast in this light, it is not surprising that the performance suffers when object dimensions provide conflicting information.

The distinction between costs and cost-reducing strategies has already been alluded to by previous researchers of task switching. For example, it has been determined that switch costs can be reduced with preparation (Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995). Thus, the MODERATE operation may preconfigure the system to minimize the cost of SHIFT when the stimulus arrives. In other words, the preventative strategies imparted by the MODERATE effect may be instantiated in anticipation of stimulus arrival.

A final, and important consideration is that although many investigations into task switching used paradigm involved in switching attention between stimulus dimensions (Allport et al., 1994, experiments 1-5; Compton & Park, 1998; Giesbrecht & Kingstone, 1998; Gopher, 1996; Meiran, 1996; Meyer et al., 1998, exp. 1; Rogers & Monsell, 1995; Stablum et al., 1994; Umiltá et al., 1992b), some studied attentional switching between *cognitive operations* carried out in response to one dimension of a stimulus (Allport et al., 1994, experiments 6 and 7; Jersild, 1927; Meyer et al., 1998, exp. 2; Potter et al., 1998; Spector & Biederman, 1976), switching attention between regions of semantic space (Allport et al., 1994; Hsieh & Allport, 1994; Neely, 1977; Potter et al., 1998), and switching between representations in working memory (Garavan, 1998).

Are the SHIFT and MODERATE operations, which were developed here in relation to the study of switching attention between object dimensions, also important for switching attention between cognitive operations, working memory representations, regions of semantic space, or regions of task space? Would these types of attentional shifts abide by the principles identified here? It is possible that one generalized system, localized to the frontal lobes, could be responsible for all these types of cognitive shifts?

It seems likely that the true state of affairs is not this simple. For example, in the study of spatial selective attention, Posner and colleagues (Posner et al., 1988) theorized that shifts *spatial* attention involve three main subcomponents, which can be differentially localized in the brain. These subcomponents, and their localizations, were as follows: (a) *disengage*, localized to the parietal lobe, (b) *move*, localized to the midbrain, and (c)

engage, localized to the thalamus. The SHIFT operation also involves disengaging attention from the previously attended stimulus dimension, moving attention to the now-relevant dimension, and engaging attention to the now-relevant dimension.

Up until now, I have drawn mostly on theoretical accounts that localize controlled processing to the frontal lobes (Monsell, 1996; Norman & Shallice, 1986; Shallice, 1988), and have attributed the activity of the TDNs of the PDP model to frontal systems. However, considering the diverse areas of the brain that contribute to shifts of spatial attention, this assumption may turn out to be a gross oversimplification of the true state of affairs. On the other hand, the cognitive operations important for selective attention to object attributes may not overlap in an obvious way with those important for spatial selective attention. For example, performance of the Stroop task appears to depend on the anterior cingulate (for a review see Posner, Abdullaev, McCandliss, & Sereno, in press), and area which was not implicated for selective spatial attention. Speculation as to the neural basis for visual selective attention points to the perigeniculate nucleus, a network interposed between the lateral geniculate nucleus and area V1, which receives direct excitatory input from the prefrontal cortex (Visser et al., in press).

Detailed consideration of the generalizability of this theory points to the ongoing controversy regarding early- versus late-selection models of selective attention (Allport, 1989; Allport, 1993; Milliken et al., 1998). Traditionally, early selective attention has been considered to act upon physical attributes of a stimulus, and late selection on semantic (i.e., meaning based) attributes. However, as pointed out by Allport (1989), this distinction appears overly simplified, considering the neuropsychological evidence for parallel processing of physical and semantic attributes (e.g., Arguin et al., 1996; Dixon, Bub, & Arguin, 1997; Dixon, Bub, & Arguin, 1998).

As an alternative to the early versus late processing distinction, Allport (1989) suggested a compatible information account, whereby attention is captured by the information source most compatible with the task in question. This account is well suited to the generalization of the PDP model presented here, as it allows the task schemas represented by the color-naming and word-reading pathways to be modified to incorporate almost any information gathering process. In theory, if the compatibility of the task and

the information source can be defined, the PDP model presented above could be modified to represent any switching operation. On the other hand, it may be that the SWITCH and MODERATE operations do not generalize to all switching operations, making the model relevant only to attentional switching between object dimensions.

As a final point regarding the early- versus late-selection attention controversy, it may be that a compromise position is possible. There is little doubt that early- and late-selection processes interact in a meaningful way. However, this does not rule out the possibility that selective attention may be necessary only at early or late stages of processing, depending on the task-at-hand, and/or the source of conflicting signals. For example, if subjects were asked to switch between naming fruit and naming objects, presentation of a disk could demand switching between the semantic representations of “ball” and “orange”, depending on the now-relevant and just-relevant tasks. However, it is obvious that this task would not involve selective attention to specific physical attributes of the stimulus. Therefore, in this case it appears that only late-selection processes would be necessary. Similarly, the task switching experiment presented in the experiments above were hypothesized to depend mostly (if not exclusively) on early-selection, for the purpose of amplifying the signal of the stimulus dimension relevant to the now-relevant task.

Existing PRP experimentation procedures may be of use in determining the involvement of early- versus late-selection. For example, following the methodology of Pashler (Pashler, 1992a; Pashler, 1992b; Pashler, 1994), degradation of the stimuli should increase the impact of SHIFT and MODERATE for selectively attending to stimulus dimensions (early selection), but should not affect attentional shifts at later stages of processing (e.g., shifts between response mappings, or shifts in semantic space). On the other hand, increasing the complexity of responses should not affect attentional shifts between stimulus dimensions, but should impact later stages of processing, such as selective attention to internal representations (Milliken et al., 1998).

I have heeded Allport’s (1989) call for “computational mechanisms by which attentional engagement is established, coordinated, maintained, interrupted, and redirected ... in the preparation and control of action” (p. 663), by presenting a working model of the cognitive processes being discussed, and specifying the nature of the interaction

between physical and semantic sources of conflict. I concur with Allport that this level of specification is the first step in fractionation of cognitive control mechanisms. Although the generalization of these operations must await further experimentation, I hope that the discussion presented here can serve as a theoretical framework against which future work can be compared.

NEUROPSYCHOLOGICAL INVESTIGATION

In the previous section, it was proposed that the cognitive control operations involved in task switching can be fractionated into isolable subcomponents. In the following section, this theoretical account will be used to explain the qualitatively different task-switching deficits associated with aging versus Parkinson's disease (PD). This section will begin with a review of selected commonly used clinical neuropsychological tests that appear to share cognitive operations with the task-switching paradigm introduced previously. Research applying these clinical tests to PD and elderly samples is also reviewed. Finally, the task-switching results of PD and elderly samples are presented, and the previously presented theoretical account of task switching applied to explain the task-switching deficits of both samples.

A large set of clinical neuropsychological tests are thought to be sensitive to deficits in executive functions. These include WAIS Similarities, the Hooper Visual Organization Test, the Stroop Test, The Wisconsin Card Sorting Test, Verbal Fluency tests, the Trail Making Test, the Cambridge Neuropsychological Test Automated Battery, the Six Element Test, and many others (Lezak, 1995; Spreen & Strauss, 1997). Instead of reporting on neuropsychological findings associated with all these tests, the present investigation will review the literature on three commonly administered clinical neuropsychological tests that appear to tap into cognitive abilities associated with the present task switching paradigm: (a) the Stroop test (Stroop, 1935), (b) the Wisconsin Card Sorting Test (WCST) (Heaton, 1981), and (c) the Controlled Oral Word Association Test (COWAT) (Benton, 1968), also known as the phonemic verbal fluency test, or the FAS-test.

The neuropsychological version of the Stroop test involves word reading or color naming in response to 50 neutral or incongruent Stroop stimuli presented on one card (10

rows of five items). The previously mentioned Cn, Ci, Wn and Wi conditions are completed and timed, and errors recorded. Color-word interference is reportedly increased for people with frontal brain damage (Perret, 1974; Richer, Decary, Lapiere, & Rouleau, 1993; Vendrell, Junque, Pujol, & Jurado, 1995), usually attributed to a failure inhibiting a prepotent response (Goel & Grafman, 1995; Spreen & Strauss, 1997; Vendrell et al., 1995), or a selective attention deficit (Dulaney & Rogers, 1994). Translation of this deficit into the terminology of Kahneman and Treisman (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992) implies a failure in selectively attending to the non-dominant dimension of a stimulus.

The WCST involves performing self-initiated EDSs of attention. In the most commonly used version of the WCST, subjects are presented with 128 response cards and four key cards with designs varying in color, geometric form, and number. The subject is instructed to match each response card to one of four key cards. Each time the subject places a card, he or she is told whether it is right or wrong, according to a criterion (color, form or number), of which only the experimenter is aware. When 10 correct responses are achieved, the experimenter then changes the sorting criterion, again only telling the subject right or wrong. Thus, the subject must self-initiate a switch in what must be considered the relevant dimension of the stimulus, and maintain this new rule until the experimenter again changes the sorting criterion. The procedure continues until the subject has successfully completed six sorting categories (i.e., 6 sorts of 10 consecutive correct responses), or until all 128 cards have been placed.

Several studies have confirmed that the WCST is sensitive to frontal lobe damage (e.g., Heaton, 1981; Milner, 1963; Robinson, Heaton, Lehman, & Stilson, 1980), but few have attempted to specify whether these deficits are associated with switching set, maintenance of set, rule deduction, memory, or the ability to incorporate feedback. The test provides several indices, some of which should be sensitive to an attention switching deficit (e.g., the number of categories achieved, and the number of perseverative errors). Factor analytic studies have confirmed that switching set dissociates from maintaining set in WCST performance (Greve, Ingram, & Bianchini, 1998; Paolo, Tröster, Axelrod, & Koller, 1995), such that either could be responsible for achieving few categories.

The COWAT requires the production of words that begin with a particular letter (e.g., F, A and S). Recent work (Troyer, Moscovitch, & Winocur, 1997a; Troyer, Moscovitch, & Winocur, 1997b; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998a; Troyer, Moscovitch, Winocur, Leach, & Freedman, 1998b) has demonstrated that successful performance on this task depends upon two dissociable cognitive abilities: (a) clustering, the production of words within clusters or subcategories; and (b) switching, the ability to switch efficiently between clusters. Moreover, patients with frontal-lobe lesions were impaired only on switching, not on the clustering measure (Troyer et al., 1997b; Troyer et al., 1998a). Deficits on the COWAT are reported for lesions to the left (Miller, 1985; Perret, 1974; Troyer et al., 1998a) and right (Miller, 1985) frontal lobes.

A few studies have investigated the effect of frontal damage on task switching and EDS performance more directly. Task switching deficits have been found for patients with damage to the left frontal cortex (Rogers et al., 1998). A related finding is that frontal patients were selectively impaired on their ability to perform EDSs of attention (Owen, Roberts, Polkey, Sahakian, & Robbins, 1991), an ability attributed to the lateral prefrontal cortex in monkeys (Brodmann area 9; Dias, Robbins, & Roberts, 1996; Robbins, 1996).

Two populations that have been heavily researched, and are thought to demonstrate executive function deficits, are people with PD, and the normal elderly (NE). The remainder of this investigation will draw on the understanding of the cognitive components of task switching developed in Experiments 1 to 7, and apply these concepts to interpret deficits associated with task switching in people with PD and people experiencing normal aging.

Experiment 8: The Effect of Parkinson's Disease on Task Switching

Parkinson's disease is a hypokinetic neurological disorder that is related to the degeneration of the substantia nigra, and to the loss of the neurotransmitter dopamine, which is produced by cells of this nucleus. The major affected structures are those in a reinforcing feedback loop from the cortex (frontal, parietal and temporal associated areas) through the basal ganglia (caudate, putamen, globus pallidus and substantia nigra) to various thalamus nuclei, and to the prefrontal cortex (Penny & Young, 1983; Penny & Young, 1986; Taylor, Saint-Cyr, & Lang, 1986).

This degeneration is associated with four major symptoms: (a) resting tremor, (b) bradykinesia (slowness of movement), (c) rigidity, and (d) postural instability, each of which may manifest in different body parts in different combinations (Penny & Young, 1986; Rajput, 1991). The prevalence rate of PD increases with age, with 0.1% of the population under the age of 60 years being affected, 1% of the population over 60 years, and 2.5% of the population over 85 years (Rajput, 1991). PD may or may not be associated with a dementia. It is estimated that about 20% of patients with PD will become demented (Brown & Marsden, 1987a).

The major difficulties in movement associated with PD tend to overshadow the relatively subtle associated cognitive deficits. Most general reviews conclude that PD without dementia is associated with deficits in memory recall (but not recognition), executive functions, and visuospatial ability, although the latter deficit is less well accepted (Brown & Marsden, 1990; Cummings, 1988; Cummings & Benson, 1988; Dubois, Boller, Pillon, & Agid, 1991; Raskin, Borod, & Tweedy, 1990).

Impairment on the Stroop test for people with PD is absent when the control groups is matched for age and intellectual function (Cools, Van Den Bercken, Horstink, Van Spaendonck, & Berger, 1984; Hietanen & Teräväinen, 1988, elderly sample; Richards, Cote, & Stern, 1993; Stam et al., 1993). Some reviews (Dubois et al., 1991; Raskin et al., 1990), which have previously concluded that PD is associated with impairment on the Stroop task, may be in error. Upon inspection, studies to which they refer did not give the incongruent condition at all (Taylor et al., 1986), did not give the neutral condition (Brown & Marsden, 1988), reported weak significance for group mean differences (Hietanen & Teräväinen, 1988, young sample), and/or did not analyze the data to separate groups differences in Stroop interference from group differences in color naming (Hietanen & Teräväinen, 1988; Lund-Johansen, Hugdahl, & Wester, 1996; Portin & Rinne, 1980). Other confounds in these studies include no screening for dementia (Lund-Johansen et al., 1996), or the study of a PD sample with more general impairments (Hietanen & Teräväinen, 1988, young sample). In summary, the evidence in favour of a PD associated Stroop deficit is somewhat tenuous, while the evidence against this association is stronger.

Poor performance on the WCST is often cited as evidence for an executive deficit for nondemented PD patients (Brown & Marsden, 1990; Cummings, 1988; Cummings & Benson, 1988; Dubois et al., 1991; Raskin et al., 1990), although often no deficit is found (Beatty & Monson, 1990; Beatty, Monson, & Goodkin, 1989a; Caltagirone, Carlesimo, Nocentini, & Vicari, 1989; Canavan et al., 1989; Mohr et al., 1990). Moreover, although some studies reported that few categories achieved by a PD sample may have been attributable (at least in part) to increased perseverative errors (interpreted as a difficulty shifting set; Beatty, Staton, Weir, Monson, & Whitaker, 1989b; Brown & Marsden, 1988; Gotham, Brown, & Marsden, 1988; Lees & Smith, 1983), few categories achieved often co-occurs with no increase in perseverative errors (Bowen, Kamienny, Burns, & Yahr, 1975; Dalrymple-Alford, Kalders, Jones, & Watson, 1994; Lichter et al., 1988; Lund-Johansen et al., 1996; Starkstein, Leiguarda, Gershanik, & Berthier, 1987; Taylor et al., 1986). Thus, it appears that PD associated deficits on the WCST may not exist, and if they do, they may not be due to difficulty switching set, but to other factors (e.g., generating and implementing a plan of action, or deficits in set maintenance; Taylor et al., 1986, Lichter, 1988 #55). Inconsistencies may be attributable to variation in sample selection (e.g., Beatty et al., 1989a; Beatty et al., 1989b; Mohr et al., 1990), or method of WCST administration and scoring (Beatty & Monson, 1990; Canavan et al., 1989).

Normal performance on the COWAT for medicated, nondemented PD patients is the prevalent finding (Auriacombe et al., 1993; Beatty & Monson, 1990; Beatty et al., 1989a; Beatty et al., 1989b; Gotham et al., 1988; Hanley, Dewick, Davies, Playfer, & Turnbull, 1990; Huber, Freidenberg, Shuttleworth, Paulson, & Christy, 1989; Lees & Smith, 1983; Levin, 1990; Matison, Mayeux, Rosen, & Fahn, 1982; Miller, 1985; Randolph, Braun, Goldberg, & Chase, 1993; Raskin, Sliwinski, & Borod, 1992; Rogers et al., 1998; St. Clair, Borod, Sliwinski, Cote, & Stern, 1998; Stam et al., 1993; Starkstein et al., 1987; Taylor et al., 1986; Weingartner, Burns, Diebel, & Lewitt, 1984). Exceptions can be explained by between-group differences in depression (Dalrymple-Alford et al., 1994) or dementia (Litvan, Mohr, Williams, Gomez, & Chase, 1991; Tröster et al., 1998; Troyer et al., 1998b). When COWAT performance was split into clustering and switching

measures, nondemented PD patients did not differ from controls on either measure (Troyer et al., 1998b).

Despite intact performance on the COWAT, and tenuous evidence for a switching deficit on the WCST, it became generally accepted that PD was associated with difficulties shifting set. This conclusion was fuelled by results using paradigms related to the WCST (Richards et al., 1993), and was restated as difficulty with “shifting aptitude” (Cools et al., 1984). These speculations led to more detailed investigations into this supposed deficit.

PD patients showed no deficit when switching between left-right discrimination and perspective manipulation in response to cued screen displays (Brown & Marsden, 1986), and IDSs posed no problem for people with PD (although EDSs were impaired; Downes et al., 1989; Owen et al., 1993; Riekkinen et al., 1998). Thus, the conclusion that a general shifting or switching deficit is associated with PD was questioned when it was noted that certain types of task switches posed a problem for people with PD, while others did not.

In an attempt to resolve these inconsistencies, Brown and Marsden (1988), using incongruent Stroop stimuli, asked a sample of PD patients to switch between word reading and color naming every 10 trials. They found pathologically large Stroop and Reverse Stroop effects for the PD sample only when the participants were not cued as to which task was currently relevant (i.e., the cue was the word ‘SHIFT’). When a task cue was provided (i.e., the cues were the words ‘WORD’ and ‘COLOUR’), a switching deficit for PD was not present.

Thus, it was tentatively concluded that pathological PD switching performance arose from a self-cueing failure (Brown & Marsden, 1988). In accordance with this conclusion, although unmedicated PD patients were impaired on switching with external *and* internal cues, medicated PD patients had difficulty only with internal cues (Fimm, Bartl, Zimmermann, & Wallesch, 1994). In addition, previous researchers had reached a similar conclusion, suggesting impairment in the spontaneous generation of self-directed strategies (Taylor et al., 1986). Moreover, the benefit of an external cue is evident clinically: while spontaneous walking may be very difficult, walking up stairs, or over a line on the floor may not be (Brown & Marsden, 1987b).

Although this was an attractive hypothesis, another possible explanation was put forward; namely, that reliance on internal cues exposed a depletion of processing resources of the SAS associated with PD (Brown & Marsden, 1988), and that external cues did not place enough demand on central processing to expose this deficit. This hypothesis was an extension of previous work on PD, whereby deficits were proposed only for “effort demanding processes” (Weingartner et al., 1984). This “depleted resources” hypothesis is a somewhat post-hoc conclusion; therefore, it was later directly tested by Brown and Marsden (1991). They had normal controls perform an SAS resource-demanding secondary task (generating random numbers) while switching between color naming and word reading. As predicted, this manipulation affected internally cued trials more severely than externally cued trials. Moreover, PD patients were much more affected by this secondary task than age-matched controls on the externally cued version of the task. Thus, for PD patients, even an externally cued switch can be severely disrupted by a concurrent task that reduces the available resources of the SAS.

Two recent studies have directly tested task switching in response to incongruent stimuli in PD (Hayes, Davidson, Keele, & Rafal, 1998; Rogers et al., 1998). One found no difference in switching ability between people with PD and a control group on an internally cued task (Rogers et al., 1998), and the other found a significant difference for an externally cued task (Hayes et al., 1998). This difference in findings may be attributable to differences in methodology. The study which did not find a switch cost used a predictable order of presentation, whereas the study finding a switch cost used a random presentation order. Random presentation may place more demands on the SAS. Neither study used tasks that differed in dominance.

In summary, little evidence for a PD associated general switching impairment, or impaired dominant task inhibition in PD, has been presented. The most promising competing hypothesis presented to date appear to be (a) depleted SAS resources (Brown & Marsden, 1991), or (b) impaired performance on EDSs, perhaps due to impaired inhibition (Robbins, 1996). Thus, the present study was an attempt to apply the task switching paradigm presented in Experiment 3 to a PD sample, and assess the impact (if

any) of nonequidominant tasks. From the literature review, a task-switching deficit may be expected if task demands exceed the SAS resources of the PD sample, or when MODERATE and SHIFT are due to the presence of EDSs. If this occurs, the PD sample should show a task-switching deficit compared to age- and education-matched controls.

Method

Participants

Participants were 34 people diagnosed as having idiopathic Parkinson's disease. They were recruited by (a) the recommendation of participating neurologist Dr. A. Moll, (b) advertisements with the Parkinson's society of Victoria, B.C., or (c) by word of mouth. Participants ranged in age from 37 to 84 ($M = 68.58$, $SD=10.70$) at the time of testing. The mean years of education completed was 13.79 ($SD=3.26$). The duration of illness ranged from less than one to 18 years ($M = 5.72$, $SD=4.40$). The sample consisted of 17 males and 17 females. All participants except one (duration of illness 1 year, age 58 years) were taking medication for the disease at the time of testing. All PD participants were able to provide the name of the neurologist who diagnosed their condition. The control group, which was matched for age and education (group mean differences in age and education were not significant, $t(66) = 0.51$, $p = .61$, $t(66) = 0.60$, $p = .55$, respectively), is described in more detail in the following experiment on aging.

Procedure and Materials

Screening Questionnaires and Tests

All subjects were initially given a consent form, and a demographic questionnaire (see Appendix D). A symptom rating scale querying PD symptoms and medication was also administered (Appendix E). Evidence for (Riekkinen et al., 1998) and against (Goldenberg, Podreka, Muller, & Deecke, 1989; Lichter et al., 1988) a correlation between the severity of motor symptoms and scores on executive tests has been reported. Similarly, there is evidence for (Bowen et al., 1975; Fimm et al., 1994; Gotham et al., 1988; Hayes et al., 1998; Lange et al., 1992) and against (Day, Dick, & Marsden, 1984; Rafal, Posner, Walker, & Friedrich, 1984) an effect of medication on cognitive performance. Finally, there is evidence that medication improves performance on only

particular types of tasks (Pullman, Watts, Juncos, Chase, & Sanes, 1988). Therefore, these measures were treated as exploratory independent variables, with no specific hypotheses.

The demographic questionnaires were followed by the Mini-Mental Status Exam (MMSE; Folstein, Folstein, & McHugh, 1975) (see Appendix F), to screen for dementia, which may have a profound impact on cognitive performance in PD (Litvan et al., 1991; Tröster et al., 1998; Troyer et al., 1998b). Depression was measured with the Geriatric Depression Scale (GDS; Brink et al., 1982) (see Appendix G), as this can also have an impact on cognitive performance in PD (Starkstein, Bolduc, Mayberg, Preziosi, & Robinson, 1990; Starkstein, Bolduc, Preziosi, & Robinson, 1989; Wertman et al., 1993; Youngjohn, Beck, Jogerst, & Caine, 1992). No participants were dropped due to pathological scores on the MMSE or the GDS. Participants were not tested if they reported suffering from any of the following health problems that may affect cognition: stroke, transient ischemic attack, epilepsy, multiple sclerosis, Huntington's disease, Alzheimer's disease, encephalitis, meningitis, brain surgery, or having been unconscious for more than 10 minutes due to head trauma. All subjects had self-reported normal color vision, and could see the computer screen clearly.

Experimental Task

The methods for the experimental task are the same as for Experiment 3. Testing began with administration of a "baseline" condition to demonstrate that a Stroop effect was present and a RS effect not present out of the context of task switching. W_i/n stimuli were presented in advance of C_i/n stimuli to avoid the TSI effect (as reported by Allport et al., 1994), but block order (incongruent vs. neutral) was randomized within response type. Thirty-five trials of W_n , W_i , C_n and C_i responses were administered for each block. The stimulus disappeared from the screen once a response was recorded. The experimenter recorded any errors manually, and advanced to the next trial by a key press.

A switching trial consisted of either (a) a pair of incongruent Stroop stimuli, where the participant was instructed to respond either word-color (W_iC_i) or color-word (C_iW_i); (b) a pair of neutral Stroop stimuli, where the participant was instructed to respond either word-color (W_nC_n) or color-word (C_nW_n); (c) a pair consisting of one incongruent and one neutral stimulus, where the participant was instructed to respond word-color (W_nC_i

or WiCn) or color-word (CnWi or CiWn). Thus, in total, eight pair types were presented (WiCi, CiWi, WiCn, WnCi, CnWi, CiWn, WnCn, CnWn). The colors and color words used for all stimuli were blue, yellow, red, green, and purple. Each participant received 35 blocked trials of each pair type. The order of presentation for these eight stimulus blocks was randomly determined.

Results

As for Experiment 3, for Experiment 8, two types of errors were recorded: (a) *incongruent*, where the now-irrelevant task was carried out (2.31% of responses), and (b) *unrelated*, where an incorrect color name was produced which would not be correct for the now-relevant or now-irrelevant task (.37% of responses). Invalid trials were recorded as those where the voice-key picked up extraneous noise, or did not record a response (3.00% of responses). Any responses longer than 6500 ms, or shorter than 300 ms, but not coded as voice-key errors during testing, were coded as voice-key errors post hoc (.08% of responses).

In order to control for the increased probability of Type I errors associated with multiple significance tests, while keeping power at the desired level (.80), an alpha level of .01 was used as the cut-off for significance for all group comparisons. Because the direction of RT cost means (greater than zero) and group means comparisons (PD > NE) were hypothesized in advance, one tailed t-tests were used (unless otherwise specified). Degrees of freedom for between-group comparisons were adjusted for inequality of variances when necessary (tested at $p < .01$, two tailed).

The regression based methodology for significance of main effects and interactions within groups was the same as for the PSY100 sample. For between-group comparisons that consider interactions, each effect was computed over and above all effects that were significant *for either group* (i.e., any effect that was not significant was excluded from between-group analyses). For between-group comparisons ignoring interactions (the rationale for this methodology is presented below), all main effects were included in the analysis. Thus, for all between-group means comparisons, effects were computed the same way for both groups.

Word Reading

Table 33 displays the mean RTs and error types for word reading conditions. Table 34 lists partialled effects for each effect of interest for the within-group comparisons.

Within-Group Effects

The three-way interaction was not significant, $t(33) = -0.48$, $p = .68$ ($M = -57$ ms). The two-way interaction effects MODx1st ($M = -8$ ms), SHFx1st ($M = -4$ ms), and SHFxMOD ($M = 66$ ms) were also not significant, $t(33) = -0.16$, $p = .44$, $t(33) = -.15$, $p = .44$, $t(33) = 1.73$, $p = .05$, respectively.

Moving to the main effects, the effect FIRST ($M = 2$ ms) was not statistically significant, $t(33) = 0.08$, $p = .47$. The effects SHIFT and MODERATE effects were assessed over and above the marginally significant SHFxMOD interaction effect, to ensure that each accounted for significant variance outside the effect of the other, despite the fact that this interaction did not reach significance. Even for this conservative analysis, both the SHIFT ($M = 139$ ms), and the MODERATE ($M = 120$ ms) effects were highly statistically significant, $t(33) = 4.55$, $p < .001$, $\eta^2 = .39$, $t(33) = 4.55$, $p < .001$, $\eta^2 = .39$, respectively (see Figure 41).

Between-group Effect Comparisons

Any effects that were found to be significant ($p < .01$) for either the PD group or the NE group were entered into regression analyses for each group, and compared between groups. Using this methodology, neither the MODERATE, SHIFT, FIRST nor SHFxMOD effects differed between the groups, $t(66) = -.06$, $p = .48$, $t(66) = .33$, $p = .44$, $t(66) = -1.72$, $p = .05$, $t(66) = .00$, $p = .50$, respectively (see Figure 42).

Between-group Effect Comparisons Ignoring Interactions

The interaction terms developed on the PSY100 sample, and tested above, were all of the same type. Namely, when two effects occurred together, RT was increased. Under the present circumstances, this type of interaction does not greatly alter interpretation of the main effects.

For example, the four data points plotted in Figure 43 represent the mean word-reading RT when SHIFT and MODERATE were not present (the mean of CnWn and

WnCn), when SHIFT was present but MODERATE was not (the mean of CnWi and WiCn), when MODERATE was present but SHIFT was not (the mean of CiWn and WnCi), and when both MODERATE and SHIFT were present (the mean of CiWi and WiCi), for the PD sample (see Table 10). The fact that a marginally significant interaction between MODERATE and SHIFT was present does not alter the direct interpretation of the main effects of MODERATE and SHIFT – namely, that RT increased when either effect was present.

This argument is particularly relevant when the effect sizes for the main effects in question are substantially larger than that of the interaction, which was the case in the present experiment, and in Experiment 3. Because a similar pattern can be observed for the elderly sample, a direct comparison of the main effects, ignoring interactions, may prove informative by simplifying interpretation. Moreover, the contrast codes for the main effects are mutually orthogonal, avoiding the complication of interpreting partialled effects.

Thus, to simplify interpretation, between-group comparisons of main effects were repeated with the interactions ignored. This analysis led to the same conclusions as when the interactions were taken into consideration. Neither the MODERATE, SHIFT nor FIRST effects differed between the groups, $t(66) = -.07$, $p = .47$, $t(66) = .49$, $p = .69$, $t(66) = -1.72$, $p = .05$, respectively (see Figure 44).

Color Naming

Table 35 displays the mean RTs and error types for color naming. Table 36 lists partialled effects for each effect of interest for the within-group comparisons.

Within-Group Effects

The three-way interaction ($M = 90$ ms) was not significant, $t(33) = 0.99$, $p = .17$. The two-way interaction effects MODx1st ($M = 78$ ms) and SHFx1st ($M = 139$ ms) accounted for significant variance, $t(33) = 2.58$, $p < .008$, $\eta^2 = .17$, $t(33) = 4.0$, $p < .001$, $\eta^2 = .33$, respectively. The SHFxMOD interaction ($M = 5$ ms) was not significant, $t(33) = 0.17$, $p = .43$.

The effects FIRST, SHIFT/Stroop and MODERATE were assessed over and above the significant interaction effects. Under these circumstances, the SHIFT/Stroop

and MODERATE effects were assessed over and above their effects in position one, and the FIRST effect for when neither SHIFT/Stroop nor MODERATE were present. Under these conditions, the SHIFT/Stroop effect ($\underline{M} = 334$ ms) was highly significant, $t(33) = 10.52$, $p < .001$, $\eta^2 = .77$, the MODERATE effect ($\underline{M} = 43$ ms) was not significant, $t(33) = 2.13$, $p = .02$, and the FIRST effect ($\underline{M} = 1$ ms) was not significant, $t(33) = 0.06$, $p = .48$ (see Figure 45).

Between-group Effect Comparisons

Effects that were significant for either the PD group or the NE group at the $p < .01$ level were compared by t-tests. The SHFxMOD effect did not differ significantly between the groups, $t(66) = -1.54$, $p = .94$. The MODx1st and SHFx1st effect comparison also did not reach significance at the $p < .01$ level, $t(66) = 1.85$, $p = .03$, $t(44.30) = 1.88$, $p = .03$, respectively. However, the SHIFT/Stroop means comparison was significant, $t(41.24) = 3.07$, $p < .002$, $\eta^2 = .19$ (see Figure 46).

Between-group Effect Comparisons Ignoring Interactions

The between-group analysis ignoring interactions led to similar conclusions as when the interactions were considered. Neither the MODERATE nor FIRST effects differed between the groups, $t(66) = 0.18$, $p = .43$, $t(43.89) = 2.13$, $p = .02$, respectively, whereas the SHIFT/Stroop effect did, $t(48.24) = 2.72$, $p < .005$, $\eta^2 = .13$ (see Figure 47).

Singles Analysis

Unexpectedly, a significant difference between the mean single ($\underline{M} = 742$ ms; $(Cn + Wn)/2$) and switching ($\underline{M} = 859$ ms; $(CnWn + WnCb)/2$) trials was present for neutral stimuli, $t(33) = 4.33$, $p < .001$, $\eta^2 = .36$. This was smaller than the difference between the mean single ($\underline{M} = 903$ ms; $(Ci + Wi)/2$) and switching ($\underline{M} = 1263$ ms; $(CiWi + WiCi)/2$) trials for incongruent stimuli, which was highly significant, $t(33) = 7.47$, $p < .001$, $\eta^2 = .63$. As expected, the Stroop effect was significant ($\underline{M} = 284$ ms; $Ci - Cn$), $t(33) = 11.57$, $p < .001$, $\eta^2 = .80$. Unexpectedly, the RS effect was also significant ($\underline{M} = 40$ ms; $Wi - Wn$), $t(33) = 4.90$, $p < .001$, $\eta^2 = .42$.

Comparing these mean effect sizes to the elderly sample, no evidence for impairment due to PD was present. The neutral switch cost, incongruent switch cost,

Stroop, and Reverse Stroop effects did not differ significantly between groups, $t(43.26) = 1.44$, $p = .15$, $t(66) = 1.79$, $p = .08$, $t(52.37) = 0.38$, $p = .70$, $t(66) = 0.77$, $p = .45$, respectively.

Medication and Motor Symptoms Effects

All significance tests for the following section were assessed at $p < .01$, two tailed. Regarding symptoms, neither an aggregate of severity of cognitive symptoms (the sum of Slowness of Thinking and Memory Loss items; see Appendix E) or severity of motor symptoms (the sum of the remaining items in Appendix E) correlated with MODERATE, SHIFT or FIRST for color naming or word reading (computed as main effects, ignoring interactions). Time since diagnosis also did not correlate with these cognitive measures.

Regarding medication, whether or not the drug was wearing off at the time of testing had no effect on MODERATE, SHIFT or FIRST for color naming or word reading. Similarly, whether or not medication was judged to be stable and effective was not significantly related to MODERATE, SHIFT or FIRST for color naming or word reading. Therefore, the present investigation appeared to support others that found no relationship between executive functions and motor symptoms (Goldenberg et al., 1989; Lichter et al., 1988) or medication (Day et al., 1984; Rafal et al., 1984). However, the use of more precise symptom rating scales and measures of medication effectiveness may provide more powerful tests of these relationships.

Discussion

Thus, people with PD appear to have no difficulty with those cognitive functions involved in task switching per se (*viz.*, MODERATE and SHIFT). This is in agreement with some previous research into task switching deficits associated with PD (Rogers et al., 1998). However, in the present project, a deficit on color naming in response to incongruent Stroop stimuli within the context of task-switching was present. Previous studies that have found no task-switching deficit for PD did not use tasks that differed in dominance (e.g., Rogers et al., 1998).

It was somewhat surprising that this effect was observed, given that impairment on the regular Stroop effect was not present. An explanation can be reached by adopting Brown and Marsden's (Brown & Marsden, 1991) conclusion that more resource

demanding tasks expose the depleted processing resources of people with PD. The SHIFT/Stroop effect may simply be a particularly taxing special case of the SHIFT effect, and may expose a depletion of central processing resources. Put another way, the resource pool available to the SAS is sufficient for SHIFT, MODERATE, and Stroop color naming outside the context of switching, but is insufficient when the largest shift of attention is necessary (the SHIFT/Stroop condition).

Review of the literature suggests that the “depleted processing resources” hypothesis can successfully be used to explain other results, such as PD deficits in selective attention (Sharpe, 1990) focussed attention (Sharpe, 1992), divided attention (Sharpe, 1996), and concurrent performance of tasks (Dalrymple-Alford et al., 1994; Malapani, Pillon, Dubois, & Agid, 1994; Robertson, Hazlewood, & Rawson, 1996). A related line of research demonstrated that people with PD have difficulty self-initiating effective strategies (Morris et al., 1988; Owen et al., 1992), perhaps causing impairment on simple RT tasks, but not choice RT tasks (Bloxham, Mindel, & Frith, 1984; Evarts, Teräväinen, & Calne, 1981; Goodrich, Henderson, & Kennard, 1989; Sheriden, Flowers, & Hurell, 1987).

Moreover, attention demanding secondary tasks can cause normal subjects’ simple RT performance to mimic that of a PD sample (Goodrich et al., 1989). This deficit in simple RT could not be diminished by medication, despite the fact that choice RT could be increased to a normal level thorough pharmaceutical treatment (Pullman et al., 1988). Clinical evidence in favour of this hypothesis includes the fact that people with Parkinson’s may “freeze” when their attention is called for by a non-motor activity (Goldenberg, Lang, Podreka, & Deecke, 1990).

Thus, the standard Stroop task may have relatively low resource requirements compared to Stroop within the context of task switching. As written by Richards, Cote and Stern (1993):

It may be that the “primary” task during the standard administration of the Stroop (i.e., reading out the color of the ink) has a relatively low resource requirement so that the presence of distractors [sic.] (the words) does not unduly increase task

difficulty in PD patients, even when the distractors [sic.] are highly competitive for attention (pp. 277-278).

These authors were attempting to explain the absence of a deficit for a PD sample on the Stroop test, in combination with impairment on an Odd-Man-Out paradigm. However, their comments are applicable to the present discrepancy between two more closely matched tasks (the SWITCH/Stroop operation within and outside the context of task switching).

Figure 48 demonstrates how the PD sample may be unable to reach maximum performance on the switching Stroop effect due to depleted SAS resources, but not on the regular Stroop effect due to the lower relative demand on SAS processing resources associated with this task. This is similar to the diagram presented by Brown and Marsden (1991, p. 219), and is based on the performance/resource curve applied to neuropsychological investigation by Shallice (1988).

Experiment 9: The Effect of Aging on Task Switching

Ample evidence has been presented suggesting that “executive functions” decline with normal aging (see Hochanadel & Kaplan, 1984; West, 1996, for reviews). As was the case for the PD literature, a vast array of clinical neuropsychological tests have been used to assess executive functions. The focus for this project, to parallel the review of the PD literature, will be on the Stroop test, the WCST, and the COWAT .

Interference on the Stroop test is commonly reported to increase with age (Cohn, Dustman, & Bradford, 1984; Daigneault, Braun, & Whitaker, 1992; Dulaney & Rogers, 1994; Houx, Jolles, & Vreeling, 1993; Spreen & Strauss, 1997; Whelihan & Leshner, 1985). This is usually attributed to a failure inhibiting a prepotent response (Goel & Grafman, 1995; Spreen & Strauss, 1997; Vendrell et al., 1995), or a selective attention deficit (Dulaney & Rogers, 1994). Translation of this deficit into the terminology of Kahneman and Treisman (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992) implies a failure in selectively attending to the non-dominant dimension of a stimulus.

A decrease in performance on the WCST with increasing age is often cited as evidence for an executive deficit in elderly people (e.g., Boone, Miller, & Lesser, 1993; West, 1996). In some studies, fewer categories achieved may have been attributable (at

least in part) to increased perseverative errors (Axelrod & Henry, 1992; Axelrod, Jiron, & Henry, 1993; Daigneault et al., 1992; Heaton, 1981; Kramer, Humphrey, Larish, Logan, & Strayer, 1994), interpreted as a difficulty switching set. However, one study reported few categories achieved in combination with no increase in perseverative errors (Boone, Miller, Lesser, Hill, & D'Elia, 1990). Overall, this evidence suggests that difficulty switching set, or performing EDSs of attention, is associated with aging.

Some researchers have concluded that age effects on the COWAT are not present (Axelrod & Henry, 1992; Bolla, Lindgren, Bonaccorsy, & Bleeker, 1990; Boone et al., 1990; Daigneault et al., 1992; Mittenberg, Seidenberg, O'Leary, & Di Giulio, 1989). Others have found a significant negative relationship between COWAT performance and aging (Benton, Eslinger, & Damasio, 1981; Veroff, 1980), although the drop-off in performance may not manifest until after 80 years of age. However, when switching and clustering were separated out, it was demonstrated that while switching ability declined slightly with age, clustering actually increased significantly (Troyer et al., 1997a). Thus, these two effects may cancel each other out to produce ambiguous results when the COWAT total words produced is associated with age. In addition, some studies may have failed to find an association between age and COWAT performance due to a restricted age range (Bolla et al., 1990; Daigneault et al., 1992; Mittenberg et al., 1989). Thus, although most studies report no age-related deficit in COWAT performance, switching deficits on this task may be hidden by increased clustering.

A subtest of the Cambridge Neuropsychological Test Automated Battery (CANTAB) provides a test of EDS performance (Robbins et al., 1998). For this test, no age differences were present for perceptual discrimination, or for applying a learned rule to new exemplars (an IDS). However, performance decreased with age when performing EDSs. The authors interpret this as an age-related deficit associated with EDS of attention. This conclusion has previously been stated using a related paradigm (Owen et al., 1991).

Some studies have directly tested the effect of age on switching tasks. Salthouse and colleagues (Salthouse et al., 1998) tested shifting cognitive operations in response to one dimensional stimuli, with internal cues. They found that task switching declined with

age (although these researchers suspected that the variance this construct shared with age was not unique to task switching). Compton and Park (Compton & Park, 1998) found an age-related task-switching deficit for two externally cued operations that involved alternating attention between two aspects of a screen display.

In summary, the evidence for switching deficits associated with aging is more substantial than that for PD. Given this evidence for switching deficits associated with aging, regardless of internal or external cueing, we would expect to see aging deficits associated with the task switching paradigms discussed earlier.

Method

Participants

Subjects were 34 people chosen to match the age and education of the PD sample. They were recruited from Victoria, B.C., by word of mouth. Participants ranged in age from 46 to 85 ($M = 69.87$, $SD=9.99$). The mean years of education completed was 14.27 ($SD=3.03$). The sample consisted of 12 males and 22 females.

Procedure and Materials

Screening Questionnaires and Tests

All subjects were initially given a consent form, and a demographic questionnaire (see Appendix D). The demographic questionnaires were followed by the MMSE, to screen for dementia, and the GDS, to screen for depression. No participants were dropped due to pathological scores on the MMSE or the GDS. Participants were not tested if they reported suffering from any of the following health problems that may affect cognition: stroke, transient ischemic attack, epilepsy, multiple sclerosis, Huntington's disease, Alzheimer's disease, encephalitis, meningitis, brain surgery, or having been unconscious for more than 10 minutes due to head trauma. All subjects had self-reported normal color vision, and could see the computer screen clearly.

Experimental Task

The methods for the experimental task are the same as for Experiment 3, and Experiment 8.

Results

For Experiment 9, as for previous experiments, two types of errors were recorded: (a) *incongruent*, where the now-irrelevant task was carried out (1.16% of responses), and (b) *unrelated*, where an incorrect color name was produced which would not be correct for the now-relevant or now-irrelevant task (.12% of responses). Invalid trials were recorded as those where the voice-key picked up extraneous noise, or did not record a response (2.87% of responses). Any responses longer than 6500 ms, or shorter than 300 ms, but not coded as voice-key errors during testing, were coded as voice-key errors post hoc (.05% of responses).

In order to control for the increased probability of Type I errors associated with multiple significance tests, while keeping power at the desired level (.80), an alpha level of .01 was used as the cut-off for significance. Because the direction of RT cost means (greater than zero) and group means comparisons (NE > PSY100) were hypothesized in advance, one tailed t-tests were used (unless otherwise specified). Degrees of freedom for between-group comparisons were adjusted for inequality of variances when necessary (tested at $p < .01$, two tailed). The regression based methodology for significance of main effects and interactions within groups and between groups was the same as for the PD sample.

Word Reading

Table 37 displays the mean RTs and error types for word reading.

Within-group Effects

The three-way interaction was not significant, $t(33) = 0.19$, $p = .43$ ($M = 7$ ms). The two-way interaction effects MODx1st ($M = 29$ ms) and SHFx1st ($M = 41$ ms) did not account for significant variance, $t(33) = -1.45$, $p = .08$, $t(33) = 1.95$, $p = .03$, respectively, whereas the SHFxMOD interaction ($M = 66$ ms) did account for significant variance, $t(33) = 2.5$, $p < .01$, $\eta^2 = .16$.

The SHIFT and MODERATE effects were assessed over and above the SHFxMOD interaction effect. Under these conditions, both the SHIFT ($M = 124$ ms), and the MODERATE ($M = 120$ ms) effects were highly statistically significant, $t(33) = 7.17$, p

< .001, $\eta^2=.61$, $t(33) = 10.06$, $p < .001$, $\eta^2= .75$, respectively. The effect FIRST ($M = 44$ ms), was also statistically significant, $t(33) = 2.81$, $p < .005$, $\eta^2= .19$ (see Figure 49).

Between-group Effect Comparisons

Effects that were significant ($p < .01$) for either the NE group or the PSY100 control group were entered into regression analyses for each group, and compared by t-tests. The MODERATE and SHIFT means comparisons were highly significant $t(50.64) = 5.67$, $p < .001$, $\eta^2=.39$, $t(47.19) = 4.00$, $p < .001$, $\eta^2=.25$, respectively. Neither the SHFxMOD or FIRST effects differed significantly between the groups, $t(65) = 0.80$, $p = .21$, $t(45.91) = 0.05$, $p = .43$, respectively (see Figure 50).

Between-group Effect Comparisons Ignoring Interactions

This analysis that disregarded interactions led to the same between-group conclusions for main effects reached when the interactions were considered. The MODERATE and SHIFT effects were significantly different between the groups, $t(45.20) = 5.29$, $p < .001$, $\eta^2=.38$. $t(50.34) = 4.53$, $p < .001$, $\eta^2=.29$, respectively. The FIRST effect was not, $t(45.91) = 0.05$, $p = .48$ (see Figure 51).

Color Naming

Table 39 displays the mean RTs and error types for word reading. The within-group significance of interactions and main effects were assessed using the same methodology as for the PSY100 sample. Table 40 lists partialled effects for each effect of interest for the within-group comparisons.

Within-group Effects

The three-way interaction was not significant, $t(33) = 0.06$, $p = .48$ ($M = 2$ ms). The two-way interaction effect MODx1st ($M = 37$ ms) was not significant, $t(33) = 1.66$, $p = .05$, whereas the two-way interactions effects SHFx1st ($M = 68$ ms) and SHFxMOD ($M = 56$ ms) were highly significant, $t(33) = 3.67$, $p < .001$, $\eta^2= .29$, $t(33) = 2.82$, $p < .004$, $\eta^2= .19$, respectively

All main effects were assessed over and above the SHFx1st and SHFxMOD effects because they were highly significant, and the MODx1st effect because it approached significance. Thus, each effect was assessed completely outside the influence of the others.

Under these circumstances, the effect FIRST ($\underline{M} = -7$ ms), and the effect MODERATE ($\underline{M} = 32$ ms) were not significant, $t(33) = -0.52$, $p = .30$, $t(33) = 1.88$, $p = .03$, respectively. The SHIFT/Stroop effect ($\underline{M} = 223$ ms) was highly significant, $t(33) = 17.65$, $p < .001$, $\eta^2 = .90$ (see Figure 52).

Between-group Effect Comparisons

Effects that were significant ($p < .01$) for either the NE group or the PSY100 control group were entered into regression analyses for each group, and compared by t-tests. The SHIFT/Stroop means comparison was highly significant $t(65) = 5.01$, $p < .001$, $\eta^2 = .28$. However, none of the other comparisons (MODERATE, FIRST, SHFxMOD, MODx1st, SHFx1st) were significant, $t(65) = 1.27$, $p = .10$, $t(55.42) = -1.83$, $p = .96$, $t(65) = 1.19$, $p = .12$, $t(42.43) = 0.70$, $p = .24$, $t(50.64) = 1.20$, $p = .12$, respectively.

Between-group Effect Comparisons Ignoring Interactions

Between-group effect comparisons ignoring interactions did not affect interpretation of group differences for the SHIFT/Stroop or FIRST effects. The SHIFT/Stroop means comparison remained highly significant $t(65) = 5.09$, $p < .001$, $\eta^2 = .28$, and the FIRST effect did not differ between groups, $t(57.39) = -0.76$, $p = .45$. On the other hand, the MODERATE means comparison became highly significant $t(47.64) = 3.45$, $p < .001$, $\eta^2 = .20$ (see Figure 54), bringing the color naming results in line with the word-reading results for the MODERATE effect.

Singles Analysis

Unexpectedly, a significant difference between the mean single ($\underline{M} = 672$ ms; $(Cn + Wn)/2$) and switching ($\underline{M} = 748$ ms; $(CnWn + WnCb)/2$) trials was present for neutral stimuli, $t(34) = 4.09$, $p < .001$, $\eta^2 = .33$. This was smaller than the difference between the mean single ($\underline{M} = 825$ ms; $(Ci + Wi)/2$) and switching ($\underline{M} = 1084$ ms; $(CiWi + WiCi)/2$) trials for incongruent stimuli, which was highly significant, $t(34) = 3.48$, $p < .002$, $\eta^2 = .26$. As expected, the Stroop effect was significant ($\underline{M} = 273$ ms; $Ci - Cn$), $t(33) = 19.54$, $p < .001$, $\eta^2 = .92$. Unexpectedly, the RS effect was also significantly different from zero ($\underline{M} = 32$ ms; $Wi - Wn$), $t(33) = 4.78$, $p < .001$, $\eta^2 = .40$.

The neutral switch cost, incongruent switch cost, and Stroop effects differed from that present in the PSY100 sample, $t(49.10) = 8.22$, $p < .001$, $\eta^2 = .58$, $t(43.65) = 7.65$, $p < .001$, $\eta^2 = .57$, $t(51) = 6.47$, $p < .001$, $\eta^2 = .45$, respectively, but the Reverse Stroop effect did not, $t(51) = 1.95$, $p = .06$.

Discussion

Aging appears to be associated with a decline in the fundamental operations involved in switching attention. This is in agreement with previous research into task switching deficits associated with aging (Compton & Park, 1998; Robbins et al., 1998; Salthouse et al., 1998). In addition, a deficit on color naming in response to incongruent Stroop stimuli, within the context of switching, was observed. This was not observed previously due to use of equidominant tasks for switching (Compton & Park, 1998; Robbins et al., 1998; Salthouse et al., 1998).

An aging deficit on the Stroop test was also found, outside the context of switching. This finding agrees with previous work (Daigneault et al., 1992; Spreen & Strauss, 1997; Whelihan & Lesher, 1985). However, a major concern in the aging literature is that information processing speed is confounded with the dependent variable associated with aging (e.g., Boone et al., 1993; Dywan, Segalowitz, & Unsal, 1992; Graf, Uttl, & Tuokko, 1995; Uttl & Graf, 1997). For example, although the overall Stroop interference effect is larger for the elderly, this difference may disappear if switch costs are expressed as proportions of time added, instead of as absolute time added. In fact, some studies found that when Stroop interference was expressed as a proportion, differences due to aging disappeared (e.g., Graf et al., 1995; Uttl & Graf, 1997). In contradiction to these latter results, when the Stroop interference effects in the present study were converted to proportions, group differences between the elderly and the young remained highly significant for the regular Stroop ($M = 21\%$ increase, $M = 36\%$ increase, respectively), $t(51) = 4.47$, $p < .001$, $\eta^2 = .28$, and the switch Stroop ($M = 27\%$ increase, $M = 34\%$ increase, respectively), $t(65) = 2.75$, $p < .004$, $\eta^2 = .10$.

The PD results of Experiment 8 suggested that the cognitive processes involved in performing the nondominant task were limited by available SAS resources. This interpretation can also be applied to aging effects on regular and switching Stroop effects.

However, due to the observed Stroop impairment in both the switch and non-switch conditions, an additional assumption must be made: the maximum performance achievable by the elderly participants (with or without PD) is lower than that achievable by young participants, due to factors *other than* available SAS resources.

Clues to what this factor may be can be gleaned from previous research on aging. Reviews have concluded that aging leads to impaired selective and divided attention (Hochanadel & Kaplan, 1984; McDowd & Birren, 1990). Thus, optimal performance on the Stroop task may be limited by an increased susceptibility to the attraction of attention produced by the dominant dimension of the stimulus. This result has been previously reported for exogenous shifts of spatial attention (Faust & Balota, 1997; Hartley, Kieley, & Slabach, 1990). Regardless of the available resources for resolving this attentional conflict, maximum performance for the elderly could be limited by this factor.

Implementing this assumption, Figure 55 demonstrates how (a) the PD sample may be impaired on the switching Stroop effect due to depleted SAS resources, but not on the regular Stroop effect due to the lower relative demand on SAS processing resources, and (b) the NE sample is impaired on the regular Stroop due to performance limitations (not due to depleted SAS resources), and on the switch Stroop (due to depleted SAS resources, or by performance limitations, depending on the precise placement of the resource availability for the elderly).

An increased difficulty overcoming the attentional capture of integrated object attributes for the elderly has been reported previously, as large age differences were found on the Stroop only when the stimulus dimensions were integrated (Hartley, 1993), as was a difficulty in reducing the attentional capture of the word dimension with extensive practice (Dulaney & Rogers, 1994). This increased susceptibility to attentional capture is reflected in the observed group differences in MODERATE and SHIFT. A reduction in the effectiveness of the SAS may cause an increase in the SHIFT effect. Moreover, the MODERATE effect must take an increased role to counteract the overactive SHIFT effect, which may not be possible due to the reduced influence of the SAS on CS.

The concern over the processing speed confound mentioned above also applies to the fundamental operations involved in this task switching paradigm (*viz.*, MODERATE

and SHIFT). However, research into task switching demonstrated that task switching ability is dissociable from processing speed (Salthouse et al., 1998), and does not contribute unique variance to EDS performance as measured by the WCST (Dywan et al., 1992). Moreover, task switching declines associated with aging have been reported over and above processing speed (Compton & Park, 1998; Salthouse et al., 1998, Figure 6). In agreement with these latter findings, for the present study, converting absolute differences to proportions did not in any way alter the previously reported conclusions regarding group differences.

As mentioned in the analysis of the PSY100 data, deficits associated with SHIFT and MODERATE lead to inefficient contention scheduling. Thus, aging appears not only to produce increased susceptibility to attentional capture, and/or reduced SAS resources, but also leads to difficulty adjusting contention scheduling to allow the SHIFT and MODERATE effects to optimize task switching performance.

GENERAL DISCUSSION

The series of experiments presented here suggest that sub-operations of the executive functions that are important for task switching can be identified. This theoretical account suggests that the SAS modules are essential for two operations involved in task switching: (a) shifting attention, and (b) moderating those attentional shifts. The evidence suggests that these operations are functionally dissociable, in that each can be carried out in absence of the other on any given trial. However, they are both proposed to be implemented by a coordinated set of cognitive operation, such that it is not obvious how one could be selectively lesioned without the other also being affected.

The present theoretical account conceptualized RT costs as attributable to time consuming, bottom-up information gathering passes (i.e., IGPs), and time consuming, top-down adjustments to the attentional weighting system (i.e., AAPs). Costs were attributed to added iterations associated with IGPs and AAPs in an optimizing network. A model was presented specifying the active operations necessary for implementing task switching, whereby inhibition and activation of attention to stimulus dimensions interacted to optimize performance. The greater the complexity of the network adjustments, the more IGPs and AAPs, and the greater the RT cost. The overall purpose of this information

gathering is to bias the neural architecture towards the response demanded by the environment.

The increase in the SHIFT/Stroop effect for the PD sample was attributed to an SAS resource deficit in PD. It has long been supposed that the SAS (or central processor) is of limited capacity, meaning that its commitment to any operation reduces its availability to perform any other operations (Allport, 1989; Logan, Zbrodoff, & Fostey, 1983; Posner & Snyder, 1975). Even spontaneous, non-explicit, “reflexive” strategies involving a strategic allocation of attention to stimulus dimensions are thought to require general resources (Logan et al., 1983). Therefore, when the conflict produced by attentional capture was the most extreme (C1 responses), SAS resource limitations were exposed due to the exceptionally large SHIFT operation necessary under these conditions.

An alternative explanation is that the Stroop operation depends upon different cognitive operations than the SHIFT operation, and that these operations are impaired in PD. Physical evidence for this dissociation has been presented: overcoming Stroop interference appears to be localizable to the anterior cingulate (Posner et al., in press; Posner & DiGirolamo, in press), whereas switching appears to involve the left prefrontal cortex (Robbins, 1996; Rogers et al., 1998). However, the fact that the performance of people with PD is intact on the traditional Stroop test (outside the context of switching) is problematic for this interpretation. However, the possibility remains that performance on the traditional Stroop test depends upon operations separate from those involved in SHIFT, and that these separate operations are also involved in switching tasks, resulting in exposure of a resources deficit for these other operations, not for those involved in SHIFT.

The present account of PD deficit (depleted SAS resource exposed by sufficiently taxing the SHIFT operation), in light of the fact that they did not demonstrate difficulty with the basic switching operations (MODERATE and SHIFT) appears incompatible with some previously presented hypotheses. For example, Goodrich, Henderson, and Kennard (1989) suggested that the disadvantage that people with PD show in SRT can be attributed to an inability to sustain attention to the maintenance of the expected response in a dynamic short-term store (an interpretation based on speculations of Frith & Done,

1986). Similarly, Shallice (1994) speculated that this deficit associated with PD is based in an inability to modulate output of the SAS on CS (contention scheduling). The present investigation found that the ability of people with PD to use the SAS to sustain, switch and moderate attention by way of the CS was basically intact, but a resource depletion could be exposed under the most difficult conditions.

The following is a summary of the differences between aging and PD in terms of the PDP model presented earlier. Compared to their respective control groups, the efficiency of the SAS influence on CS was impaired for the elderly sample, resulting in inefficient attention switching and moderating. Conversely, attention switching and moderating were not impaired for the PD sample. However, if task demands were high, which was the case when the conflict produced by attentional capture was the most extreme (Ci responses), SAS resource limitations were exposed by the most taxing SHIFT/Stroop operation, and the PD sample was impaired on these trials. The elderly sample may have also suffered from a resource depletion, but it was impossible to distinguish between this and an increased susceptibility to attentional capture.

This “depleted SAS resource” interpretation provides an opportunity for an investigation on normal elderly subjects. Increasing cognitive load should not affect the MODERATE and SHIFT effects (hypothesized to be well within the range of available SAS resources), but should affect the Stroop effect within the context of task switching. For example, randomly generating numbers should deplete the resources of the SAS available for SHIFT, and cause the elderly performance to resemble that of a PD sample. As a control condition, generating sequential numbers should have relatively little impact on the switching Stroop performance. In other words, the task-switching performance of an elderly sample, with this distracter task in place, should mimic that of a PD sample, and affect only color naming in response to incongruent Stroop stimuli within the context of task switching.

Other research paths that test the resource depletion argument include:

1. Depleting the resources of the young sample may affect the Stroop effect within the context of task-switching, but not the traditional Stroop interference (see Figure 55).

2. The prediction made in point 1 for young people should also apply to elderly people (see Figure 55).

3. Depleting the resources of people with PD should affect both Stroop tasks, but the regular Stroop task should be affected more than the switching Stroop task (see Figure 55).

4. These manipulations should not affect the word-reading MODERATE and SHIFT effects, or the color-naming MODERATE effect, despite the postulation that traditional Stroop performance is a special case of the SHIFT operation.

5. Diluting attention (Kahneman & Chajczyk, 1983), and spatially separating word and color dimensions (Kahneman & Henik, 1981; MacLeod, 1998), should affect the MODERATE and SHIFT operations, but not the FIRST effect.

6. Performing task-switching in response to poor examples of objects, or non-objects, should reduce the SHIFT and MODERATE costs (see Ward & Goodrich, 1996) according to Kahneman and Treisman's account of the Stroop effect (Kahneman & Treisman, 1984; Kahneman & Treisman, 1992).

Thus, future work involving all three populations (PD, elderly and young) can be carried out to test this theoretical framework.

In addition to the present theoretical accounts of switch costs, and those already mentioned (Allport et al., 1994; Rogers & Monsell, 1995, who proposed conflicting S-R mappings), other investigators have speculated as to the source of task-switch costs. Within the context of attentional blink research, central capacity limitations have been suggested, in the form of a serial bottleneck, or competition between parallel processes for limited resources (Potter et al., 1998). Within the context of investigation of self-initiated EDS of attention, EDSs have been described as involving "inhibition" and "disinhibition" (Downes, Sharp, Costall, Sagar, & Howe, 1993; Robbins, 1996) of previous responses. Although these researchers have touched on issues addressed in the present investigation, they have not provided working models of their hypotheses, and have lacked clarity on the detail of the mechanisms responsible for switch costs.

The goal of the present study was to gain an understanding of the executive processes involved in task-switching, and extend this knowledge to the task-switching

deficits associated with aging and PD. A theoretical framework was proposed that met this goal, and led to a functional fractionation of the SAS, and the nature of its influence on CS. Moreover, a multilayer, linear, PDP model was presented to demonstrate how these cognitive processes may be implemented by the cognitive system. This theoretical account appears to have opened a new path for conceptualization of the costs associated with switching tasks, and may make a contribution towards solving the persistent puzzle of the executive system.

REFERENCES

- Allport, A. (1989). Visual attention. In M. I. Posner (Ed.), *Foundations of Cognitive Science* (pp. 631-682). Cambridge, MA: MIT Press.
- Allport, A. (1993). Attention and control: Have we been asking the wrong questions? A critical review of twenty-five years. In D. E. Meyer & S. Kornblum (Eds.), *Attention and Performance XIV*. Cambridge: MIT Press.
- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umiltá & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421-452). Cambridge, MA: MIT Press.
- Arguin, M., Bub, D. N., & Dudek, G. (1996). Shape integration for visual object recognition and its implication in category specific visual agnosia. *Visual Cognition*, 3, 221-275.
- Auriacombe, S., Grossman, M., Carvell, S., Gollomp, S., Stern, M. B., & Hurtig, H. I. (1993). Verbal fluency deficits in Parkinson's disease. *Neuropsychology*, 7, 182-192.
- Axelrod, B. N., & Henry, R. R. (1992). Age-related performance on the Wisconsin Card Sorting, Similarities, and Controlled Oral Word Association tests. *The Clinical Neuropsychologist*, 6, 16-26.
- Axelrod, B. N., Jiron, C. C., & Henry, R. R. (1993). Performance of adults ages 20 to 90 on the abbreviated Wisconsin Card Sorting Test. *The Clinical Neuropsychologist*, 7, 205-209.
- Baddeley, A. (1992). Working memory. *Science*, 255, 556-559.
- Baddeley, A. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Neuropsychology*, 49A, 5-28.
- Baddeley, A. (1998). The central executive: A concept and some misconceptions. *Journal of the International Neuropsychological Society*, 4, 523-526.
- Baddeley, A., & Della Sala, S. (1996). Working memory and executive control. *Philosophical Transactions of the Royal Society of London B*, 351, 1397-1404.
- Beatty, W. W., & Monson, N. (1990). Problem solving in Parkinson's disease: Comparison of performance on the Wisconsin and California card sorting tests. *Journal of Geriatric Psychiatry and Neurology*, 3, 163-171.

- Beatty, W. W., Monson, N., & Goodkin, D. E. (1989a). Access to semantic memory in Parkinson's disease and multiple sclerosis. *Journal of Geriatric Psychiatry and Neurology*, 2, 153-162.
- Beatty, W. W., Staton, R. D., Weir, W. S., Monson, N., & Whitaker, H. A. (1989b). Cognitive disturbances in Parkinson's disease. *Journal of Geriatric Psychiatry and Neurology*, 2, 22-33.
- Behrmann, M., & Tipper, S. P. (1994). Object-based attentional mechanisms: Evidence from Patients with Unilateral Neglect. In C. Umiltá & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 351-375). Cambridge, MA: MIT Press.
- Benton, A. L. (1968). Differential behavioral effects in frontal lobe disease. *Neuropsychologia*, 5, 53-60.
- Benton, A. L., Eslinger, P. J., & Damasio, A. R. (1981). Normative observations on neuropsychological test performances in old age. *Journal of Clinical Neuropsychology*, 3, 33-42.
- Besner, D., Stolz, J. A., & Boutilier, C. (1997). The Stroop effect and the myth of automaticity. *Psychonomic Bulletin & Review*, 2, 221-225.
- Bloxham, C. A., Mindel, T. A., & Frith, C. D. (1984). Initiation and execution of predictable and unpredictable movements in Parkinson's disease. *Brain*, 107, 1273-1279.
- Bolla, K. I., Lindgren, K. N., Bonaccorsy, C., & Bleeker, M. L. (1990). Predictors of verbal fluency in the healthy elderly. *Journal of Clinical Psychology*, 46, 623-628.
- Boone, K. B., Miller, B. L., & Lesser, I. M. (1993). Frontal lobe cognitive functions in aging: Methodological considerations. *Dementia*, 4, 232-236.
- Boone, K. B., Miller, B. L., Lesser, I. M., Hill, E., & D'Elia, L. (1990). Performance on frontal lobe tests in healthy, older individuals. *Developmental Neuropsychology*, 6, 215-223.
- Bowen, F. P., Kamienny, R. S., Burns, M. M., & Yahr, M. D. (1975). Parkinsonism: Effects of levodopa treatment on concept formation. *Neurology*, 25, 701-704.
- Brink, T. L., Yesavage, J. A., Lum, O., Heersema, P. H., Adey, M., & Rose, T. S. (1982). Screening tests for geriatric depression. *Clinical Gerontologist*, 1, 37-43.

- Brown, R. G., & Marsden, C. D. (1986). Visuospatial functions in Parkinson's Disease. *Brain*, *109*, 987-1002.
- Brown, R. G., & Marsden, C. D. (1987a). How common is dementia in Parkinson's disease? *Lancet*, *2*, 1262-1265.
- Brown, R. G., & Marsden, C. D. (1987b). Neuropsychology and cognitive function in Parkinson's disease: an overview. In C. D. Marsden & S. Fahn. (Eds.), *Movement Disorders 2* (pp. 99-123). London: Butterworths.
- Brown, R. G., & Marsden, C. D. (1988). Internal versus external cues and the control of attention in Parkinson's disease. *Brain*, *111*, 323-345.
- Brown, R. G., & Marsden, C. D. (1990). Cognitive function in Parkinson's disease: From description to theory. *Trends in Neuroscience*, *13*, 21-29.
- Brown, R. G., & Marsden, C. D. (1991). Dual task performance and processing resources in normal subjects and patients with Parkinson's disease. *Brain*, *114*, 215-231.
- Bub, D., & Gum, T. (1990). *Psychlab. McGill Technical Manuals*. Montreal: McGill University.
- Caltagirone, C., Carlesimo, A., Nocentini, U., & Vicari, S. (1989). Defective concept formation in Parkinsonians is independent from mental deterioration. *Journal of Neurology, Neurosurgery, and Psychiatry*, *52*, 334-337.
- Canavan, A. G. M., Passingham, R. E., Marsden, C. D., Quinn, N., Wyke, M., & Polkey, C. E. (1989). The performance on learning tasks of patients in the early stages of Parkinson's Disease. *Neuropsychologia*, *27*, 141-156.
- Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*, 332-361.
- Cohen, J. D., & Huston, T. A. (1994). Progress in the use of interactive models for understanding attention and performance. In C. Umiltá & M. Moscovitch (Eds.), *Attention and Performance XV* (pp. 453-476). Cambridge, MA: MIT Press.
- Cohen, J. D., Servan-Schreiber, D., & McClelland, J. L. (1992). A parallel distributed processing approach to automaticity. *American Journal of Psychology*, *105*, 239-269.

- Cohn, N. B., Dustman, R. E., & Bradford, D. C. (1984). Age-related decrements in Stroop color test performance. *Journal of Clinical Psychology, 40*, 1244-1250.
- Compton, B. J., & Park, D. C. (1998). *The locus of age-related task-switching costs*, Atlanta, GA.
- Cools, A. R., Van Den Bercken, J. H. L., Horstink, M. W. I., Van Spaendonck, K. P. M., & Berger, H. J. C. (1984). Cognitive and motor shifting aptitude disorder in Parkinson's disease. *Journal of Neurology, Neurosurgery, & Psychiatry, 47*, 443-453.
- Cummings, J. L. (1988). Intellectual impairment in Parkinson's disease: clinical, pathologic, and biochemical correlates. *Journal of Geriatric Psychiatry nad Neurology, 1*, 24-36.
- Cummings, J. L., & Benson, D. F. (1988). Psychological dysfunction accompanying subcortical dementias. *Annual Review of Medicine, 39*, 53-61.
- Daigneault, S., Braun, C. M. J., & Whitaker, H. A. (1992). Early effects of normal aging on perseverative and non-perseverative prefrontal measures. *Developmental Neuropsychology, 8*, 99-114.
- Dalrymple-Alford, J. C., Kalders, A. S., Jones, R. D., & Watson, R. W. (1994). A central executive deficit in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery, and Psychiatry, 57*, 360-367.
- Day, B. L., Dick, J. P. R., & Marsden, C. D. (1984). Patients with Parkinson's disease can employ a predictive motor strategy. *Journal of Neurology, Neurosurgery, and Psychiatry, 47*, 1299-1306.
- Dias, R., Robbins, T. W., & Roberts, A. C. (1996). Dissociation in prefrontal cortex of affective and attentional shifts. *Nature, 380*, 69-72.
- Dixon, M., Bub, D., & Arguin, M. (1997). The interaction of object form and object meaning in the identification performance of a patient with category specific visual agnosia. *Cognitive Neuropsychology, 14*, 1085-1130.
- Dixon, M., Bub, D., & Arguin, M. (1998). Visual and semantic determinants of face recognition in a prosopagnosic patient. *Journal of Cognitive Neuroscience, 10*, 362-376.
- Downes, J. J., Roberts, A. C., Sahakian, B. J., Evenden, J. L., Morris, R. G., & Robbins, T. W. (1989). Impaired extra-dimensional shift performance in medicated and unmedicated Parkinson's disease: Evidence for a specific attentional dysfunction. *Neuropsychologia, 27*(1329-1343).

- Downes, J. J., Sharp, H. M., Costall, B. M., Sagar, H. J., & Howe, J. (1993). Alternating fluency in Parkinson's disease. *Brain, 116*, 887-902.
- Dubois, B., Boller, F., Pillon, B., & Agid, Y. (1991). Cognitive deficits in Parkinson's disease. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology, Vol. 5*. Amsterdam: Elsevier Science Publishers.
- Dulaney, C. L., & Rogers, W. A. (1994). Mechanisms underlying reduction in Stroop interference with practice for young and old adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 470-484.
- Duncan, J. (1995). Attention, intelligence, and the frontal lobes. In M. S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (pp. 721-733). Cambridge, MA: The MIT Press.
- Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30*, 257-303.
- Dywan, J., Segalowitz, S. J., & Unsal, A. (1992). Speed of information processing, health, and cognitive performance in older adults. *Developmental Neuropsychology, 8*, 473-490.
- Evarts, E. V., Teräväinen, H., & Calne, D. B. (1981). Reaction time in Parkinson's disease. *Brain, 104*, 167-186.
- Faust, M. E., & Balota, D. A. (1997). Inhibition of return and visuospatial attention in healthy older adults and individuals with dementia of the Alzheimer type. *Neuropsychology, 11*, 13-29.
- Fimm, B., Bartl, G., Zimmermann, P., & Wallech, C.-W. (1994). Different mechanisms underlying shifting set on external and internal cues in Parkinson's disease. *Brain and Cognition, 25*, 287-304.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*, 189-198.
- Frith, C. D., & Done, D. J. (1986). Routes to action in reaction time tasks. *Psychological Research, 48*, 169-177.
- Gabrieli, J. D. E., Brewer, J. B., Desmond, J. E., & Glover, G. H. (1997). Separate neural bases of two fundamental memory processes in the human medial temporal lobe. *Science, 276*, 264-266.

- Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition*, 26, 263-276.
- Giesbrecht, B., & Kingstone, A. (1998). *Decoupling the costs of switching between objects and object-dimensions*. Paper presented at the Banff Annual Seminar in Cognitive Science, Banff, AB.
- Goel, V., & Grafman, J. (1995). Are the frontal lobes implicated in "planning" functions? Interpreting data from the Tower of Hanoi. *Neuropsychologia*, 33, 623-642.
- Goldenberg, G., Lang, W., Podreka, I., & Deecke, L. (1990). Are cognitive deficits in Parkinson's disease caused by frontal lobe dysfunction? *Journal of Psychophysiology*, 4, 137-144.
- Goldenberg, G., Podreka, I., Muller, C., & Deecke, L. (1989). The relationship between cognitive deficits and frontal lobe function in patients with Parkinson's disease: An emission computerized tomography study. *Behavioural Neurology*, 2, 79-87.
- Goodrich, S., Henderson, L., & Kennard, C. (1989). On the existence of an attention-demanding process peculiar to simple reaction time: Converging evidence from Parkinson's disease. *Cognitive Neuropsychology*, 6, 309-311.
- Gopher, D. (1996). Attentional control: Explorations of the work of an executive controller. *Cognitive Brain Research*, 5, 23-29.
- Gotham, A. M., Brown, R. G., & Marsden, C. D. (1988). "Frontal" cognitive function in patients with Parkinson's disease "on" and "off" levodopa. *Brain*, 111, 299-321.
- Graf, P., Uttl, B., & Tuokko, H. (1995). Color- and picture-word Stroop tests: Performance changes in old age. *Journal of Clinical and Experimental Neuropsychology*, 17, 390-415.
- Greve, K. W., Ingram, F., & Bianchini, K. J. (1998). Latent structure of the Wisconsin Card Sorting Test in a clinical sample. *Archives of Clinical Neuropsychology*, 13, 597-609.
- Hanley, J. R., Dewick, H. C., Davies, A. D. M., Playfer, J., & Turnbull, C. (1990). Verbal fluency in Parkinson's disease. *Neuropsychologia*, 28, 737-741.
- Hartley, A. A. (1993). Evidence for the selective preservation of Spatial Selective attention in old age. *Psychology and Aging*, 8, 371-379.

- Hartley, A. A., Kieley, J. M., & Slabach, E. H. (1990). Age differences and similarities in the effects of cues and prompts. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 523-538.
- Hayes, A. E., Davidson, M. C., Keele, S. W., & Rafal, R. D. (1998). Toward a functional analysis of the basal ganglia. *Journal of Cognitive Neuroscience*, *10*, 178-198.
- Heaton, R. K. (1981). *Wisconsin Card Sorting Test Manual*. Odessa, FLA: Psychological Assessment Resources.
- Henik, A., Singh, J., Beckley, D. J., & Rafal, R. D. (1993). Disinhibition of automatic word reading in Parkinson's disease. *Cortex*, *29*, 589-599.
- Hietanen, M., & Teräväinen, H. (1988). The effect of age of disease onset on neuropsychological performance in Parkinson's disease. *Journal of Neurology, Neurosurgery, and Psychiatry*, *51*, 244-249.
- Hochanadel, G., & Kaplan, E. (1984). Neuropsychology of normal aging. In M. Albert (Ed.), *Clinical Neurology of Aging* (pp. 231-244). New York: Oxford University Press.
- Houx, P. J., Jolles, J., & Vreeling, F. W. (1993). Stroop interference: Aging effects assessed with the Stroop color-word test. *Experimental Aging Research*, *19*, 209-224.
- Howard, D., & Franklin, S. (1988). *Missing the Meaning?: A Cognitive Neuropsychological Study of the Processing of Words by an Aphasic Patient*. Cambridge: MIT Press.
- Hsieh, S., & Allport, A. (1994). Shifting attention in a rapid visual search paradigm. *Perceptual and Motor Skills*, *79*, 315-335.
- Huber, S. J., Freidenberg, D. L., Shuttleworth, E. C., Paulson, G. W., & Christy, J. A. (1989). Neuropsychological impairments associated with severity of Parkinson's disease. *Journal of Neuropsychiatry and Clinical Neurosciences*, *1*, 154-158.
- Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, *89*.
- Jordan, M. I. (1986). An introduction to linear algebra in parallel distributed processing. In J. L. McClelland & D. E. Rumelhart (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition. Volume 1: Foundations*. (pp. 365-422). Cambridge: MIT Press.

- Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, *274*, 114-116.
- Kahneman, D., & Chajczyk, D. (1983). Tests of automaticity of reading: Dilution of Stroop effects by color-irrelevant stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, *9*, 497-509.
- Kahneman, D., & Henik, A. (1981). Perceptual organization and attention. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization*. Hillsdale: Erlbaum.
- Kahneman, D., & Treisman, A. (1984). Changing Views of Attention and Automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of Attention* (pp. 29-61). New York: Academic Press.
- Kahneman, D., & Treisman, A. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*, 175-219.
- Kim, C., & Myung, I. J. (1995). *Incorporating real-time effects in neural networks: A temporal summation mechanism*. Paper presented at the Seventeenth Annual Meeting of the Cognitive Science Society, Pittsburgh, PA.
- Kosslyn, S. M. (1988). Aspects of a cognitive neuroscience of mental imagery. *Science*, *240*, 1621-1626.
- Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging*, *9*, 491-512.
- Lange, K. W., Robbins, T. W., Marsden, C. D., James, M., Owen, A. M., & Paul, G. M. (1992). L-Dopa withdrawal in Parkinson's disease selectively impairs cognitive performance in tests sensitive to frontal lobe dysfunction. *Psychopharmacology*, *107*, 394-404.
- Lees, A. J., & Smith, E. (1983). Cognitive deficits in the early stages of Parkinson's disease. *Brain*, *106*, 257-270.
- Levin, B. E. (1990). Spatial cognition in Parkinson's disease. *Alzheimer's Disease and Associated Disorders*, *4*, 161-170.
- Lezak, M. D. (1995). *Neuropsychological Assessment (3rd ed.)*. New York: Oxford University Press.

- Lichter, D. G., Corbett, A. J., Fitzgibbon, G. M., Davidson, O. R., Hope, J. K. A., Goddard, G. V., Sharples, K. J., & Pollock, M. (1988). Cognitive and motor dysfunction in Parkinson's disease: Clinical, performance, and computed tomographic correlations. *Archives of Neurology*, *45*, 854-860.
- Lindsay, D. S., & Jacoby, L. L. (1994). Stroop process dissociations: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 219-234.
- Litvan, I., Mohr, E., Williams, J., Gomez, C., & Chase, T. N. (1991). Differential memory and executive functions in demented patients with Parkinson's and Alzheimer's disease. *Journal of Neurology, Neurosurgery, and Psychiatry*, *54*, 25-29.
- Logan, G. D. (1979). When it helps to be misled: Facilitative effect of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*, *7*, 166-174.
- Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, *12*, 523-553.
- Logan, G. D. (1985). Executive control of thought and action. *Acta Psychologica*, *60*, 193-210.
- Logan, G. D., Zbrodoff, N. J., & Fostey, A. R. W. (1983). Costs and benefits of strategy construction in a speeded discrimination task. *Memory & Cognition*, *11*, 485-493.
- Logan, G. D., Zbrodoff, N. J., & Williamson, J. (1984). Strategies in the color-word Stroop task. *Bulletin of the Psychonomic Society*, *22*, 135-138.
- Lorch, R. F., & Myers, J. L. (1990). Regression analyses of repeated measures data in cognitive research. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *16*, 149-157.
- Lund-Johansen, M., Hugdahl, K., & Wester, K. (1996). Cognitive function in patients with Parkinson's disease undergoing stereotaxic thalamotomy. *Journal of Neurology, Neurosurgery, and Psychiatry*, *60*, 564-571.
- MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163-203.
- MacLeod, C. M. (1998). Training on integrated versus separated Stroop tasks: The progression of interference and facilitation. *Memory & Cognition*, *26*, 201-211.

- MacLeod, C. M., & Dunbar, K. (1988). Training and Stroop-like interference: Evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *14*, 126-135.
- Malapani, C., Pillon, B., Dubois, B., & Agid, Y. (1994). Impaired simultaneous cognitive task performance in Parkinson's disease: A dopamine-related dysfunction. *Neurology*, *44*, 319-326.
- Matison, R., Mayeux, R., Rosen, J., & Fahn, S. (1982). "Tip-of-the-tongue" phenomenon in Parkinson's disease. *Neurology*, *32*, 567-570.
- McDowd, J. M., & Birren, J. E. (1990). Aging and attentional processes. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the Psychology of Aging, Third Edition* (pp. 222-233). San Diego, CA: Academic Press.
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *22*, 1423-1442.
- Meyer, D. E., Evans, J. E., Lauber, E. J., Gmeindl, L., Rubinstein, J., Lunck, L., & Koeppel, A. (1998). *The role of dorsolateral prefrontal cortex for executive cognitive processes in task switching*. Paper presented at the Fifth Annual Meeting of the Cognitive Neuroscience Society, San Francisco, CA.
- Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*, 749-791.
- Miller, E. (1985). Possible frontal impairments in Parkinson's disease: A test using a measure of verbal fluency. *British Journal of Clinical Psychology*, *24*, 211-212.
- Milliken, B., Joordens, S., Merikle, P. M., & Seiffert, A. (1998). Selective attention: A reevaluation of the implications of negative priming. *Psychological Review*, *105*, 203-229.
- Milner, B. (1963). Effects of different brain lesions on card sorting. *Archives of Neurology*, *9*, 90-100.
- Mittenberg, W., Seidenberg, M., O'Leary, D. S., & Di Giulio, D. V. (1989). Changes in cerebral functioning associated with normal aging. *Journal of Clinical and Experimental Neuropsychology*, *11*, 918-932.

- Mohr, E., Juncos, J., Cox, C., Litvan, I., Fedio, P., & Chase, T. N. (1990). Selective deficits in cognition and memory in high-functioning Parkinsonian patients. *Journal of Neurology, Neurosurgery, and Psychiatry*, *53*, 603-606.
- Monsell, S. (1996). Control of Mental Processes. In V. Bruce (Ed.), *Unsolved Mysteries of the Mind: Tutorial Essays in Cognition* (pp. 93-143). Hove: Erlbaum.
- Morris, R. G., Downes, J. J., Sahakian, B., Evenden, J. L., Heald, A., & Robbins, T. W. (1988). Planning and spatial working memory in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry*, *51*, 757-766.
- Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General*, *106*, 226-254.
- Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (pp. 1-18). New York: Plenum.
- Owen, A. M., James, M., Leigh, P. N., Summers, B. A., Marsden, C. D., Quinn, N. P., Lange, K. W., and , & Robbins, T. W. (1992). Fronto-striatal cognitive deficits at different stages of Parkinson's disease. *Brain*, *115*, 1727-1751.
- Owen, A. M., Roberts, A. C., Hodges, J. R., Summers, B. A., Polkey, C. E., & Robbins, T. W. (1993). Contrasting mechanisms of impaired attentional set-shifting in patients with frontal lobe damage or Parkinson's disease. *Brain*, *116*, 1159-1179.
- Owen, A. M., Roberts, A. C., Polkey, C. E., Sahakian, B. J., & Robbins, T. W. (1991). Extra-dimensional versus intra-dimensional set shifting performance following frontal lobe excisions, temporal lobe excisions or amygdalo-hippocampectomy in man. *Neuropsychologia*, *29*, 993-1006.
- Paolo, A. M., Tröster, A. I., Axelrod, B. N., & Koller, W. C. (1995). Construct validity of the WCST in normal elderly and persons with Parkinson's disease. *Archives of Clinical Neuropsychology*, *10*, 463-473.
- Parkin, A. J. (1998). The central executive does not exist. *Journal of the International Neuropsychological Society*, *4*, 518-522.
- Pashler, H. (1992a). Attentional limitations in doing two tasks at the same time. *Current Directions in Psychological Science*, *1*, 44-48.

- Pashler, H. (1992b). Dual-task interference and elementary mental mechanisms. In D. E. Meyer & S. Kornblum (Eds.), *Attention and Performance XIV*. Cambridge, MA: MIT Press.
- Pashler, H. (1994). Overlapping mental operations in serial performance with preview. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *47A*, 161-191.
- Pedhazur, E. J. (1982). *Multiple Regression in Behavioral Research: Explanation and Prediction*. Toronto: Holt, Rinehart and Winston.
- Penny, J. B., & Young, A. B. (1983). Speculations on the functional anatomy of basal ganglia disorders. *Annual Review of Neuroscience*, *6*, 73-94.
- Penny, J. B., & Young, A. B. (1986). Striatal inhomogeneities and basal ganglia function. *Movement Disorders*, *1*, 3-15.
- Perret, E. (1974). The left frontal lobe of man and the suppression of habitual responses in verbal categorical behavior. *Neuropsychologia*, *12*, 323-330.
- Pinker, S. (1991). Rules of language. *Science*, *253*, 530-535.
- Plaut, D. C., & Shallice, T. (1994). *Connectionist modelling in cognitive neuropsychology: A case study*. Hillsdale: Erlbaum.
- Portin, R., & Rinne, U. K. (1980). Neuropsychological responses of Parkinsonian patients to long-term levodopa treatment. In U. K. Rinne, M. Klinger, & G. Stamm (Eds.), *Parkinson's disease - Current progress, problems and management* (pp. 271-304). Amsterdam: Elsevier.
- Posner, M. I., Abdullaev, Y. G., McCandliss, B. D., & Sereno, S. C. (in press). Anatomy, circuitry and plasticity of word reading. In J. Everatt (Ed.), *Visual and attentional processes in reading and dyslexia*.
- Posner, M. I., & DiGirolamo, G. J. (in press). Conflict, target detection and cognitive control. In R. Parasuraman (Ed.), *The Attentive Brain*. Cambridge: MIT Press.
- Posner, M. I., Petersen, S. E., Fox, P. T., & Raichle, M. E. (1988). Localization of cognitive operations in the human brain. *Science*, *240*, 1627-1631.
- Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information Processing and Cognition: The Loyola Symposium*. Hillsdale, N. J.: Erlbaum.

- Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 979-992.
- Pullman, S. L., Watts, R. L., Juncos, A. L., Chase, T. N., & Sanes, J. N. (1988). Dopaminergic effects on simple and choice reaction time performance in Parkinson's disease. *Neurology*, *38*, 249-254.
- Rafal, R. D., Posner, M. I., Walker, J. A., & Friedrich, F. J. (1984). Cognition and the basal ganglia. *Brain*, *107*, 1083-1094.
- Rajput, A. H. (1991). Epidemiology and etiology of Parkinson syndrome, *National Conference on Parkinson's Disease - Programs and Abstracts - Guidelines for the 90s*. (pp. 2): The Medicine Group.
- Randolph, C., Braun, A. R., Goldberg, T. E., & Chase, T. N. (1993). Semantic fluency in Alzheimer's, Parkinson's, and Huntington's disease: Dissociation of storage and retrieval failures. *Neuropsychology*, *7*, 82-88.
- Raskin, S. A., Borod, J. C., & Tweedy, J. (1990). Neuropsychological aspects of Parkinson's disease. *Neuropsychology Review*, *1*, 185-221.
- Raskin, S. A., Sliwinski, M., & Borod, J. C. (1992). Clustering strategies on tasks of verbal fluency in Parkinson's disease. *Neuropsychologia*, *30*, 95-99.
- Richards, M., Cote, L. J., & Stern, Y. (1993). Executive function in Parkinson's disease: Set-shifting or set-maintenance? *Journal of Clinical and Experimental Neuropsychology*, *15*, 266-279.
- Richer, F., Decary, A., Lapierre, M.-F., & Rouleau, I. (1993). Target detection deficits in frontal lobectomy. *Brain and Cognition*, *21*, 203-211.
- Riekkinen, P. J., Kejonen, K., Laakso, M. P., Soininen, H., Partanen, K., & Riekkinen, M. (1998). Hippocampal atrophy is related to impaired memory, but not frontal functions in non-demented Parkinson's disease patients. *Neuroreport: An International Journal for the Rapid Communication of Research in Neuroscience*, *9*, 1507-1511.
- Robbins, T. (1996). Dissociating executive functions of the prefrontal cortex. *Philosophical Transactions of the Royal Society of London B*, *351*, 1463-1471.

- Robbins, T. W., James, M., Owen, A. M., Sahakian, B. J., Lawrence, A. D., McInnes, L., & Rabbitt, P. (1998). A study of performance on tests from the CANTAB battery sensitive to frontal lobe dysfunction in a large sample of normal volunteers: Implications for theories of executive functioning and cognitive aging. *Journal of the International Neuropsychological Society*, *4*, 474-490.
- Roberts, R. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, *12*, 105-126.
- Robertson, C., Hazlewood, R., & Rawson, M. D. (1996). The effects of Parkinson's disease on the capacity to generate information randomly. *Neuropsychologia*, *34*, 1069-1078.
- Robertson, L. C., Lamb, M. R., & Knight, R. T. (1988). Effects of lesions of temporal-parietal junction on perceptual and attentional processing in humans. *The Journal of Neuroscience*, *8*, 3757-3769.
- Robinson, A. L., Heaton, R. K., Lehman, R. A. W., & Stilson, D. W. (1980). The utility of the Wisconsin Card Sorting Test in detecting and localizing frontal lobe lesions. *Journal of Consulting and Clinical Psychology*, *48*(605-614).
- Rogers, R. D., & Monsell, S. (1995). Costs of a Predictable Switch Between Simple Cognitive Tasks. *Journal of Experimental Psychology: General*, *124*, 207-231.
- Rogers, R. D., Sahakian, B. J., Hodges, J. R., Polkey, C. E., Kennard, C., & Robbins, T. W. (1998). Dissociating executive mechanisms of task control following frontal lobe damage and Parkinson's disease. *Brain*, *121*, 815-842.
- Salthouse, T. A., Fristoe, N., McGuthry, K. E., & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychology and Aging*, *13*, 445-461.
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and Automatic Information Processing: I. Detection, Search, and Attention. *Psychological Review*, *84*, 1-66.
- Seidenberg, M. S. (1997). Language acquisition and use: Learning and applying probabilistic constraints. *Science*, *275*, 1599-1603.
- Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.

- Shallice, T. (1994). Multiple levels of control processes. In C. Umiltá & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 395-420). Cambridge, MA: MIT Press.
- Shallice, T., & Burgess, P. (1993). Supervisory control of action and thought selection. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness, and control: A tribute to Donald Broadbent* (pp. 171-187). New York: Oxford University Press.
- Shallice, T., & Burgess, P. (1996). The domain of supervisory processes and temporal organization of behaviour. *Philosophical Transactions of the Royal Society of London B*, *351*, 1405-1412.
- Sharpe, M. H. (1990). Distractability in early Parkinson's disease. *Cortex*, *26*, 239-246.
- Sharpe, M. H. (1992). Auditory attention in early Parkinson's disease: An impairment in focussed attention. *Neuropsychologia*, *30*, 101-106.
- Sharpe, M. H. (1996). Is there a divided attention deficit in patients with early Parkinson's Disease? *Cortex*, *32*, 747-753.
- Sheriden, M. R., Flowers, K. A., & Hurell, J. (1987). Programming and execution of movement in Parkinson's disease. *Brain*, *110*, 1247-1271.
- Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review*, *84*, 127-190.
- Spector, A., & Biederman, B. (1976). Mental set and mental shift revisited. *American Journal of Psychology*, *89*, 669-679.
- Spreen, O., & Strauss, E. (1997). *A compendium of neuropsychological tests: Administration, norms, and commentary*. (2nd ed.). New York: Oxford University Press.
- St. Clair, J., Borod, J. C., Sliwinski, M., Cote, L. J., & Stern, Y. (1998). Cognitive and affective functioning in Parkinson's disease patients with lateralized motor signs. *Journal of Clinical and Experimental Neuropsychology*, *20*, 320-327.
- Stablum, F., Leonardi, G., Mazzoldi, M., Umiltá, C., & Morra, S. (1994). Attention and control deficits following closed head injury. *Cortex*, *30*, 603-618.

- Stam, C. J., Visser, S. L., Op de Coul, A. A. W., De Sonnevile, L. M. J., Schellens, R. L. L. A., Brunia, C. H. M., de Smet, J. S., & Gielen, G. (1993). Disturbed frontal regulation of attention in Parkinson's disease. *Brain, 116*, 1139-1158.
- Starkstein, S. E., Bolduc, P. L., Mayberg, H. S., Preziosi, T. J., & Robinson, R. G. (1990). Cognitive impairments and depression in Parkinson's disease: A follow up study. *Journal of Neurology, Neurosurgery, and Psychiatry, 53*, 597-602.
- Starkstein, S. E., Bolduc, P. L., Preziosi, T. J., & Robinson, R. G. (1989). Cognitive impairments in different stages of Parkinson's disease. *Journal of Neuropsychiatry and Clinical Neurosciences, 1*, 243-248.
- Starkstein, S. S., Leiguarda, R., Gershanik, O., & Berthier, M. (1987). Neuropsychological disturbances in hemiparkinson's disease. *Neurology, 37*, 1762-1764.
- Strayer, D. L., & Kramer, A. F. (1994a). Strategies and automaticity: I. Basic findings and conceptual framework. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 318-341.
- Strayer, D. L., & Kramer, A. F. (1994b). Strategies and automaticity: II. Dynamic aspects of strategy adjustment. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 342-365.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-661.
- Taylor, A. E., Saint-Cyr, J. A., & Lang, A. E. (1986). Frontal lobe dysfunction in Parkinson's disease: The cortical focus of neo-striatal outflow. *Brain, 109*, 845-883.
- Tipper, S. P., & Bermann, M. (1996). Object-centered not scene-based visual neglect. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1261-1278.
- Trainham, T. N., Lindsay, D. S., & Jacoby, L. L. (1997). Stroop process dissociations: Reply to Hillstrom and Logan (1997). *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1579-1587.
- Treisman, A. (1986). Properties, parts, and objects. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance, Vol. 2: Cognitive processes and performance*. (pp. 1-70). New York: John Wiley & Sons.

- Treisman, M., & Williams, T. C. (1984). A theory of criteria setting with an application to sequential dependencies. *Psychological Review*, *91*, 68-111.
- Tröster, A. I., Fields, J. A., Testa, J. A., Paul, R. H., Blanco, C. R., Hames, K. A., Salmon, D. P., & Beatty, W. W. (1998). Cortical and subcortical influences on clustering and switching in the performance of verbal fluency tasks. *Neuropsychologia*, *36*, 295-304.
- Troyer, A. K., Moscovitch, M., & Winocur, G. (1997a). Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology*, *11*, 138-146.
- Troyer, A. K., Moscovitch, M., & Winocur, G. (1997b). The effect of focal frontal- and temporal-lobe lesions on verbal fluency clustering and switching. *Journal of the International Neuropsychological Society*, *3*, 37.
- Troyer, A. K., Moscovitch, M., Winocur, G., Alexander, M. P., & Stuss, D. (1998a). Clustering and switching on verbal fluency: The effects of focal frontal- and temporal-lobe lesions. *Neuropsychologia*, *36*, 499-504.
- Troyer, A. K., Moscovitch, M., Winocur, G., Leach, L., & Freedman, M. (1998b). Clustering and switching on verbal fluency tests in Alzheimer's and Parkinson's disease. *Journal of the International Neuropsychological Society*, *4*, 137-143.
- Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science*, *247*, 301-306.
- Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling the Stroop effects by manipulating expectations for color words. *Memory and Cognition*, *20*, 727-735.
- Umiltá, C., Nicoletti, R., Simion, F., Tagliabue, M. E., & Bagnara, S. (1992a). The cost of a strategy. *European Journal of Cognitive Psychology*, *4*, 21-40.
- Uttl, B., & Graf, P. (1997). Color-word Stroop test performance across the adult life span. *Journal of Clinical and Experimental Neuropsychology*, *19*, 405-420.
- Vendrell, P., Junque, C., Pujol, J., & Jurado, M. A. (1995). The role of prefrontal regions in the Stroop task. *Neuropsychologia*, *33*, 341-352.
- Veroff, A. E. (1980). The neuropsychology of aging: Qualitative analysis of visual reproductions. *Psychological Research*, *41*, 259-268.

- Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (in press). Attentional switching in spatial and non-spatial domains: Evidence from the attentional blink. *Psychological Bulletin*.
- Ward, R., & Goodrich, S. (1996). Differences between objects and nonobjects in visual extinction: A competition for attention. *Psychological Sciences*, 7, 177-180.
- Weingartner, H., Burns, S., Diebel, R., & Lewitt, P. A. (1984). Cognitive impairments in Parkinson's disease: Distinguishing between effort-demanding and automatic cognitive processes. *Psychiatry Research*, 11, 223-235.
- Wertman, E., Speedie, L., Shemesh, Z., Gilon, D., Raphael, M., & Stessman, J. (1993). Cognitive disturbances in Parkinsonian patients with depression. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology*, 6, 31-37.
- West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, 120, 272-292.
- Whelihan, W. M., & Lesher, E. L. (1985). Neuropsychological changes in frontal functions with aging. *Developmental Neuropsychology*, 1, 371-380.
- Woodward, T. S., Dixon, M. J., Mullen, K. T., Christensen, K. M., & Bub, D. N. (1999). Analysis of errors in color agnosia: A single-case study. *Neurocase*, 5, 95-108.
- Youngjohn, J. R., Beck, J., Jogerst, G., & Caine, C. (1992). Neuropsychological impairment, depression, and Parkinson's disease. *Neuropsychology*, 6, 149-158.
- Zbrodoff, N. J., & Logan, G. D. (1986). On the autonomy of mental processes: A case study of arithmetic. *Journal of Experimental Psychology: General*, 115, 118-130.

Table 1

Effects that may have been present for the second position word-reading RTs of the control (**WiWi**) and experimental (**CiWi**) conditions of Experiments 1a and 1b. Note that all four contrast across the **CiWi** - **WiWi** comparison.

	Task Repetition Benefit (list-wise and position-wise)	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost
WiWi	Yes	No	No	No
CiWi	No	Yes	Yes	Yes

Table 2

Effects that are present for the second position word-reading RTs of the control (**CnWi**) and experimental (**CiWi**) conditions of the proposed methodology. Note that only DTS contrasts across the **CiWi** - **CnWi** comparison.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost
CnWi	No	Yes	Yes	No
CiWi	No	Yes	Yes	Yes

Table 3

Effects that may have been present for the first position word-reading RTs of the control (**WiWi**) and experimental (**WiCi**) conditions of Experiments 1a and 1b. Note that five of the six contrast across the **WiCi** - **WiWi** comparison.

	Task Repetition Benefit (list-wise)	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost (carry-over)	Anticipation of an EDS	Cost Associated with First Position
WiWi	Yes	No	No	No	No	Yes
WiCi	No	Yes	Yes	Yes	Yes	Yes

Table 4

Effects that may be present for the third position word-reading RTs of the control (**WiCnWi**) and experimental (**WiCiWi**) conditions of Experiment 2a.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost
WiCnWi	No	Yes	Yes	No
WiCiWi	No	Yes	Yes	Yes

Table 5

Effects that may be present for the first position word-reading RTs of the control (WiCnWi) and experimental (WiCiWi) conditions of Experiment 2a.

	Task Repetition Benefit (carry-over)	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost	Anticipation of an EDS	Cost Associated with First Position
<u>WiCnWi</u>	Yes	Yes	No	No	No	Yes
<u>WiCiWi</u>	Yes	Yes	No	No	Yes	Yes

Table 6

Effects that may be present for the second position color-naming RTs of the control (CiCi) and experimental (WiCi) conditions of Experiments 1a and 1b. Note that all five contrast across the WiCi - CiCi comparison.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost	Anticipation of an EDS
<u>CiCi</u>	Yes	No	No	No	No
<u>WiCi</u>	No	Yes	Yes	Yes	Yes

Table 7

Effects that may be present for the first position color-naming RTs of the control (CiCi) and experimental (CiWi) conditions of Experiments 1a and 1b. Note that five of the six contrast across the CiWi - CiCi comparison.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost	Anticipation of an EDS	Cost Associated with First Position
<u>CiCi</u>	Yes	No	No	No	No	Yes
<u>CiWi</u>	No	Yes	Yes	Yes	Yes	Yes

Table 8

Effects that may be present for the third position color-naming RTs of the control (CiWnCi) and experimental (CiWiCi) conditions of Experiment 2b, random condition.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost	Anticipation of an EDS
<u>CiWnCi</u>	No	Yes	Yes	No	Yes
<u>CiWiCi</u>	No	Yes	Yes	Yes	Yes

Table 9

Effects that may contrast across the first position color-naming RTs of the control (**CiWnCi**) and experimental (**CiWiCi**) conditions of Experiment 2b, blocked condition.

	Task Repetition Benefit	Dual Task-set Cost	Switch Costs over and above DTS	DTS Cost	Anticipation of an EDS	Cost Associated with First Position
CiWnCi	Yes	Yes	No	No	No	Yes
CiWiCi	Yes	Yes	No	No	Yes	Yes

Table 10

Word-reading RT means, standard deviations, and percentage errors (out of 1155 responses; Experiment 3).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
CiWi	650.76	107.74	1.42	0.09	1.90
WiCi	691.94	121.17	1.34	0.09	1.90
CiWn	566.23	65.33	0.35	0	1.82
WnCi	598.01	58.32	0.09	0	1.04
CnWi	560.25	70.87	0.52	0.09	1.21
WiCn	611.94	88.28	0.43	0	0.95
CnWn	515.65	53.87	0.09	0	1.13
WnCn	562.03	52.03	0	0.09	1.13

Table 11

Word-reading effects associated with various switching conditions.

	SHIFT	MODERATE	SHFxMOD
CiWi	Yes	Yes	Yes
WiCi	Yes	Yes	Yes
CiWn	No	Yes	No
WnCi	No	Yes	No
CnWi	Yes	No	No
WiCn	Yes	No	No
CnWn	No	No	No
WnCn	No	No	No

Table 12

Reverse Stroop effect. Effects contrasting across switching conditions (position one).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
WiCi – WnCn	SHIFT & MODERATE & SHFxMOD	130 ms
WiCi – WnCi	SHIFT & SHFxMOD	94 ms
WiCn – WnCn	SHIFT	50 ms

Table 13

Reverse Stroop effect. Effects contrasting across switching conditions (position two).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
CiWi – CnWn	SHIFT & MODERATE & SHFxMOD	135 ms
CiWi – CiWn	SHIFT & SHFxMOD	85 ms
CnWi – CnWn	SHIFT	45 ms

Table 14

Word-reading effects contrasting across switching conditions (context effects, position one).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
WiCi – WiCn	MODERATE & SHFxMOD	80 ms
WnCi – WnCn	MODERATE	36 ms

Table 15

Word-reading effects contrasting across switching conditions (context effects, position two).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
CiWi – CnWi	MODERATE & SHFxMOD	91 ms
CiWn – CnWn	MODERATE	51 ms

Table 16

Word-reading order effects. Effects contrasting across switching conditions.

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
WiCi – CiWi	FIRST	41
WiCn – CnWi	FIRST	52
WnCi – CiWn	FIRST	32
WnCn – CnWn	FIRST	46

Table 17

All word reading costs derived from manual partialling.

	SHIFT	MODERATE	SHFxMOD	FIRST	MODx1st	SHFx1st	3-WAY
WiCi	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CiWi	Yes	Yes	Yes	No	No	No	No
WiCn	Yes	No	No	Yes	No	Yes	No
CnWi	Yes	No	No	No	No	No	No
WnCi	No	Yes	No	Yes	Yes	No	No
CiWn	No	Yes	No	No	No	No	No
WnCn	No	No	No	Yes	No	No	No
CnWn	No	No	No	No	No	No	No

Table 18

Effects partialled out in regression analysis (word reading, Experiment 3).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT	SHF×MOD
MODERATE	SHF×MOD
FIRST	
SHF×MOD	SHIFT, MODERATE, SHF×1st, MOD×1st
MOD×1st	MODERATE, FIRST, SHF×MOD, SHF×1st
SHF×1st	SHIFT, MODERATE, FIRST, SHF×MOD, MOD×1st
3-WAY	SHIFT, MODERATE, FIRST, SHF×MOD, SHF×1st, MOD×1st

Table 19

Correlations between contrast vectors.

	3-WAY	SHIFT	MODERATE	SHF×MOD	SHF×1st	MOD×1st	FIRST
3-WAY	1						
SHIFT	0.38	1					
MODERATE	0.38	0	1				
SHF×MOD	0.65	0.58	0.58	1			
SHF×1st	0.65	0.58	0	0.33	1		
MOD×1st	0.65	0	0.58	0.33	0.33	1	
FIRST	0.38	0	0	0	0.58	0.58	1

Table 20

Color-naming RT means, standard deviations, and error percentages (out of 1155 responses; Experiment 3).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
<u>Ci</u> Wi	907.77	101.54	2.60	0.43	1.39
Wi <u>Ci</u>	821.14	96.91	2.68	0.78	1.47
<u>Ci</u> Wn	851.63	95.16	2.60	0.69	1.56
Wn <u>Ci</u>	784.16	78.76	2.08	0.43	1.04
<u>Cn</u> Wi	699.02	60.05	0	0.61	0.87
Wi <u>Cn</u>	654.16	64.20	0	0.43	0.95
<u>Cn</u> Wn	670.09	59.78	0	0.69	0.43
Wn <u>Cn</u>	646.51	65.94	0	0.87	0.78

Table 21

Color-naming costs associated with various switching conditions.

	MODERATE	SHIFT/Stroop	SHFxMOD
CiWi	Yes	Yes	Yes
WiCi	Yes	Yes	Yes
CiWn	No	Yes	No
WnCi	No	Yes	No
CnWi	Yes	No	No
WiCn	Yes	No	No
CnWn	No	No	No
WnCn	No	No	No

Table 22

Stroop effects. Activation threshold operations contrasting across switching conditions (between-ambiguity comparisons, position one).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
CiWi - CnWn	SHIFT/Stroop & MODERATE & SHFxMOD	238 ms
CiWi - CnWi	SHIFT/Stroop & SHFxMOD	209 ms
CiWn - CnWn	SHIFT/Stroop	182 ms

Table 23

Stroop effects. Activation threshold operations contrasting across switching conditions (between-ambiguity comparisons, position two).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
WiCi - WnCn	SHIFT/Stroop & MODERATE & SHFxMOD	175 ms
WiCi - WiCn	SHIFT/Stroop & SHFxMOD	167 ms
WnCi - WnCn	SHIFT/Stroop	138 ms

Table 24

Activation threshold operations contrasting across switching conditions (context effects, position one).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
CiWi - CiWn	MODERATE & SHFxMOD	56 ms
CnWi - CnWn	MODERATE	29 ms

Table 25

Operations contrasting across switching conditions (context effects, position two).

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
WiCi - WnCi	MODERATE & SHFxMOD	37 ms
WiCn - WnCn	MODERATE	8 ms

Table 26

Color-naming order effects. Activation threshold operations contrasting across switching conditions.

	<i>Contrasted Cost Producing Operations</i>	<i>RT Difference</i>
CiWi - WiCi	FIRST	87
CiWn - WnCi	FIRST	45
CnWi - WiCn	FIRST	67
CnWn - WnCn	FIRST	24

Table 27

All color naming costs derived through manual partialling.

	MODERATE	SHIFT/ Stroop	FIRST	SHFxMOD	MODx1st	SHFx1st	3-WAY
CiWi	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WiCi	Yes	Yes	No	Yes	No	No	No
CiWn	No	Yes	Yes	No	No	Yes	No
WnCi	No	Yes	No	No	No	No	No
CnWi	Yes	No	Yes	No	Yes	No	No
WiCn	Yes	No	No	No	No	No	No
CnWn	No	No	Yes	No	No	No	No
WnCn	No	No	No	No	No	No	No

Table 28

Effects partialled out in regression analysis (color naming, Experiment 3).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT/Stroop	SHFxMOD, SHFx1st
MODERATE	SHFxMOD, MODx1st
FIRST	SHFx1st, MODx1st
SHFxMOD	SHIFT/Stroop, MODERATE, SHFx1st, MODx1st
MODx1st	MODERATE, FIRST, SHFxMOD, SHFx1st
SHFx1st	SHIFT/Stroop, FIRST, SHFxMOD, MODx1st
3-WAY	SHIFT/Stroop, MODERATE, FIRST, SHFxMOD, SHFx1st, MODx1st

Table 29

Word-reading RT means, standard deviations, and percentage errors (out of 455 responses; Experiment 7).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
CiWi	707.23	78.62	1.32	0	2.20
WiCi	802.52	98.80	1.10	0	1.32
CiWn	642.96	65.73	0	0.66	2.64
WnCi	732.09	106.86	0	0	1.32
CnWi	644.88	76.24	0.22	0	1.54
WiCn	726.51	99.46	0	0.22	1.10
CnWn	605.55	76.46	0	0	2.42
WnCn	662.46	86.78	0.22	0	2.20

Table 30

Effects partialled out in regression analysis (word reading, Experiment 7).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT	
MODERATE	
FIRST	
SHFxMOD	SHIFT, MODERATE, MODx1st, SHFx1st
MODx1st	MODERATE, FIRST, SHFxMOD, SHFx1st
SHFx1st	SHIFT, FIRST, SHFxMOD, MODx1st
3-WAY	SHIFT, MODERATE, FIRST, SHFxMOD, SHFx1st, MODx1st

Table 31

Color-naming RT means, standard deviations, and error percentages (out of 455 responses; Experiment 7).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
CiWi	893.11	87.23	1.76	0	1.10
WiCi	811.73	83.50	1.54	0	2.20
CiWn	844.73	89.16	1.54	0.22	1.76
WnCi	789.77	80.82	1.98	0.22	2.64
CnWi	734.09	70.12	0	0.22	1.54
WiCn	720.28	81.70	0	0.67	1.98
CnWn	737.95	77.31	0	0	1.54
WnCn	718.91	90.60	0	0.22	2.86

Table 32

Effects partialled out in regression analysis (color naming, Experiment 7).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT/Stroop	SHF _x MOD, SHF _x 1st,
MODERATE	SHF _x MOD
FIRST	SHF _x 1st
SHF _x MOD	SHIFT/Stroop, MODERATE, SHF _x 1st, MOD _x 1st
MOD _x 1st	MODERATE, FIRST, SHF _x MOD
SHF _x 1st	SHIFT/Stroop, FIRST, SHF _x MOD, MOD _x 1st
3-WAY	SHIFT/Stroop, MODERATE, FIRST, SHF _x MOD, SHF _x 1st, MOD _x 1st

Table 33

Word-reading RT means, standard deviations, and percentage errors (out of 1156 responses; PD).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
CiWi	1122.96	377.43	5.71	0.17	5.28
WiCi	1104.52	380.98	2.60	0	2.34
CiWn	901.56	267.98	0.17	0.09	5.88
WnCi	915.45	278.32	0	0	1.99
CnWi	920.35	356.57	1.82	0	3.20
WiCn	938.05	414.01	1.38	0	2.16
CnWn	793.16	268.97	0.18	0	1.69
WnCn	786.25	216.36	0.09	0	1.21

Table 34

Effects partialled out in regression analysis (word reading; PD).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT	SHF _x MOD
MODERATE	SHF _x MOD
FIRST	
SHF _x MOD	SHIFT, MODERATE, SHF _x 1st, MOD _x 1st
MOD _x 1st	MODERATE, FIRST, SHF _x MOD, SHF _x 1st
SHF _x 1st	SHIFT, FIRST, SHF _x MOD, MOD _x 1st
3-WAY	SHIFT, MODERATE, FIRST, SHF _x MOD, SHF _x 1st, MOD _x 1st

Table 35

Color-naming RT means, standard deviations, and error percentages (out of 1155 responses; PD).

	Mean RT	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
<u>CiWi</u>	1532.64	490.31	5.80	0.43	5.54
<u>WiCi</u>	1292.39	364.63	6.49	1.04	4.67
<u>CiWn</u>	1386.90	501.21	7.35	0.35	3.89
<u>WnCi</u>	1269.20	318.35	5.19	0.52	3.55
<u>CnWi</u>	1035.01	321.51	0.09	0.78	2.60
<u>WiCn</u>	978.47	235.45	0	1.47	2.68
<u>CnWn</u>	939.57	206.94	0.36	0	0.80
<u>WnCn</u>	915.78	182.58	0.09	0.69	1.56

Table 36

Effects partialled out in regression analysis (color naming; PD).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT/Stroop	SHF×1st
MODERATE	MOD×1st
FIRST	SHF×1st, MOD×1st
SHF×MOD	SHIFT/Stroop, MODERATE, SHF×1st, MOD×1st
MOD×1st	MODERATE, FIRST, SHF×MOD, SHF×1st
SHF×1st	SHIFT/Stroop, FIRST, SHF×MOD, MOD×1st
3-WAY	SHIFT/Stroop, MODERATE, FIRST, SHF×MOD, SHF×1st, MOD×1st

Table 37

Word-reading RT means, standard deviations, and percentage errors (out of 1156 responses; NE).

	<i>Mean RT</i>	<i>SD</i>	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
<u>CiWi</u>	947.07	223.88	3.03	0	5.80
<u>WiCi</u>	998.63	263.42	1.82	0	3.89
<u>CiWn</u>	780.03	140.71	0	0	3.55
<u>WnCi</u>	786.63	140.48	0.09	0	1.47
<u>CnWi</u>	748.12	165.62	0.95	0	2.77
<u>WiCn</u>	825.20	182.51	1.04	0	2.08
<u>CnWn</u>	643.25	104.04	0.09	0	1.30
<u>WnCn</u>	682.42	103.99	0	0	0.95

Table 38

Effects partialled out in regression analysis (word reading; NE).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT	SHF×MOD
MODERATE	SHF×MOD
FIRST	
SHF×MOD	SHIFT, MODERATE, SHF×1st, MOD×1st
MOD×1st	MODERATE, FIRST, SHF×MOD, SHF×1st
SHF×1st	SHIFT, FIRST, SHF×MOD, MOD×1st
3-WAY	SHIFT, MODERATE, FIRST, SHF×MOD, SHF×1st, MOD×1st

Table 39

Color-naming RT means, standard deviations, and error percentages (out of 1155 responses; NE).

	Mean RT	SD	<i>Incongruent Errors (%)</i>	<i>Unrelated errors (%)</i>	<i>Invalid Responses (%)</i>
CiWi	1245.19	283.55	3.03	0.17	5.19
WiCi	1146.79	214.21	3.37	0.43	4.76
CiWn	1120.07	194.75	2.42	0.09	4.67
WnCi	1059.99	154.80	2.77	0.17	1.90
CnWi	897.40	153.73	0	0.26	2.85
WiCn	868.47	124.88	0	1.04	2.08
CnWn	829.36	106.23	0	0.35	0.29
WnCn	836.27	116.01	0	0.35	1.38

Table 40

Effects partialled out in regression analysis (color naming; NE).

<i>Effect of Interest</i>	<i>Effects partialled</i>
SHIFT/Stroop	SHF×MOD, SHF×1st
MODERATE	SHF×MOD, MOD×1st
FIRST	SHF×1st, MOD×1st
SHF×MOD	SHIFT/Stroop, MODERATE, SHF×1st, MOD×1st
MOD×1st	MODERATE, FIRST, SHF×MOD, SHF×1st
SHF×1st	SHIFT/Stroop, FIRST, SHF×MOD, MOD×1st
3-WAY	SHIFT/Stroop, MODERATE, FIRST, SHF×MOD, SHF×1st, MOD×1st

Figure 1. Mean second-position RTs as a function of Presence of a Switch and Response Type (random pair presentation order).

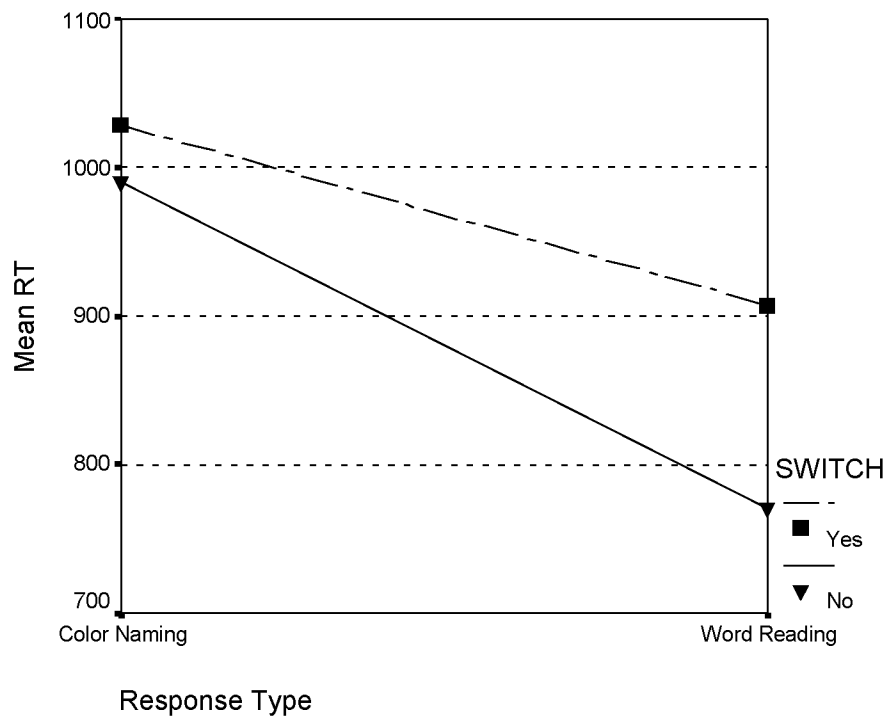


Figure 2. Mean second-position RTs as a function of Presence of a Switch and Response Type (blocked pair presentation).

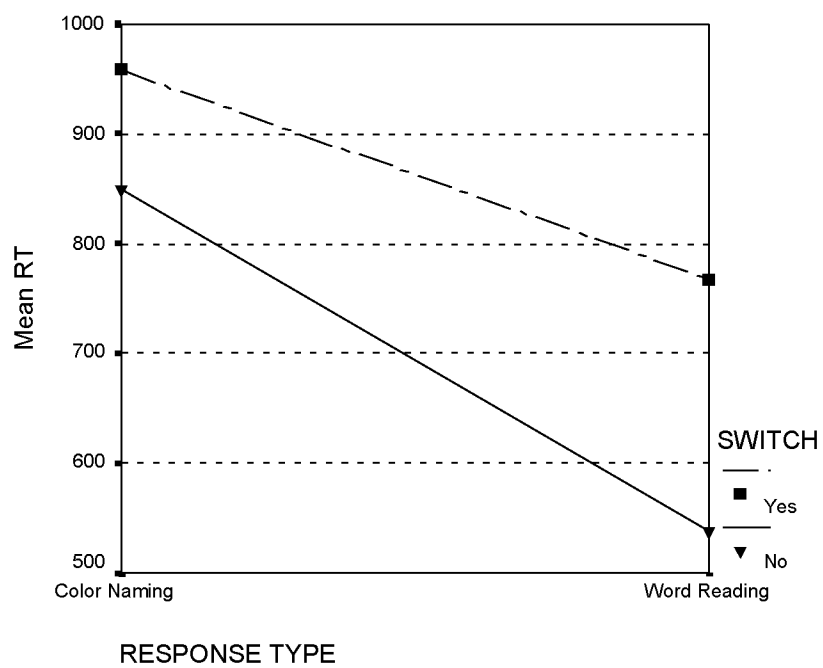


Figure 3. Mean repeated RTs as a function of Order of Presentation and Response Type (blocked pair presentation).

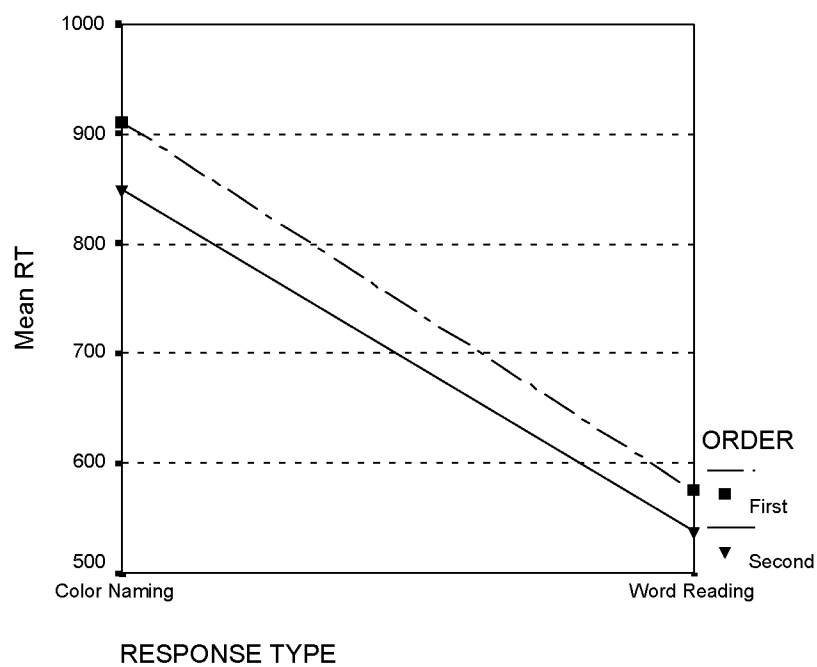


Figure 4. Mean repeated RTs as a function of Order of Presentation and Response Type (random pair presentation).

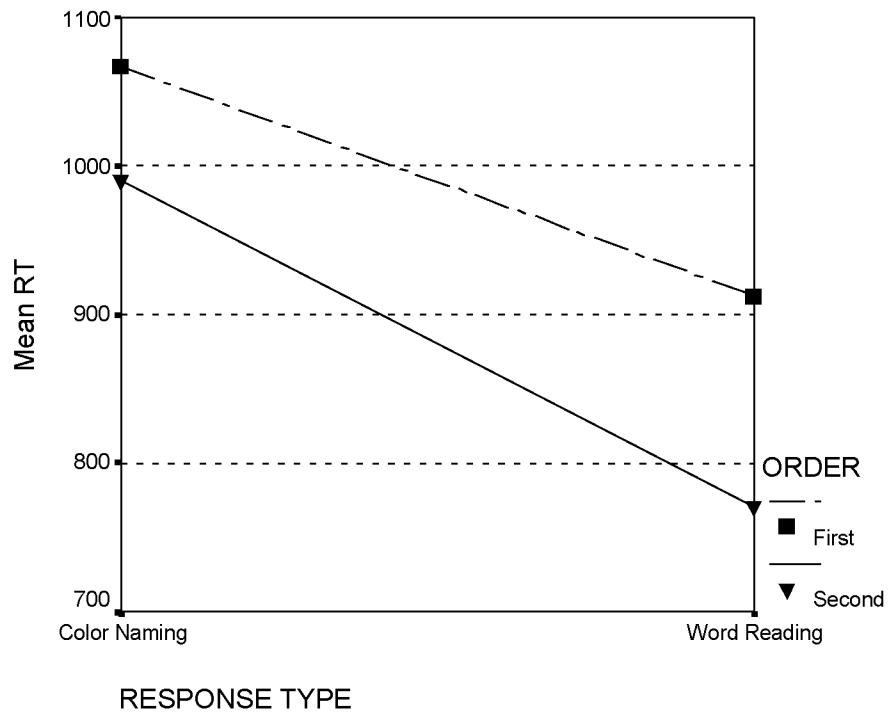


Figure 5. Mean switching RTs as a function of Order of Presentation and Response Type (blocked pair presentation).

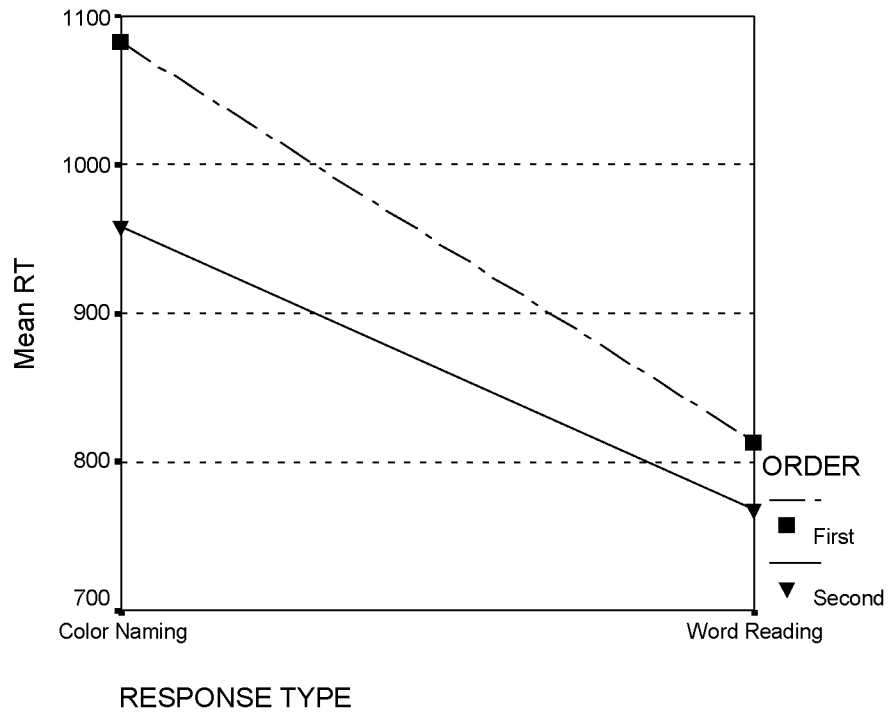


Figure 6. Mean switching RTs as a function of Order of Presentation and Response Type (random pair presentation).

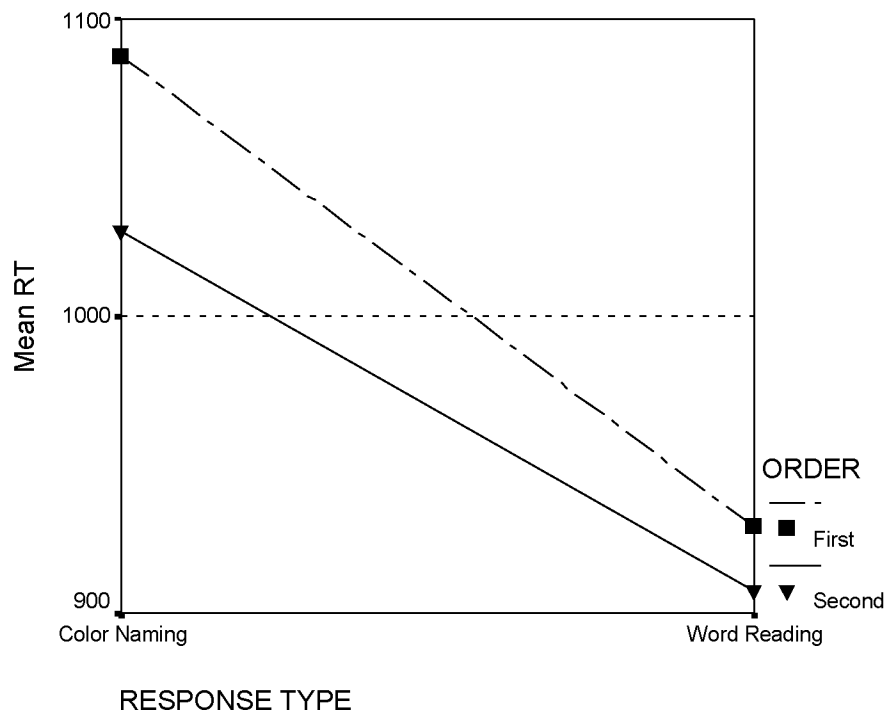


Figure 7. Mean first-position RTs as a function of Presence of a Switch and Response Type (blocked pair presentation).

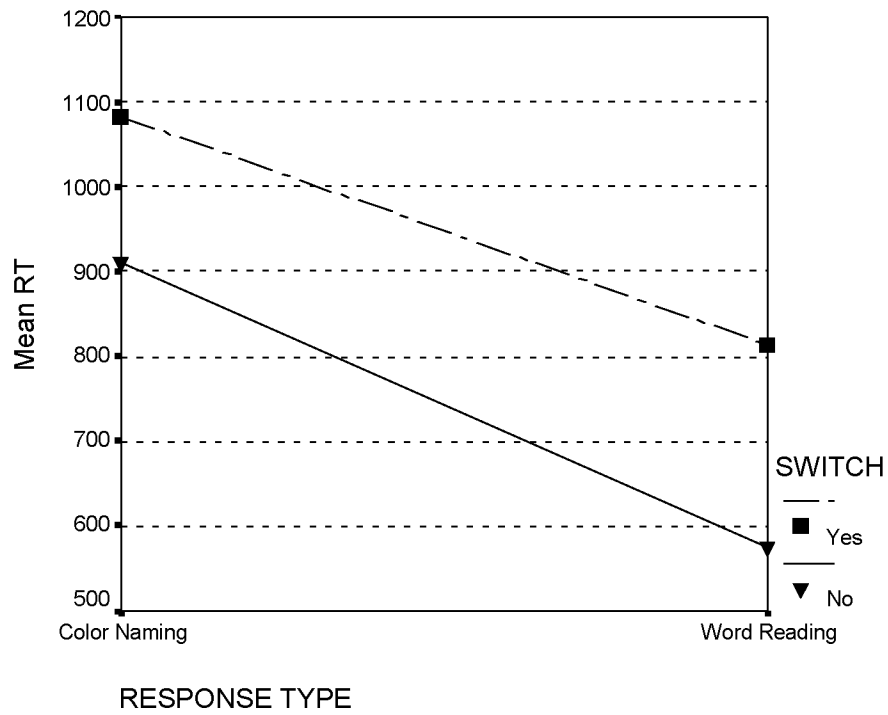


Figure 8. The effect of Stimulus Position and Predictability on RT for WiCiWi triplets.

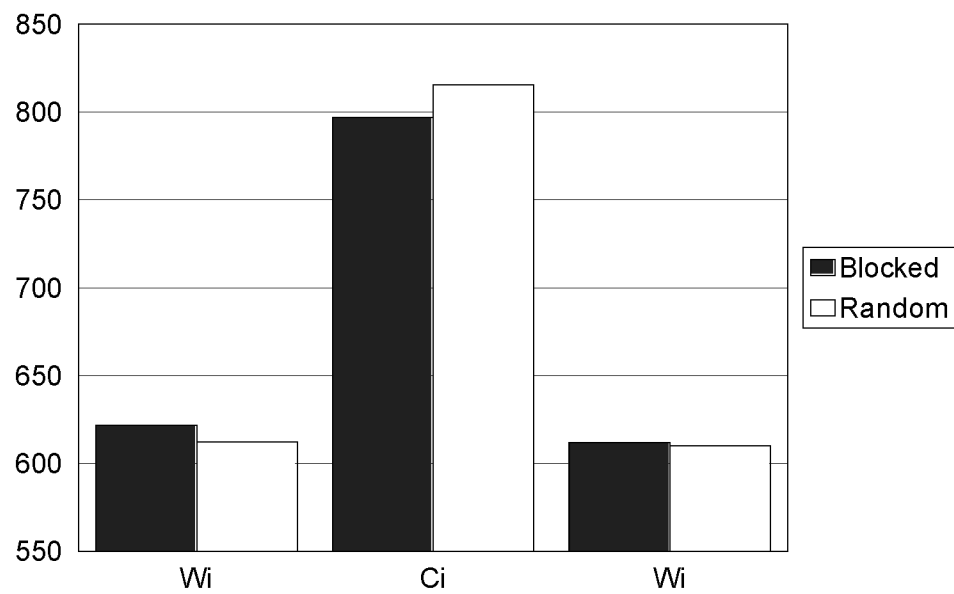


Figure 9. The effect of Stimulus Position and Predictability on RT for WiCnWi triplets.

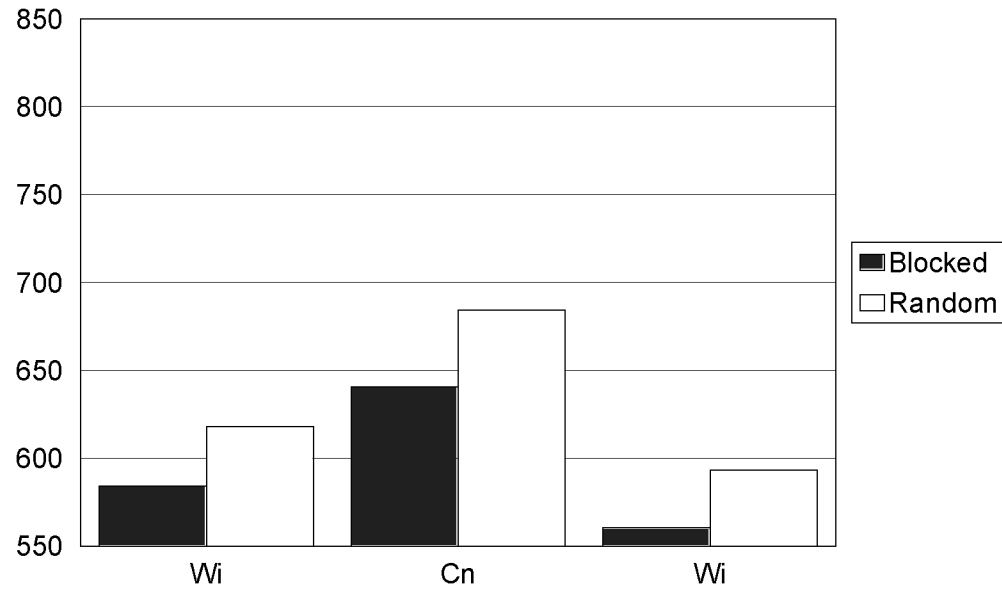


Figure 10. The effect of Stimulus Position and Triplet Type on RT for WiCi/nWi triplets (random condition).

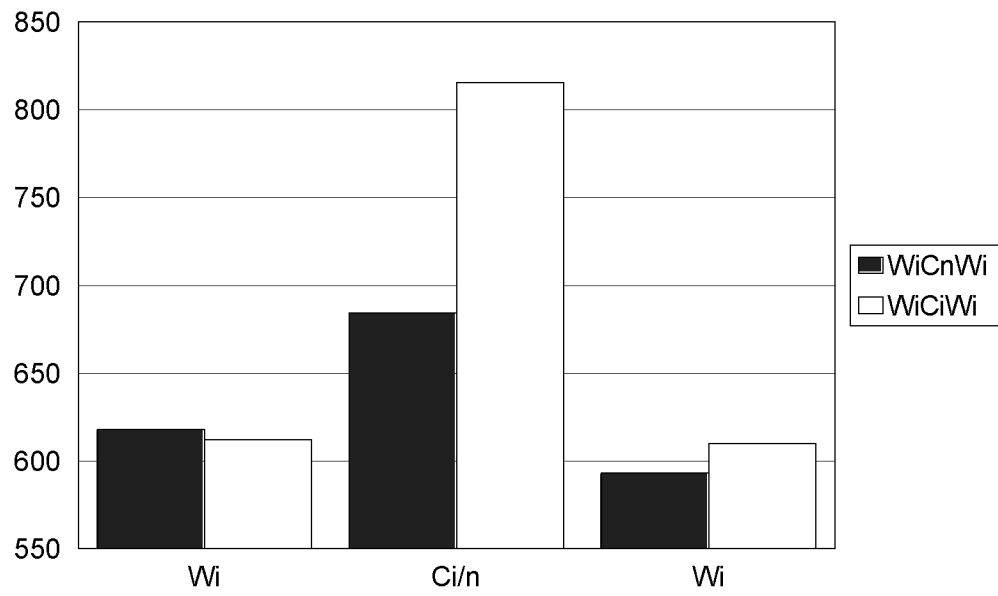


Figure 11. The effect of Stimulus Position and Predictability on RT for CiWiCi triplets.

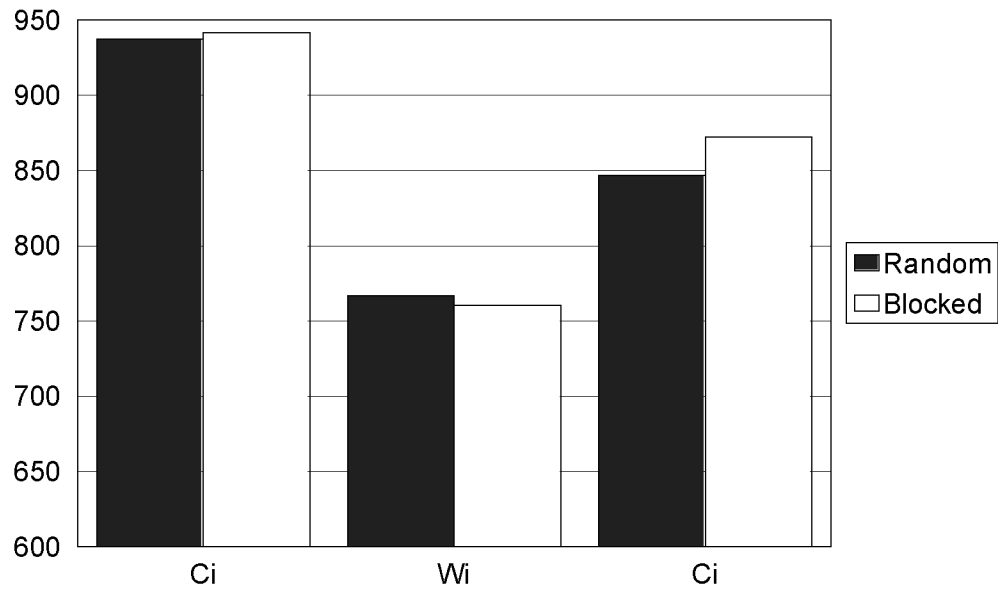


Figure 12. The effect of Stimulus Position and Predictability on RT for CiWnCi triplets.

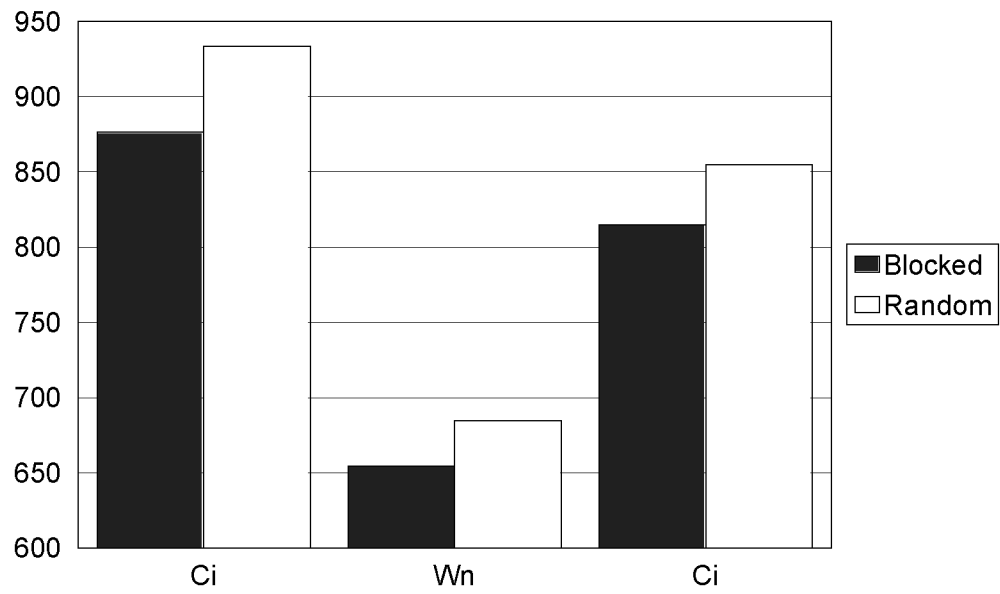


Figure 13. The effect of Stimulus Position and Triplet Type on RT for CiWi/nCi triplets (random condition).

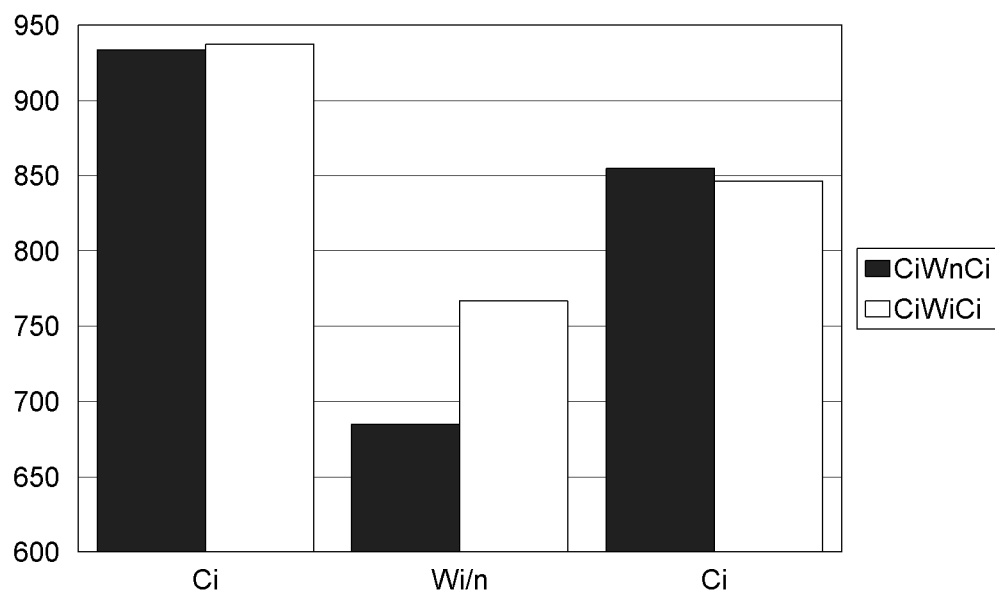


Figure 14. Reverse Stroop Effect, position one, plotted as a function of task switching condition, with 95% confidence intervals.



Figure 15. Reverse Stroop Effect, position two, plotted as a function of task switching condition, with 95% confidence intervals.

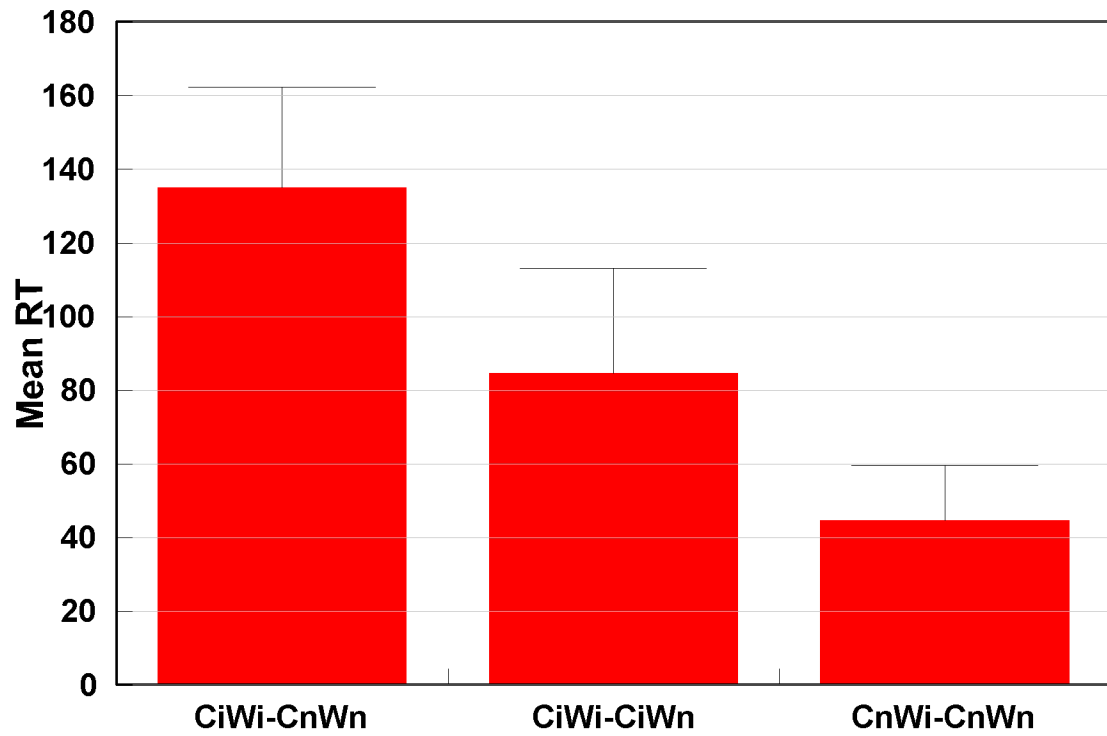


Figure 16. Model of cognitive processes involved in task switching, with node type labels.

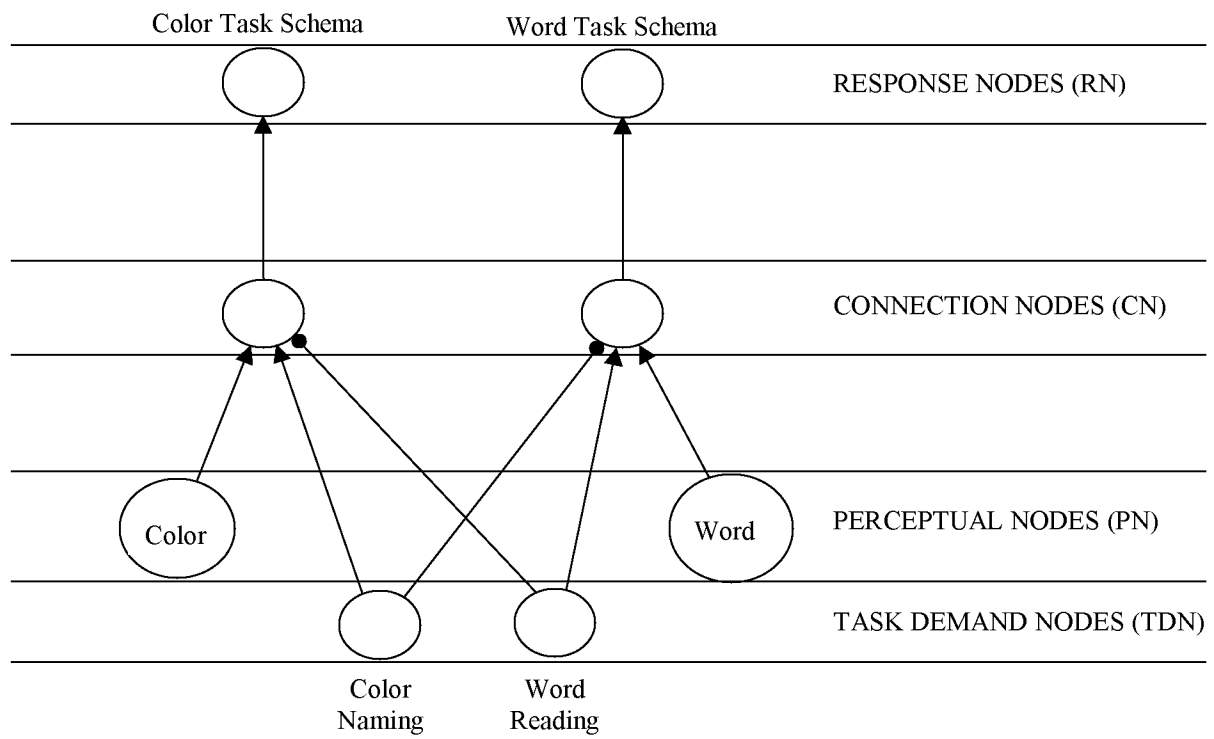


Figure 17. Model of cognitive processes involved in task switching: Task Schemas (PNs, CNs, RNs, PN→CN pathways, CN→RN pathways)

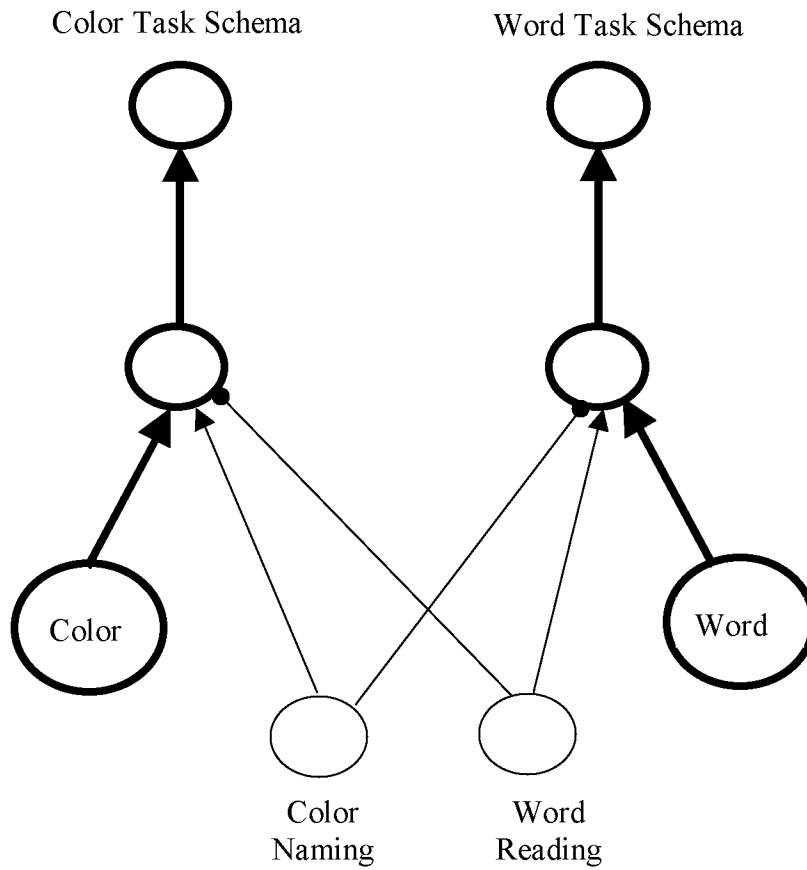


Figure 18. Model of cognitive processes involved in task switching: Contention Scheduling (CNs; CN→PN pathways)

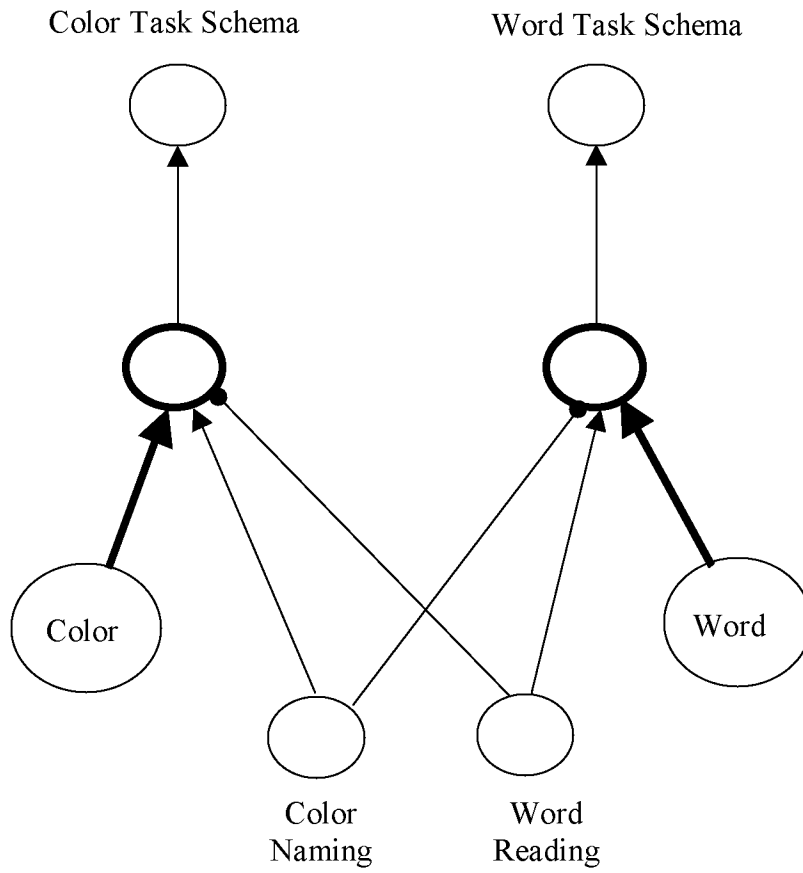


Figure 19. Model of cognitive processes involved in task switching: Stimulus Dimensions (PNs)

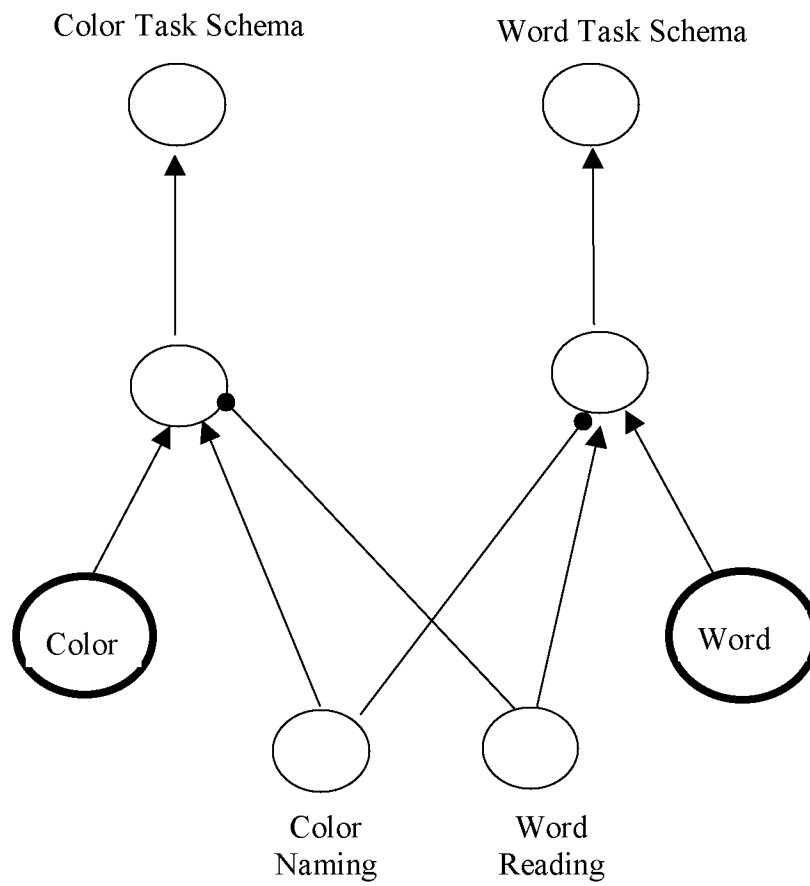


Figure 20. Model of cognitive processes involved in task switching: Supervisory Attentional System (TDN, TDN→CN excitatory pathways, and TDN| CN inhibitory pathways)

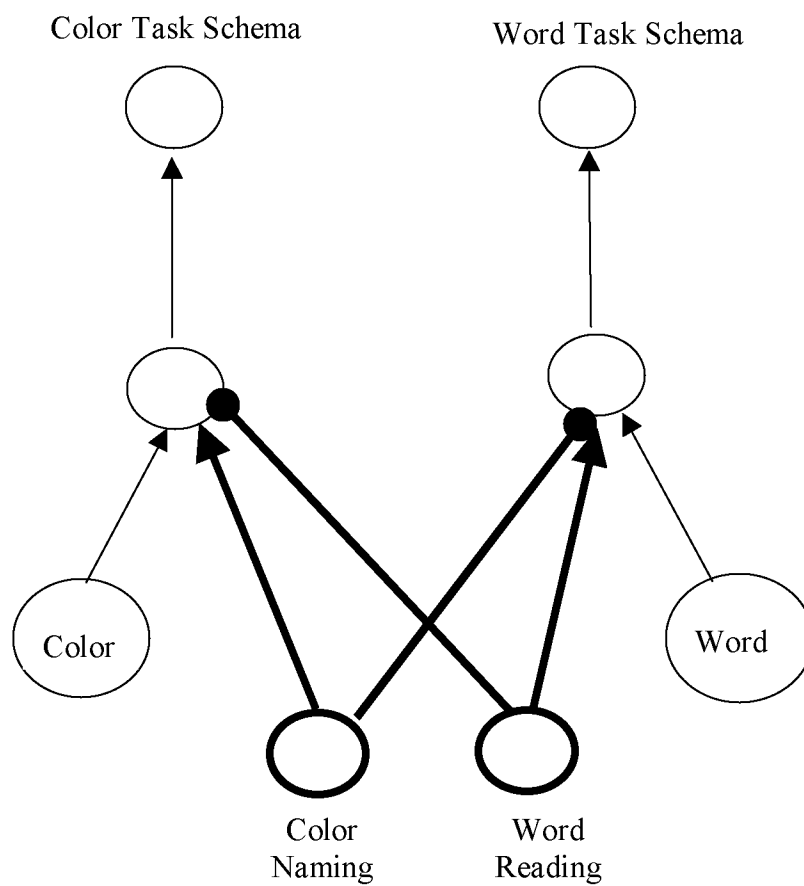


Figure 21. Context effect, word reading, position one, plotted as a function of task switching condition, with 95% confidence intervals.

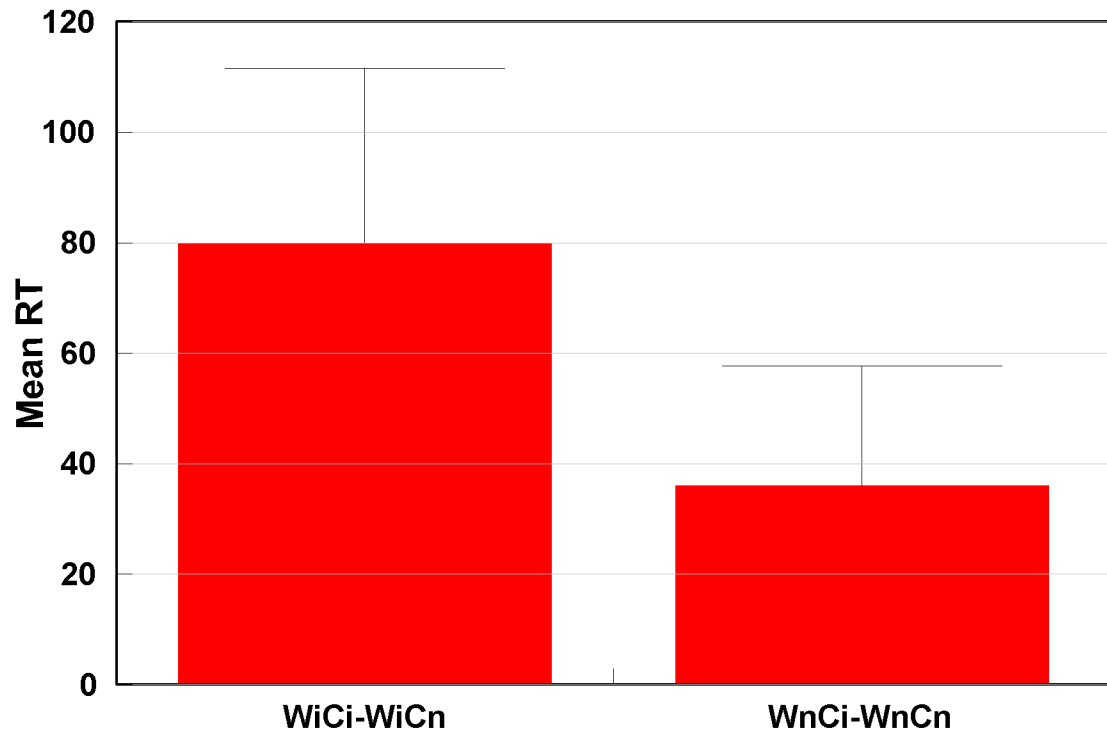


Figure 22. Context effect, word reading position two, plotted as a function of task switching condition, with 95% confidence intervals.

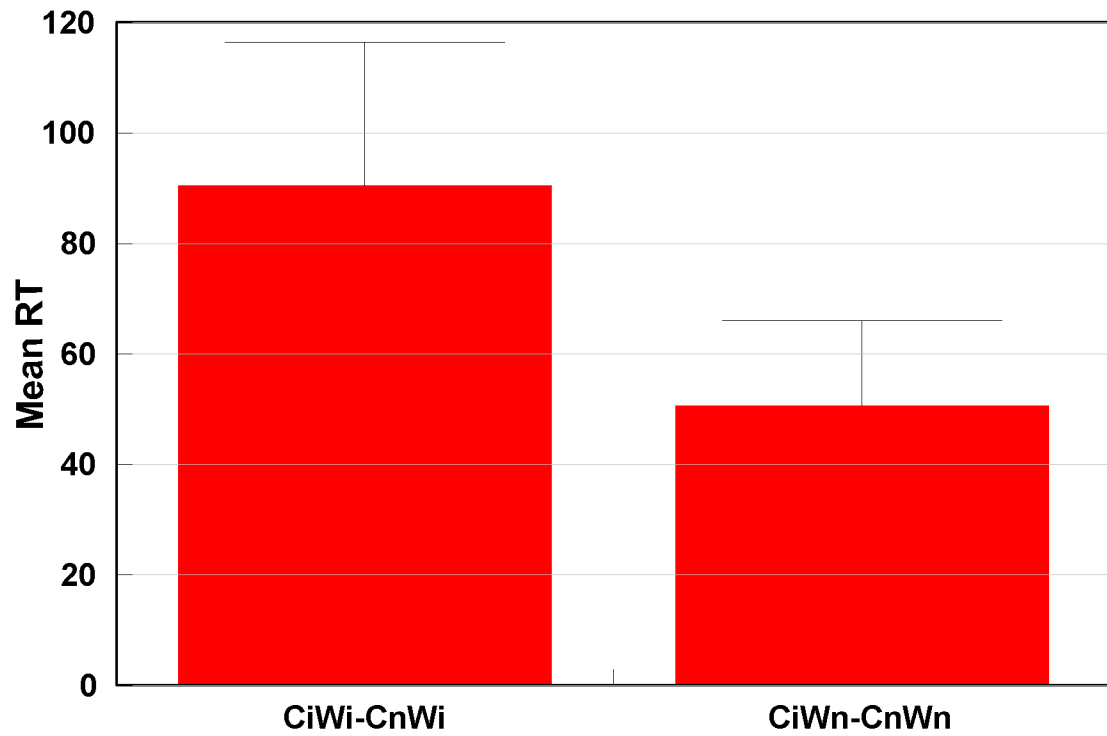


Figure 23. Word reading beta weights, with 95% confidence intervals (Experiment 3).

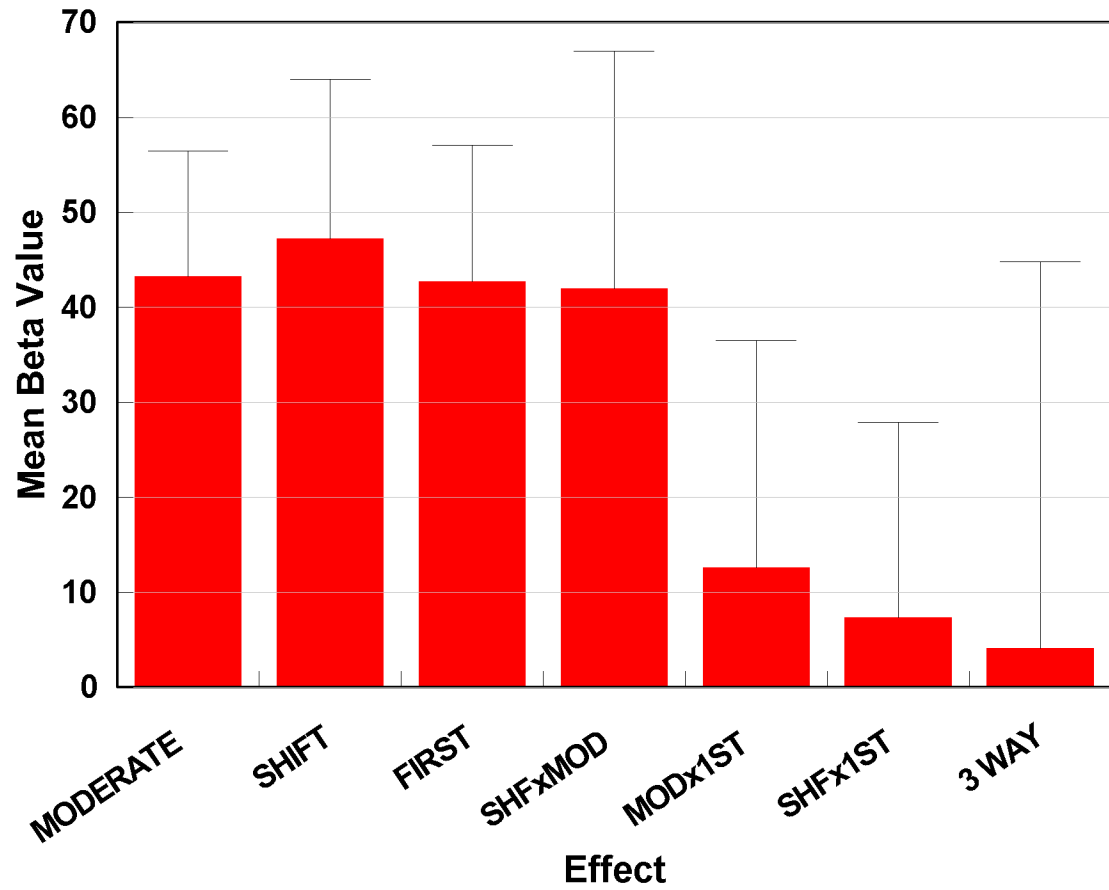


Figure 24. Stroop Effect, position one, plotted as a function of task switching condition, with 95% confidence intervals



Figure 25. Stroop Effect, position two, plotted as a function of task switching condition, with 95% confidence intervals.

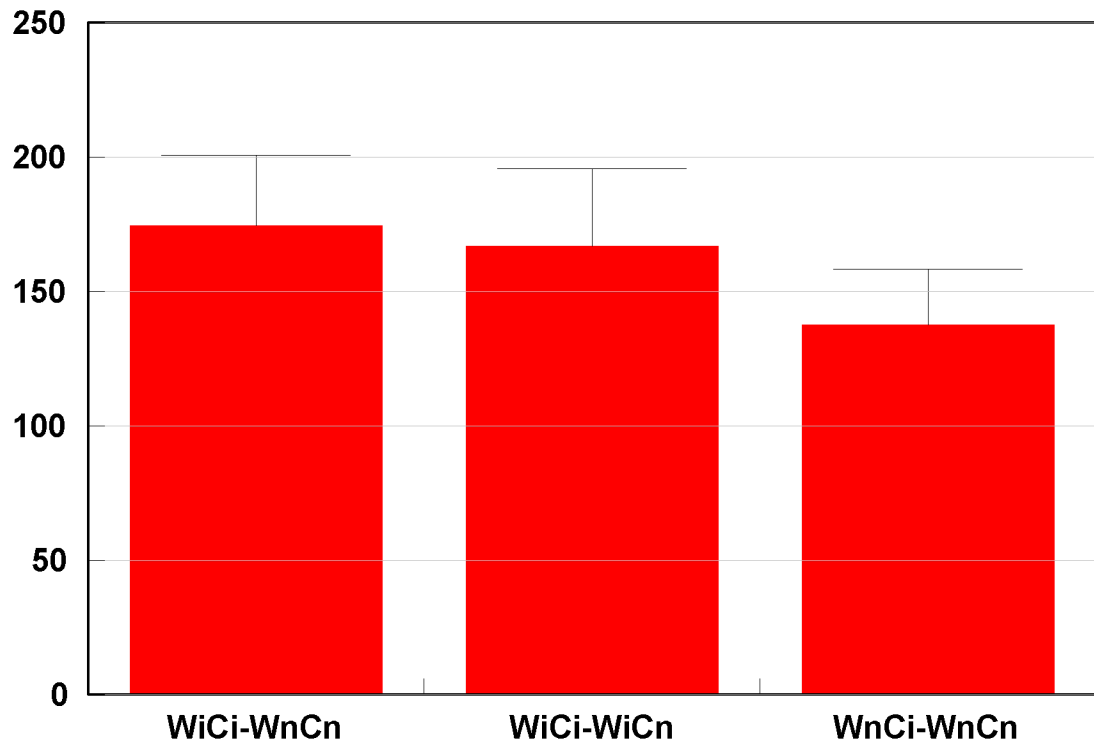


Figure 26. Context effects for color, position one, plotted as a function of task switching condition, with 95% confidence intervals.

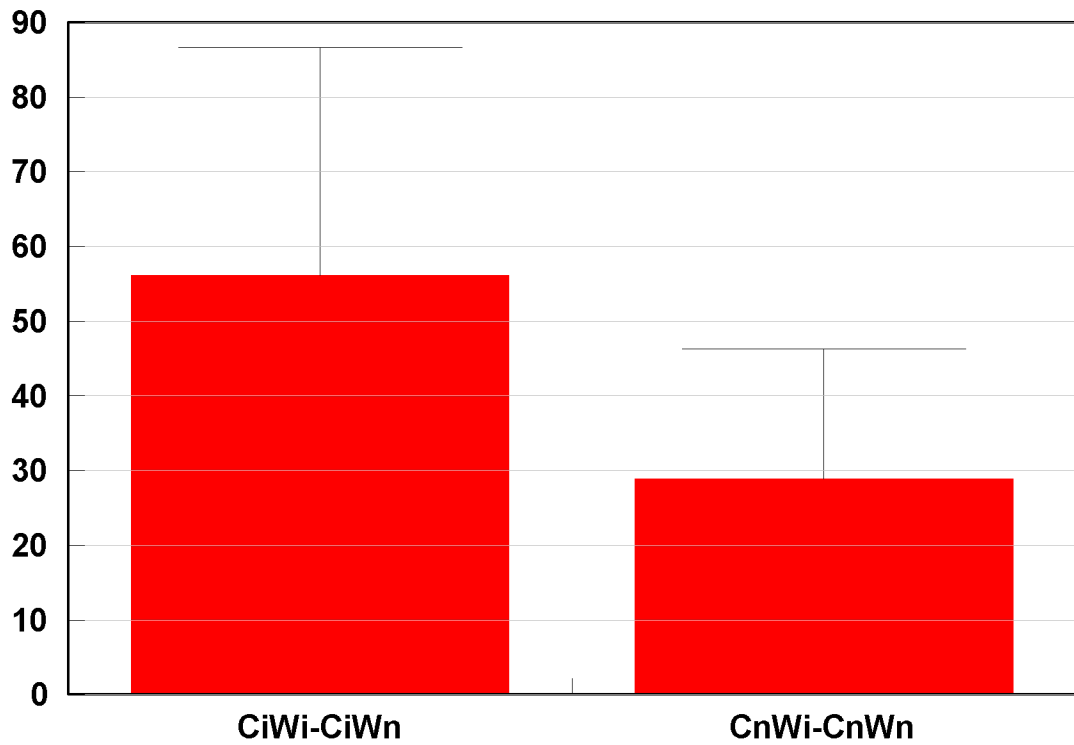


Figure 27. Context effects for color, position two, plotted as a function of task switching condition, with 95% confidence intervals.

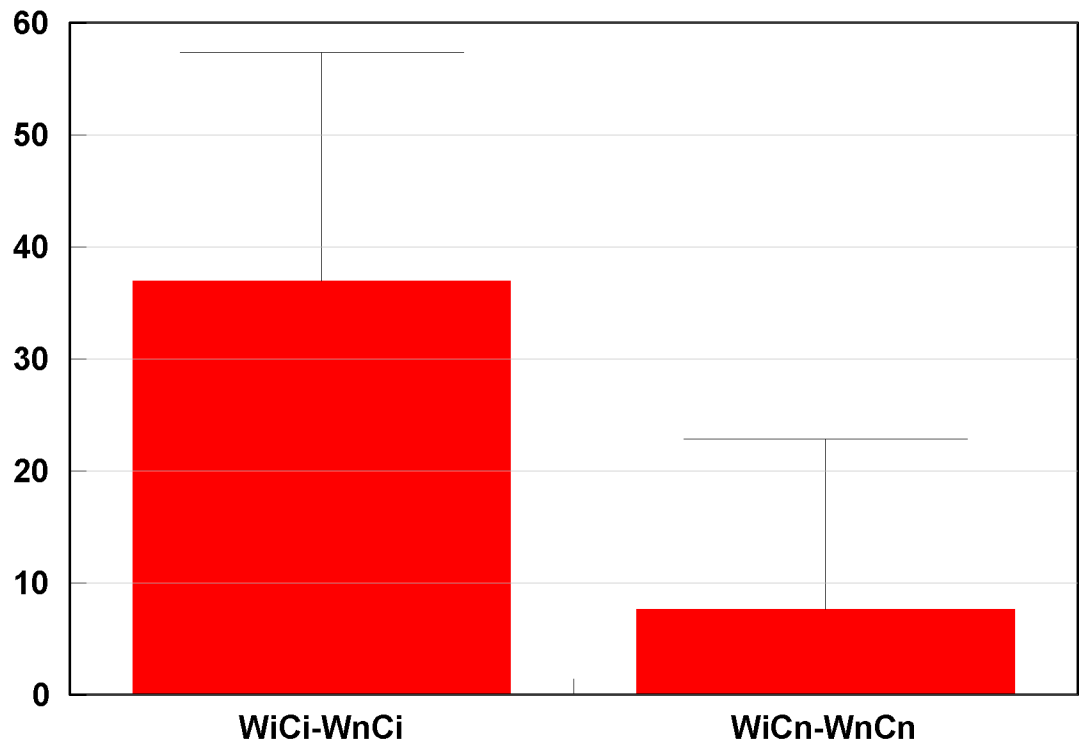


Figure 28. Color naming beta weights, with 95% confidence intervals (Experiment 3).

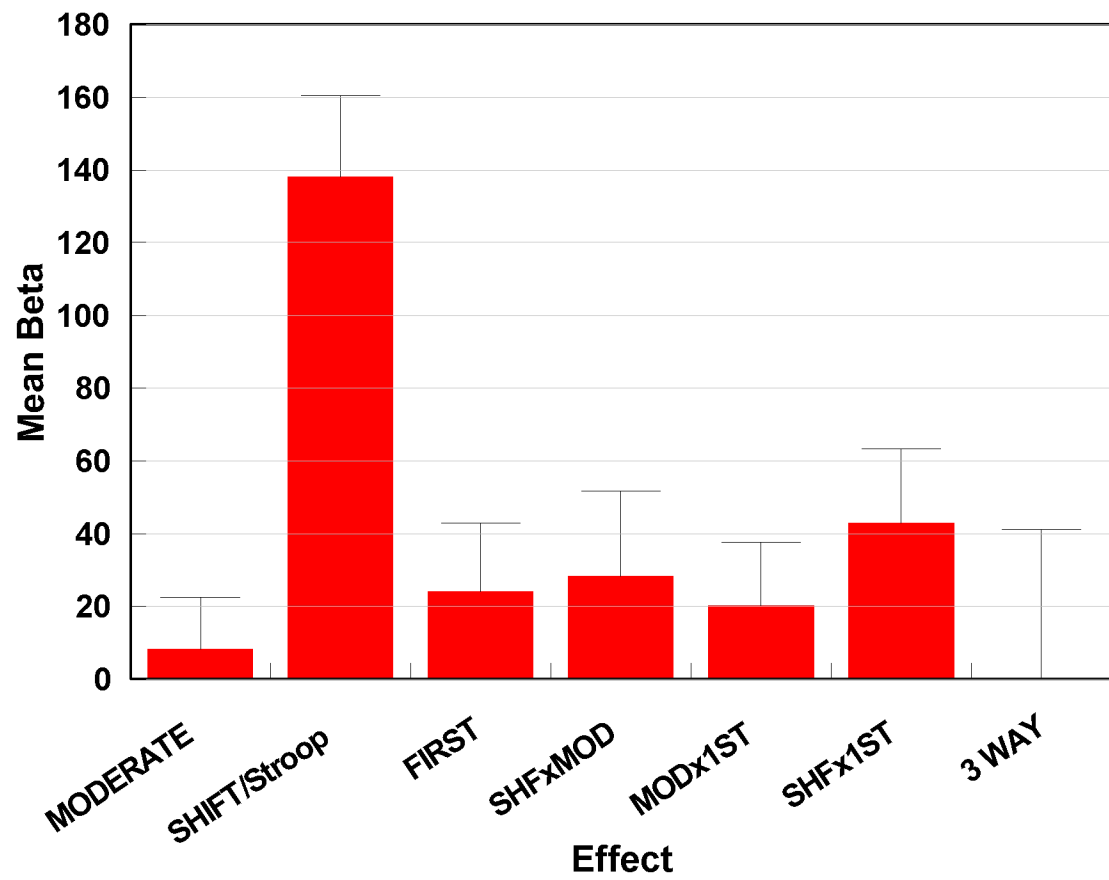
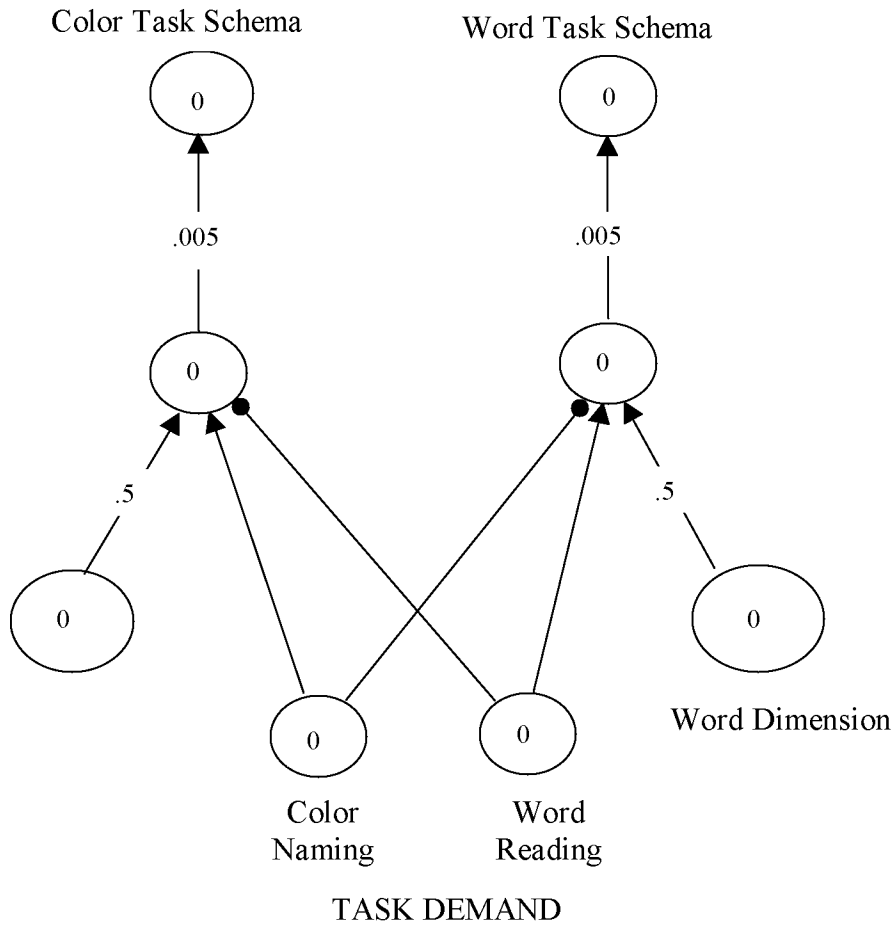


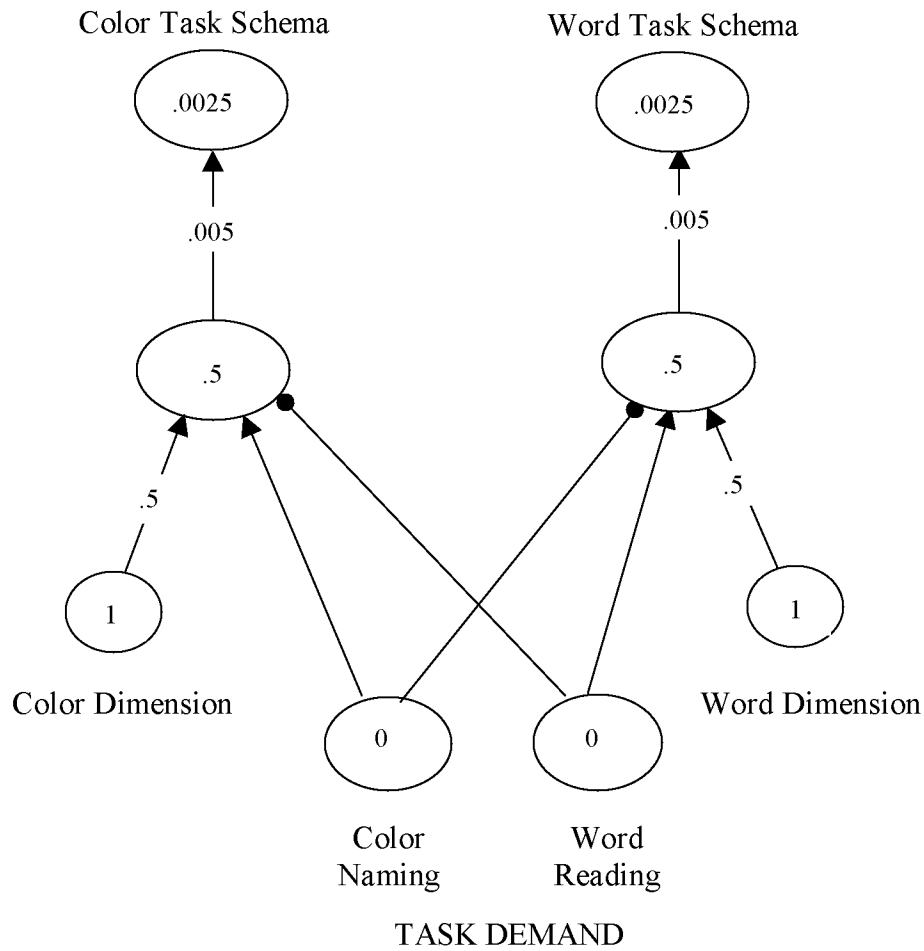
Figure 29. Model of cognitive processes involved in task switching, subsequent to the CnWi response, but prior to CnWi.



Matrix representation of model state:

$$[0 \ 0 \ 0 \ 0] * \begin{bmatrix} .5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & .5 \end{bmatrix} * \begin{bmatrix} .005 & 0 \\ 0 & .005 \end{bmatrix} = [0 \ 0]$$

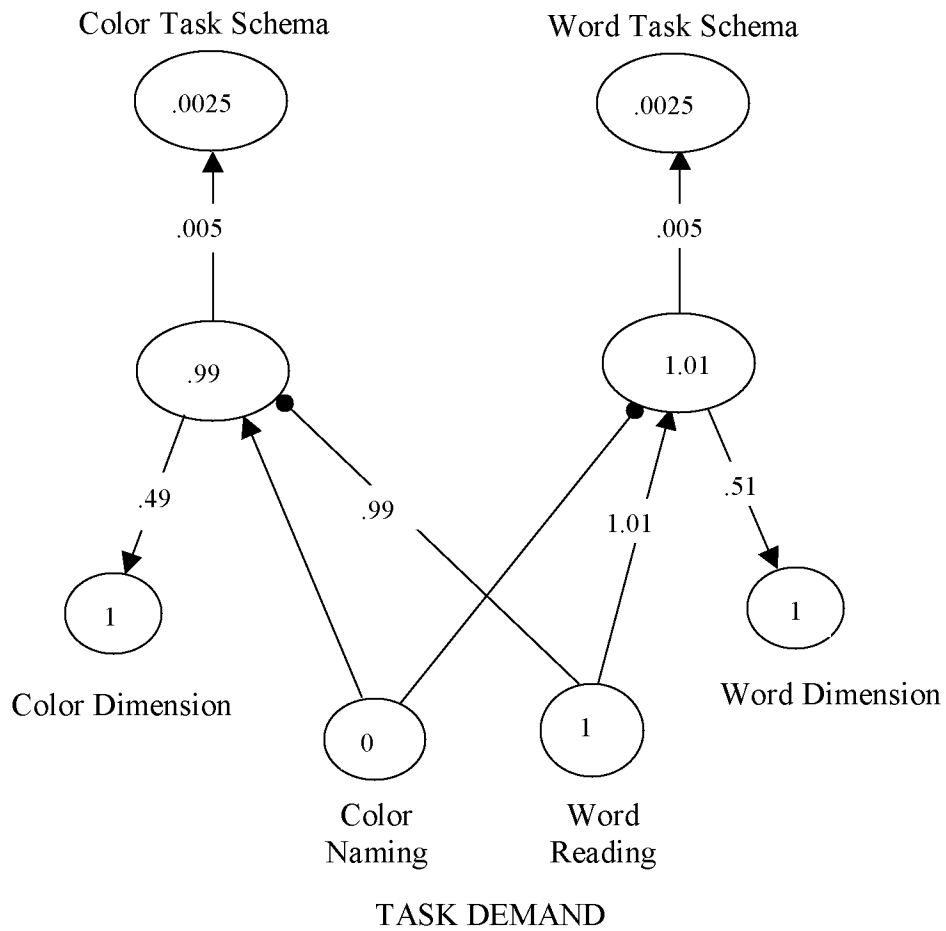
Figure 30. Model of cognitive processes involved in task switching, **CnWi** response. Information gathering pass (IGP) one: stimulus is viewed, RNs become activated.



Matrix representation of model state:

$$[1 \ 0 \ 0 \ 1] * \begin{bmatrix} .5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & .5 \end{bmatrix} * \begin{bmatrix} .005 & 0 \\ 0 & .005 \end{bmatrix} = [.0025 \ .0025]$$

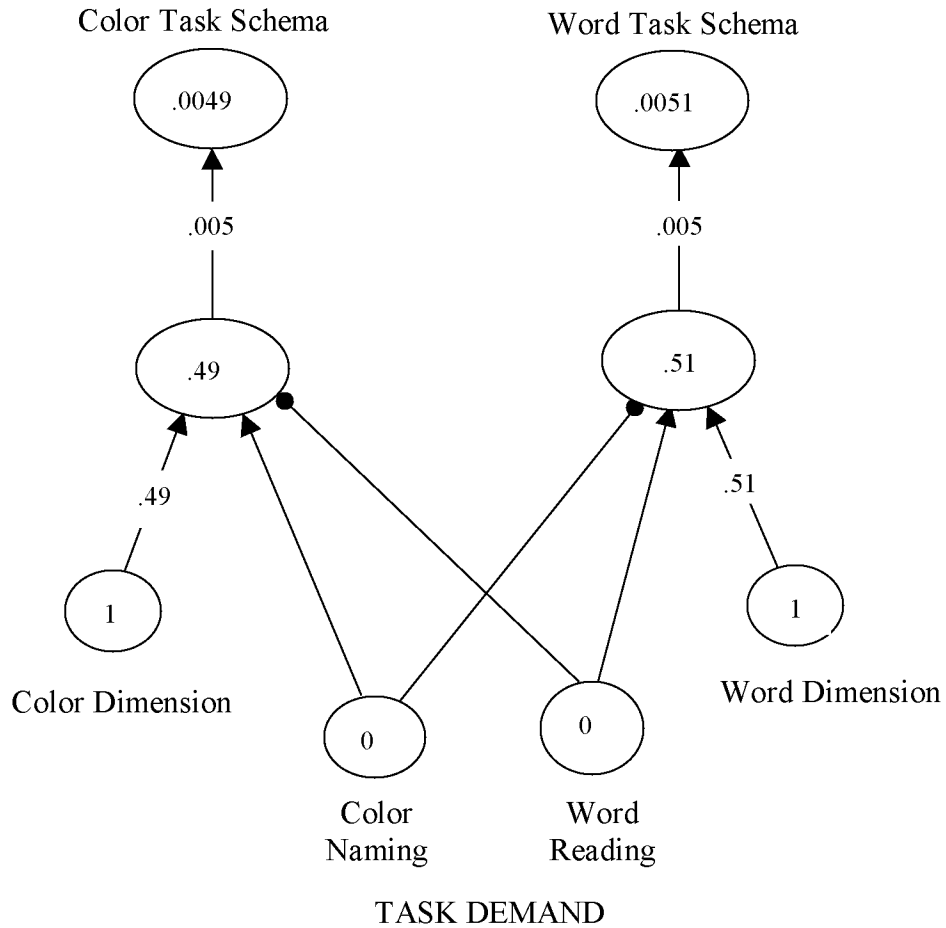
Figure 31. Model of cognitive processes involved in task switching, **CnWi** response. Attentional adjustment pass (AAP) one: attentional weights (PN → CN pathways) are adjusted according to state of task demand nodes.



Matrix representation of model state:

$$[0 \ 1] * \begin{bmatrix} 0 & 0 \\ .99 & 1.01 \end{bmatrix} * \begin{bmatrix} .5 & 0 \\ 0 & .5 \end{bmatrix} = [.49 \ .51]$$

Figure 32. Model of cognitive processes involved in task switching, CnWi response. IGP two: the system accumulates evidence biasing the system towards a response.

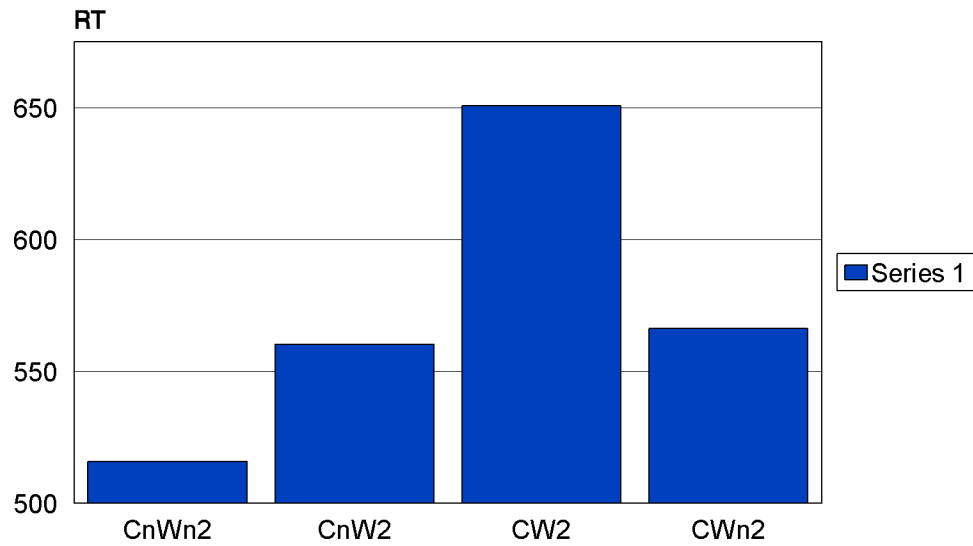


Matrix representation of model state:

$$\begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} .49 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & .51 \end{bmatrix} * \begin{bmatrix} .005 & 0 \\ 0 & .005 \end{bmatrix} = \begin{bmatrix} .0024 & .0026 \end{bmatrix} + \begin{bmatrix} .0025 & .0025 \end{bmatrix} = \begin{bmatrix} .0049 & .0051 \end{bmatrix}$$

Figure 33. Simulation of selected word reading RTs using the PDP model.

Word Reading RT



Word Reading Model

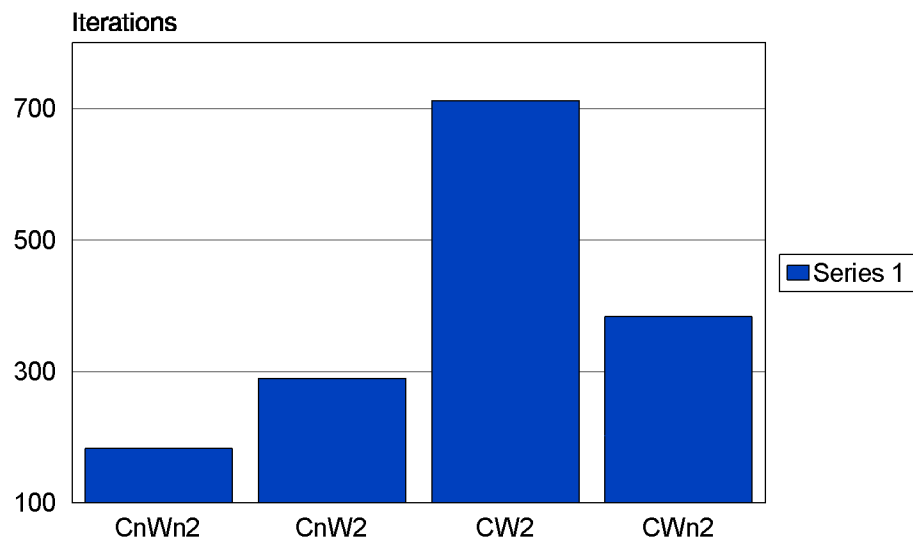
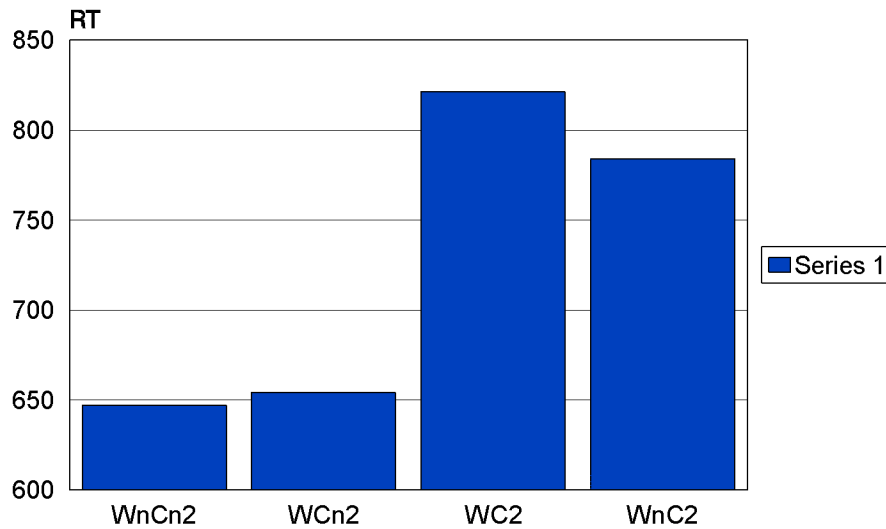


Figure 34. Simulation of selected color naming reading RTs using the PDP model.

Color Naming RT



Color Naming Model

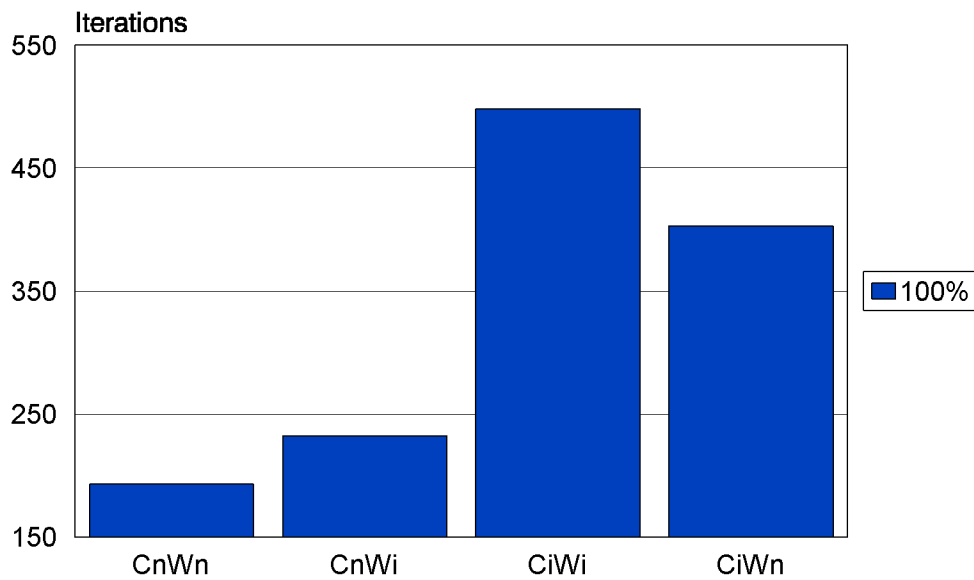


Figure 35. Color-naming response latencies for CiWi pairs by percentage of appearance.

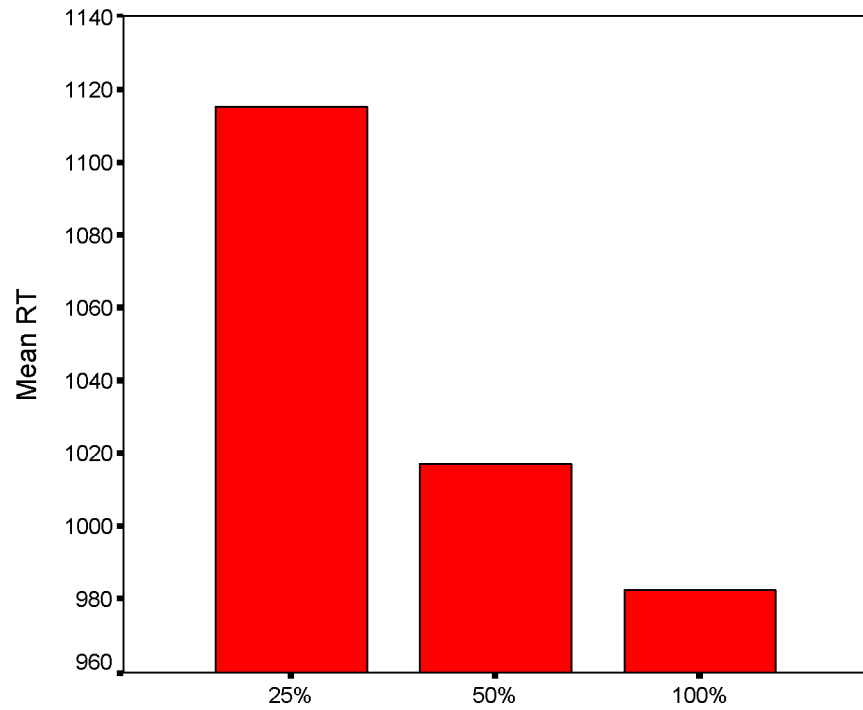


Figure 36. Word-reading response latencies for CiWi pairs by percentage of appearance.

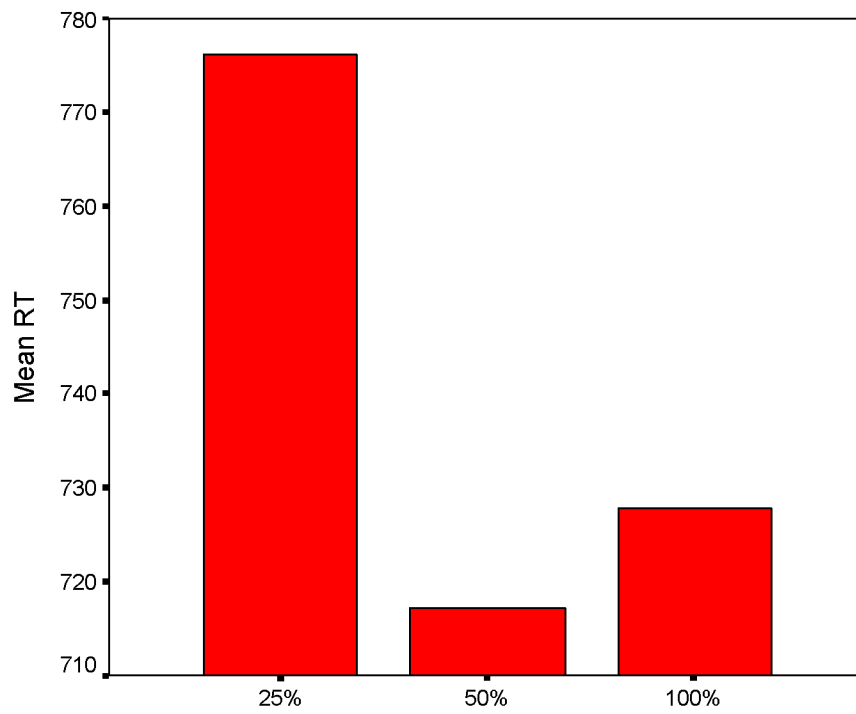


Figure 37. Word-reading responses by congruency with 95% confidence intervals.

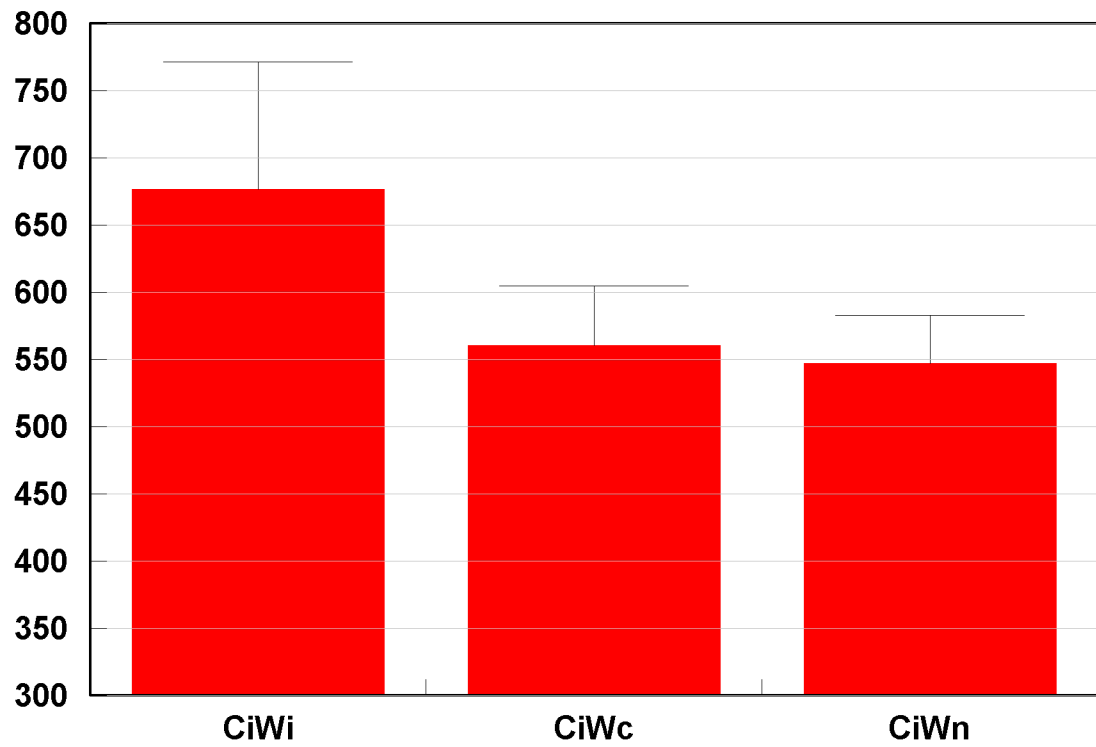


Figure 38. Color-naming responses by congruency with 95% confidence intervals.

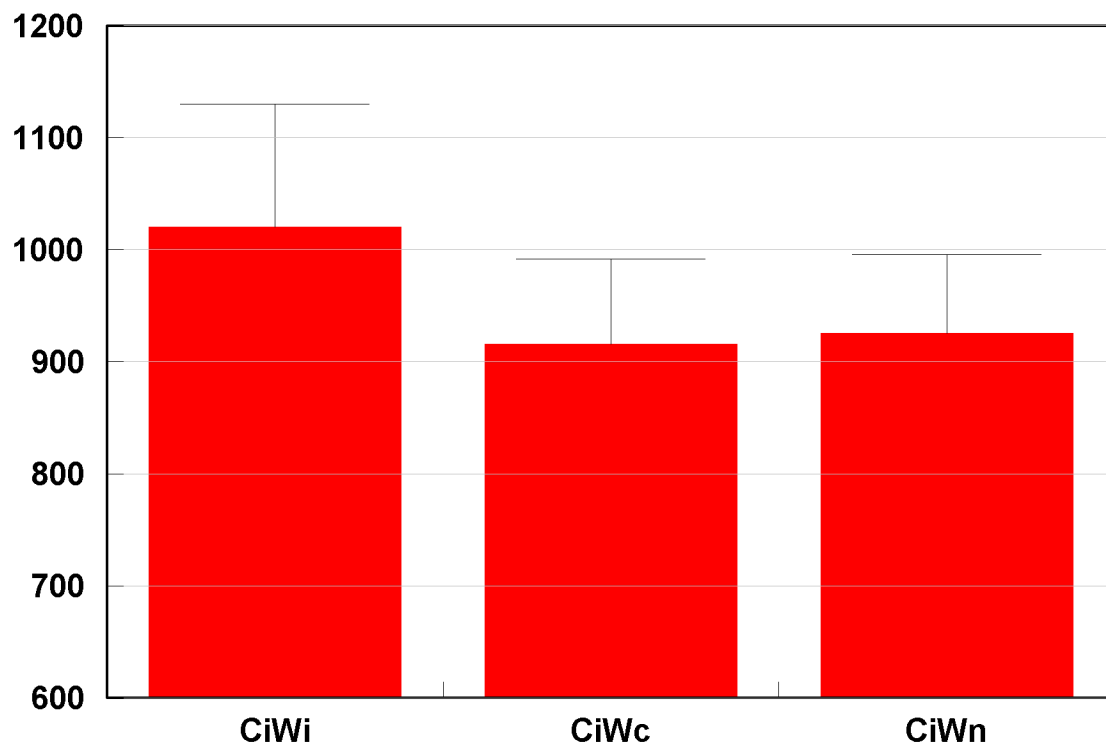


Figure 39. Word reading effect sizes, with 95% confidence intervals (Experiment 7).

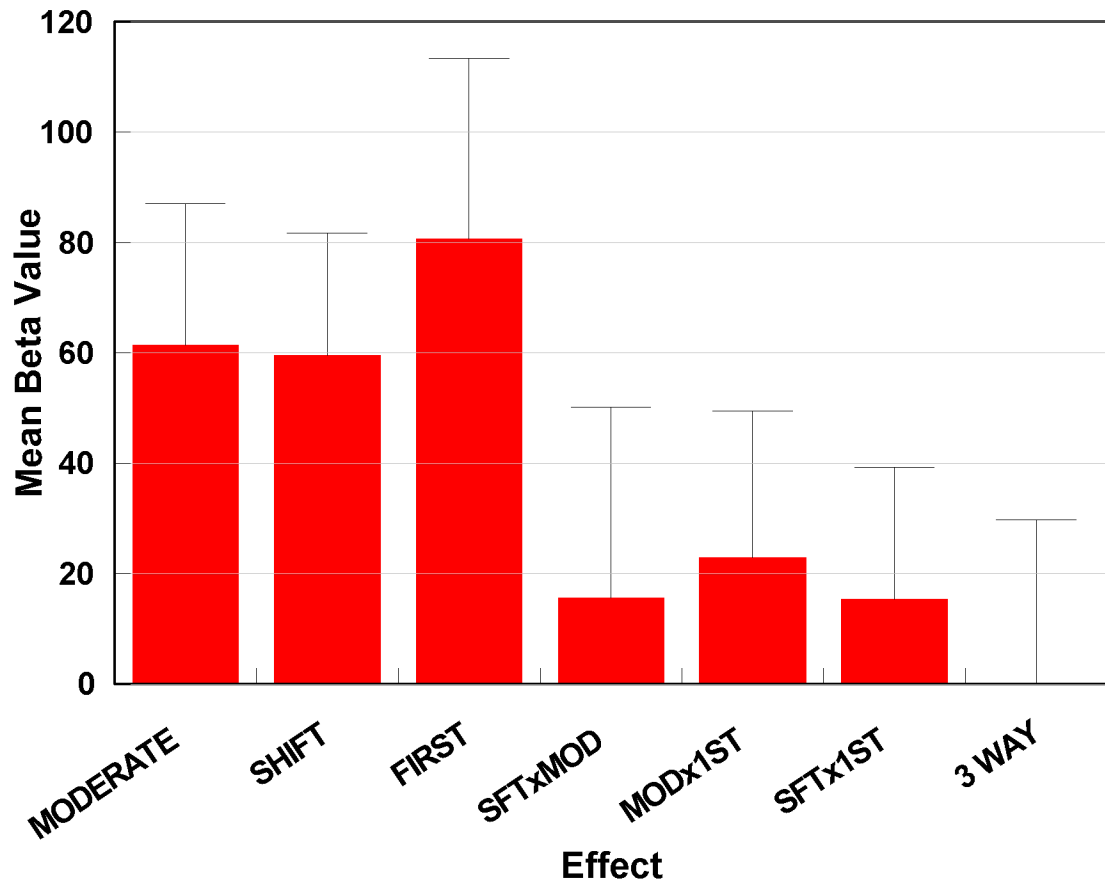


Figure 40. Color naming effect sizes, with 95% confidence intervals (Experiment 7).

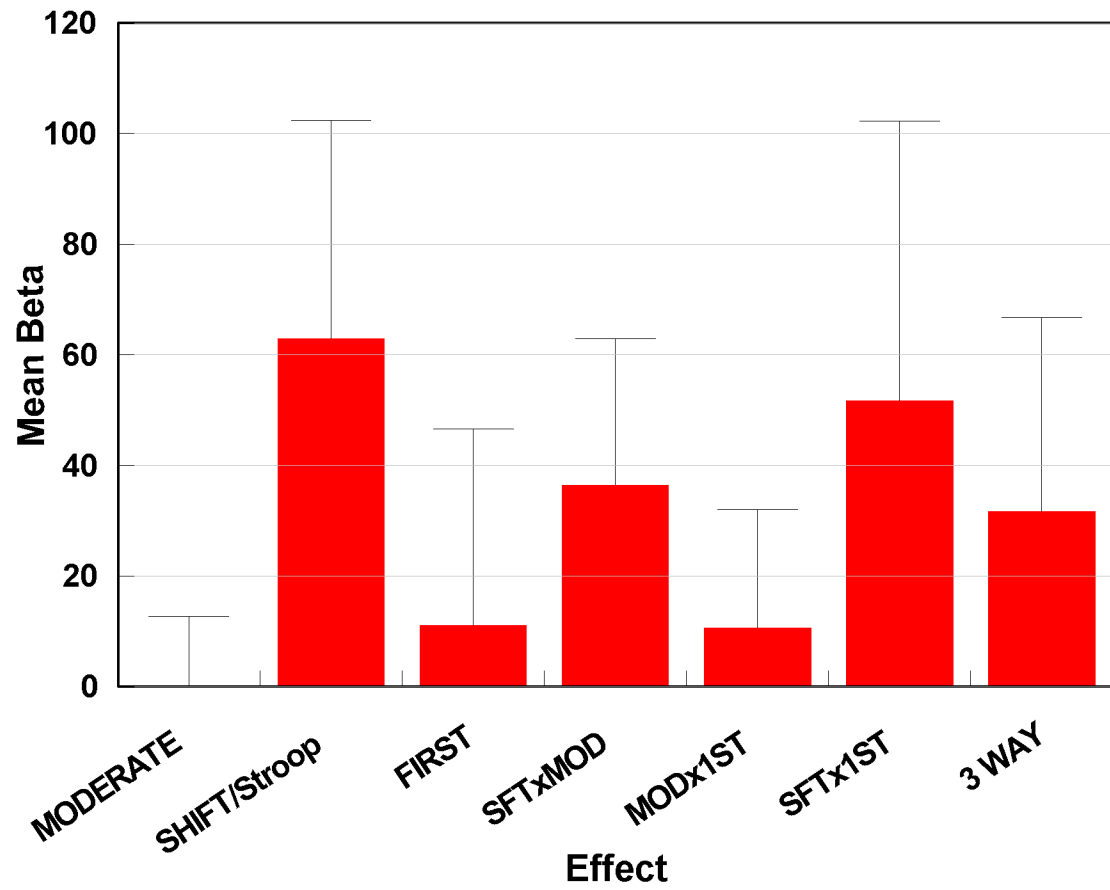


Figure 41. Word-reading effects with 95% confidence intervals (PD).

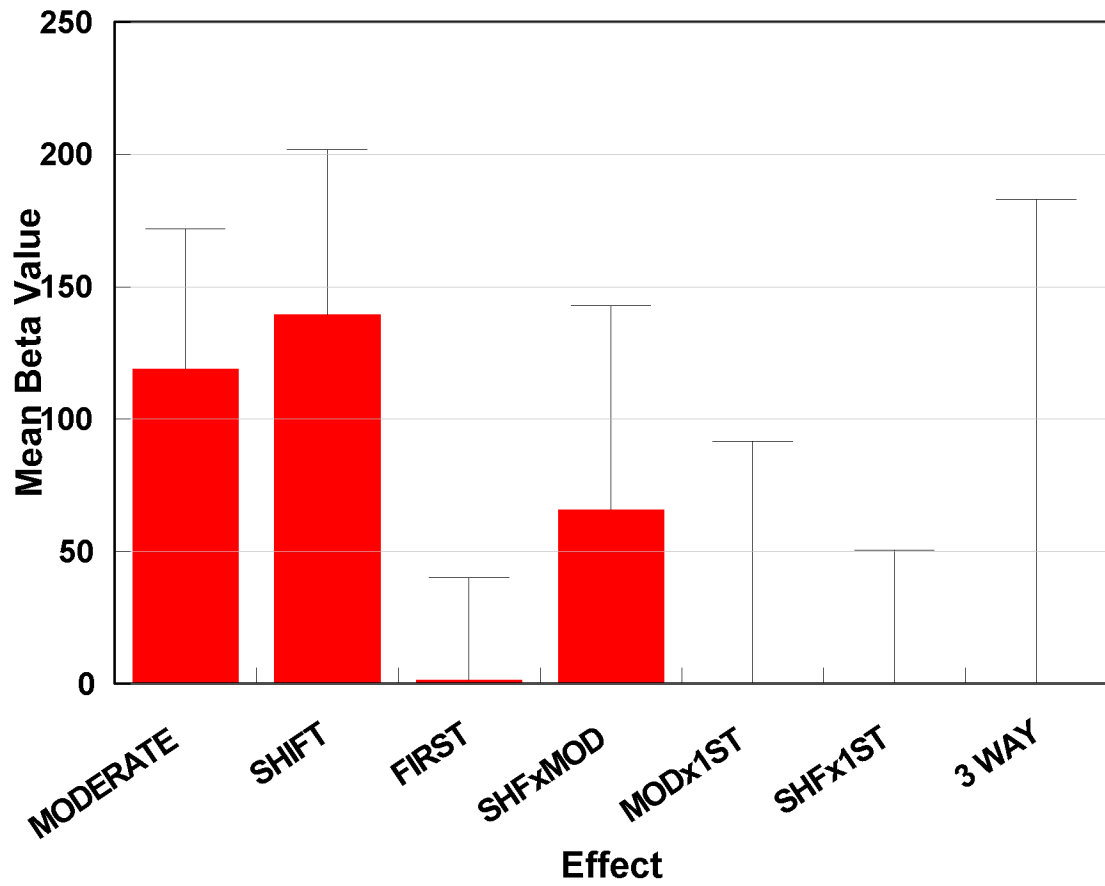


Figure 42. Comparison of Elderly and Parkinson's samples on word-reading effects (95% confidence intervals).

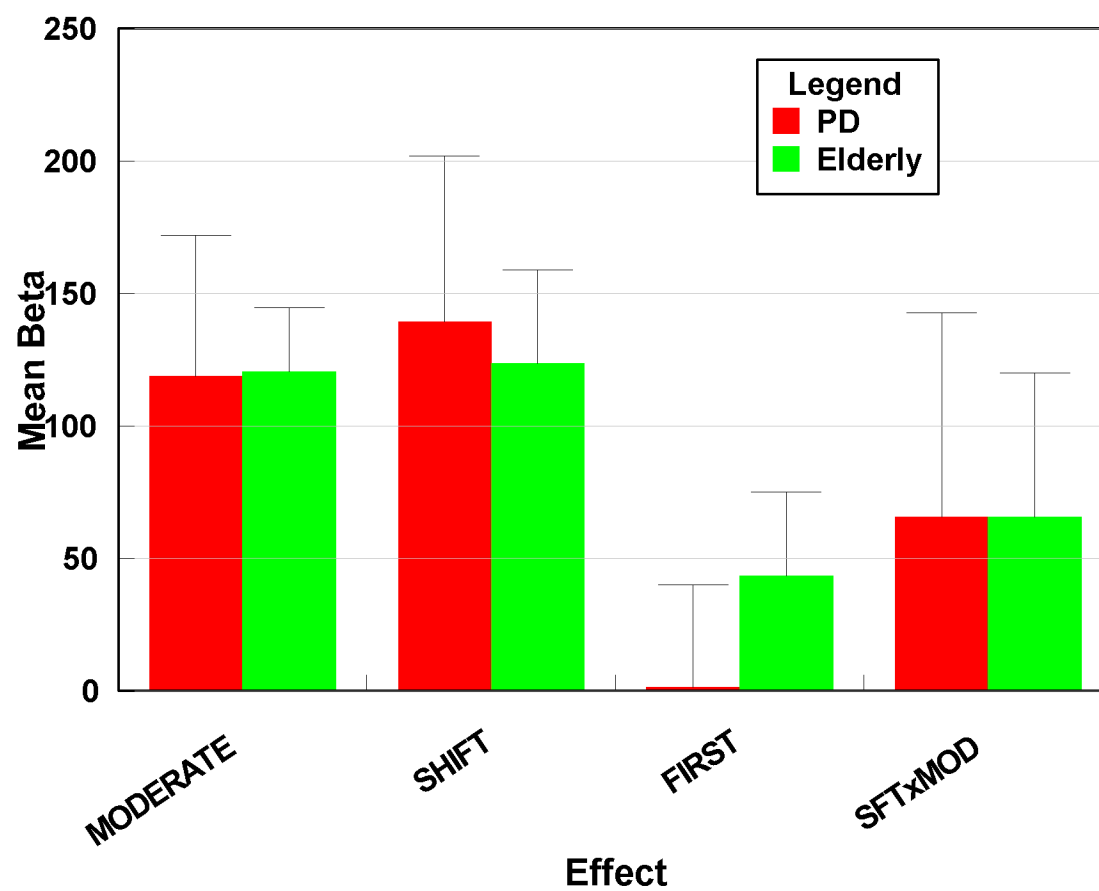


Figure 43. Word-reading RT plotted as a function of SHIFT and MODERATE for the PD sample.

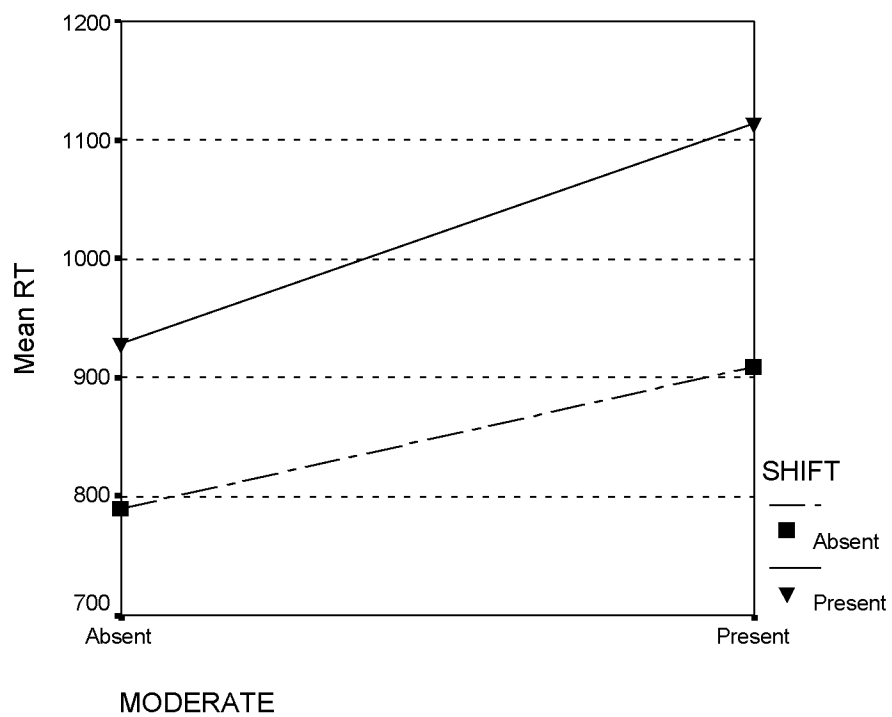


Figure 44. Comparison of Elderly and Parkinson's samples on word-reading effects (95% confidence intervals, interactions ignored).

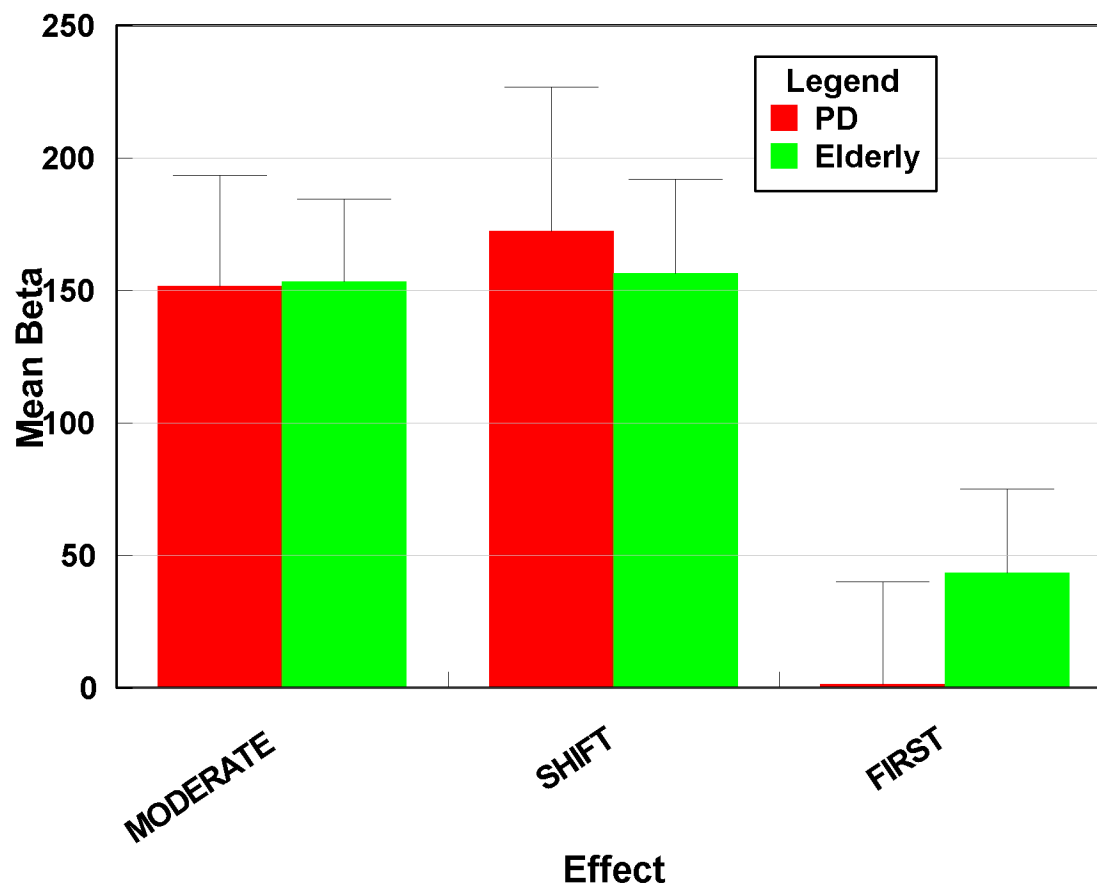


Figure 45. Color naming effects with 95% confidence intervals (PD).

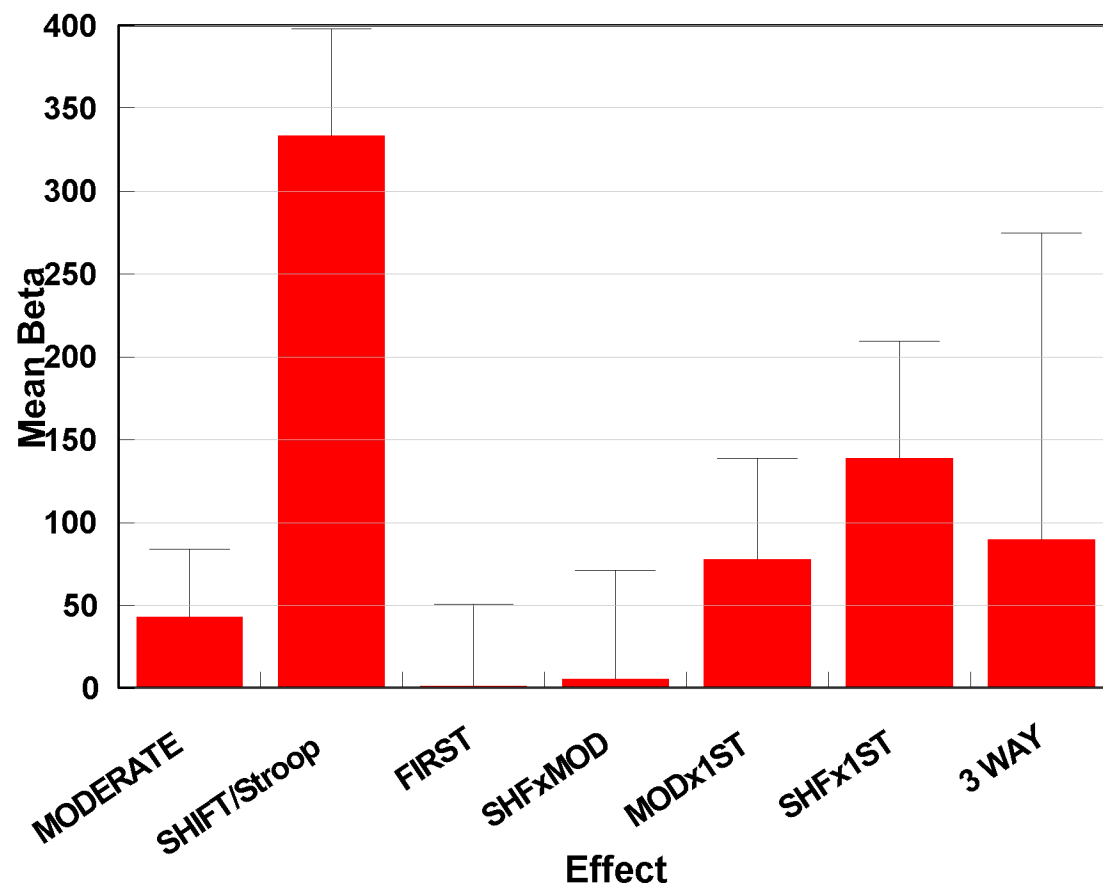


Figure 46. Comparison of Elderly and Parkinson's samples on color-naming effects (with 95% confidence intervals).

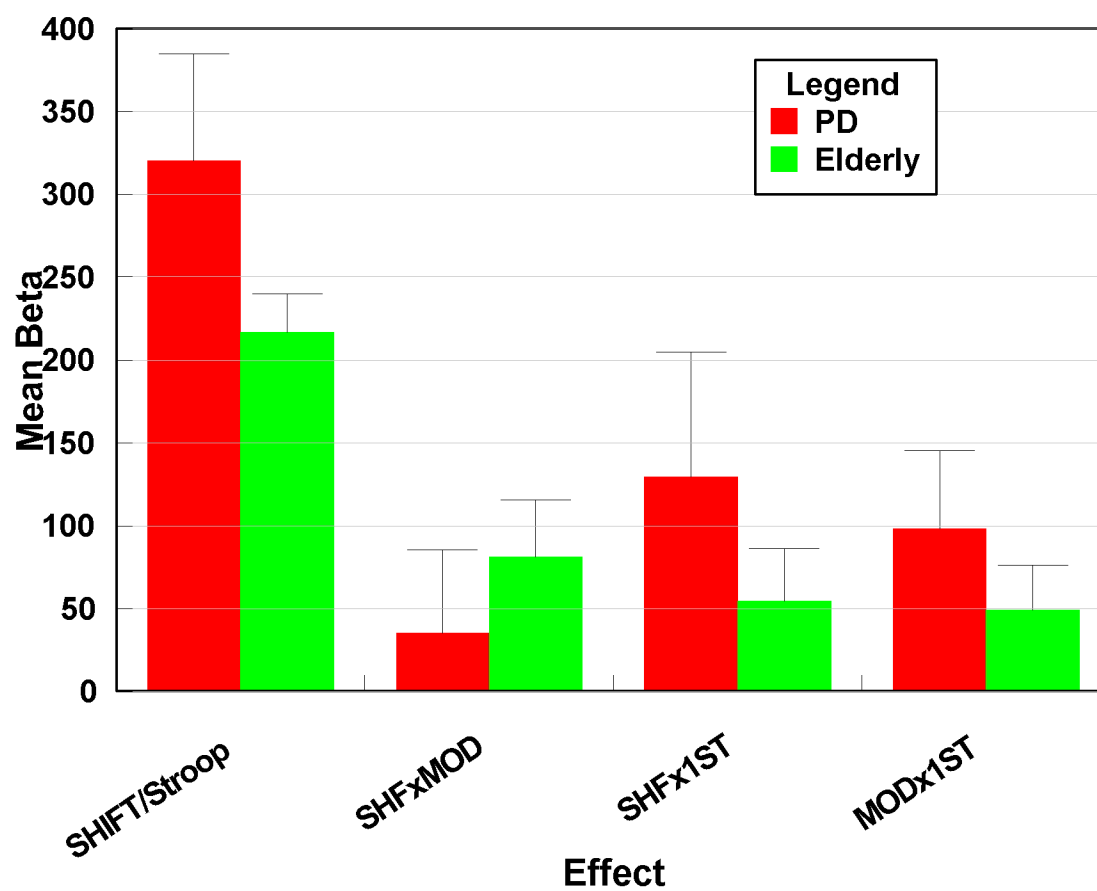


Figure 47. Comparison of Elderly and Parkinson's samples on color-naming effects (with 95% confidence intervals, interactions ignored).

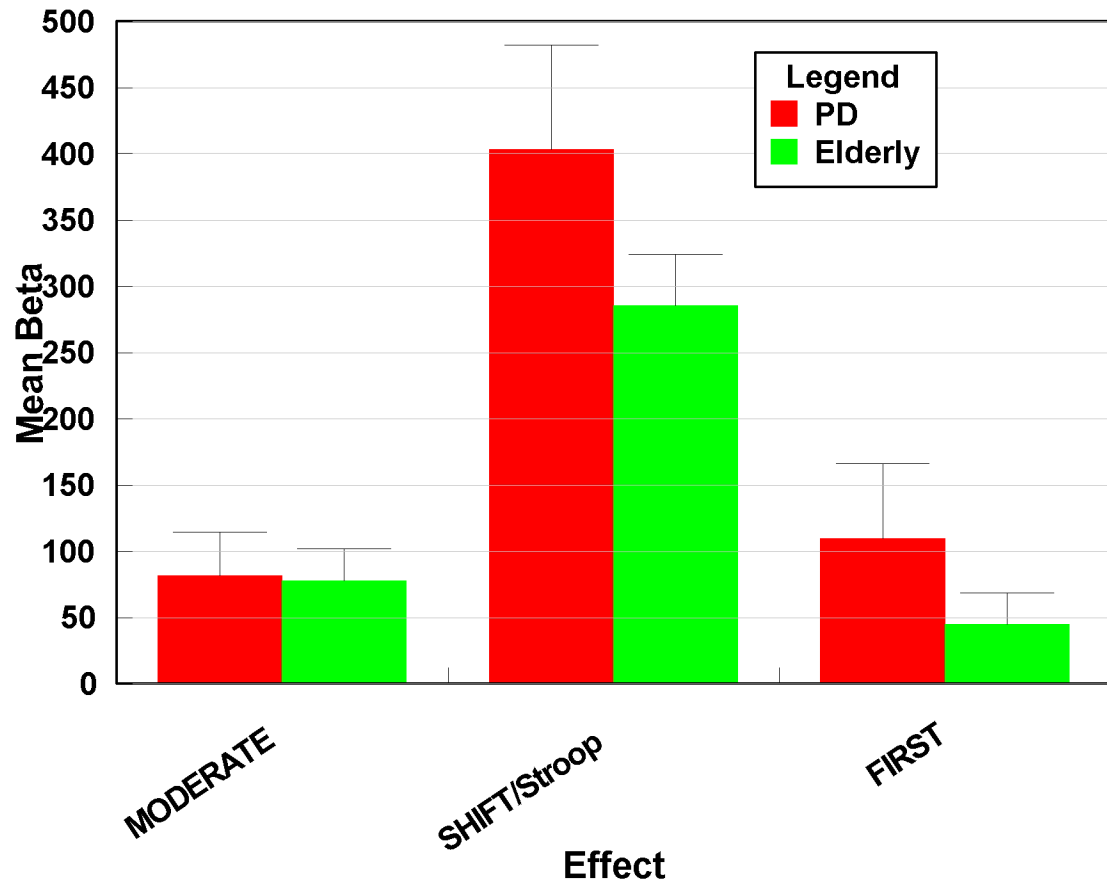


Figure 48. Resource Curve displaying deficit for PD compared to NE sample.

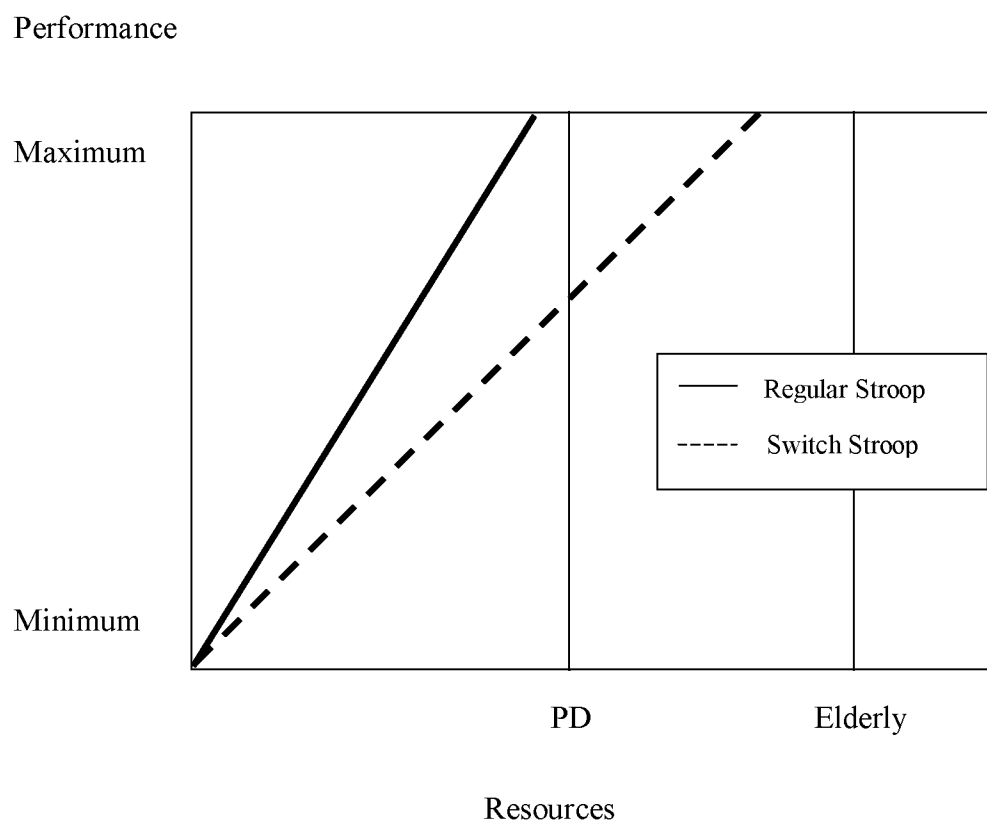


Figure 49. Word reading effects (NE) with 95% confidence intervals.

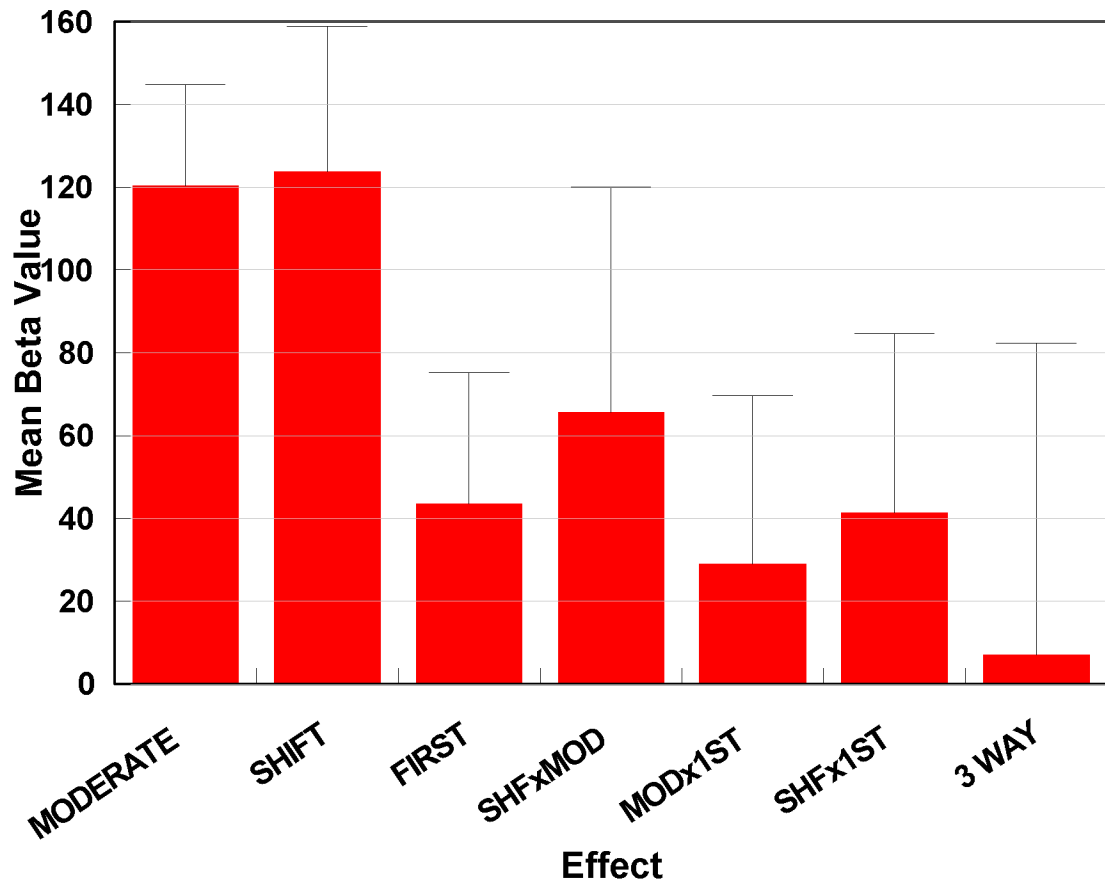


Figure 50. Word reading effects (NE vs. PSY100) with 95% confidence intervals.

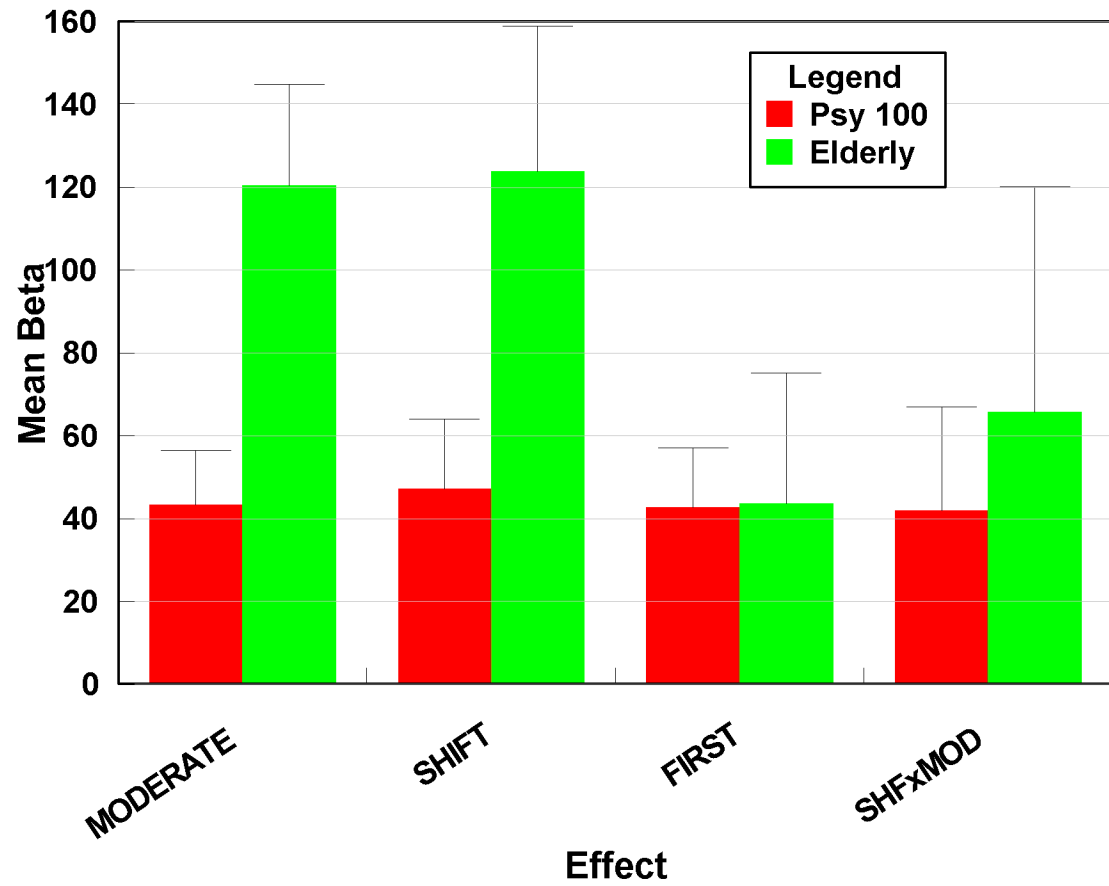


Figure 51. Word reading effects ignoring interactions (NE vs. PSY100) with 95% confidence intervals.

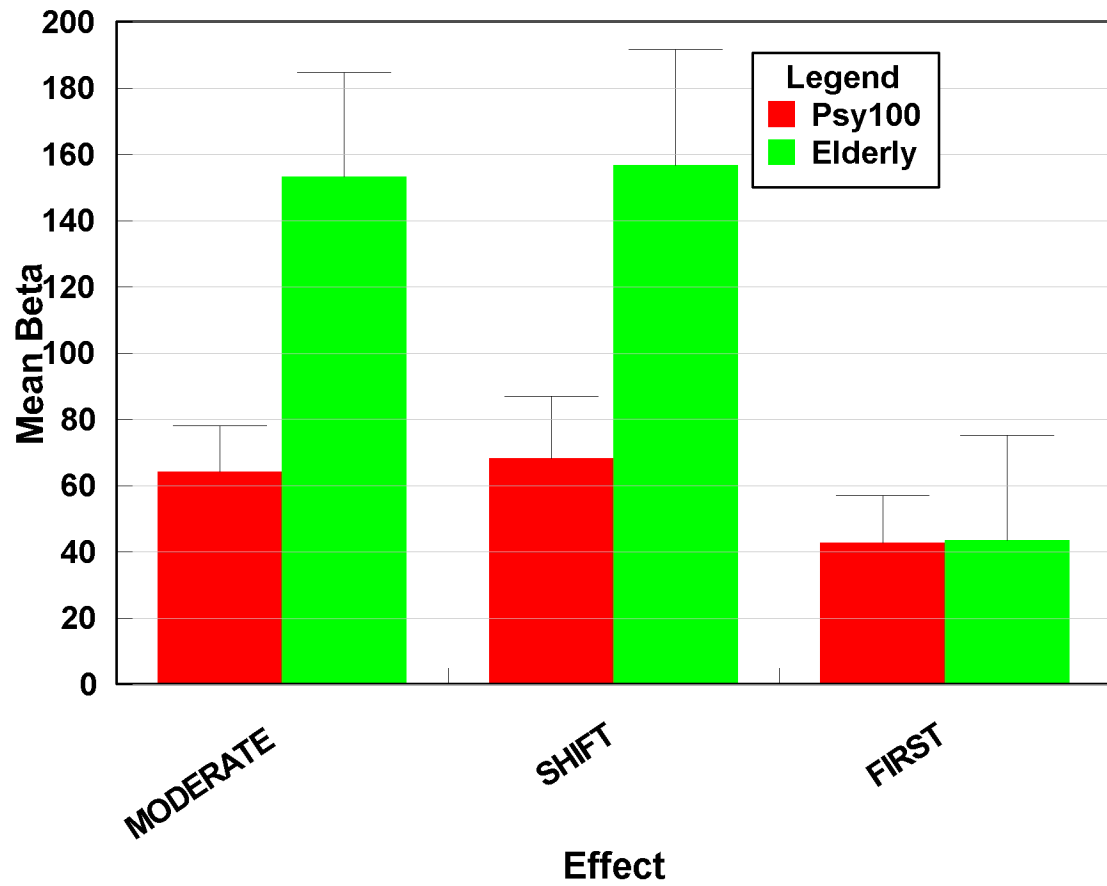


Figure 52. Color naming effects (NE) with 95% confidence intervals.

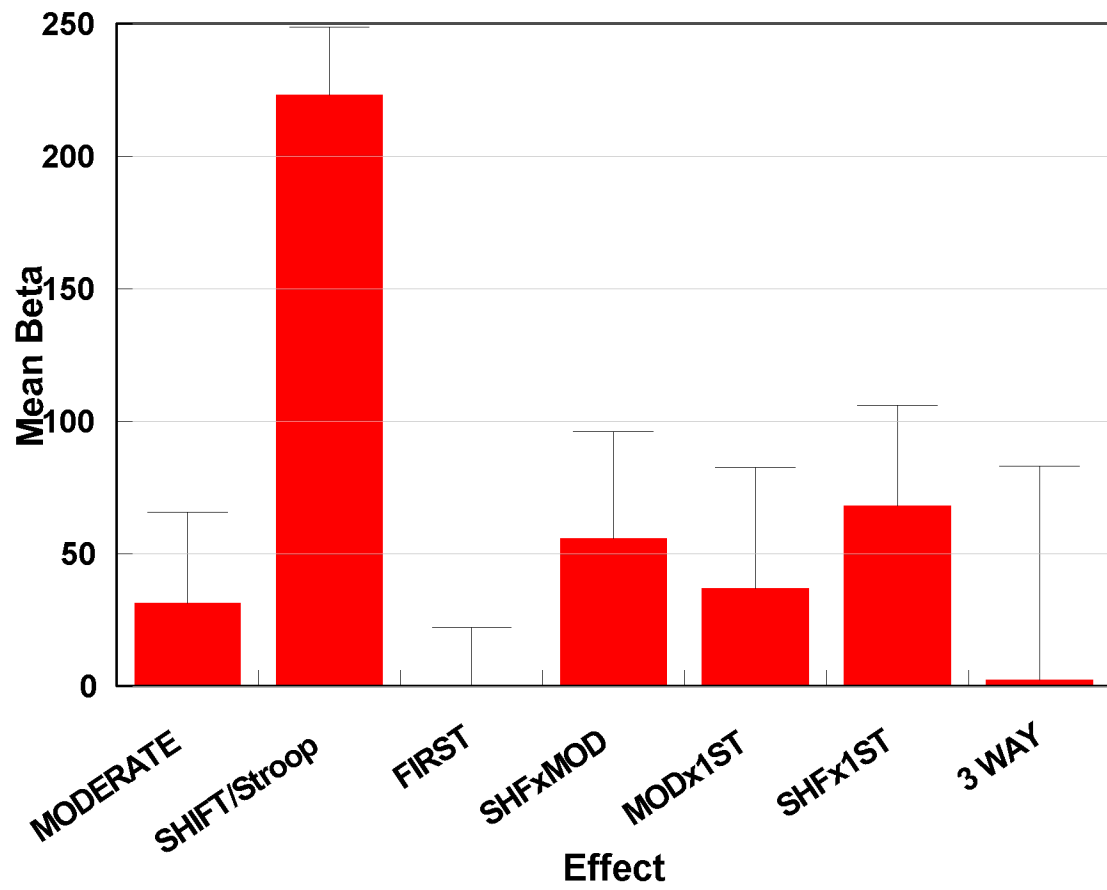


Figure 53. Color naming effects (NE vs. PSY100) with 95% confidence intervals.

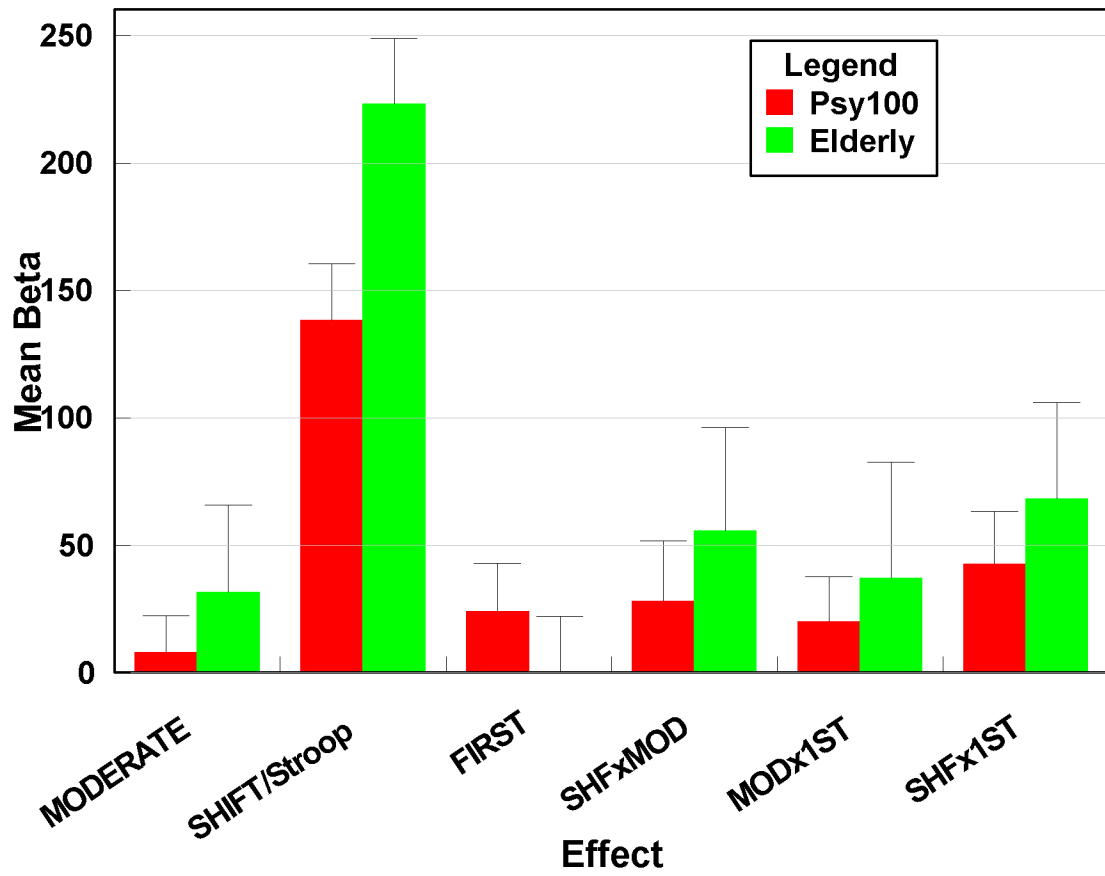


Figure 54. Color naming effects ignoring interactions (NE vs. PSY100) with 95% confidence intervals.

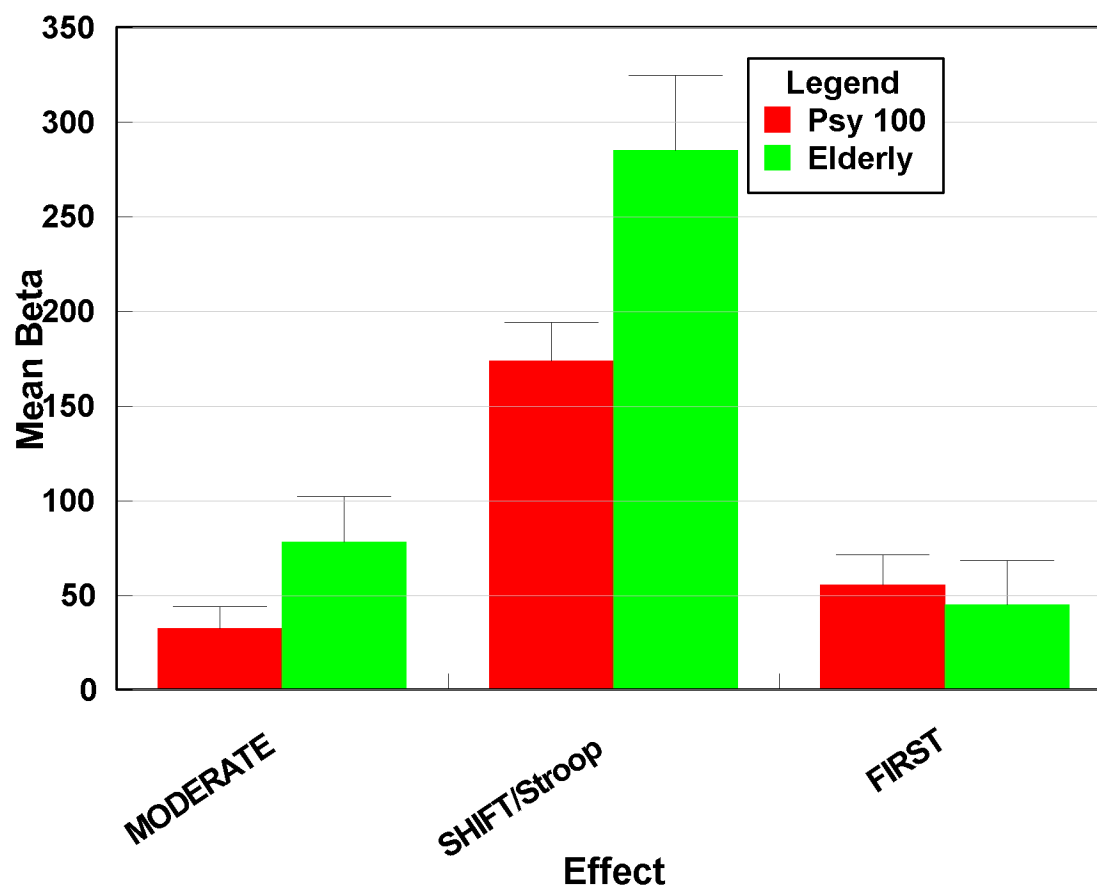
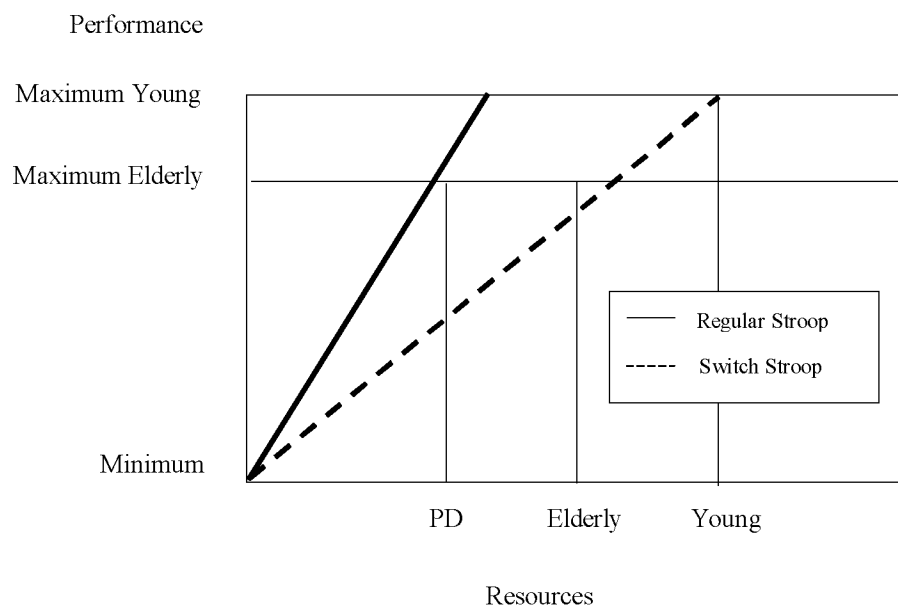


Figure 55. Resource Curve displaying deficit for PD, NE and PSY100 samples.



APPENDIX A - EFFECTS DETERMINING WORD READING RTS

- MODERATE – temporary inhibition of the word-reading task set
- SHIFT – shifting attention from the color to the word dimension
- FIRST – overcoming a general pre-response decrease in network activation
- SHFxMOD – a cost due to a sharing of SAS resources by MODERATE and SHIFT
- MODx2nd (DTS) – suppression of the dominant task in position two
- SHFx1st – overcoming a general pre-response decrease in SAS activation

Note. See Appendix C for an explanation of the homogeneity of the discrepancy term.

Word Reading Effects Present for each Pair

	MODERATE	SHIFT	FIRST	SHFxMOD	MODx2nd (DTS)	SHFx1st
<u>WiCi</u>	Yes	Yes	Yes	Yes	No	Yes
<u>CiWi</u>	Yes	Yes	No	Yes	Yes	No
<u>WiCn</u>	No	Yes	Yes	No	No	Yes
<u>CnWi</u>	No	Yes	No	No	No	No
<u>WnCi</u>	Yes	No	Yes	No	No	No
<u>CiWn</u>	Yes	No	No	No	Yes	No
<u>WnCn</u>	No	No	Yes	No	No	No
<u>CnWn</u>	No	No	No	No	No	No

Methods of Computation

Methods of Computing SHIFT

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
<u>CnWi</u> – <u>CnWn</u>	SHIFT	44.61 ms

Methods of Computing MODERATE

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
<u>WnCi</u> - <u>WnCn</u>	MODERATE	35.98 ms

Methods of Computing SHFxMOD

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using Pairs <u>WiCi</u> <u>WnCi</u> <u>WnCn</u> <u>WiCn</u>		
<u>(WiCi – WnCi) – (WiCn – WnCn)</u>	(SHIFT & SHFxMOD & SHFx1st) – (SHIFT & SHFx1st)	93.93 – 49.91 = 44.02 ms
<u>(WiCi – WiCn) – (WnCi – WnCn)</u>	(MODERATE & SHFxMOD) – MODERATE	80.00 – 35.98 = 44.02 ms
Using Pairs <u>CiWi</u> <u>CnWi</u> <u>CnWn</u> <u>CiWn</u>		
<u>(CiWi – CnWi) – (CiWn – CnWn)</u>	(MODERATE & SHFxMOD & DTS) – (MODERATE & DTS)	90.51 – 50.61 = 39.90 ms

$(\underline{CiWi} - \underline{CiWn}) - (\underline{CnWi} - \underline{CnWn})$	(SHIFT & SHFxMOD) - SHIFT	84.50 – 44.61 = 39.89 ms
Discrepancy Between Pair Set Computations		(4.12 ms)

Methods of Computing FIRST

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
$\underline{WnCn} - \underline{CnWn}$	FIRST	46.38 ms

Methods of Computing MODx2nd (DTS)

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using pairs \underline{CiWi} \underline{CnWi} \underline{WiCi} \underline{WiCn}		
$(\underline{WiCi} - \underline{CiWi}) - (\underline{WiCn} - \underline{CnWi})$	(FIRST & (DTS - SHFx1st)) – (FIRST & SHFx1st)	51.69 – 41.18 = 10.51 ms
$(\underline{CiWi} - \underline{CnWi}) - (\underline{WiCi} - \underline{WiCn})$	(MODERATE & SHFxMOD & DTS) – (MODERATE & SHFxMOD)	90.51 – 80.00 = 10.51 ms
Using Pairs \underline{WnCn} \underline{CnWn} \underline{WnCi} \underline{CiWn}		
$(\underline{WnCn} - \underline{CnWn}) - (\underline{WnCi} - \underline{CiWn})$	FIRST - (FIRST & DTS)	46.38 – 31.75 = 14.63 ms (reduces cost associated with First)
$(\underline{CiWn} - \underline{CnWn}) - (\underline{WnCi} - \underline{WnCn})$	(MODERATE & DTS) - MODERATE	50.61 – 35.98 = 14.63 ms
Discrepancy Between Pair Set Computations		(4.12 ms)

Methods of Computing SHFx1st

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using pairs \underline{WiCi} \underline{WnCi} \underline{CiWi} \underline{CiWn}		
$(\underline{WiCi} - \underline{WnCi}) - (\underline{CiWi} - \underline{CiWn})$	(SHIFT & SHFxMOD & SHFx1st) – (SHIFT & SHFxMOD)	93.93 – 84.50 = 9.43 ms
$(\underline{WiCi} - \underline{CiWi}) - (\underline{WnCi} - \underline{CiWn})$	(FIRST & (DTS - SHFx1st)) - FIRST & DTS	41.18 – 31.75 = 9.43 ms
Using pairs \underline{WiCn} \underline{CnWi} \underline{WnCn} \underline{CnWn}		
$(\underline{WiCn} - \underline{CnWi}) - (\underline{WnCn} - \underline{CnWn})$	(FIRST & SHFx1st) - FIRST	51.69 – 46.38 = 5.31 ms
$(\underline{WiCn} - \underline{WnCn}) - (\underline{CnWi} - \underline{CnWn})$	(SHIFT & SHFx1st) - SHIFT	49.91 – 44.61 = 5.30 ms
Discrepancy Between Pair Set Computations		(4.12 ms)

APPENDIX B - EFFECTS DETERMINING COLOR NAMING RTS

- MODERATE – temporary inhibition of the color-naming task set
- SHIFT/Stroop – shifting attention from the word to the color dimension, and the Stroop effect
- FIRST – overcoming a general pre-response decrease in network activation
- SHFxMOD – a cost due to a sharing of SAS resources by MODERATE and SHIFT
- MODx1st – overcoming a general pre-response decrease in SAS activation
- SHFx1st – overcoming a general pre-response decrease in SAS activation

Note. See Appendix C for an explanation of the homogeneity of the discrepancy term.

Color Naming Effects Present for each Pair

	MODERATE	SHIFT/ Stroop	FIRST	SHFxMOD	MODx1st	SHFx1st
<u>CiWi</u>	Yes	Yes	Yes	Yes	Yes	Yes
<u>WiCi</u>	Yes	Yes	No	Yes	No	No
<u>CiWn</u>	No	Yes	Yes	No	No	Yes
<u>WnCi</u>	No	Yes	No	No	No	No
<u>CnWi</u>	Yes	No	Yes	No	Yes	No
<u>WiCn</u>	Yes	No	No	No	No	No
<u>CnWn</u>	No	No	Yes	No	No	No
<u>WnCn</u>	No	No	No	No	No	No

Methods of Computation

Methods of Computing MODERATE

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
<u>WiCn</u> - <u>WnCn</u>	MODERATE	7.64 ms

Methods of Computing SHIFT/Stroop (Stroop)

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
<u>WnCi</u> - <u>WnCn</u>	SHIFT/Stroop	137.64 ms

Methods of Computing SHFxMOD

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using Pairs <u>WiCi</u> <u>WiCn</u> <u>WnCi</u> <u>WnCn</u>		
(<u>WiCi</u> - <u>WiCn</u>) - (<u>WnCi</u> - <u>WnCn</u>)	(SHIFT/Stroop & SHFxMOD) - SHIFT/Stroop	166.98 - 137.64 = 29.34 ms
(<u>WiCi</u> - <u>WnCi</u>) - (<u>WiCn</u> - <u>WnCn</u>)	(MODERATE & SHFxMOD) - (MODERATE)	36.98 - 7.64 = 29.34 ms
Using Pairs <u>CiWi</u> <u>CnWi</u> <u>CiWn</u> <u>CnWn</u>		
(<u>CiWi</u> - <u>CnWi</u>) - (<u>CiWn</u> - <u>CnWn</u>)	(SHIFT/Stroop & SHFxMOD & SHFx1st) - (SHIFT/Stroop & SHFx1st)	208.75 - 181.54 = 27.21 ms

$(\underline{C_iW_i} - \underline{C_iW_n}) - (\underline{C_nW_i} - \underline{C_nW_n})$	(MODERATE & SHFxMOD & MODx1st) – (MODERATE & MODx1st)	56.14 – 28.93 = 27.21 ms
Discrepancy Between Pair Set Computations		(2.13 ms)

Methods of Computing FIRST

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
$\underline{C_nW_n} - \underline{W_nC_n}$	FIRST	23.57 ms

Methods of Computing MODx1st

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using Pairs $\underline{C_iW_i}$ $\underline{C_iW_n}$ $\underline{W_iC_i}$ $\underline{W_nC_i}$		
$(\underline{C_iW_i} - \underline{C_iW_n}) - (\underline{W_iC_i} - \underline{W_nC_i})$	(MODERATE & SHFxMOD & MODx1st) – (MODERATE & SHFxMOD)	56.14 – 36.98 = 19.16 ms
$(\underline{C_iW_i} - \underline{W_iC_i}) - (\underline{C_iW_n} - \underline{W_nC_i})$	(FIRST & MODx1st & SHFx1st) – (FIRST & SHFx1st)	86.63 – 67.47 = 19.16 ms
Using Pairs $\underline{C_nW_i}$ $\underline{C_nW_n}$ $\underline{W_iC_n}$ $\underline{W_nC_n}$		
$(\underline{C_nW_i} - \underline{C_nW_n}) - (\underline{W_iC_n} - \underline{W_nC_n})$	(MODERATE & MODx1st) – (MODERATE)	28.93 – 7.64 = 21.29 ms
$(\underline{C_nW_i} - \underline{W_iC_n}) - (\underline{C_nW_n} - \underline{W_nC_n})$	(FIRST & MODx1st) – (FIRST)	44.86 – 23.57 = 21.19 ms
Discrepancy Between Pair Set Computations		(2.13 ms)

Methods of Computing SHFx1st

<i>Source</i>	<i>Contrasted Effects</i>	<i>Actual RT Difference</i>
Using Pairs $\underline{C_iW_i}$ $\underline{C_nW_i}$ $\underline{W_iC_i}$ $\underline{W_iC_n}$		
$(\underline{C_iW_i} - \underline{C_nW_i}) - (\underline{W_iC_i} - \underline{W_iC_n})$	(SHIFT/Stroop & SHFxMOD & SHFx1st) – (SHIFT/Stroop & SHFxMOD)	208.75 – 166.98 = 41.77 ms
$(\underline{C_iW_i} - \underline{W_iC_i}) - (\underline{C_nW_i} - \underline{W_iC_n})$	(FIRST & MODx1st & SHFx1st) – (FIRST & MODx1st)	86.63 – 44.86 = 41.77 ms
Using Pairs $\underline{C_iW_n}$ $\underline{C_nW_n}$ $\underline{W_nC_i}$ $\underline{W_nC_n}$		
$(\underline{C_iW_n} - \underline{C_nW_n}) - (\underline{W_nC_i} - \underline{W_nC_n})$	(SHIFT/Stroop & SHFx1st) – SHIFT/Stroop	181.54 – 137.64 = 43.90 ms
$(\underline{C_iW_n} - \underline{W_nC_i}) - (\underline{C_nW_n} - \underline{W_nC_n})$	(FIRST & SHFx1st) – (FIRST)	67.47 – 23.57 = 43.90 ms
Discrepancy Between Pair Set Computations		(2.13 ms)

APPENDIX C - HOMOGENEITY OF THE DISCREPANCY TERM

Using a series of RT differencing operations, additive effects that combined to determine any given RT difference for word reading or color naming were computed. The number of milliseconds that each operation takes to complete was also approximated. Moreover, reliability of these effects was assessed by checking agreement between effects that are, as a by-product of the experimental design, measured twice for each individual.

Note that the sets of pairs that are compared for the reliability check *do not overlap*. Four RT pairs are needed to compute any given effect size, and the remaining four pairs can be used to check the replicability of a given effect size. For example, the SHFx1st effect for color naming can be computed by differencing particular combinations of the following set of pairs: {CiWi CnWi WiCi WiCn}. This effect can also be computed by differencing combinations of the remaining four pairs: {CiWn CnWn WnCi WnCn}. The RT cost attributed to the SHFx1st operation using the first set of pairs was 41.77 ms. Using the latter set of pairs, the computed cost was 43.90 ms, a disagreement of only 2.13 ms.

A counterintuitive characteristic of these results was that the disagreement between effect measurements computed using non-overlapping sets of pairs (measured in milliseconds) was constant for all effects within one response type. Although this may appear curious at first glance, it can be explained as follows: all combinations of RT comparisons can be reduced to the following algebraic equation:

$$\varepsilon = x_8 - x_7 - x_6 + x_5 - x_4 + x_3 + x_2 - x_1, \quad (1)$$

where $x_8 = \underline{\mathbf{WiCi}}$, $x_7 = \underline{\mathbf{CiWi}}$, $x_6 = \underline{\mathbf{WiCn}}$, $x_5 = \underline{\mathbf{CnWi}}$, $x_4 = \underline{\mathbf{WnCi}}$, $x_3 = \underline{\mathbf{CiWn}}$, $x_2 = \underline{\mathbf{WnCn}}$, $x_1 = \underline{\mathbf{CnWn}}$ for word reading, $x_8 = \underline{\mathbf{CiWi}}$, $x_7 = \underline{\mathbf{WiCi}}$, $x_6 = \underline{\mathbf{CiWn}}$, $x_5 = \underline{\mathbf{WnCi}}$, $x_4 = \underline{\mathbf{CnWi}}$, $x_3 = \underline{\mathbf{WiCn}}$, $x_2 = \underline{\mathbf{CnWn}}$, $x_1 = \underline{\mathbf{WnCn}}$ for color naming, and ε represents the degree to which redundant information in the set of RTs disagrees due to measurement error (measured in milliseconds). For example, the SHFx1st effect mentioned above can be written using this notation by rearranging terms:

$$IW_{ts}1st = ((x_8 - x_7) - (x_4 - x_3)) - ((x_6 - x_5) - (x_2 - x_1)). \quad (2)$$

All word reading and color naming effects introduced below can be represented in this way, by assigning RTs to the corresponding algebraic terms.

Although the RT sets appear contain redundant information, this does not imply that the same RTs are being recycled in any way, but that the same effects are being repeatedly measured. The differencing procedures give a measure of the reliability of the effects by comparing their size. The greater the unreliability of the effects, the larger the ε term.

Equation 1 demonstrates that all the effects must be used at least once to explain the RTs associated with set of pairs $\{x_8 = \underline{\mathbf{WiCi}}$, $x_5 = \underline{\mathbf{CnWi}}$, $x_3 = \underline{\mathbf{CiWn}}$, $x_2 = \underline{\mathbf{WnCn}}\}$, and that the RTs of $\{x_7 = \underline{\mathbf{CiWi}}$, $x_6 = \underline{\mathbf{WiCn}}$, $x_4 = \underline{\mathbf{WnCi}}$, $x_1 = \underline{\mathbf{CnWn}}\}$. For each of these sets, SHIFT is measured twice, MODERATE is measured twice, SHFxMOD is measured once, FIRST is measured twice, DTS is measured once and SHFx1st is measured once. Any difference in the RTs attributable to these effects is captured in the term ε from equation 1. Moreover, when any effect is isolated, and that common to the comparison sets

subtracted out, the error term is attributed to the difference between the sets of pairs, or, in other words, to the effect of interest. That is why the same error term is associated with all effects.

Because the effects determining the speed of word reading are not the same as those determining the speed of color naming, they are reported separately. For color naming reliability checks, $\epsilon=2.13$ ms, while for word reading reliability checks $\epsilon = 4.12$ ms.

APPENDIX D - GENERAL DEMOGRAPHIC QUESTIONNAIRE

In order to better understand the results of our study, I'd like to ask you a few questions about yourself and your background. We will use this information for research purposes only, and it will be kept strictly confidential.

1. Gender (circle one): Male Female
2. What is your birthdate? _____
 What is your current age? _____ years
3. Which hand do you write with? (circle one) Right Left Both
4. What is the highest level of full-time education that you have completed?
 (circle one)
 (Do not include part-time or extension courses taken for interest.)

Grade School	1 2 3 4 5 6 7 8
High School	9 10 11 12 13
Technical, trade, nursing or business school	1 2 3 4 5 6 7 8
University (B.A./B.Sc.)	1 2 3 4 5 6 7 8
Graduate School (M.A./M.Sc./Ph.D.)	1 2 3 4 5 6 7 8
5. What is your first language? _____

Now I would like to ask you some questions about your health.

6. Are you presently taking any drugs or medications (prescription or other)?
 (circle one)
 - a. Yes

What are your current medications?

 - b. No

APPENDIX E - QUESTIONS SPECIFIC TO PARKINSON'S DISEASE

1. How old were you when you were told that you had PD?
_____ years old
2. What is the name and qualification of the doctor who provided you with the diagnosis?
_____ Family Dr./ Neurologist / other specialist? (circle as appropriate)
3. Are you receiving any drug treatment for PD at the present time?
(circle yes or no)
 - a. Yes

Circle the names of the medications you are receiving.

Sinemet Prolopa Bromocriptine Parlodel Pergolide Deprenyl Artane other _____
 - b. No
4. Do you feel that your present drug treatment is: (circle one)
 - a. Helping considerably?
 - b. Helping moderately?
 - c. Making no difference?
 - d. Making you worse?
 - e. Making you very much worse?
5. Which of the following descriptions is appropriate for your reaction to drug treatment:
 - a. The medication is effective for a few hours only, then “wears off” noticeably.
 - b. I experience frequent fluctuations in my ability to perform physical activities, unrelated to the timing of my medications (“on-off effects”)
 - c. My medication provides predictable and consistent relief from Parkinsonian symptoms.
 - d. None of the above.
6. How many hours have passed since you last took your Parkinson’s pills ? _____
7. Are you noticing wearing off of the drug right now?
8. What other side or unwanted effects do you feel you are getting from your present treatment, if any?

I would like you to think about various aspects of your health during the last six months. Think throughout these questions of how you are when you are feeling at your worst. Please rate the difficulty of each task on a scale of 1 - 5, where 5 is the most difficult.

- a. Writing

1 2 3 4 5
 no difficultygreat difficulty

Describe writing difficulties (Circle any that apply).

Getting Started

Progressively smaller letters

Stopping

Other: _____

b. Walking

1 2 3 4 5
 no difficulty.....great difficulty

Describe walking difficulties (Circle any that apply)

Getting Started

Stopping

Taking very short steps

Getting stuck in one spot

Poor balance

Other: _____

c. Negotiating doorways or walking in confined spaces

1 2 3 4 5
 no difficulty.....great difficulty

d. Sitting down

1 2 3 4 5
 no difficulty.....great difficulty

e. Getting out of chairs

1 2 3 4 5
 no difficulty.....great difficulty

f. Getting into bed

1 2 3 4 5
 no difficulty.....great difficulty

g. Getting out of bed

1 2 3 4 5

no difficulty.....great difficulty

h. Turning over in bed

1 2 3 4 5
no difficulty.....great difficulty

i. Speaking clearly

1 2 3 4 5
no difficulty.....great difficulty

Which of the following symptoms do you experience? Please rate how severely they affect you on a scale of 1 - 5, where 5 is the most severe.

a. Tremor (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

b. Rigidity (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

c. Slowness of movement (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

d. "Freezing" (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

e. "Sticky" movement (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

f. Difficulty starting a movement (which limb(s)?) _____

1 2 3 4 5
no effectvery severe

g. Difficulty stopping a movement (which limb(s)?) _____

1 2 3 4 5

no effectvery severe

h. Slowness of thinking

1 2 3 4 5
no effectvery severe

i. Memory Loss

1 2 3 4 5
no effectvery severe

APPENDIX F - MINI MENTAL STATUS EXAMINATION

Orientation

What is the (date) (day) (month) (year) (time)? 5 points

Where do you live? (city) (province) (country) (Street) (house number)? 5 points

Registration

I am going to name 3 objects. Then I want you to repeat all 3 after I have said them. (apple, penny, table) 1 point for each correct. 3 points

Attention and Calculation

Count backwards from 100 by 7's; start with 100 and subtract 7 each time (93, 86, 79, 72, 65). 1 point for each correct. Stop at 5 answers. 5 points

OR: Spell WORLD. Now spell WORLD backwards (DLROW). 1 point for each correct. 5 points

Recall

What were the three objects I asked you to name a while ago? 1 point for each correct. 3 points

Language Tests

What is this? (pencil/pen, watch) 2 points

Repeat after me: "No ifs, ands, or buts" 1 point

Follow this command: "Take the paper in your right hand, fold it in half, and put it on the table." 3 points

Read and obey what it says on this card: CLOSE YOUR EYES. 1 point

Write a short sentence that contains a subject, a verb, and that makes sense. 1 point

Copy the design that is on this card. 1 point

TOTAL 30 POINTS

APPENDIX G - GERIATRIC DEPRESSION SCALE

1. Are you basically satisfied with your life? yes/no
2. Have you dropped many of your activities and interests? yes/no
3. Do you feel that your life is empty? yes/no
4. Do you often get bored? yes/no
5. Are you hopeful about the future? yes/no
6. Are you bothered by thoughts you can't get out of your head? yes/no
7. Are you in good spirits most of the time? yes/no
8. Are you afraid that something bad is going to happen to you? yes/no
9. Do you feel happy most of the time? yes/no
10. Do you often feel helpless? yes/no
11. Do you often get restless and fidgety? yes/no
12. Do you prefer to stay at home rather than going out and doing new things? yes/no
13. Do you frequently worry about the future? yes/no
14. Do you feel you have more problems with memory than most? yes/no
15. Do you think it is wonderful to be alive now? yes/no
16. Do you often feel downhearted and blue? yes/no
17. Do you feel pretty worthless the way you are now? yes/no
18. Do you worry a lot about the past? yes/no
19. Do you find life very exciting? yes/no
20. Is it hard for you to get started on new projects? yes/no
21. Do you feel full of energy? yes/no
22. Do you feel that your situation is hopeless? yes/no
23. Do you think that most people are better off than you are? yes/no
24. Do you frequently get upset over little things? yes/no
25. Do you frequently feel like crying? yes/no
26. Do you have trouble concentrating? yes/no
27. Do you enjoy getting up in the morning? yes/no
28. Do you prefer to avoid social gatherings? yes/no
29. Is it easy for you to make decisions? yes/no
30. Is your mind as clear as it used to be? yes/no