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A dual task account of non-color word interference on color naming

Michael Reynolds[1], Claudio Mulatti[2], Francesca Peressotti[2], Remo Job[3], & Roberto DellôAcqua[2]

[1] Trent University, Canada

[2] University of Padova, Italy

[3] University of Trento, Italy

Corresponding Author:
Claudio Mulatti
DPSS ï University of Padova
Via Venezia, 8
35131 Padova ï IT
Phone: +39 049 827 6564
Fax: +39 049 827 6511
Email: claudio.mulatti@unipd.it
Web: http://colab.psy.unipd.it

Abstract

The color-word interference task, a variant of the Stroop task, requires participants to name the ink-color (e.g., ñredò) of non-color words (e.g., ñcatò) while ignoring the identity of the words. The standard finding is that the time to name the ink-color is affected by factors known to affect how long it takes to read aloud the non-color word (e.g., word frequency). Here, we propose that performance in this task is best understood using a dual-task framework. According to this account, the color-word interference task consists of an overt color naming task (word production) and a covert word reading task. Each of these tasks contains processes that compete for access to the same resource limited system. Four experiments are reported testing the predictions of the dual-task framework using the so-called cognitive-slack logic. The dual-task framework successfully accounts for six effects in the color-word interference task.

Introduction

The Stroop task has been widely employed as a tool for gaining insight into cognitive processing (Stroop, 1935). In the present study, we examine a variant of the Stroop task in which the meaning of distractor words does not have a congruent/incongruent relationship with the ink-color (e.g., Klein, 1964; Warren, 1974). We refer to this variant as the Color-Word Interference (CWI) task. The purpose of the present paper is to assess whether conceptualizing the CWI task as a dual-task situation provides a useful framework for thinking about how the properties of a distractor word affect color naming performance.

What makes the CWI task so interesting is that the time to report the ink-color is affected by properties of the distractor word despite the absence of any benefit from doing so. Indeed, recent evidence suggests that *virtually all* factors that affect how long it takes to recognize visually presented distractor words affect how long it takes to report the color. For instance, it takes longer to report the ink color for nonword distractors than for word distractors (Burt, 2002; Monsell, Taylor, & Murphy, 2001) and the time to name the ink-color is faster for words that have been repetition primed than for control words (Burt, 1994). One of the seminal observations in the color-word interference literature is that the time to identify the ink-color is affected by how frequently the distractor word is encountered in print (Burt, 1994, 1999, 2002; Fox, Schor, & Steinman, 1971; Klein, 1964; Monsell et al., 2001). Despite early work suggesting that high-frequency words yield greater interference than low-frequency words (i.e., Fox et al., 1971; Klein et al., 1964), more recent evidence seems to suggest that the opposite is true. That is, the ink-color is identified faster for high-frequency words than for low-frequency words (Burt, 1994; 1999; 2002; Monsell et al., 2001). An effect that has also been observed in the context of picture naming (Miozzo & Caramazza, 2003).

Accounts of the CWI task have changed over the last 30 years but they all propose that (1) information about the color and the word are processed in parallel and (2) the output from these systems interfere during response selection. Consider Warrenӧs initial framing of the distractor word-frequency effect in terms of a horse-race model (Warren, 1972; 1974). In this account, word and color dimensions of the stimulus are processed in parallel. The output from these parallel processes is passed to a capacity limited response buffer that can deal with only a single response at a time. When the word response enters the response buffer *before* the color response, there is a delay while the inappropriate response (i.e., the response to the word) is unloaded from the buffer. This model accounted for Kleinӧs (1964) initial observation that high-frequency distractor words interfere more than low-frequency distractor words because high-frequency distractors will reach the response-buffer faster than low-frequency distractors and therefore have a greater chance of entering the buffer before of the color name. Obviously, the recent demonstrations that high-frequency words interfere less than low-frequency words are inconsistent with the horse race model as conceptualized by Warren.

An alternative account of task performance in the color-word interference task is in terms of competing task sets (Monsell et al., 2001). According to this account, the CWI task requires configuring the cognitive system to ignore the word and focus on the color. The word continues to affect performance, however, because reading is an over-practiced task the presentation of a word exogenously drives the activation of the associated task set of reading. The partial activation of the *task set of reading* competes with the activation of the *task set of color naming* and interferes with the process of mapping the visual representation of the color into the corresponding name. This explains why a color patch alone is named faster than a color patch with a superimposed distractor (e.g., Klein, 1964).

Although subsequent research has provided converging evidence that performance in the standard Stroop task is affected by task set interference (Steinhauser & Hubner, 2009), task set interference by itself has difficulty explaining faster performance for high frequency words than for low frequency words.   Monsell et al. (2001) suggested that distractor specific effects could arise if task set is conceptualized as a type of filter that reduces the probability of a stimulus eliciting a response tendency. When a distractor makes it through the filter and results in the computation of a phonological code, additional competition will need to be resolved by the response selection mechanism leading to slower performance.

Given that faster colour naming responses were observed for high frequency words compared to low frequency words, Monsell et al. discussed two ways in distractor word frequency could affect competition in the response mechanisms. One the one hand, they noted that since high-frequency words are processed faster than low-frequency words, high-frequency distractor words are dealt with faster than low-frequency distractor words (Miozzo & Caramazza, 2003; Mulatti & Coltheart, 2011). On the other hand, they also note that because the high frequency words should be activated more strongly, they should be more difficult to reject (as suggested by Warren (1972, 1974) and by strength of association accounts of the standard Stroop task (Cohen, Dunbar, & McClelland, 1990). Thus at present, although it is possible to incorporate item specific effects into the task set account, it does not explicitly predict a specific effect of distractor word frequency.

Given that there are now several demonstrations that the time to name the ink-color is faster for high frequency words than low frequency words (Burt, 1994, 1999, 2002) and converging evidence for this effect from picture naming (Miozzo & Caramazza, 2003) here we propose a new account of performance in the CWI task that predicts faster responses to the ink color in the presence of high frequency compared to low frequency words. According to this account, the CWI task consists of a covert task that involves retrieval of the printed word's phonology (word reading) and an overt task that involves retrieval of the color's name (color naming / word production). This dual-task conceptualization of performance in the CWI task is similar to other accounts insofar as performance arises from two parallel processing streams – one for the color and one for the distractor word and can be seen as an extension of the task set account proposed by Monsell et al. (2001). Unlike previous accounts, however, the dual-task framework emphasizes the consequences of both processes requiring access to a limited capacity processing mechanism. The goal of the present paper is to propose this account and examine its explanatory power.

The Psychological Refractory Period (PRP) paradigm

One of the most widely employed experimental methods for examining dual-task performance is the Psychological Refractory Period (PRP) paradigm (Johnston, McCann, & Remington, 1995; Pashler, 1984, 1991, 1994; Telford, 1931). This dual-task methodology employs two speeded tasks. The stimuli for each task are typically presented asynchronously with the stimuli associated with Task1 presented before the stimuli for Task2. Subjects are instructed to give priority to Task1 but to perform both tasks as quickly and accurately as possible. The stimuli for each task are typically selected from different sense modalities (e.g., visual and auditory) in order to avoid limitations of the sensory apparatus (e.g., having to look at two different spatial locations at the same time). Similarly, the response for each task typically utilizes different effectors (Meyer & Kieras, 1997; Pashler, 1984). When these conditions are met, it is assumed that the tasks avoid processing overlap in peripheral input and output systems. As such, it is possible to examine performance in both tasks as a function of the stimulus onset asynchrony (SOA) and make inferences about the central (i.e., post-sensory and pre-motor) processing capacity demands of both tasks (Footnote 1).

The standard finding in the PRP paradigm is that as SOA decreases, the time to respond to Task2 increases, whereas response times to Task1 remain largely constant (see Tombu & Jolicouer, 2003). The dramatic increase in Task2 performance is attributed to both tasks using the same central cognitive resource and part of the second task being temporally postponed while having to wait for the central resource to become available (Meyer & Kieras, 1997; Navon & Miller, 2002; Pashler, 1994; Tombu & Joliceour, 2003) [Footnote 2].

[Figure 1 about here]

In addition to producing an effect that many have found interesting *per se*, the PRP paradigm has also been used as a tool to localize the stage of processing affected by a specific factor manipulation. The most commonly used approach for framing how factors will affect performance when the tasks are performed simultaneously is the so-called cognitive-slack logic (McCann & Johnston, 1992; Pashler & Johnston, 1989). According to cognitive-slack logic, the effect of a variable that occurs before the bottleneck in Task2 will be absorbed into the slack created while waiting for the bottleneck to be released by Task1 (see Figure 1A). Therefore, if a variable affects Task2 performance before the bottleneck, its effect will be eliminated when the tasks are performed concurrently (i.e., the effect will be underadditive with decreasing SOA). In contrast, if the effect of a variable affects Task2 performance at or after the bottleneck, then it will be unchanged when the tasks are performed concurrently (i.e., the effect will be additive with decreasing SOA). The joint effects of SOA with a Task2 variable on Task2 performance can therefore provide insight into when in the processing stream a variable is having its effects ï the persistence of an effect when the two tasks overlap would suggest that the process likely uses a limited capacity processor, and the elimination of an effect in Task2 when the tasks are performed concurrently suggests an early effect.

Cognitive-slack logic in the context of the PRP paradigm has been used to examine the widely held assumption that skilled visual word recognition occurs automatically, independent of attention or other processing limitations. To test this assumption a number of studies have examined the joint effects of variables known to affect lexical processing and SOA in Task2 of the PRP paradigm (McCann & Johnston, 1992; McCann, Remmington, & Van Selst, 2000; OÕMalley, Reynolds, Stolz, & Besner, 2008; Reynolds & Besner, 2006). In these studies it was hypothesized that if lexical processing did not require a limited capacity processing system, then the effects of lexical variables will have their effects prior to the bottleneck and therefore should be absorbed into cognitive-slack. Inconsistent with this prediction, the effects of lexical variables were shown to be additive with SOA suggesting that lexical processing during visual word recognition requires the central processing bottleneck. Overall, studies examining written language suggest that the translation of orthographic representations into phonological representations in single word reading requires, or occurs after, the central processing bottleneck (McCann, Remmington, & Van Selst, 2000; OÕMalley, Reynolds & Besner, 2007; Reynolds & Besner, 2006).

[Figure 2 about here]

In order to discriminate between central and late processes it is necessary to manipulate a factor in Task1 and assess whether or not it carries forward to Task2 when the two tasks are performed concurrently. The reason for the carry forward of this delay is illustrated in Figure 2. As can be seen in the figure, a factor that affects either early processing (Figure 2A) or central processing (Figure 2B) in Task1 will carry forward to Task2, whereas a factor affecting post-central processing in Task1 will not carry forward to Task2 (Figure 2C).

A seminal application of this technique was reported by Ferreira and Pashler (2002). In their study, Task1 was picture-word naming and Task2 was tone discrimination. A common finding is that people take longer to name the picture when the distractor word is semantically related to the picture and are faster to name the picture when the distractor is phonologically related to the picture name. According to theories of word production semantic interference effects occur prior to phonological facilitation. In order to test this assumption Ferreira and Pashler (2002) reported two experiments in which picture naming was Task1. They found that semantic interference effects observed in Task1 propagated on to Task2 at a short SOA, whereas phonological facilitation did not propagate forward to Task2. This suggests that semantic interference occurs either before or during the bottleneck, whereas phonological facilitation arises at post-central stages of processing (see also Ayora, Peressotti, Alario, Pluchino, Job, & DellôAcqua, 2011; DellôAcqua, Job, Peressotti, & Pascali, 2007).

Overall, the data from PRP studies of language suggest that both word reading and word production require a limited capacity processing bottleneck and that this bottleneck corresponds to lexical processing. These findings have clear implications for an account of the CWI effect that presupposes performance in the task arises because people are concurrently performing a word reading and a word production task.

Color-Word Interference as Dual-Task Interference

Here we use cognitive-slack logic to assess whether new insight into the CWI task can be gained by conceptualizing it as a dual-task situation (with a covert task ï i.e., word reading ï and an overt task ï i.e., word production) where both tasks are being performed at the same time.

The observation that word reading and word production both require access the central processing bottleneck has clear implications for performance in a dual-task account of the CWI task. One implication is that the visual word recognition and word production processing streams will compete for access to the central processing bottleneck. Furthermore, the observation that *lexical* processing in visual word recognition and word production requires access to the same limited capacity mechanism has specific implications for performance in the CWI task.

Interestingly, one assumption that must be made by the dual-task interpretation of the CWI task is that word reading must gain access to the processing bottleneck first. This is necessary to explain two well-established findings (1) the observation that people take longer to identify the color in the presence of a distractor word (Klein, 1964, Monsell et al., 2001), and (2) the observation that color naming latencies are affected by the frequency of the distractor word (Burt, 1994, 1999, 2002; Fox et al., 1971; Klein, 1964; Monsell et al., 2001). The rationale is illustrated in Figure 1B. As can be seen in the figure, if color naming serves as Task1 and is therefore given priority access to the central bottleneck, then performing the two tasks simultaneously will not affect how long it takes to perform the color naming task. As can be seen in Figure 1, this arises because central processes in Task2 do not affect the time to respond to Task1. This suggests that in order to yield an increase in color naming responses in the presence of a distractor word, the distractor word must be given priority and treated as Task1. In this way, word frequency, which affects the central processing bottleneck, would affect color naming responses: The effect of word frequency carries forward because color-naming waits for the bottleneck to become available. This can be seen in Figure 2B.

The experiments reported here test three predictions of the dual task account derived using cognitive-slack logic. Experiment 1, tests the prediction that increasing the duration of bottlenecked stage of distractor processing will affect color naming response times. Experiment 2 tests the prediction that factors affecting response selection in both processing streams should yield additive effects. Experiments 3 and 4 test the critical assumption that distractor processing gains priority access to the processing bottleneck.

Experiment 1

The present experiment assesses whether the time to report the ink-color of a target is affected by how frequently a distractor word occurs in print. Early research examining the effects of distractor frequency on color naming reported that low-frequency words yielded less interference than high-frequency words inconsistent with the predictions of the dual-task account (Fox et al., 1971; Klein, 1964). However, more recent work has found either null effects (Burt, 1994; 1999) or less interference for high-frequency words compared to low-frequency words (Burt, 1994; 1999; 2002; Monsell et al., 2001). That said, faster color naming performance for high- compared to low-frequency words reported by Burt (1994; 1999; 2002) occurred in the context of a priming design. Furthermore, although Monsell et al. (2001) consistently reported faster color naming times for high-frequency items, the effect was not always statistically significant.

Resolving this ambiguity surrounding how the frequency of the distractor affects performance in the CWI task is important because the dual task account predicts that responses should be faster in the presence of high-frequency distractors than low-frequency distractors. This is made clear in Figure 2B. If word reading functions as Task1, then manipulating the bottlenecked process in word reading will carry forward to the color naming task (Task2). Evidence suggests that lexical processing during word reading is a central process (e.g., McCann et al., 2000; Reynolds & Besner, 2006). Therefore a manipulation of lexical processing of the distractor word should directly affect how long people take to report the ink-color. One factor known to affect the duration of the central stage of distractor processing is the distractorõs printed word frequency (McCann et al., 2000). Since high-frequency distractor words should occupy the central processor for a shorter period of time than low-frequency distractor words, the prediction is that color naming will be faster for high-frequency compared than low-frequency distractor words. Here we test this prediction using a novel set of stimuli and a different language (Italian).

Method

Participants. Nine students at the University of Padova participated in the experiment. The subjects were paid or received course credit for their participation. All subjects had normal or corrected-to-normal acuity, normal color vision, and none reported a history of prior neurological disorders. The procedures used in Experiments 1 to 4 were approved by the Ethical Committee of the University of Padova. Verbal consent was obtained from each participant before the beginning of each of the present Experiments, as required by the Regulation of the Ethical Committee regarding cognitive/behavioral studies involving adult human participants.

Materials. Ninety-two words were selected from the COLFIS database (Laudanna, Thornton, Brown, Burani, & Marconi (1995). Half of them were high-frequency words (mean printed frequency of occurrence: 405.7 / million; range: 212.4ï808.2) and half were low-frequency words (mean printed frequency of occurrence: 0.7 / million; range: 0.3ï1.3). High- and low-frequency words were balanced in terms of number of letters (6.6 vs. 6.6, $t < 1$), number of syllables (2.7 vs. 2.7, $t < 1$), and orthographic neighborhood size (4.0 vs. 3.8, $t < 1$). Words were displayed in one of four possible colors (i.e., yellow, blue, green, and red) on a uniformly black background. Phonological overlap between the name of the color and the phonology of the distractor was avoided at run-time by reiterating the randomization of the experimental list whenever the first two letters of the words matched the first two letters of the color. This algorithm was used in all present Experiments.

Apparatus. The experiment took place in a sound attenuated and dimly lit room. The stimuli were displayed on a 17ò cathode-ray tube monitor controlled by a 686 IBM-clone and E-prime software. The onset of vocal responses was detected using a high-impedance microphone connected to the apparatus. This apparatus was used in all present Experiments.

Procedure. Participants were tested individually. On each trial, a fixation point (+) was presented for 500 ms at the center of the monitor. Following the fixation offset, a blank screen was displayed for 80 ms, followed by the presentation of the stimulus, that remained visible until a vocal response was detected or 3 s elapsed. Participants were instructed to name the color of the words as quickly and accurately as possible, disregarding the wordsô meaning. The experiment was conducted with the constant presence of an experimenter who scored each response as correct, incorrect (including inadvertent sounds other than colorôs name), or a mistrial (e.g., voice-key failure). The experimental session was preceded by a brief practice session including 22 trials with stimuli that were not part of the experimental stimulus set. The stimuli were presented in a different random order for each participant.

Results

Naming errors and apparatus failures (1.1%) were removed prior to analysis. Correct reaction times (RTs) were submitted to Van Selst and Jolicî urôs (1994) outlier removal procedure, resulting in the elimination of 1.5% of trials. Separate pairwise comparisons via t-test were conducted on individual mean RTs and proportion of naming errors, considering word frequency (high vs. low) as factor. In the present and following experiments, Studentôs t statistics are reported as absolute values.

RTs. Color naming was significantly faster with high-frequency words (568 ms) than with low-frequency words (583 ms), t(8) = 2.9, p < .05.

Percentage Error. The 0.1% difference in errors between trials with high- frequency distractor words (1.0%) and trials with low- frequency distractor words (1.1%) was not reliable (t < 1).

Discussion

The aim of the present experiment was to test a fundamental prediction of the dual-task account of the CWI task, namely, that high-frequency distractor words interfere less than low-frequency distractor words. The results were in line with this prediction. According to the dual-task account, the CWI task consists of a covert task (word reading) and an overt task (color naming) that both require central processing resources, with the word reading task gaining access to the central processor first. Given that word frequency affects central processing (Ferreira & Pashler, 2002; McCann et al., 2000), high-frequency distractor words clear the central processor earlier than low-frequency distractor words. As a consequence, central resources can be allocated to color processing earlier in the former case than in the latter case.

The observation that high-frequency distractor words yielded less interference than low-frequency distractor words also extends recent work by Burt (1994, 1999, 2002) and of Monsell et al. (2001) to Italian words. As such, the present findings add to the growing body of evidence suggesting that the early work by Klein (1964) and Fox et al. (1971) was incorrectly understood. The cause of these discrepancies may have to do with the composition of the stimulus lists and whether a discrete-trial or a list-reading format was used. For instance, in Kleinǒs study there were four distractors per condition and those distractors were repeated 20 times throughout the experiment, whereas in our study (and Burt,1999; & Monsell et al., 2001) the distractors were never repeated and were only repeated once in Burt (1994; 2002). In addition, while Klein had 80 stimuli per trial from the same condition and the dependent variable was the total naming time, we (as well as Burt, 1994; 1999; 2002; & Monsell et al., 2001) used single stimulus trials in random order and RTs were measured for each trial. It is clear that our procedure is more controlled. The conclusion that can be drawn is that when the stimuli are presented one time in a discrete-trial procedure and the task is color naming, a low-frequency distractor word interferes more than a high-frequency distractor word.

Experiment 2

Experiment 2 tests a second prediction of the dual task account. As can be seen in Figure 2, when two tasks are performed concurrently, the dual-task framework explicitly predicts that factors affecting central processing in the two tasks should yield additive effects. In order to test the prediction that for the (covert) word reading and (overt) color naming streams are functionally independent processes subject to a bottleneck under task overlap conditions, factors known to affect response selection were manipulated in each task. Response selection is widely believed to constitute the central processing bottleneck (Ayora et al., 2011; Johnston et al., 1995; McCann & Johnston, 1992; McCann et al., 2000; Meyer & Kieras, 1997; Navon & Miller, 2002; OôMalley et al., 2007; Pashler, 1984, 1991, 1994; Pashler & Johnston, 1992; Reynolds & Besner, 2006; Telford, 1931; Tombu & Joliceour, 2003;). Here, distractor frequency was used to affect the duration of central processing bottleneck in the covert word reading task. Response set size ï i.e., the number of colors the stimuli were colored with (Karlin & Kestenbaum, 1968) ï was used to affect the duration of the central processing bottleneck in overt color naming task. In the small response set-size condition, the stimuli appeared in one of three possible colors, whereas in the large response set-size condition, the stimuli appeared in one of five possible colors. Evidence suggests that the number of response alternatives ï response set-size, in our terminology ï is a manipulation tapping central processing stages (Karlin & Kestenbaum, 1968), which ï according to the PRP literature ï are the stages underpinning response selection (see Pashler, 1994). According to the dual-task account of the CWI task, we should observe (a) an effect of distractor frequency, (b) an effect of the response set-size, and (c) additive effects of distractor frequency and response set-size.

Method

Participants. Seventeen students at the University of Padova participated in the experiment. They were paid or received course credit for their participation. All participants had normal or corrected-to-normal acuity, normal color vision, and none reported a history of prior neurological disorders.

Materials. The words used in Experiment 2 were identical to those used in Experiment 1. The 92 high- and low-frequency words were displayed twice in two separate blocks of trials, one in which words were displayed in one of three possible colors (i.e., yellow, blue, and red), and one in which words were displayed in one of five possible colors (i.e., yellow, blue, red, green, and purple).

Procedure. The procedure was the same as that of Experiment 1, with the exception that participants performed two blocks of trials, one block with words displayed in one of three colors, and one block with words displayed in one of five colors. The order of presentation of the two blocks was counterbalanced across participants. At the beginning of each block, participants were informed about the number of colors used to display words via written instructions reported on screen. Each block was preceded by a practice session consisting of 22 trials.

Results

Naming errors and apparatus failures (1.2%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicœur's (1994) outlier removal procedure, resulting in the elimination of 1.2% of trials. Separate analyses of variance (ANOVAs) were performed on individual mean RTs and proportion of naming errors considering response set-size (3 vs. 5 to-be-named colors) and word frequency (high vs. low) as within-subject factors. A summary of the results is reported in Table 1.

RTs. Color naming was approximately 79 ms slower with 5-color words than with 3-color words, $F(1, 16) = 50.2$, $MSE = 2129$, $p < .001$. Furthermore, color naming was significantly faster with high-frequency words than with low-frequency words, $F(1, 16) = 18.6$, $MSE = 467$, $p < .001$. Importantly, the analysis showed that response set-size and word frequency factors produced non-interactive (i.e., additive) effects, $F < 1$. The power to detect a 25 ms interaction, two tailed, alpha .05 was .90. [footnote 3]

Percentage Error. Neither the main effects nor the interaction were reliable ($Fs < 1$).

[Table 1, about here]

Discussion

The purpose of Experiment 2 was to test the prediction that central processes that affect response selection will be independent in the two tasks. Response selection in the (covert) word reading task was indexed using distractor frequency and response selection in the overt colour naming task was indexed using response set-size. Consistent with the dual task account, both distractor frequency and response set-size affected performance. Crucially, the joint effects of distractor frequency and response set-size were additive, consistent with predictions from the dual-task account of the CWI task. According to this account, distractor wordsôlexical frequency and response set-size separately affect the duration of central processing for each (covert and overt) task. The covert reading task gains access to the central processor first, with the overt color naming task functionally postponed until the processor is released. Central resources are allocated to color processing earlier for high-frequency distractor words than low-frequency distractor words, because the former clear the central processor earlier. Although response set-size also affects the central processor, processing cannot be undertaken until the central processor is released by the distractor. The consequence is that the effect of response set size adds to the effect of distractor frequency.

Which of the Two Tasks Access Central Resources First?

The purpose of the two forthcoming experiments is to test a central assumption of the dual-task account of performance in the CWI task. According to the dual-task account of the CWI task proposed here, the distractor word is given priority access to the processing bottleneck. To determine whether the distractor word gains priority access to the processing bottleneck, we exploited cognitive-slack logic, which makes clear predictions about how performance should be affected when two tasks are performed at the same time. As noted earlier, it is well established that if the effect of a variable manipulated in Task2 is eliminated when the tasks are performed concurrently, then the effect arises before the bottleneck (see Figure 1A). In contrast, the effect of a variable that affects processing prior to the bottleneck in Task1 carries forward to Task2 (see Figure 2A). In these situations, task order is known, and the locus of a variables effect is unknown. However, the predictions of the logic are sufficiently specific to permit it being applied in reverse. If the effect of a variable known to affect pre-bottleneck processing *is not observed*, then the processing stream associated with that variable *must* gain access to the bottleneck second (i.e., it is Task2). Thus, the dual-task framework makes the counterintuitive prediction that the effect of a variable known to affect an early process in either word reading or color naming will disappear in the CWI task. Following cognitive-slack logic, the null effect of a factor known to tap an early process will provide a clear indication of which processing stream constitutes Task2 in a CWI context, the assumption being that such factor effects would be absorbed into cognitive-slack.

Although there are several variables that affect early processing during reading (e.g., cAse AltErNaTiOn; Mayall, Humphreys, & Olson, 1997), the same cannot be said for color-naming. One possibility is the quantity of color in the display, that is the number of colored letters. The purpose of Experiment 3 is to assess whether the quantity of the target color affects performance in color naming (e.g., Besner, Stolz, & Boutilier, 1997). Experiment 4 will then reveal the relative order in which word reading and color naming gain access to central processing stages.

Experiment 3

The purpose of the present study is to assess whether color naming is affected by the number of colored letters, i.e., by the quantity of color available. The stimuli consisted of strings of ñXsò of different length. In the high-color condition all of the ñXsò were colored. In the low-color condition only one ñXò was colored. It is expected that performance will be faster in the high-color condition than in the low-color condition.

Method

Participants. Eight participants at the University of Padova participated in the experiment. They were paid or received course credit for their participation. All participants had normal or corrected-to-normal acuity, normal color vision, and none reported a history of prior neurological disorders.

Materials. Ninety-two strings composed of horizontally aligned ñXsò were used as stimuli in the present experiment. The strings varied in length, ranging from 4 to 10 ñXs,ò with a mean length of 6.6 ñXs.ò The strings were displayed twice in two separate blocks of trials, one in which the strings were displayed in white with a single ñXò (whose position in the string was varied randomly from trial to trial) colored in one of four possible colors (i.e., yellow, blue, green, and red), and one in which the entire string of ñXsò was uniformly colored using the same color set.

Procedure. The procedure was the same as that of Experiments 1, with the exception that participants performed two blocks of trials, one block with strings of white ñXsò only one of which was colored, and one block with strings composed of uniformly colored ñXs.ò The order of presentation of the two blocks was counterbalanced across participants. At the beginning of each block, participants were informed about the distribution of color within the strings of ñXsò via written instructions reported on screen. Each block was preceded by a practice session consisting of 22 trials.

Results

Naming errors and apparatus failures (1.3%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicî urôs (1994) outlier removal procedure, resulting in the elimination of 1.6% of trials. Separate pairwise comparisons via t-test were conducted on individual mean RTs and proportion of naming errors, considering color density (one ñXò vs. all ñXsò) as factor.

RTs. Color naming was faster when all ñXsò in a string were colored (513ms) relative to when only one ñXò was colored (539 ms). The 26ms difference was significant, $t(7) = 3.5$, $p < .01$.

Percentage Error. The 0.2% difference in errors between trials with all the ñXsò in a string colored (0.9%) and trials with only one ñXò was colored (0.7%) was not reliable (t < 1).ò

Discussion

As predicted, the time to report the target color decreased as the quantity of available color increased. The quantity of available color is therefore used in Experiment 4 as a manipulation of early processing during color naming.

Experiment 4

The purpose of the present experiment is to test a third prediction of the dual task account of performance in the CWI task, that the distractor word processing gains access to central attention before color processing. Case (same vs. aLtErNaTeD) was used to index early processing of the distractor word. The standard effect of case alternation is that it takes longer to read aloud words and nonwords when the case is alternated compared to when it is the same (e.g., Mayall et al., 1997; McCann & Besner, 1987). The quantity of color (one letter colored vs. all letters colored) was used to index early processing of the target color. According to the cognitive-slack logic, when two tasks are performed concurrently, the effect of a variable affecting early stages of Task2 will be absorbed into the cognitive-slack created by central processing of Task1. Therefore, the variable that does not affect performance during the CWI task will indicate which task is gaining access first. If the case of the distractor affects performance and the quantity of color does not, distractor processing accesses central bottleneck stages with priority (i.e., the quantity of color effect will be absorbed into the cognitive-slack). Vice-versa, if the quantity of color affects performance and the case of the distractor does not, color naming accesses central bottleneck stages with priority (i.e., the case alternation effect will be absorbed into the cognitive-slack).

Method

Participants. Fifteen students at the University of Padova participated in the experiment. They were paid or received course credit for their participation. All participants had normal or corrected-to-normal acuity, normal color vision, and none reported a history of prior neurological disorders.

Materials. Two different sets of 46 words were selected as stimuli for the present experiment. The number of letters of each word had a 1-to-1 correspondence with the number of Xs composing the colored strings used in Experiment 3, so as to equate the present stimuli to those of Experiments 3 for color density (see below). The words in the two sets were matched for frequency (653 vs. 644, $t < 1$), orthographic neighborhood size (3.3 vs. 3.6, $t < 1$), and number of letters (6.5 vs. 6.6, $t < 1$). Two distinct experimental lists of stimuli were generated by randomly intermixing words from one set displayed in uppercase letters (e.g., NUMERO), and words from the other set in alternated case letters (e.g., CenTRo). A color density manipulation identical to that implemented in the design of Experiment 3 was combined orthogonally with the case manipulation. Words composing one experimental list were displayed in white with a single randomly chosen letter colored in yellow, blue, red, or green, whereas words in the other experimental list were uniformly colored using the same color set.

Procedure. The procedure was the same as that of Experiment 3. Participants performed two blocks of trials, one block including the experimental list composed of words with a single colored letter, and one block including the experimental list composed of words with all colored letters. Both the order of presentation of the two experimental lists and the manipulation of letter case were counterbalanced across participants. At the beginning of each block, participants were informed about the distribution of color within words via written instructions reported on screen. Each experimental list was preceded by a practice session consisting of 22 trials.

Results

Naming errors and apparatus failures (1.3%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicî urôs (1994) outlier removal procedure, resulting in the elimination of 1.2% of trials. Separate ANOVAs were performed on RTs and percentage of errors, considering color density (one letter vs. all letters) and case (uniform vs. alternated) as within-subject factors. A summary of the results is reported in Table 2.

RTs. Color naming was significantly faster with uniformed-case words than with alternated-case words, $F(1, 9) = 22.8$, $MSE = 2496$, $p < .005$. Neither the effect of color density nor the interaction between case and color density were significant, $Fs < 1$.

Percentage Error. Neither the main effects nor the interaction were reliable ($Fs < 1$).

[Table 2, about here]

Discussion

The goal of the present study was to test a critical assumption of the dual-task account of performance in the CWI task, namely, that the covert word reading task gains priority access to the central processing bottleneck despite instructions to ignore the word. Predictions about task performance were derived using cognitive-slack logic. According to cognitive-slack logic, the effect of the early variable that affects Task2 processing should not be observed when the tasks overlap. Consistent with word reading gaining priority access to the processing bottleneck, the effect of case alternation was observed and the effect of color quantity was not observed in the CWI task.

General Discussion

The goal of the present studies was to examine the explanatory power of a dual-task account of performance in the CWI task. According to this account, two processing streams are initiated upon stimulus onset, one triggered by the color of the stimulus (color naming) and one triggered by the form of the stimulus (word reading). Critically, both processing streams require the use of a limited capacity processing bottleneck. Processing in the second stream that requires the bottleneck is functionally postponed until first stream releases the bottleneck.

We tested three predictions that stem from this account. Experiment 1, tested the prediction that increasing the duration of bottlenecked stage of distractor processing will affect color naming response times. Consistent with this prediction, high-frequency distractors yielded less interference than low-frequency distractors (see Burt, 1994; 1999; 2002; Monsell et al., 2001). Experiment 2 tested the prediction that factors affecting response selection in both processing streams should yield additive effects. Consistent with this prediction, distractor frequency and response set size effect yielded additive effects. Experiments 3 and 4 tested the critical assumption that distractor processing gains priority access to the processing bottleneck. To test this assumption factors affecting pre-bottleneck processing of the distractor word and the target color were manipulated. Consistent with processing of the distractor word gaining priority access to the bottleneck, color naming response times were affected by case alternation of the distractor word, but not by the amount of color in the display.

Taken together, the results of Experiment 1 to 4 suggest that a dual-task framework provides a useful account of performance in the CWI task: Upon the presentation of a CWI stimulus two processing streams are triggered, color naming and distractor processing. Both of these processes require the use of a limited capacity bottleneck. The consequence is that the two processes involved in the CWI task compete for gaining access to this limited resource, central mechanism.

Repetition Priming and Lexicality

Experiment 4 suggests that processes in visual word recognition that either occur before the bottleneck or affect the bottleneck will affect the time to report the target color. Reynolds and Besner (2006) showed that the repetition priming facilitation (faster word reading RTs when the prime and target are the same word with respect to when they are two different words) affects word reading performance prior to the bottleneck. This suggests that repetition priming of the distractor word should affect color naming times and that the responses to the target color should be faster for repeated (old) distractors than unrepeated (new) distractors. Consistent with this prediction, Burt (2002) found that repetition priming affects color naming where responses are faster in the repeated condition with respect to the unrelated condition.

Another factor that has been shown to affect word processing at or prior to the processing bottleneck is lexicality (2002). It is commonly reported that people are faster to respond to words than to nonwords both in lexical decision and reading aloud tasks. McCann et al. (2000) report evidence that at least some part of the lexicality effect affects processing at or before the processing bottleneck in lexical decision. In addition, Reynolds and Besner (2006) report evidence that the process of translating print into sound is bottlenecked for both words and nonwords. This suggests, therefore, that it should take more time to name a color when the distractor is a nonword (e.g., blark) compared to a word (e.g., bland). Consistent with this prediction, Burt (2002) found that nonwords interfere with color naming more than words. Monsell et al. (Monsell et al., 2001), also report some support for this prediction in that they found that nonwords interfered with color naming as much as low-frequency words and more than high-frequency words.

Dual-Task vs. Task Set Accounts

The dual-task account here is similar to the task set account of the CWI task in that it hypothesizes that task performance arises from two processing streams, one associated with colour naming and one associated with word naming. The two accounts differ in the sources and nature of interference. The dual task account articulated here has one locus of interference due to a central capacity limited processing bottleneck, whereas Monsell et al.ǒs (2001) task set account of the CWI task hypothesizes two sources of interference (1) interference from competing task sets and (2) response interference from the distractor. Although the dual-task account does not invoke interference between competing task sets to account for existing findings, there is some evidence that dual task performance is affected by having to maintain both task sets. For instance, it takes longer to respond in a dual task context compared to a single task context even when the SOA is sufficiently long that the two tasks can be completed separately. This suggests that the competition between task sets may be active in the present context and is consistent with dual task performance.

The more critical difference between the two accounts concerns how they explain item specific effects. According to the task-set account, the activation of a given task-set is a function of the strength of association between stimulus properties and the task set. According to Monsell et al. (2001) this process is driven exogenously and likely occurs sublexically and is unaffected by the properties of words or lexicality (presence of letters or homogeneity/heterogeneity of the letter string)[Footnote 4]. In order to explain the observation that colors are named faster for high frequency words than for low frequency words, Monsell et al. hypothesized that on a subset of trials participants fail to efficiently suppress the task set of reading, and the phonology of the distractor is accidentally activated. In these cases, the response selection stage possesses a response that needs to be rejected to favor color name processing. The implications of this conflict for performance are unclear. On the one hand, Monsell et al. argued that since high-frequency words are processed faster than low-frequency words, high-frequency distractor words are dealt with faster than low-frequency distractor words. This would yield faster response times for high frequency distractors than for low frequency distractors. On the other hand, Monsell et al. argued that it should take longer to reject the high frequency words because they should elicit a stronger response code more quickly. This would yield longer response times for high frequency distractors than for low frequency distractors. Therefore, the task set account does not explicitly predict how factors that affect how long it takes to process the word should be observed in color naming response time. In addition, Monsell et al. struggled with how the late response selection processes would know that the selected response corresponds to a specific stimulus dimension. The dual-task account addresses both of these issues.

The dual task account easily addresses why high frequency words yield less interference than low frequency words. Both dimensions of the stimulus are processed through to response selection (phonology) and this requires accesses to a limited capacity processing bottleneck that can be conceptualized as operating on the two stimulus dimensions sequentially (McCann & Johnston, 1992;Pashler, 1994). The word recognition processes gain access to the bottleneck first, therefore the time to respond to the color is delayed by the amount of time that the word occupies the bottleneck. Because high frequency words occupy the bottleneck for less time than low frequency words, color naming is delayed less for these items.

An additional advantage of the PRP account is that it also explains why the impact of variables known to affect how quickly a distractor is named are attenuated in the color naming task. Monsell et al. (2001) observed that the response time differences for their distractor items were consistently larger when they were named compared to when they served as a distractor during colour naming. For instance, the frequency effect was magnitudes larger during distractor naming than during colour naming. In addition, the correlation between distractor naming RT and colour naming RT for the same items was small. According to the PRP account of the colour naming task, the time to name the colour will only be affected by early and central word reading processes. Thus, factors that are likely to impact the late processes (e.g., articulation) are unlikely affect performance.

The two accounts differ in other ways; for instance, Monsell et al. (2001) proposed that words are processed to phonology on only a subset of trials, reflecting occasional failures to effectively suppress the word reading task set. In contrast, the dual-task logic employed here presumes that both task sets are always operating on each trial, implying that distractor processing occurs on the majority of trials. Therefore, if it is assumed that rejecting incorrect word responses is faster for high frequency compared to low frequency words, then the main difference in predictions can be seen as one of degree, where the task set account predicts that response time distributions should be composed of dual-task trials (covert word reading with overt color naming) and single-task trials (overt color naming only). These accounts do make different predictions and therefore can be discriminated. For instance, the dual-task account predicts that early Task2 processes should be eliminated, whereas the task set account allows these effects to be eliminated when all the trials involve the activation of both task sets, and attenuated when the proportion is lower. Though testing these classes of predictions is beyond the scope of the present study, our stance here is to propose the dual-task account of the CWI task, highlighting the precision of itsôpredictions, a subset of which are empirically supported by the present findings, that can be submitted to formal/quantitative testing using, for instance, artificial (modeling) architectures.

Strength of Association & Dimensional Discriminability

The present findings are consistent with the (covert) word reading task gaining access to the central bottleneck prior to the (overt) word production task. An important question is why. There are a number of possibilities including word recognition is a more automatic task (but see Reynolds & Besner, 2006) or speed of processing. For instance, according to the speed of processing account, early visual processing associated with reading is completed prior to the early visual processing associated with color identification. Although this may be the case, here we consider two other possibilities that have been influential in accounts of the standard Stroop task, namely strength of association (Cohen et al., 1990; MacLeod, 1991) and Dimensional Discriminability (Melara & Mounts, 1993; Melara & Algom, 2003). Both of these factors have been shown to be relevant in explanations of the standard Stroop task.

Strength of association refers to the strength of association between the stimulus and a task (Cohen et al., 1990). Cohen et al. proposed that the magnitude of interference between the two relevant dimensions on a standard Stroop trial (the ink color and the color word) is a function of the strength of association between each dimension and the task. According to this account, the color word interferes with naming the ink color in the standard Stroop task because words have a stronger association between its form and its name than does a color. Similarly, the ink color does not interfere with naming the color word because the association between ink color and naming is weaker than it is for the word.

Here we suggest that another consequence of strength of association may be priority access to the central processing bottleneck. If so, then it should be possible to change the order in which the two tasks gain access to the bottleneck through training. Evidence suggests that it is possible to change the pattern of interference in the Stroop task so that after extensive training colours interfere with word reading (Dulaney & Rogers, 1994). If this arises, in part, due to a change in the priority that the two processes access the central bottleneck, then this should lead to early effects of colour processing (e.g., amount of color) affecting word naming time and not the reverse.

A second factor that has been demonstrated to change the relative pattern interference between ink-color and the color-word is dimensional discriminability. Melara and Mounts (1993) demonstrated that the asymmetry of interference in the Stroop task (word on color, but not color on word) can be attributed to how easily the different values in a dimension can be discriminated. In the standard Stroop task it is more difficult to discriminate between the colors than to discriminate between the color words. They argued that this provides the words a greater opportunity to disrupt classification of the colors. To test this possibility they examined performance when the discriminability of the dimensions is reversed so that it is more difficult to discriminate between the words than to discriminate between the colors. Consistent with expectations, the ink-color now interfered with the time to report the identity of the words and the words did not affect the time to identify the ink-color.

Here we suggest that priority access may be given to the more discriminable dimension during the course of an experiment. If so, then it should be possible to change the order in which the two tasks gain access to the bottleneck by changing the relative discriminability of the two dimensions. If discriminability affects the priority with which a processing stream gains access to the central bottleneck, then reversing the discriminability of the dimensions this should lead to early effects of colour processing (e.g., amount of colour) affecting word naming time and not the reverse.

Should one of these factors affect priority access to the central bottleneck, this will provide important insight into the processes involved in the color-word interference task examined here. In addition, it will provide insight into the similarities between the color-word interference task and the standard Stroop task. This insight may lead to a unified account reminiscent of Kleinôs semantic gradient explanation of both phenomena.

Conclusion

The dual-task framework for understanding performance in the color-word interference task provides a single coherent explanation for (1) the distractor frequency effect, (2) slower color naming in the presence of nonwords than words, (3) repetition priming effects on color naming, (4) smaller effects of factors that affect distractor naming times during color naming, (5) the additivity of distractor word frequency and color set size, as well as (6) the failure to observe an effect of quantity of color in the color-word interference task. The account also makes straightforward predictions about how other lexical variables should affect performance in the colour word interference task. The account also provides a means for integrating findings from the color-word interference task with research from picture naming, visual word recognition, dual task performance, task switching and even more standard Stroop tasks. Consequently, we believe that the dual-task account provides a useful approach for understanding performance in the color naming of non-color word interference task.

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Footnotes

Footnote 1: In the present experiments a single stimulus is used and a response is not required for the hypothesized hidden word reading task. Previous research reported by Fagot and Pashler (1992) tested the assumption that the bottleneck is a perceptual phenomenon using only a single visual stimulus in a dual task context and concluded that the bottleneck was functionally equivalent in this and more traditional contexts involving two stimuli. Similarly, studies examining dual-task performance have reported evidence for dual task slowing even when a response to the one of the tasks is not required (Fagot & Pashler, 1992).

Footnote 2: Although there is some disagreement about the properties of this resource, it is widely assumed to have a structural capacity limit and that it therefore functions as a central processing bottleneck (McCann & Johnston, 1992; Pashler, 1994). There is also some debate as to whether the tasks share the processing bottleneck (capacity sharing) or whether it can only be occupied by a single processes, with others being postponed until the resource becomes available (all-or-none bottleneck, Pashler & Johston, 1989). Evidence suggests that the capacity sharing and all-or-none bottleneck accounts both provide excellent fits to the data in vast majority of studies (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). In addition, capacity sharing and all-or-none bottleneck models make identical predictions about how Task2 performance will be affected by SOA variations. For instance, both accounts of the bottleneck make the same predictions about how variables manipulated in Task2 that have their effects before, during, or after the bottleneck will interact with SOA (Tombu & Jolicoeur, 2003).

Footnote 3: Power was calculated using Cohen (1988). We based our estimate the effect size for the interaction on studies that have jointly manipulated stimulus quality and word frequency. We chose the stimulus quality x frequency interaction for two reasons. First, in these studies stimulus quality typically yields an effect that is comparable in magnitude (~100ms) to the effect of response size in the present study (~80ms). Second, whether an interaction is observed between stimulus quality and word frequency depends on context. In the context of lexical decision the joint effects are additive (e.g., Yap & Balota, 2007) and in the context of naming and animacy judgment the joint effects are interactive (O'Malley, Reynolds & Besner, 2007; Yap & Balota, 2007). When an interaction between SQ and word frequency is observed in the context of semantic categorization and word reading, the magnitude of the interaction is approximately 1/3 of the magnitude of the SQ effect in these studies. Using this ratio and the 80ms effect of response size, we therefore estimated the effect size of the response size by distractor frequency interaction to be 25 ms.

Footnote 4: It should be noted, that if lexical factors affected task set activation, then activation should be stronger in the case of high frequency words. At the level of task set competition, therefore, one might assume that the competition is enhanced for high frequency words with respect to low frequency words, which should produce longer response times for high frequency than for low frequency words. This pattern is the opposite to what is observed.

Figure 1: An illustration of cognitive-slack logic in the context of the psychological refractory period (PRP) paradigm. Panel A illustrates absorption of an early effect into cognitive-slack. Panels B and C illustrate how the effect of central and late effects in Task2 are unaffected by task overlap.

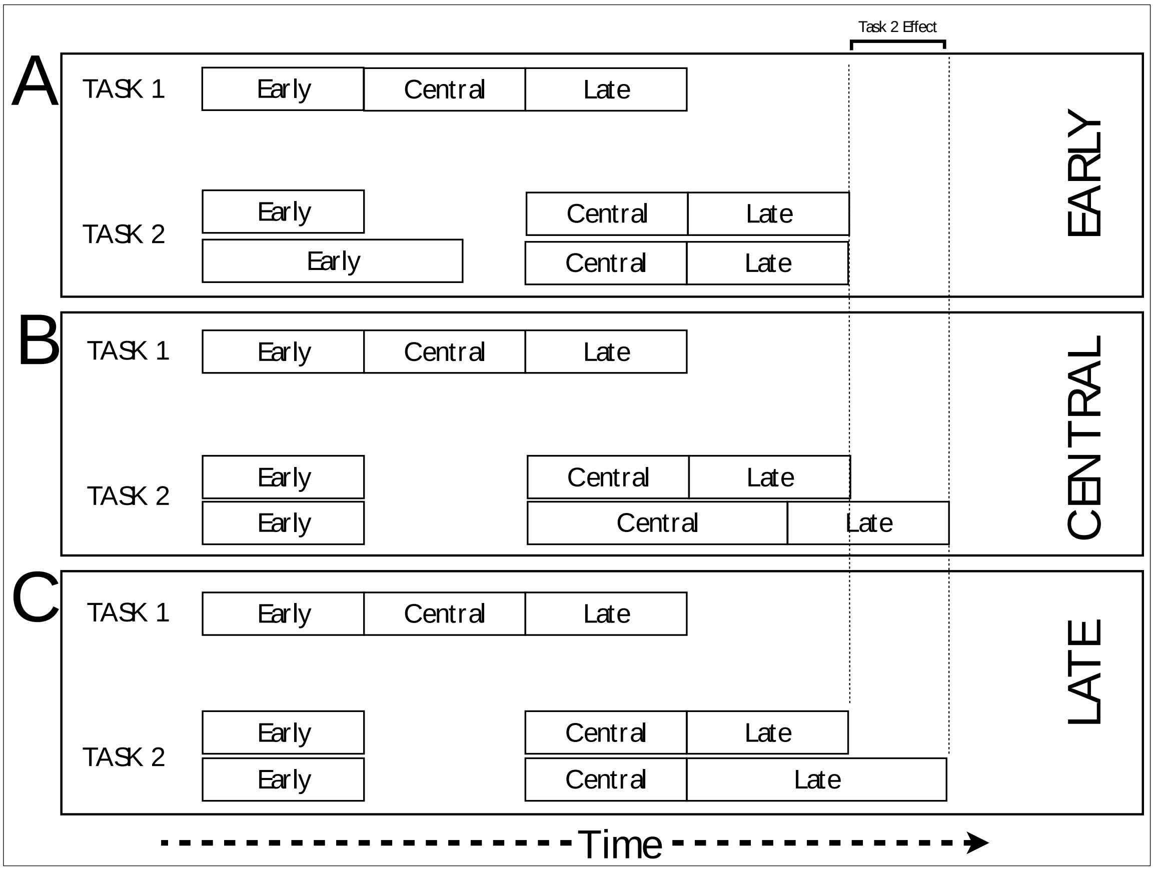

Figure 2: An illustration of cognitive-slack logic in the context of the psychological refractory period (PRP) paradigm. Panels A and B illustrate the carry forward of early and central effects in Task1 onto Task2. Panel C illustrates how a late effect in Task1 does not carry forward to Task2.

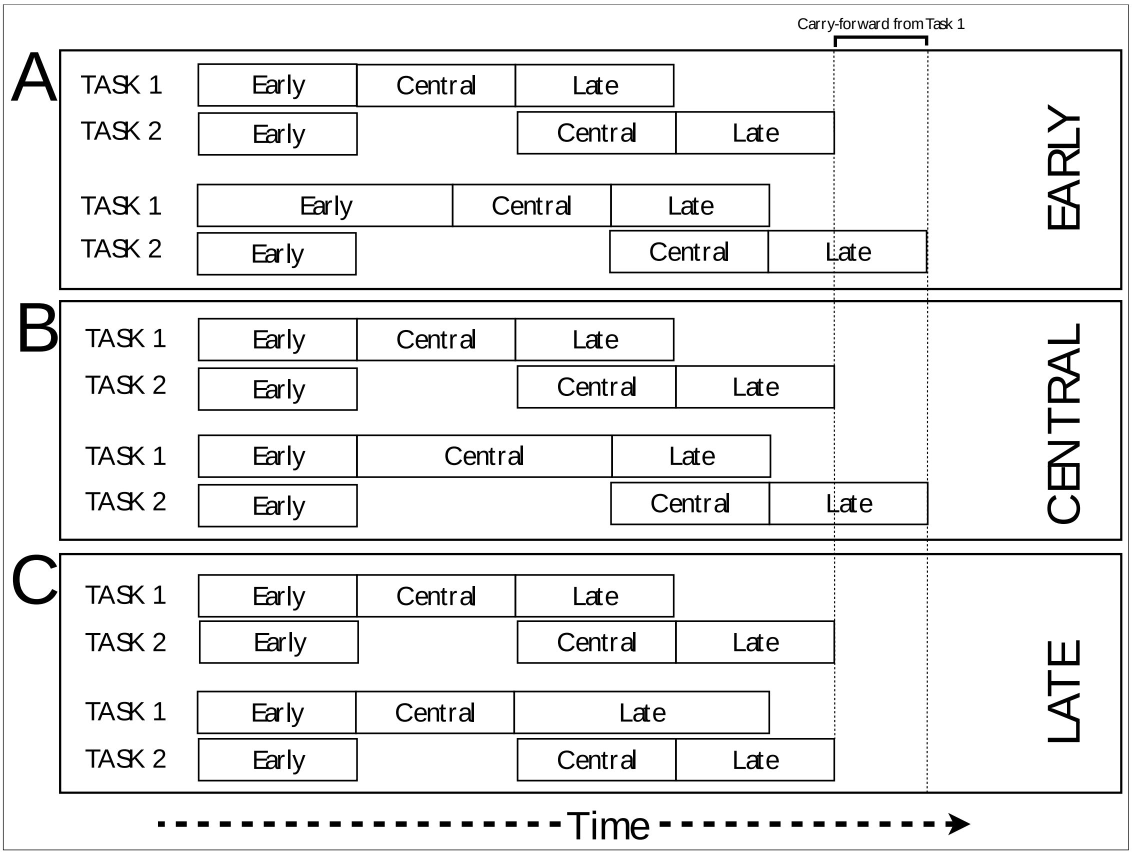

Table 1. Mean RTs and percentage of error (%E) as a function of response set size and distractor frequency in Experiment 2.

	Response Set Size				
	3 colors		5 colors		
	RT	%E	RT	%E	***Difference (RT)***
Distractor Frequency					
Low	603	1.1	682	1.2	***79***
High	580	1.0	659	1.0	***79***
Difference	***23***	***0.1***	***23***	***0.2***	

Table 2. Mean RTs and percentage of error (%E) as function of Quantity of Color and Case Alternation in Experiment 4.

	Quantity of Color				
	One letter		All letters		
	RT	%E	RT	%E	***Difference (RT)***
Case Alternation					
Different	587	0.8	586	0.9	***1***
Same	571	0.7	569	0.8	***2***
Difference	***16***	***0.1***	***17***	***0.1***	