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Contribution of Cognitive and Semantic Control to Performance on Stroop Tasks

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Abstract

The Stroop effect is perhaps the most recognized cognitive phenomenon in psychology. People are slowed at naming ink colors, when the ink is used to represent a word denoting a color. Some theories suggest early perceptual conflict, whereas others suggest that later response conflict is the cause of the effect. We examined whether adding a divergent thinking aspect to a Stroop experiment would enhance the effect, as this would occur only at the response selection stage. In a controlled experiment, we found that making a choice at the response stage produced a Stroop effect of identical magnitude to the traditional incongruent condition of the Stroop task. This may suggest that Stroop effects can be produced at the response generation stage. However, correlation and regression analyses hinted that this was linked to the processing limits of semantic control, rather than domain-general cognitive control, which may underlie the traditional Stroop effect.

Keywords: Executive function; divergent thinking; convergent thinking; Reading; free choices

Since its first description over 90 years ago, the Stroop effect (Stroop, 1935) has been widely applied as an experimental research method (MacLeod, 2005a), and a clinical cognitive assessment (Maclead, 2005b). Despite the sustained attention on the Stroop effect, the cause of the effect remains unclear. In the basic Stroop procedure, words are printed on a card in which the ink color and the meaning of the words are incongruous. The words printed are the names of colors (e.g., the word RED, is shown in blue). The participant is asked to make a response indicating the color of the ink. Within experimental psychology, it is now common to use manual responses to indicate the ink (e.g., a button press) to a single stimulus on each trial. However, the original method used by Stroop, and the method still widely employed in clinical cognitive assessments (e.g., Delis et al., 2001; Periáñez Morales et al., 2021), was to require oral responses to the completion of a set of words presented simultaneously on a card.

Performance on that incongruous condition is substantially slower than on conditions that lack incongruity, typically naming ink colors of text that lack meaning (e.g., 'XXXX' [in blue ink]) or reading color words printed in black and white (e.g., 'RED').

With either manual or oral methods of recording participant responses, it has been common to calculate an index of the Stroop effect as an interference score. That is the difference between performance scores in the incongruous condition minus scores in the control conditions (e.g., word reading or color naming). The Stroop interference effect has been considered highly replicable, producing consistently large effect sizes (MacLeod, 2005a). However, it has been argued more recently that such difference scores, although reliable in terms of within-participant variation, compound measurement errors, rendering them poor measures of between-participant variation (Hedge, Powell & Sumner, 2018).

Furthermore, difference scores produce a form of data loss, as they represent relative performance. From a cognitive perspective, examining absolute performance on different conditions and comparing them can be more informative, particularly when attempting to elucidate the cognitive mechanisms that produce the Stroop effect. Such elucidation is required, as despite the popularity of the Stroop test (and several other commonly applied procedures), the cause of the effect is highly debated, and a lack of appreciation of that fact is contributing to misinterpretations of mental processes (Poldrack et al., 2011).

When explaining the Stroop effect, a common assumption is that reading is automatic, and that leads to activation of the incorrect response (when the participant is attempting to name the ink). The consequent conflict requires top-down cognitive control to resolve, that is, to override the automatic tendency to read, and instead focus attentive processing on ink naming. Relatively good (i.e., fast and accurate) performance on the Stroop task is therefore often interpreted as requiring efficient executive functions, for example, working memory (Kane & Engle, 2003; Delis et al., 2001; Periáñez Morales et al., 2021).

One problem with this interpretation of the Stroop effect is that it is questionable whether reading is always automatic, and thus an impediment to deliberate action control. In the usual Stroop incongruent condition, words are shown in an ink that differs from the color meaning of the word (e.g., RED written in blue ink). However, if only one letter is colored, and the task is to say that color, the Stroop interference effect does not happen (Besner & Boutilier, 1997). A further problem for automatic interpretation is that the Stroop effect is negatively correlated with reading ability, beyond that caused by color naming speed (Protopapas et al., 2007).

One interpretation of these effects is that the mental set is a substantial cause of the Stroop effect. In some experiments

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in which the task instructions alter the participants' interpretation, but not their actual responses, the Stroop effect can be eliminated (Bauer & Besner, 1997). Further experimental evidence suggests that whether or not a read word is processed semantically is dependent on endogenous attention (Kinoshita, Mills, & Norris, 2018). This places the Stroop effect occurring early within the overall processing from stimulation to response.

An even stronger explanation that proposes early processing issues to produce the Stroop effect is the perceptual conflict hypothesis. This suggests that the different dimensions, i.e., ink color and word form, are both processed, causing a delay due to limited attention or serial processing mechanism resulting in early perceptual conflict (Williams, 1977, Mager et al., 2007). In contrast, other theories have suggested that the Stroop effect is caused by conflict at the stage of response output.

Brain activations during the Stroop incongruent condition suggest that areas of the frontal lobes associated with response competition are activated (Mead et al., 2002). Experimental evidence (Kane & Engle, 2003; Roelofs, 2021), also suggests that part of the Stroop effect is caused by conflicting possible responses. If so, then increasing the cognitive load at the response generation stage should produce exaggerated Stroop effects.

The current study explored this possibility. We were particularly interested in whether reduction in the routineness of responses would slow Stroop task performance by delaying the response generation stage. If, as is frequently argued, Stroop task performance requires top-down executive cognitive control, the effect may be limited by the relative routineness of the goal of the task (i.e., to say the name of the ink one is looking at).

It has recently been argued that many procedures used to measure cognitive control, such as the Stroop task, induce cognitive sets that bias participants to think convergently (Pluck et al., 2023). This invokes the classic dichotomy between convergent and divergent thought suggested by J.P. Guilford (Guilford, 1956, 1974). Appropriate responses by participants in Stroop tasks require that they maintain a focus on producing the single correct response on each trial. In contrast, divergent thinking would require them to produce non-routine responses. This would be more consistent with most definitions of top-down control that stress avoiding routine response generation.

In particular, several lines of research have supported a distinction between cognitive control and semantic control (Hoffman et al., 2013; Jackson, 2021). Experimental evidence suggests that divergent task performance tends to require semantic control, whereas convergent task performance involves cognitive control mechanisms (Patel et al., 2025).

From this line of thought, we designed a novel Stroop task that was biased toward divergent, rather than convergent responses. Basically, the participant is required to say a different color to the one that they are attending to. For example, when the stimulus is the word RED, in red ink, a correct response would be to say 'Blue', or to say 'Green' (either would be considered correct). Although the choices that the participant can make are highly constrained, they must, nonetheless, make a choice. We hypothesized that this would enhance the Stroop effect, relative to the traditional Incongruence condition due to the additional task demands for top-down semantic choice of responses.

We further hypothesized that performance would be dependent on semantic processing, and that would be revealed by a link between reading speed and performance in our novel Stroop procedure, the Choice Condition. In contrast, the traditional Stroop effect would, we hypothesized, be more in line with domain-general cognitive control, as measured by a separate, non-Stroop test of executive function.

To test these hypotheses, an experiment was performed in which different trials measured different aspects of Stroop task performance so that separate performance scores could be calculated and compared.

Method

Design

A within-subjects experiment was performed with four conditions. In each condition, the participant was required to make oral responses to a card showing 50 separate stimuli. The dependent variable was the total time to respond to all 50 stimuli on the card. In each condition, the responses were to say a color. There were two trials performed within each condition.

Participants

A sample of 91 participants was recruited, all university students, with a mean age of 22.2 years (*SD* = 1.0), and the majority were female (60/91, 66%).

Materials

Stroop Experiment We reproduced the Stroop test format from a commercially sold battery of executive function assessments used in neuropsychology – The Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001). However, adaptions were made because i) that assessment is in English and all our participants were Thai speakers, ii) to produce a 'divergent' version that required a choice to be made, and iii) to produce additional trials.

A single trial on the D-KEFS Stroop task involves the participant being presented with a white A4 page in landscape orientation that contains 50 stimuli. The participant must process all 50 stimuli as quickly as possible. The materials that we produced for the four experimental conditions were:

Color Naming Condition: The page contains 50 rectangles arranged in 10 columns of 5 rows. The colors of the rectangles were red, blue, or green. The sequence was semi-random, such that the same color was never used in two consecutive rectangles. Two different versions were produced to allow two data collection trials. On the first of these two trials, an additional ten colored rectangles were added for practice to become familiarized with the task. In this condition, participants had to say the color of each rectangle.

Word Reading Condition: These were equivalent in structure to the trials in the Color Naming Condition; however, instead of colored rectangles, words were printed in black type. The words used were in the Thai language: แดง (red), ฟ้า (blue), เขียว (green). Participants were asked to read each word aloud.

Incongruent Condition: This is the standard configuration that produces the Stroop effect. The materials were equivalent in structure to those described above. However, the words and the ink colors were incongruent (e.g. แดง [meaning 'red'] printed in blue ink). Participants were asked to name the ink color of each word.

Choice Condition: We have named this condition by the task demands for ease of comprehension. However, the materials are equivalent to what is usually known as the congruent condition (e.g. แดง [meaning 'red'] printed in red ink). For background to the congruent condition, see MacLeod (2005a). Otherwise, our stimuli configurations, page size, etc., were all equivalent to the other conditions. Participants were asked to say a different ink color to the one they were attending to (e.g., if they saw a word printed in red ink, the correct answer would be saying either 'blue' or 'green').

Examples of the experimental stimuli used are shown in Figure 1.

Color Trails Test We included a standard assessment of executive function, the Color Trails Test (Maj et al., 1993). This is administered as a pen-and-paper test in which the participant draws lines to join numbered circles in sequence, while alternating between pink and yellow filled circles. It is widely used as a neuropsychological assessment of executive functioning (e.g., Tyburski et al., 2020), but also used in experimental studies of executive function with healthy participants (e.g., Ben Yair et al., 2023). The numbers 1 through 25 are presented on each page, with each number appearing twice (one within a yellow-filled circle and once within a pink-filled circle). Three different versions were produced so that three trials could be completed per person. Further details of the construction of the Color Trails Test can be found elsewhere (Pluck et al., 2026).

Procedure

Participants were tested individually in a quiet, well-lit room and sat at a table with the experimenter seated opposite. All participants provided written, informed consent, consistent with the IRB-approved study protocol. The Stroop experimental conditions were administered in a counter-balanced order, performing two trials in each condition. The first trial of each condition involved a brief practice. During a single trial, the participant would be told the task instructions, and then an A4 page card would be placed in front of them, flat on the table. Their task was to articulate all 50 items on the page as quickly as possible, reading from left to right and top to bottom. The experimenter recorded the time taken to complete all 50 items. If a mistake was made, the participant was instructed to restart from the last correct response, without pausing the timer, and so errors would result in longer trial-completion times. However, the number of errors was not recorded. After each trial, there was a brief pause for a few seconds before the next trial commenced. In total, there were 8 trials.

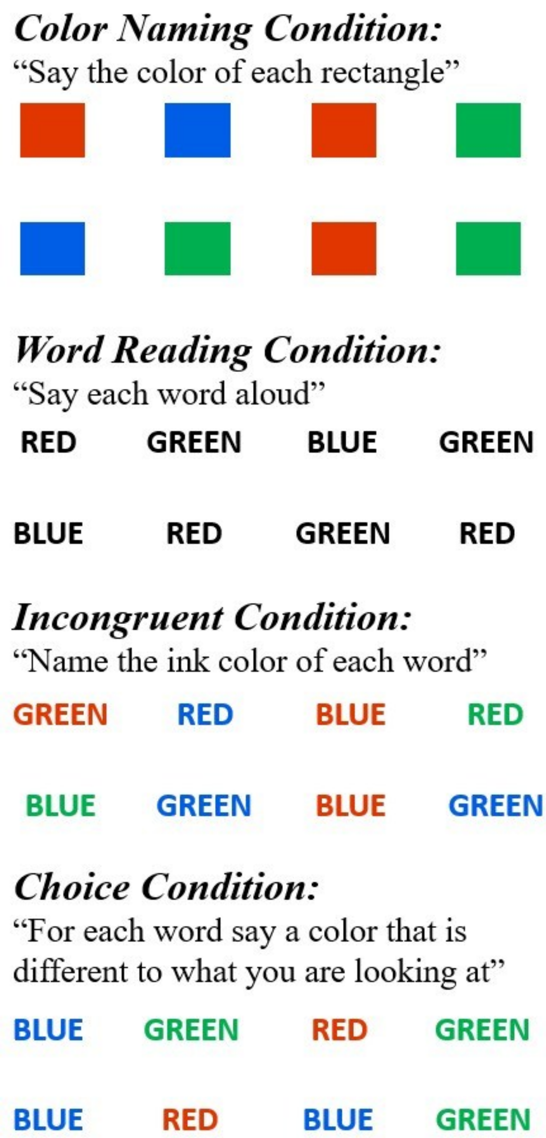

Figure 1: Examples of stimuli types in the four conditions. These are shown in English, however, the actual version applied used Thai words.

All participants were also part of a second experiment which involved the Color Trails Test. The full experiment is not analyzed here, only the scores from the Color Trails Test. The administration followed the same rules as described above. However, participant responses were manual (drawing lines on pages), and three trials were performed, with a mean time to completion calculated as the summary of performance efficiency.

Results

The mean scores from each condition are shown in Figure 2. This shows a typical Stroop effect, that is, a substantial difference between the times to completion in the Incongruent condition, compared to either the Word Reading or Color Naming conditions. A similarly large difference can be seen for the Choice condition (in which participants had to say any other color other than the one being viewed). To confirm these differences with ANOVA, the data were first square-root transformed, as all distributions were non-normal. The ANOVA confirmed the overall effect, $F(3,270) = 451.72$, $p < .001$, $\eta^2 = .83$. Planned contrasts confirmed that the Incongruent condition produced slower completion times than the Word Reading, $F(1,90) = 648.47$, $p < .001$, $\eta^2 = .88$, or the Color Naming condition, $F(1,90) = 244.58$, $p < .001$, $\eta^2 = .73$. However, there was no significant difference between the Incongruent condition and the Choice condition, $F(1,90) = 0.12$, $p = .73$, $\eta^2 < .01$.

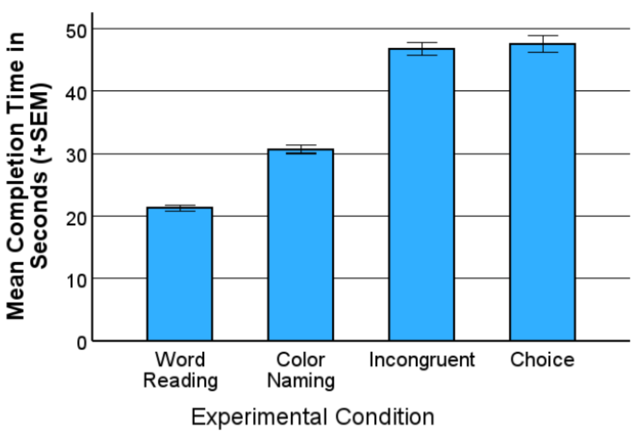

Figure 2: Mean task completion times in the four experimental conditions.

If we compare the actual cost of the Stroop effect on time to complete the task, we see that the Incongruent condition slowed performance, relative to the Color Naming condition by 80%. A similar figure was found for the Choice condition, in which the cost was 83%. These indicate substantial Stroop effects in both versions of the task, and resemble the figures originally reported by Stroop (1935), who reported a 74% cost.

As the Choice condition presented here produced a Stroop effect of at least the same magnitude as the traditional Incongruent condition, questions remain as to the underlying cognitive mechanisms. As an initial exploration of this, we examined the pairwise correlations. Pearson methods were used on the transformed scores. Shown in Table 1, these results revealed significant positive correlations between all but one pair of variables. There was no correlation between Color Trails Test (our measure of general executive control) and performance in the Word Reading condition. Of the other correlations, better performance on one task was associated with better performance on the other task.

Table 1: Pairwise correlations between variables.

No.		1	2	3	4
1	Word Reading				
2	Color Naming	.63**			
3	Incongruent Condition	.41**	.72**		
4	Choice Condition	.47**	.54**	.61**	
5	Color Trails	.08	.25*	.37**	.24*

* p < .05, ** p < .001

Given the high level of interrelations between variables, in the next analyses we used linear regression to examine which aspects of task performance independently predicted completion times on the two different Stroop-effect inducing conditions, the Incongruent and Choice conditions. For both regression models that were run, raw data were used, and the distribution of residuals did not differ from a normal distribution (Kolmogorov-Smirnov test, both $p > .20$). There was also no evidence of multicollinearity, with all VIF values < 2.0.

In the first model, to predict the standard Stroop effect, completion times in the Incongruent condition were used as the dependent variable, and completion times for the Color Naming and Word Reading conditions were entered as independent variables. We also included scores on the separate Color Trails Test as a general measure of executive function. This produced a significant model predicting completion time in the Incongruent condition, $R = .75$ (adjusted $R^2 = .54$), $F(3,87) = 36.52$, $p < .01$. The model is shown in Table 2, where it can be seen that two factors significantly, and independently, predicted Incongruent condition performance: Color Naming condition times, and also scores on the general executive function assessment-Color Trails Test. Word Reading condition scores were not a significant predictor. This suggests that the factors independently limiting performance in the standard Incongruent condition of the Stroop task were speed of decoding colors into words and executive cognitive control.

Table 2. Linear regression to predict performance in the Incongruent condition.

Variable	*b*	*t*	*p*-value
Constant		1.69	0.10
Word Reading	-0.02	-0.17	0.86
Color Naming	0.69	7.16	<.01
Color Trails Test	0.19	2.54	.01

In the second model, the same predictors were entered as independent variables; however, the to-be-predicted variable, Choice condition performance, was used as the dependent variable. This also produced a significant model predicting performance with $R = .58$ (adjusted $R^2 = .33$), $F(3,87) = 14.57$, $p < .01$. However, the variables that were independent and statistically significant predictors were different. These are shown in Table 3. An important observation here is that now Word Reading condition times are a significant predictor, but scores on the general executive function assessment, the Color Trails Test, are not. Completion times in the Color Naming condition were a significant predictor, as they were in the standard Incongruent condition of the Stroop task.

Table 3. Linear regression to predict performance in the Incongruent condition.

Variable	*b*	*t*	*p*-value
Constant		0.81	0.42
Word Reading	0.23	2.00	0.05
Color Naming	0.37	3.15	<.01
Color Trails Test	0.11	1.17	0.25

Discussion

To summarize the results, we administered the Stroop task using the traditional card method procedure with oral responses, robustly replicating the results of Stroop (1935). The most challenging condition in this procedure was the Incongruent condition, in which participants must name the ink color of words that denote a different color. We also found that, with regression analysis, one independent predictor of the 'Stroop effect' was the speed at which people were able to name colors. Given that the Stroop effect was measured chronometrically, this is reasonable and may indicate some aspect of the general speed of processing under visual attention. Indeed, that condition has previously been linked to working memory and visual search efficiency (Periáñez Morales et al., 2021).

However, we also confirmed that another independent predictor was performance on a separate cognitive test, used to measure general executive function (the Color Trails Test). Although performance on this test was also measured chronometrically, it seems likely that the relative variance is related to more general executive cognitive control. We can assume this because Color Naming condition scores and Color Trails Test Scores were statistically independent predictors of performance of the Incongruent condition. As hypothesized, the Stroop effect was linked to cognitive control. This supports the widely held belief that the Stroop effect is due to recruitment of limited executive resources (e.g., Kane & Engle, 2003; Delis et al., 2001; Periáñez Morales et al., 2021).

We also included a novel condition within the experiment, in which participants were requested to say a different color to the one that they were attending to. For example, to be a correct response to the word RED in red ink, the participant would have to say either 'blue' or 'green'. This has similarities to the Incongruent condition, in that better performance is achieved by not responding routinely to what is perceived. However, it also requires a simple choice to be made, and removes one relatively routine way to respond, that is, naming the ink color.

This Choice condition was included as we hypothesized that reducing the cognitive set that biases towards convergent thinking would enhance the Stroop effect. Although performance in this condition was somewhat worse than in the standard Incongruent condition, the difference was not significant. In fact, despite the quite different task instructions, the mean trial completion scores in the two challenging conditions were surprisingly similar, 46.8 and 47.6 seconds. Thus, our hypothesis that requiring less convergent responding would enhance the Stroop effect was not supported.

On the other hand, our novel Choice condition was obviously challenging to perform, and substantially more difficult to perform than the routine conditions (Word Reading and Color Naming). Given the different task demands, the reasons that it produces substantially slowed task performance may be different from those that cause the Stroop effect. This hypothesis was supported. In the regression analyses, we found that the two independent predictors of Choice condition performance were completion times in the Color Naming and Word Reading conditions. Remarkably, despite the Choice condition being equally as challenging as the Incongruent condition of the standard Stroop procedure, performance was not correlated with performance of a different assessment of executive function - the Color Trails Test.

What then can explain the processing differences between the two Conditions, given that both appear to be very challenging to participants? The patterns of correlations and regression analyses imply different contributing factors for the performance of each task.

We suggest that the distinction between cognitive control and semantic control may be important. Cognitive neuropsychological evidence suggests that semantic and cognitive control involve separate systems (Hoffman et al., 2013). This is supported by brain imaging research, which suggests a semantic control system as part of the wider semantic network, centered on specific parts of the left hemisphere frontal and temporal lobes, but not including the parietal lobes (Jackson, 2021). That is contrasted with cognitive control, or the multiple-demand system of the brain, which is bilateral and based in specific frontal and parietal lobe regions, but not including the temporal lobes (Duncan, 2010). These broad brain networks appear to represent different aspects of tasks, despite both being involved with top-down control of processing (Gao et al., 2021).

Tentatively, we suggest that the standard Stroop effect can be explained by the task requirements which invoke domain-general cognitive control. However, the Choice version used here is biased toward more semantic control mechanisms. We argue that this is because the Choice condition changes the cognitive set to divergent thinking, which is itself linked particularly to the semantic control network of the brain (Cogdell-Brooke et al., 2020).

Staying with evidence from neuroscience, it has been suggested that the processes underlying Stroop task performance are functionally separate from other verbal executive tasks which require divergent responding, such as the Hayling Test (Moore et al., 2024). The contrasting experimental tasks used here, the Incongruent and Choice conditions, may similarly tap those different processes.

Our results also suggest that the Stroop effect can occur at response selection. This contrasts with theories which have suggested that perceptual conflict is the cause of the delays in responding (Williams, 1977; Mager et al., 2007). This is because the features of the Choice condition remove the perceptual conflict - the word meaning and ink color are congruent. It seems reasonable, therefore, that responses are slowed in the Choice condition for similar reasons as they are slowed in the Incongruent condition, that is, resolution of the competition between different possible responses (Kane & Engle, 2003).

Further research could explore the potential of the Choice condition within the Stroop task to elucidate the mechanisms of this enigmatic psychological effect. Our suggestion that the Choice condition may index semantic control, as opposed to domain-general cognitive control, should be assessed more directly. Although a relatively simple modification, it may also be worth investigating whether it has similar associations to other divergent-executive procedures. For example, the Hayling Test requires participants to orally complete sentences in a deliberately nonconventional way, and performance on this task has been shown to predict real-life success in education and workplace performance, beyond what can be explained by general intelligence (Pluck et al., 2019, 2020).

We would also acknowledge that our methodology or recoding Stroop task completion time, but not errors, may limit interpretation of our findings. The method we used of Stroop task administration was the classic 'card' method, still widely used in neuropsychology (e.g., Delis et al., 2001; Periáñez Morales et al., 2021). In that method, total time to complete a whole set of items is recorded, and errors influence performance because the participant has to reattempt the word. However, this provides relatively coarse temporal resolution and also means that speed-accuracy tradeoffs cannot be assessed. In light of these methodological limitations, our conclusions have to be tentative, pending further research using more modern data collection methods.

In summary, we provide evidence that Stroop effects can occur without any perceptual conflict. We very tentatively, suggest that the disruptive effects of differing ink color and word meaning may have more to do with response conflict. Again, stressing caution in interpretation, we also suggest that the typical Stroop effect involves a domain-general cognitive control system (e.g., the multiple-demand system), given its association with a different assessment of executive function. In contrast, a simple change to the stimuli and instructions, to bias responses toward more divergent thinking, can produce a Stroop effect of equivalent magnitude. We very tentatively suggest that the causes of that effect may have greater overlap with processes involved in semantic control.

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