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A repetition-suppression account of between-trial effects in a modified Stroop paradigm

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ABSTRACT

Theories that postulate cognitive inhibition are very common in psychology and cognitive neuroscience [e.g., Hasher, L., Lustig, C., & Zacks, R. T. (2007). Inhibitory mechanisms and the control of attention. In A. Conway, C. Jarrold, M. Kane, A. Miyake, A. Towse, & J. Towse (Eds.), *Variation in working memory* (pp. 227–249). New York, NY: Oxford, University Press], although they have recently been severely criticized [e.g., MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhibition. In H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 43, pp. 163–214). Elsevier Science]. This paper poses and attempts to answer the question whether a research program with cognitive inhibition as its main theoretical assumption is still worth pursuing. We present a set of empirical data from a modified Stroop paradigm that replicates previously reported findings. These findings refer to between-trial effects previously described in the literature on Stroop, negative priming, and inhibition-of-return. Existing theoretical accounts fail to explain all these effects in an integrated way. A repetition-suppression mechanism is proposed in order to account for these data. This mechanism is instantiated as a computational cognitive model. The theoretical implications of this model are discussed.

One of the typical functions of cognitive control is interference resolution – that is, protecting the execution of task-relevant sequences of actions against interference and distraction. It is currently under debate whether *cognitive inhibition* (also referred to as *cognitive suppression*) is one of the mechanisms of interference resolution. Some authors assert that cognitive inhibition is essential for cognitive control (Aron, 2007; Druey & Hubner, 2008; Hasher et al., 2007; Houghton & Tipper, 1996); others say that it is unnecessary (Egner & Hirsch, 2005; Hommel, Proctor, & Vu, 2004; MacLeod et al., 2003; Rothermund, Wentura, & De Houwer, 2005).

This paper attempts to disentangle these two concurrent theoretical positions regarding cognitive control. In this paper the theoretical stance postulating that cognitive suppression is not necessary for interference resolution will be referred to as "the no-suppression theory". The theoretical stance postulating that cognitive suppression is essential for interference resolution will be referred to as "the suppression theory". In order to disentangle these two concurrent theories we will impose two methodological constraints: (1) a viable theoretical account should be able to simultaneously explain a large range of effects, and (2) it should be expressed in computational terms and be able to make numerical predictions (Anderson, 2007; Christie & Klein, 2008; Meehl, 1990).

A modified Stroop paradigm will be used to test the verisimilitude of the two theories. The Stroop task is a landmark task for studying cognitive control (Miyake et al., 2000); an extensive body of literature has accumulated over many years to endorse the robustness of the Stroop task's behavioral effects as well as to aid with understanding the cognitive mechanisms responsible for these effects (MacLeod, 1991). We have modified the classical Stroop paradigm by changing the response registration procedure. Details about the modified Stroop paradigm are presented together with the description of the first study.

The following section presents the first empirical study aimed at replicating the known between-trial effects in the Stroop task. Section 2 shows how these empirical data challenge established theories and models of cognitive control and presents an alternative account. Section 3 presents a computational model that implements this alternative account and makes detailed predictions for all the interactions among within-trial and between-trial effects observed in the first study. Section 4 presents the second empirical study aimed at testing model predictions. Section 5 concludes the paper with a discussion about the plausibility of cognitive inhibition as one of the mechanisms of cognitive control.

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1. First study

In one of the most comprehensive reviews of research on the Stroop task, MacLeod (1991) described a series of between-trial effects and proposed a suppression mechanism to account for all of them:

> "When the irrelevant word on trial $n-1$ is the name of the target ink color on trial *n*, interference with color naming will be enhanced temporarily; when the ink color on trial $n-1$ matches the word on trial *n*, there will be some facilitation of color naming on trial *n*. If the word on trial $n-1$ is repeated on trial *n*, then the word is already suppressed and will cause less interference in naming a different ink color on trial *n*. An interesting study would be to mix these two types of repetition effects in the same experiment, directly comparing their size."

> "My own bias [...] is to invoke a suppression idea so that the facilitation and interference effects as a result of item sequence have a common grounding" (MacLeod, 1991, p. 178).

It was our intention to conduct such an "interesting study" to replicate all these between-trial effects and to investigate whether a single integrated account can explain all of them as suggested by MacLeod in 1991. However, MacLeod has recently advocated against cognitive inhibition as an explanatory mechanism for attention and memory phenomena including negative priming and inhibition-of-return (MacLeod, 2007a, 2007b, 2003). Thus, the research question we address here is whether this integrated account should be based on suppression (cognitive inhibition) or not. This question has inspired a plethora of recent empirical research and theoretical analyses (e.g., Aron, 2007; Christie & Klein, 2008; Druey & Hubner, 2008; Hasher et al., 2007; MacLeod, 2007a, 2007b; to name just a few).

1.1. Method

1.1.1. Participants

Fifty-three participants were recruited from Carnegie Mellon University's community via a website advertisement. Participant age ranged from 18 to 59 years with an average of 24. There were 16 women and 37 men. They received a fixed amount of monetary compensation for their participation.

1.1.2. Design

There were three within-subject conditions: incongruent, congruent, and neutral. Every participant received 150 trials, 50 trials for each condition. The three trial types corresponding to the three conditions were randomly mixed (non-blocked). Trial order was randomized for each participant. Between-trial conditions occurred from this random sequencing of the three trial types.

1.1.3. Apparatus and procedure

The standard Stroop task was adapted for screen-based administration and manual response. Stimuli were color names (red, blue, yellow and green) and neutral words colored with one of the four colors denoted by the mentioned color names. The neutral words were 53 common English words unrelated semantically or phonologically to any of the color names. They were selected from the most frequent nouns in English and their relatedness to the color names was judged by the experimenters. Stimuli were presented one at a time in the center of the screen and they remained on the screen until the participant responded. A fixation cross was presented in the middle of the screen for 1.5 s before the onset of a new stimulus. Two response options were also displayed flanking the stimulus on its left and right sides. Response options were non-colored (i.e., in black) color names. One response option contained the correct answer and the other one an incorrect answer. In the incongruent condition the incorrect answer was identical to the distractor word. The location of stimuli on the screen was kept constant.

Instead of verbally naming the color of the stimulus as in the classical Stroop task, participants were instructed to select as fast as possible the response option that matched the color of the stimulus from the two options presented on the left and right sides of the stimulus by pressing a key for each option. The reason for altering the standard response registration procedure is presented in the following paragraph.

This task was part of a larger study aimed at investigating the cognitive control aspects of multi-tasking. We were interested in interference control in tasks that involve perceptual, cognitive, and motor components; the vocal component was not of interest for us in this project. For this reason we considered using a manual version of the task. However, the typical manual Stroop task, in which each color is mapped on a unique manual response, has been shown to produce reduced levels of interference and fast decrease in interference with practice (see MacLeod (1991), for a review). The reduced interference is probably caused by the direct association that is formed with practice between the perception of colors and the associated manual responses. The mapped key presses loose their dimensional overlap with color concepts (Kornblum, 1994) because the retrieval of a color name is likely to be bypassed. When memory retrievals are bypassed, the main source of interference in the Stroop task, that is reading and retrieving color names, no longer exists. By asking participants to select the right answer from two options given on the screen, we reintroduced the words as source of interference. This way, naming a color involves going through a verbal step. Thus, having to select names of colors presented on screen makes the manual Stroop task more compatible with the standard (vocal) Stroop task, by bringing back its semantic and linguistic components. Interference arises from the possibility to retrieve an incorrect color name as in the vocal variant of the task. Each response option has an equal probability to appear on the left or right side of the stimulus, thus, preventing the selection process from becoming automated.

The session started with a short computer-guided tutorial that emphasized the correct response. During the task no feedback was provided.

1.2. Results

The data of one participant were excluded from the analysis, because the reaction times exceeded 2000 ms on average (this criterion had previously been used to exclude data from analysis in Miyake et al., 2000). A number of trials (5.12%) were excluded from the analysis because they had very low (lower than 300 ms) or very high (higher than 2000 ms) reaction times.

Sometimes when the reaction time is used as a dependent measure it is log-transformed in order to correct for its skewed distribution. In our case, the results with and without the log-transformation of RT were similar. We decided to use the original (non-transformed) variable so that the magnitudes of all effects are always expressed in meaningful units (s). No other manipulation of the data was done.

1.2.1. Within-trial effects

Accuracy data were consistent with previous studies, showing less than 2% errors for the congruent and neutral conditions and less than 10% errors for the incongruent condition (Table 1). Reaction time data were also consistent with other studies in the Stroop literature, showing Stroop interference in the incongruent condi-