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Editorial

Inspired by the past and looking to the future of the Stroop effect

Throughout the years, researchers of attention and cognitive control have employed various experimental tasks such as the Stroop, flanker, go-no-go, stop-signal, and Simon task. The Stroop task stands out as a paradigmatic task for failure of selective attention and the operations involved in cognitive control (e.g., inhibition). The original task was published by John Ridley Stroop in 1935 to examine the potential interference of word reading on color naming and vice versa. Since this publication, the task or its variations have been used by many researchers (MacLeod's, 1991 review paper mentioned over a thousand articles but this number keeps mounting today). Moreover, the name *Stroop* has become part of titles such as emotional Stroop, numerical Stroop, spatial Stroop, picture Stroop, etc. This attests to the use of the task or its variations in numerous areas of psychology. In spite of its wide usage, several issues remained unresolved.

One unresolved issue concerns the contribution of bottom-up and top-down processes to the Stroop effect. It is believed that cognitive control is achieved by top-down modulation and in particular, by involvement of cortical structures like the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC). Yet, in contrast with these suggestions, it has been suggested that the Stroop effect or modulations of the effect by select manipulations could be explained by bottom-up processes (e.g., Melara & Algom, 2003), and that they involve lower or subcortical brain structures (Munakata et al., 2011). One example for the bottom-up vs. top-down debate is the item-specific proportion congruency effect. This is the pattern whereby the Stroop effect is exacerbated for items (e.g., words BLUE and YELLOW) that mostly appear in a congruent color compared to items (e.g., words GREEN and RED) that mostly appear in an incongruent color. This effect was explained by bottom-up processes such as contingency learning (e.g., Schmidt, 2013) or by retrieval of top-down control settings. Whitehead, Brewer, Patwary, and Blais (2018) manipulated both conflict and contingency and found that the two interact. Accordingly, they suggested that top-down and bottom-up processes contribute to the Stroop effect and more generally, speak to cognitive control. Bugg and Diede (2018) reached a similar conclusion. It is well known that list composition modulates the Stroop effect. When the list is mostly congruent (MC, e.g., 80% congruent trials and 20% incongruent trials), the Stroop effect is larger than when the list is mostly incongruent (MI, e.g., 20% congruent and 80% incongruent trials). Explicit expectations, based on top-down control, may modulate this effect but their modulation is restricted to MC lists, with no effect on MI lists (Bugg, Diede, Cohen-Shikora, & Selmeczy, 2015). It was suggested that this effect might be related to a within-participant experimental design. Hence, in the current work, Bugg and Diede (2018) manipulated expectation (i.e., cues regarding the MC vs. MI list composition) between participants. The pattern of results, in the within-participant design, was replicated. There was a general effect of list composition (i.e., experience) with a larger Stroop effect for the MC than MI lists, and cueing (i.e., expectation) was effective only for MC lists. Accordingly, the authors suggested that both experience-driven (bottom-up) and expectation-driven (top-down) processes modulate the Stroop effect. Saban, Gabay, and Kalanthroff (2018) also examined the issue of top-down vs. bottom-up effects on the Stroop task, but they adopted the approach of investigating the brain structures involved in the effect. In particular, they examined same eye vs. different eye presentations of Stroop stimuli. To this end, they decomposed the Stroop color word stimulus into a non-color word presented with adjacent (above and below) color bars. Namely, RED with two red bars was a congruent condition and RED with two green bars was incongruent. Using a stereoscope, the word and the bars were presented to the same eye or to different eyes (bars to one eye and the word to the other eye). They found that same eye presentations resulted in a larger Stroop effect than different eye presentations. This suggests involvement of peripheral sub-cortical brain structures (i.e., bottom-up process) in the Stroop effect.

Another unresolved issue concerns the characteristics of different types of conflict in the Stroop task, such as relative automaticity. In 1964, Klein suggested that interference with color naming appeared not only with incongruent color names but also with other stimuli. He compared the effects of nonsense syllables, rare words, common words, color-related meanings (e.g., sky), distant color-names (i.e., color names not included in the response set), and close color-names (i.e., standard incongruent trials). He reported a graded interference, with the largest effect for the standard incongruent condition, a smaller effect for the distant color names, and so on. The color-related words, like sky and lemon, have been used in quite a few works to distinguish between the response conflict created by the standard incongruent condition and the semantic effect indicated by the color-related words. White and Besner (2018) used the psychological refractory period (PRP) method in order to examine how automatic the response conflict and semantic conflicts are. Participants performed two tasks; task 1 was tone identification and the subsequent task 2 was a vocal Stroop task. In one experiment the stimuli were incongruent color words or neutral words (probing response conflict) and in another, the stimuli were incongruent color-related words or neutral words (probing semantic conflict). In addition, the interval between the two tasks was manipulated. Both Stroop effects were additive with the interval between the two tasks. This additivity was taken by the authors to imply that both conflicts were structurally bottlenecked. That is, the processes involved in both conflicts must wait until some capacity required for task 1 is freed up before the conflict, which also needs capacity, can appear.

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Hence, according to the criterion of capacity limitation, semantic activation is not automatic nor is response conflict. Augustinova, Silvert, Spatola, and Ferrand (2018) also examined semantic and response components of the Stroop effect and in addition, they examined task conflict. Task conflict occurs between two competing tasks. For example, naming the ink color (the relevant task) and reading the irrelevant but automatic word (the irrelevant task). Both semantic and response conflicts were significant regardless of response mode (manual vs. vocal). In contrast, the effect of task conflict was significant only with vocal responding. Similar to White and Besner, Augustinova and colleagues were interested in the issue of automaticity or control. In order to examine effects of control, they manipulated the response-stimulus interval (RSI); in particular, they used either 500 ms or 2000 ms RSIs. RSI had an effect only on response conflict—short RSI reduced the response conflict effect compared to long RSI. Interestingly, these results support White and Besner's conclusion regarding the non-automaticity of response conflict but suggest that semantic conflict is automatic when another criterion—the ability to control rather than capacity limitation—is taken into account. Besides capacity limitation and limited control, another criterion for automaticity is awareness or the lack of awareness. Bugg and Diede (2018) used a secondary stimulus-detection task in their work. They found that the secondary task did not disrupt experience-driven control but did affect the expectation-driven use of pre-cues. Hence, it seems that experience-driven effects are more automatic compared to expectation-driven effects. Similar to the above studies, Shichel and Tzelgov (2018) examined the components of the Stroop effect. They examined all three types of conflict: task, semantic, and response conflict. They dealt with the last two conflicts differently from the previous researchers. Response conflict in their studies was examined by mapping colors to two responses only. In the manual experiment (Experiment 1), they used four colors that were mapped to two rather than four different responses (e.g., the colors red and blue were assigned to one key while the colors yellow and green were assigned to another key). In the vocal experiment (Experiment 2), they used four color words and only two colors, so that color names were classified as belonging to or not belonging to the response set. Accordingly, there were four Stroop conditions: congruent, non-word neutral, incongruent-same response (i.e., stimuli were part of the response set in the vocal experiment) and incongruent-different response (i.e., stimuli not part of the response set in the vocal experiment). The latter two conditions enabled examining the semantic and the response (motor) components of the conflict. In addition, following the suggestion that the larger proportion of neutrals decreases control (Tzelgov, Henik, & Berger, 1992), Shichel and Tzelgov manipulated the proportion of neutral trials (low proportion of 25% neutrals vs. high proportion of 75% neutrals). They concluded that control (i.e., neutral proportion) modulated the task conflict and semantic conflict; both were reduced when the proportion of neutrals was low. In contrast, the response (motor) conflict (i.e., incongruent-different response vs. incongruent-same response) was not affected by manipulation of control. Interestingly, Shichel and Tzelgov's conclusion seems to deviate from the conclusions drawn from previous works. In particular, Augustinova and colleagues suggested that task conflict is not affected by manipulation of control (i.e., manipulation of RSI) whereas response conflict is modulated by control. However, Augustinova and colleagues defined response conflict as the difference between the standard incongruent condition and the incongruent condition based on color-related words (e.g., sky). This is a much less restrictive definition of response conflict than Shichel and Tzelgov's definition. Accordingly, it seems that both the specific manipulation of control (e.g., RSI vs. neutral proportions) and the precise definition of Stroop components contribute to seemingly different conclusions regarding the effects of control and automaticity on the Stroop effect.

Hasshim and Parris (2018) examined the effect of Klein's (1964) distant color names under the heading of response set effects. They used the standard incongruent stimuli and also incongruent color words that were not in the response set. In general, the response set effect is indicated by larger interference when the incongruent trials belong to the response set than when they are non-response set trials. Hasshim and Parris presented response set and non-response set trials in pure blocks or in mixed blocks. The response set effect was larger for the pure than the mixed blocks. They suggest that this pattern of results cannot be explained by strategic or top-down control. In addition, they found that reaction times (RTs) to standard incongruent trials in the pure blocks were relatively long. In their view, the latter effect was not consistent with results and predictions coming from manipulation of congruent-incongruent or neutral proportions. They wrote: "One prediction from this account of the proportion congruency effect is that RTs to incongruent trials should be shorter when presented in pure blocks than when presented in mixed blocks; a prediction not supported by the findings from the present study." Interestingly, this might be related to Shichel and Tzelgov's (2018) finding that response conflict was unaffected by the neutral proportion manipulation. Alternatively, both pure and mixed blocks in Hasshim and Parris' study were mostly incongruent so that the effect of trial proportion might have been negligible, or we should note Bugg and Diede's (2018) summary that MC blocks are affected by expectation (at least explicitly) whereas MI blocks are not.

Examples for use of derivations of the Stroop task in various areas of research appear in the following three articles. Pires, Leitão, Guerrini, and Simões (2018) employed a spatial Stroop task, in which task-relevant and irrelevant information was integrated within the same stimulus. In this task, an arrow pointing to the left or to the right appeared on the left or the right of the center of the screen. Participants were asked to attend to the direction of the arrow and to ignore its position. The arrow's direction and position could be congruent or incongruent. The authors were interested in control indicated by sequential effects; namely, the effect that the congruity in trial n-1 may have on the congruity effect in the following trial (i.e., trial n). They pit one against the other theory. One theory suggests that a conflict between alternative responses is resolved by focusing on the task's relevant dimension, which reduces interference from the task's irrelevant dimension. An alternative theory suggests that the conflict between alternative responses is resolved by a cost-effectiveness analysis that leads to the suppression of the incorrect action plan, leaving only the correct action plan available for execution. Both focusing and suppression linger from trial n-1 to trial n and thus create the sequential effects. The results of three experiments support both theories but according to the authors, the second theory (i.e., the one that involves suppression of the incorrect action plan) is supported by a larger number of results (see summary in Table 1 in Pires et al.). Sharma (2018) examined proactive control by testing whether previously studied words would cause interference in a color-naming task. Participants first studied non-color words and then were asked to name colors of studied and not studied words. Presentation of studied and not studied words was either in pure blocks or in mixed blocks. Pure blocks of unstudied words were processed faster than mixed blocks were. However, in the first half of the test there was no difference between studied and unstudied words that appeared in the mixed blocks and in the second half, studied words showed larger interference than unstudied words taken from pure or mixed blocks. The second half not only showed stronger priming interference effects but also showed a sequential modulation effect in which studied words slowed down the responses of studied words on the next trial. Sharma suggests that this pattern of results is due to reduced control in accordance with the proactive-control/task-conflict (PC-TC) model suggested by Kalanthroff, Avnit, Henik, Davelaar, and Usher (2015). Huang, Tse, and Xie (2018) examined the issue of directionality in judgment of conceptual metaphors (e.g., life is a journey). In many cultures, darkness is associated with negative concepts like evil, death, and sadness, whereas brightness is associated with positive concepts like life and happiness. Similarly, valence is also associated with brightness (*black sheep* refers to an odd or disreputable member of a group and *white lie* is a lie told with good intentions). Huang and colleagues were interested in finding out if brightness-valence metaphoric associations have a directional (e.g., valence to brightness) or bi-directional effect. In a Stroop-like task (Experiment 1), they presented participants with single words in black or white and asked them, in separate blocks, to judge valence (positive vs. negative) or brightness (bright vs. dark). Stimuli could be congruent (e.g., positive in white – wisdom in white) or incongruent (e.g., negative in white – grief in white). The metaphoric congruity effect was significant for valence judgments but not for brightness judgments. In terms of directionality, there was an effect in the brightness-to-valence direction, but not the valence-to-brightness direction. Interestingly, when non-words were added to the stimuli and participants were asked to respond only to the words and not respond to the non-words (Experiment 3), the valence-to-brightness metaphoric congruency was significant. It seems that the metaphoric effect is bidirectional but valence information accrues relatively slowly and thus might not affect brightness judgments, especially when the latter are very fast.

Conclusion

Classic studies on the Stroop effect (Klein, 1964; Stroop, 1935) continue to inspire present-day researchers to explore the processes that contribute to the difficulty faced when attempting to name the colors of conflicting color words or color-related words that can alternatively be read. In the past, much work was devoted to studying the source of interference (i.e., the meaning of the word). Today, it seems that much work is devoted to control processes involved in interference and the participant's ability to control interference. Accordingly, the Stroop task has been changed from a task indicative of automaticity of word reading to a task that probes control and goal-directed behavior. The studies in this special issue highlight 1) both bottom-up (e.g., contingencies, experience) and top-down (e.g., expectations) processes contribute to the Stroop effect and its modulation; 2) the presence of multiple types of conflict within the Stroop task and their overlapping and unique characteristics, including the degree to which each is automatic or influenced by control; and 3) the clever ways in which researchers are modifying the Stroop task to advance our understanding of long-standing (e.g., congruency sequence effects) and newer phenomena (e.g., mnemonic consequences of proactive control) in the literature on cognitive control. We hope that this special issue will inspire the next generation of research on these important issues.

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Avishai Henik[a,*], Julie M. Bugg[b], Liat Goldfarb[c]

[a] *Ben-Gurion University of the Negev, Israel*

[b] *Washington University in St. Louis, USA*

[c] *University of Haifa, Israel*

E-mail address: henik@bgu.ac.il*E-mail address:* henik@bgu.ac.il (A. Henik)

* Corresponding author.