Acta Psychologica 133 (2010) 146–153

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Attention, temporal predictability, and the time course of context effects in naming performance

Ardi Roelofs *

Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, The Netherlands

ARTICLE INFO

Article history:
Received 9 June 2009
Received in revised form 9 October 2009
Accepted 2 November 2009
Available online 5 December 2009

PsycINFO classification:
2300
2323
2340
2346
2720

Keywords:
Attention
Context effects
Naming
Stroop
Temporal predictability

ABSTRACT

Models of attention and context effects in naming performance should be able to account for the time course of color–word Stroop interference revealed by manipulations of the stimulus onset asynchrony (SOA) between color and word. Prominent models of Stroop task performance (Cohen, Dunbar, & McClelland, 1990; Cohen & Huston, 1994; Phaf, Van der Heijden, & Hudson, 1990) fail to account for the fact that response time (RT) and Stroop interference peak at zero SOA and diminish with word preexposure. The models may be saved by assuming that the time course of interference is determined by a strategic orienting of attention to color onsets when SOA is predictable. To test this temporal predictability hypothesis, SOA was blocked or randomly mixed in Experiment 1. In addition, the time interval between color onsets was randomly variable in Experiment 2. Although RTs were affected, none of the randomization manipulations influenced the typical shape of the time course of Stroop effects. These findings provide evidence against the temporal predictability hypothesis and thereby against prominent models of the Stroop task.

1. Introduction

Attention includes the ability to formulate goals and plans of action and to follow these while facing distraction (e.g., Posner & Raichle, 1994). A widely employed task in studying attention is the color–word Stroop task (Stroop, 1935), which is sometimes called the "gold standard of attentional measures" (MacLeod, 1992). The task involves naming the ink color of incongruent or congruent color words (e.g., the word GREEN or RED printed in red; say "red") or a nonverbal control stimulus (e.g., a series of Xs in red). Alternatively, participants name color patches with superimposed words rather than their ink colors (e.g., Glaser & Glaser, 1982). Response time (RT) is typically longer in the incongruent than the control condition, descriptively called *interference*, and often shorter in the congruent than the control condition, descriptively called *facilitation* (see MacLeod, 1991, for a review).

Several computationally implemented models of Stroop task performance not only seek to account for the basic Stroop interference and facilitation effects, but also for the typical time course of the effects, as assessed by manipulating the stimulus onset asynchrony (SOA) between color patch and word (Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990; Roelofs, 2003). RTs and Stroop interference maximize when color patch and word are presented close to each other in time (i.e., around zero SOA), and interference falls off sharply when the word is presented earlier (at preexposure SOAs) or later than the color (at postexposure SOAs). Facilitation in RTs is obtained and remains constant at word preexposure SOAs (e.g., Glaser & Glaser, 1982). Elsewhere (Roelofs, 2003, 2005a), I argued that the time course of the Stroop effects challenges the models of Cohen et al. (1990), Cohen and Huston (1994), and Phaf et al. (1990), whereas models like WEAVER++ (Roelofs, 2003) explain the time course findings.

In this article, I first describe the characteristic time course of the Stroop effects in more detail and make clear that the models of Cohen et al. (1990), Cohen and Huston (1994), and Phaf et al. (1990) fail to explain the time course findings. Cohen and colleagues (Cohen et al., 1990; Cohen & Huston, 1994) suggest that their models fail to account for the time course findings because the models lack strategic processes that could compensate for prior presentation of a distracting stimulus. It is possible that the models can be saved by assuming that the time course of Stroop effects is determined by a strategic

* Address: Donders Institute for Brain, Cognition and Behaviour, Centre for Cognition, Radboud University Nijmegen, Spinoza Building B.01.08, Montessorilaan 3, 6525 HR, Nijmegen, The Netherlands.
E-mail address: A.Roelofs@donders.ru.nl

0001-6918/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.actpsy.2009.11.003

orienting of attention to color onsets when SOA is blocked (see Wright & Ward, 2008, for a review of the literature on the orienting of attention). Next, I present the results of two RT experiments that tested whether a strategic orienting of attention determines the time course of effects in Stroop task performance. Finally, theoretical implications of the data are discussed.

2. Theoretical importance of the time course of Stroop effects

Following a seminal study by Dyer (1971) using word preexposure SOAs only, Glaser and Glaser (1982) examined the time course of Stroop effects in naming color patches by presenting incongruent and congruent words and neutral stimuli (i.e., a row of Is) with a wide range of both word preexposure and postexposure SOAs. The color was presented on a dark background as a colored rectangle and the word or control stimulus was superimposed in white on the color. The onset of the presentation of the distractor word or control stimulus could be 400, 300, 200, or 100 ms before the onset of the presentation of the color patch, the onset of distractor and color could coincide (zero SOA), or the distractor could follow the color patch with a lag of 100, 200, 300 or 400 ms. Henceforth, word preexposure SOAs are indicated by a minus sign (e.g., −400 ms). Trials were blocked by SOA. Consistent with Dyer (1971), Glaser and Glaser observed that RTs and interference in the incongruent condition increased considerably as the preexposure time of the word became shorter. Interference at SOA = −400 ms (i.e., 25 ms) was only about a third of that at zero SOA (72 ms). The interference also decreased as the postexposure time of the word became longer. Interference at SOA = 200 ms (i.e., 24 ms) was only about a third of the interference at zero SOA. Facilitation was constant at word preexposure SOAs.

These SOA patterns have been replicated with the Stroop task by Glaser and Glaser (1989) and Long and Lyman (1987). The SOA patterns are not only obtained using written words, but also using auditory words (Roelofs, 2005a). Moreover, the patterns are also obtained using the picture-word variant of the color–word Stroop task (e.g., Glaser & Düngelhoff, 1984; Rayner & Springer, 1986; Roelofs, 1992, 2006; Starreveld & La Heij, 1996). Thus, the findings are not restricted to context effects in the Stroop task, but generalize to other types of naming performance. In all these studies, trials were blocked by SOA. To summarize, when the color and word information is presented sequentially, RTs and interference maximize when color and word are close to each other in time, and interference falls off sharply when the word is presented earlier or later than the color. Facilitation in RTs is obtained and remains constant at word preexposure SOAs.

The findings on the time course of context effects in naming performance (Glaser & Düngelhoff, 1984; Glaser & Glaser, 1982, 1989; Long & Lyman, 1987; Rayner & Springer, 1986; Roelofs, 2003, 2005a, 2006; Starreveld & La Heij, 1996) are of great theoretical importance. I have argued that the time course of the Stroop effects challenges a number of important models of the Stroop phenomenon (Roelofs, 2003, 2005a). According to the prevailing account in the literature, Stroop interference and facilitation effects in RTs reflect the built-up of activation along color naming and word reading pathways in associative memory (Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990). This predicts maximal impact of words at preexposure SOAs.

The model of Cohen et al. (1990) assumes that activation from perceived colors and words accumulates at a response level. Computer simulations by Cohen and colleagues revealed that Stroop interference and facilitation effects in this model are largest with preexposure of the word (i.e., the effects are predicted to be much larger at SOA = −400 ms than at zero SOA). Absolute RTs are much larger at SOA = −400 ms than zero SOA in the incongruent condition and much shorter at SOA = −400 ms than zero SOA in the congruent condition. Increasing the word preexposure time in the model increases the amount of activation that will have been built-up along the word pathway when the target color is presented. Consequently, increasing the word preexposure SOA leads to an increase of RTs on incongruent trials and it leads to a decrease of RTs on congruent trials. In the models of Cohen and Huston (1994) and Phaf et al. (1990) network activation quickly settles into a stable state corresponding to the word, so that making the word preexposure SOA longer or shorter has no effect. Consequently, the increase of RTs on incongruent trials and decrease of RTs on congruent trials remains constant at word preexposure SOAs. Absolute RTs do not differ between SOA = −400 ms and zero SOA in these models. Thus, none of these models in the literature (i.e., Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990) accounts for the empirical fact that Stroop interference peaks around zero SOA (Dyer, 1971; Glaser & Glaser, 1982, 1989; Long & Lyman, 1987). Moreover, none of these models explains why absolute RTs are much smaller at SOA = −400 ms than at zero SOA. Thus, the empirically observed time course of the Stroop effect challenges these models (Roelofs, 2003, 2005a).

Elsewhere (Levelt, Roelofs, & Meyer, 1999; Roelofs, 1992, 1997, 2003, 2006, 2008a, 2008b, 2008c, 2008d; Roelofs & Hagoort, 2002), I presented a computationally implemented model of naming performance and its attentional control, called WEAVER++, in which maximal distractor impact occurs at short SOAs (for a related model, see Starreveld & La Heij, 1996). In performing tasks requiring selective attention, such as the color–word Stroop task, WEAVER++ employs at least two kinds of selective attention, referred to as "stimulus set" and "response set" by Broadbent (1970, 1971), and Broadbent and Gregory (1964). Stimulus set (input filtering) indicates selection on the basis of a perceptual attribute or source, such as spatial location, color, or shape. Response set indicates selection on the basis of the vocabulary of allowable responses. In a typical Stroop experiment, the irrelevant words correspond to the allowable responses, so selection by response set is not possible. However, some kind of input filtering is possible in Stroop task performance. WEAVER++ favors processing of the color attribute over the word shape attribute by reactively blocking the latter. The model assumes that colors and words activate corresponding information in an associative network. Because of distractor blocking and spontaneous decay of activation, there is little activation from preexposed words in the network around color onset. Similarly, there is little network activation from postexposed words around color onset. Because word activation in the network is maximal when the word is presented around color onset, interference is maximal at short SOAs in the model. Facilitation is constant at preexposure SOAs because of a floor effect in speeding up responding. Computer simulations reported in Roelofs (2003) revealed that WEAVER++ not only successfully accounts for the time course of Stroop effects, but also for several other classic data sets on RTs in Stroop task performance, mostly taken from the review by MacLeod (1991). With only three free parameters, the model accounts for 96% of the variance of 16 classic studies (250 data points).

3. The temporal predictability hypothesis

Cohen and colleagues (Cohen et al., 1990; Cohen & Huston, 1994; Cohen, Dunbar, Barch, & Braver, 1997) pointed out that their models fail to account for the time course of the Stroop effects "most likely because both models lack any adaptive mechanisms (e.g., habituation or strategic processes) that could compensate for prior presentation of a distracting stimulus" (Cohen & Huston, 1994, p. 467). In Roelofs (2003), I presented evidence that habituation is not a critical variable in determining the time course of Stroop effects. However, it is possible that the models can be saved by assuming strategic processes concerning temporal input modulation.

In previous studies, trials were blocked by SOA (e.g., Dyer, 1971; Glaser & Glaser, 1982, 1989; Long & Lyman, 1987; Roelofs, 2003, 2005a, 2006). This raises the possibility that participants strategically exploit the advance knowledge of the timing of color and word in a block of trials by employing an attentional filter that selectively modulates the visual input over time. The temporal predictability of color and word allows for the strategic opening or closing of a time window for incoming stimuli. In Broadbent's (1970, 1971) terms, the stimulus set may include instants of time (cf. Nobre, 2001). Such strategic process may attenuate the impact of the word at preexposure and postexposure SOAs compared to zero SOA, giving rise to the characteristic time course of the Stroop effects. Recently, Yu and Choe (2006) demonstrated the utility of such an account through computer simulations of the time course of the Stroop effects. However, direct empirical evidence for the temporal predictability hypothesis of SOA effects is lacking.

In WEAVER++, distractor words are reactively blocked, so the characteristic time course of the Stroop effects should be obtained regardless of whether participants have advance knowledge about the timing of color and word. In contrast, according to the temporal predictability hypothesis, the characteristic time course of Stroop effects depends on prior knowledge about the timing of color and word. Blocking of trials by SOA would allow for the strategic orienting of attention to the color onset, whereas mixing of SOAs would not. I am aware of only one Stroop study that did not block trials by SOA, namely an experiment by Schooler, Neumann, Caplan, and Roberts (1997). Schooler et al. suggest that Goolkasian (1981) also randomized SOAs, but this seems incorrect, because Goolkasian claims to have counterbalanced the SOAs (p. 1250). The evidence from Schooler et al. (1997) does not support the temporal predictability hypothesis, but also not the predictions by WEAVER++.

Different from what the temporal predictability hypothesis would predict, Schooler et al. (1997) found maximal Stroop interference in RTs at short SOAs, even though SOAs were randomized. Moreover, maximal interference was obtained at SOA = 100 ms rather than zero SOA, which Schooler et al. took as evidence that the time course of Stroop effects differs between mixed and blocked SOAs. However, this claim was based on a comparison between separate studies, namely between Schooler et al. (1997) and Glaser and Glaser (1982). Such a comparison is somewhat problematic, because the studies differed in many respects, including language and participant population. Still, even with randomized SOAs, the characteristic pattern of Stroop interference is obtained, with the effect being much greater at SOA = 100 ms than SOA = 300 or −300 ms. This finding challenges the temporal predictability account and thereby several models of the Stroop phenomenon in the literature (i.e., Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990). However, in the experiment of Schooler et al. (1997) facilitation did not remain constant at word preexposure SOAs, as is typically observed (e.g., Glaser & Glaser, 1982, 1989, Long & Lyman, 1987), but facilitation was maximal at SOA = 200 ms. This finding challenges the WEAVER++ model (Roelofs, 2003). To conclude, evidence from Schooler et al. (1997) on Stroop task performance with randomized SOAs challenges all models of the Stroop phenomenon discussed above. However, the findings of Schooler et al. (1997) have not been replicated and their study did not directly compare performance in blocked and mixed SOA conditions.

4. Plan of the present study

The present article reports two experiments that aimed to examine to what extent temporal predictability of color and word determines the time course of the Stroop effects by directly comparing blocked and mixed SOA conditions. Participants named color patches while ignoring color words. The SOAs between word and color were −400, −200, 0, and 200 ms. Trials were blocked by SOA or they were randomly mixed (in both experiments) and the time interval between target colors was constant (Experiment 1) or randomly variable (Experiment 2). Blocking of trials by SOA would allow for the strategic orienting of attention to the color onset, whereas mixing of SOAs would not. Moreover, a constant timing of color targets between trials (i.e., a constant inter-stimulus interval, ISI) would allow for a temporal orienting of attention to color onsets (cf. Naccache, Blandin, & Dehaene, 2002), whereas a mixing of the timing of color targets (i.e., variable ISIs) would not.

If the Stroop accounts of Cohen et al. (1990), Cohen and Huston (1994), and Phaf et al. (1990) hold true and temporal predictability is a critical variable in determining the time course of the Stroop effects, then the following predictions are made. With *mixed* SOAs and ISIs, maximal RTs and interference should be obtained at SOA = −400 ms (Cohen et al.) or RTs and interference should be constant at preexposure SOAs (Cohen and Huston; Phaf et al.). However, with *constant* SOAs and ISIs, RTs should be largest and interference should peak at zero SOA (Cohen et al.; Cohen and Huston; Phaf et al.). These predictions are made because with constant SOAs and ISIs, orienting of attention to the color onset is possible, whereas with mixed SOAs and ISIs it is not. The strategic orienting of attention to the color onset should attenuate the impact of the word at nonzero SOAs with constant SOAs and ISIs. In contrast, if the temporal predictability of color and word is not responsible for the characteristic time course of the Stroop effects (Roelofs, 2003, 2005a), RTs and interference should peak at zero SOA and facilitation should be constant at preexposure SOAs regardless of whether SOAs and ISIs are constant or variable. Thus, observing maximal absolute RTs and Stroop interference at zero SOA with mixed SOAs and ISIs would disconfirm the temporal predictability hypothesis.

5. Experiment 1

In the first experiment, participants named color patches while trying to ignore color words. Trials were blocked by SOA or SOAs were randomly mixed. The ISI between target colors was constant. Blocking of trials by SOA allows for the orienting of attention to the color onset time-locked to the beginning of a trial, whereas mixing of SOAs does not.

5.1. Method

5.1.1. Participants

The experiment was carried out with 16 paid students of Radboud University Nijmegen. All were young adults and native speakers of Dutch.

5.1.2. Materials and design

The stimuli consisted of red, green, and blue color patches and the corresponding Dutch color words ROOD, GROEN, and BLAUW. The colors were presented as colored rectangles of 1.5 cm high and 4.5 cm wide. The written words were presented in 36-points lowercase Arial font. A row of 5 Xs served as stimulus in the control condition. This control stimulus was chosen to be similar to the row of Vs used by Dyer (1971) and the row of Is used by Glaser and Glaser (1982).

There were three independent variables, which were varied within participants. The first independent variable was *Stroop condition*. There were three congruent pairings (ROOD–red, GROEN–green, BLAUW–blue), three incongruent pairings (ROOD–blue, GROEN–red, BLAUW–green), and three control stimuli (the color patches combined with the row of Xs). With three color patches, three color words, and a series of Xs, there are six possible color–word combinations in the incongruent condition, but only three combinations in the congruent condition and three in the control condition. In order to have an equal number of stimuli in each of the Stroop conditions, incongruent trials were, therefore, constructed by repeatedly pairing one color word with one color patch (i.e., ROOD–blue, GROEN–red, BLAUW–green). Roelofs (in press) observed that this does not affect the time course of Stroop effects compared with fully crossing colors and words. The second independent variable was *SOA* with four levels: −400, −200, 0, and 200 ms. The third independent variable was *block type*. In a block of trials, SOA was constant or randomly variable. Half the participants first received the constant-SOA trials and then the variable-SOA trials, and vice versa for the other half of the participants. The order of the constant-SOA blocks was counterbalanced across participants using a Latin square. Each of the congruent, incongruent, and control stimuli occurred four times within an SOA block. The stimuli were presented in a random order.

5.1.3. Procedure and apparatus

The participants were tested individually. They were seated in front of a CRT monitor (NEC Multisync) and a Sennheiser microphone connected to an electronic voice key. The distance between participant and screen was approximately 50 cm. The participants were asked to name the color patches as quickly as possible while trying to make no mistakes.

A trial started with the presentation of the color–word stimulus with the appropriate SOA. The stimuli remained visible for 1.5 s after color onset. Following stimulus presentation, the screen was blank for 1 s, after which the next trial began. An IBM compatible computer controlled the stimulus presentation and data collection.

5.1.4. Analysis

Five types of incorrect responses were distinguished: wrong response word, wrong pronunciation of the word, a disfluency, triggering of the voice key by a non-speech sound, and failure to respond within 1.5 s after target presentation. Incorrect responses were excluded from the statistical analyses of the RTs. The RTs and errors were submitted to analyses of variance with the crossed variables Stroop condition, SOA, and block type. All variables were tested within participants. Interactions between variables were statistically explored through paired *t*-tests. Planned comparisons tested for Stroop facilitation (i.e., congruent vs. control) and interference (i.e., incongruent vs. control) at each SOA.

5.2. Results and discussion

Fig. 1 gives the mean color naming RTs and error rates for Stroop condition, SOA, and block type. The figure shows that responding was slowest in the incongruent condition and fastest in the congruent condition. This held for both the constant- and variable-SOA conditions. The time course of the Stroop interference and facilitation effects did not depend much on whether SOA was constant or variable. At the SOAs of −400, −200, 0, and 200 ms, the interference was, respectively, 33 ms, 39 ms, 115 ms, and 46 ms in the constant-SOA condition, and 41 ms, 45 ms, 108 ms, and 31 ms in the variable-SOA condition. Thus, the interference was about twice as large at zero SOA than at the other SOAs, regardless of block type. At the preexposure SOAs of −400 and −200 ms, the facilitation was, respectively, 39 ms and 28 ms in the constant-SOA condition, and 25 ms and 31 ms in the variable-SOA condition. Thus, facilitation was present at preexposure SOAs, regardless of block type. Error rates were highest for the incongruent condition at all SOAs except SOA = −400 ms in both the constant- and variable-SOA blocks.

The statistical analysis of the errors yielded a main effect of Stroop condition, $F(2, 30) = 7.21$, $p < .003$, but not of SOA and block type, *ps* > .88. There was an interaction of Stroop condition and SOA, $F(6, 90) = 2.75$, $p < .02$, but not of any other combination of factors, *ps* > .28. The analysis confirms that the error rate was highest for the incongruent condition depending on the SOA, for both the constant- and variable-SOA blocks. Most errors were made in the slowest condition, excluding a speed-accuracy trade-off in the data.

The statistical analysis of the RTs yielded effects of Stroop condition, $F(2, 30) = 47.97$, $p < .001$, and SOA, $F(3, 45) = 22.00$, $p < .001$, but not of block type, $F(1, 15) < 1$, $p > .70$. As expected, Stroop condition and SOA interacted, $F(6, 90) = 8.28$, $p < .001$. Stroop condition did not interact with block type, $F(2, 30) < 1$, $p > .53$, but there was an interaction of SOA and block type, $F(3, 45) = 4.86$, $p < .005$. There was no interaction of Stroop condition, SOA, and block type, $F(6, 90) < 1$, $p > .92$, indicating that the Stroop effects and their time course did not depend on SOA blocking. Planned comparisons revealed that Stroop interference was present at all SOAs, all *ps* < .01. The magnitude of interference was larger at zero SOA than at the other SOAs, all *ps* < .001. Stroop facilitation was obtained at the SOAs of −400 and −200 ms, *ps* < .01, but not at the other ones, *ps* > .23. The magnitude of Stroop facilitation with word preexposure did not depend on the SOA, $F(1, 15) < 1$, $p = .70$. Absolute RTs were much longer at zero SOA than at SOA = −400 ms, $F(1, 15) = 38.56$, $p < .001$, independent of SOA blocking, $F(1, 15) = 1.19$, $p > .29$. Exploration of the interaction of SOA and block type through pairwise comparisons revealed that responding at SOA = −400 ms was overall faster in the variable-SOA than in the constant-SOA condition (i.e., means, respectively, 573 and 597 ms), $p < .03$. The overall RTs did not differ between the block types at SOA = −200 ms and zero SOA, *ps* > .65. However, responding at SOA = 200 ms was overall slower in the variable- than in the constant-SOA condition (i.e., means, respectively, 674 and 649 ms), $p < .04$.

To summarize the interaction of SOA and block type in the RTs suggests that temporal predictability has an effect in the Stroop task. However, the characteristic time course of Stroop interference and facilitation is independent of the blocking versus mixing of SOAs. Stroop interference was larger and the absolute RTs were longer at zero SOA than at SOA = −400 ms in both the constant and variable SOA conditions. Facilitation was constant at preexposure SOAs with both constant and variable SOAs. These findings challenge the temporal predictability hypothesis.

6. Experiment 2

In the first experiment, the SOAs were blocked or mixed. Mixing of SOAs should make it impossible to open and close a window for color targets that is time-locked to the beginning of a trial. Still, it is possible that participants utilize another orienting strategy. Perhaps attentional templates are used that are time-locked to the estimated onset of the target color patch rather than the onset of the beginning of a trial (cf. Naccache et al., 2002). Schooler et al. (1997) did not randomize ISIs, so their findings obtained with randomized SOAs are compatible with the temporal predictability hypothesis provided that participants estimated the onset of the color target on each trial. If participants oriented attention depending on the estimated onset of the target, this should attenuate the influence of the word regardless of the constancy of SOAs, as observed in the first experiment. To prevent such attentional strategy, the size of the time intervals between the color onsets was made randomly variable in Experiment 2. In the constant-SOA condition, participants may still exploit the advance knowledge about the sequential order of word and color. For example, if the word

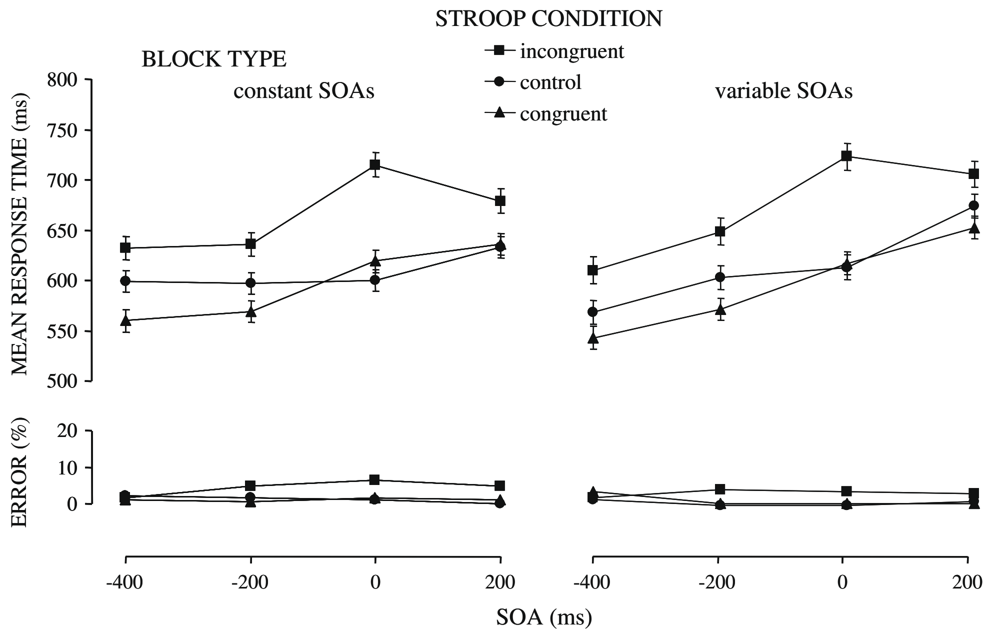

Fig. 1. Mean response times and error percentages per SOA and Stroop condition for the constant- and variable-SOA blocks at constant intertrial-intervals in Experiment 1. The error bars indicate the standard error of the mean. SOA = stimulus onset asynchrony.

always appears before the color in a block of trials, processing of the first stimulus that appears on the screen (the word) may be suppressed. However, in the variable SOA condition, such strategy is not possible. Thus, if the RTs are longest and interference is maximal at zero SOA in the variable SOA condition, then the temporal predictability hypothesis is disconfirmed.

6.1. Method

The design of the experiment was the same as that of Experiment 1 except that the time interval between the target color patches was now randomly variable. The experiment was carried out with 16 new participants. A trial started with the presentation of the color–word stimulus with the appropriate SOA. The stimuli remained visible for 1.5 s after color onset. Before the start of the next trial there was a blank interval of 1 s plus a random delay of 0, 400, 800, or 1200 ms (in Naccache et al., 2002, the targets appeared randomly after 810, 1094, or 1449 ms). Each delay occurred equally often for each condition (SOA, Stroop condition, and block type).

6.2. Results and discussion

Fig. 2 gives the mean color naming RTs and error rates for Stroop condition, SOA, and block type. The figure shows that responding was slowest in the incongruent condition and fastest in the congruent condition. This held for both the constant and variable SOA conditions. The time course of the Stroop interference and facilitation effects did not depend much on whether SOA was constant or variable. At the SOAs of −400, −200, 0, and 200 ms, the interference was, respectively, 50 ms, 48 ms, 104 ms, and 50 ms in the constant-SOA condition, and 48 ms, 67 ms, 108 ms, and 42 ms in the variable-SOA condition. Thus, the interference was about twice as large at zero SOA than at the other SOAs, regardless of block type. At the preexposure SOAs of −400 and −200 ms, the facilitation was, respectively, 42 ms and 40 ms in the constant-SOA condition, and 34 ms and 40 ms in the variable-SOA condition. Thus, facilitation was present at preexposure SOAs, regardless of block type. The error rates were slightly higher for the incongruent condition than the other conditions in both the constant- and variable-SOA blocks.

The statistical analysis of the errors yielded a main effect of Stroop condition, $F(2, 30) = 5.97$, $p < .007$, but not of any other factor or combination of factors. Most errors were made in the slowest condition, which excludes a speed-accuracy trade-off in the data.

The statistical analysis of the RTs yielded effects of Stroop condition, $F(2, 30) = 95.84$, $p < .001$, and SOA, $F(3, 45) = 44.48$, $p < .001$, but not of block type, $F(1, 15) < 1$, $p > .55$. Stroop condition and SOA interacted, $F(6, 90) = 11.81$, $p < .001$. Stroop condition did not interact with block type, $F(2, 30) < 1$, $p > .94$, but there was an interaction of SOA and block type, $F(3, 45) = 5.39$, $p < .003$. There was no interaction of Stroop condition, SOA, and block type, $F(6, 90) < 1$, $p > .84$, indicating that the Stroop effects and their time course did not depend on SOA blocking. Planned comparisons revealed that Stroop interference was present at all SOAs, all *ps* < .001. The magnitude of interference was larger at zero SOA than at the other SOAs, all *ps* < .001. Stroop facilitation was obtained at the SOAs of −400 and −200 ms, *ps* < .001, but not at the other ones, *ps* > .20. The magnitude of Stroop facilitation with word preexposure did not depend on the SOA, $F(1, 15) < 1$, $p = .70$. Absolute RTs were much longer at zero SOA than at SOA = −400 ms, $F(1, 15) = 54.96$, $p < .001$, independent of SOA blocking, $F(1, 15) = 2.51$, $p > .13$. Exploration of the interaction of SOA and block type through pairwise comparisons revealed that the overall RTs did not differ between the block types, *ps* > .15, except at SOA = 200 ms, $p < .05$. At this SOA, responding was overall slower in the variable-SOA than in the constant-SOA blocks (i.e., means, respectively, 623 and 587 ms), as in Experiment 1. Although at SOA = −400 ms, the RTs were shorter in the variable-SOA than the constant-SOA condition (i.e., 529 vs. 545 ms) as in Experiment 1, this difference now did not reach significance ($p = .15$, two-tailed).

The interaction of SOA and block type in the RTs suggests that temporal predictability has an effect in the Stroop task. Again, however, the specific Stroop effects and their time course remain unaffected. Stroop interference was larger and the absolute RTs were longer at zero SOA than at SOA = −400 ms in both the constant and variable SOA conditions. Facilitation was constant at preexposure SOAs. These findings disconfirm the temporal predictability hypothesis.

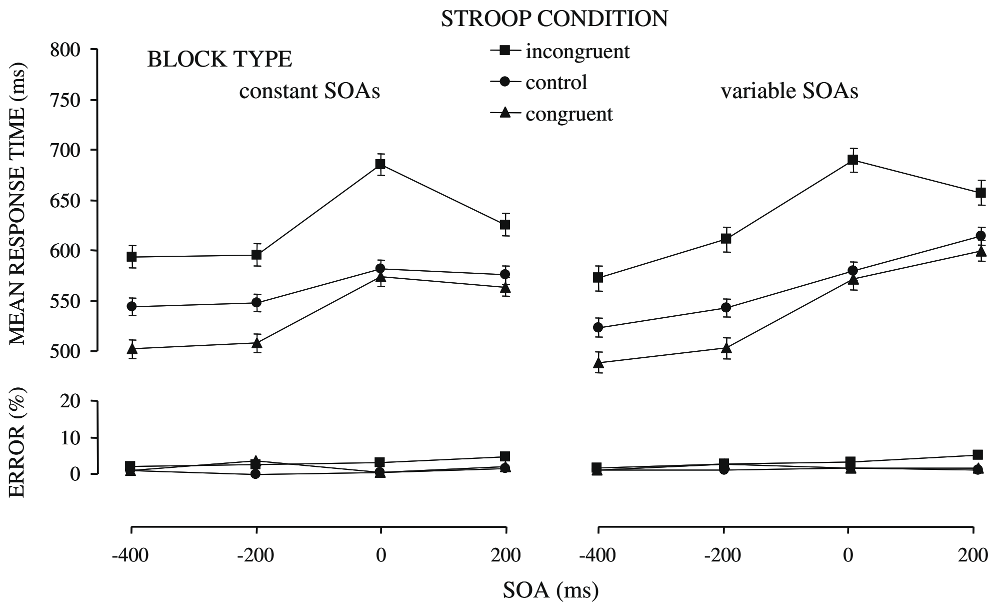

Fig. 2. Mean response times and error percentages per SOA and Stroop condition for the constant- and variable-SOA blocks at variable intertrial-intervals in Experiment 2. The error bars indicate the standard error of the mean. SOA = stimulus onset asynchrony.

7. Combined analysis of Experiments 1 and 2

To examine whether there were any differences between experiments (constant vs. variable ISIs), the RTs and errors were submitted to a joint analysis of variance with experiment as a between-participant factor. There was no effect of experiment on the RTs, $F(1, 30) = 2.15$, $p > .15$, and experiment did not interact with the factors Stroop condition, SOA, and block type, or any combination of factors, all $ps > .38$. There was also no effect of experiment on the errors, $F(1, 30) < 1$, $p > .64$, and there were also no interactions, all $ps > .08$. Thus, whether the ISIs were constant or variable did not affect the Stroop effects and their time course.

8. General discussion

Attention and context effects in naming performance have been extensively investigated using the color–word Stroop task. Past research (e.g., Dyer, 1971; Glaser & Glaser, 1982, 1989; Long & Lyman, 1987) demonstrated that when the SOA between color and word is manipulated, less Stroop interference is obtained when participants know that the irrelevant word is presented earlier or later than the target color compared with a simultaneous presentation. Facilitation is constant at word preexposure SOAs. The time course of effects challenges important models of attention in naming performance (i.e., Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990). Cohen and colleagues (Cohen et al., 1990, 1997; Cohen & Huston, 1994) suggested that their models fail to account for the time course findings because the models lack strategic processes that could compensate for prior presentation of a word when SOAs are blocked: the temporal predictability hypothesis.

In the present article, two experiments were reported that examined to what extent temporal predictability determines the time course of context effects in Stroop task performance. In both experiments, participants named color patches while trying to ignore color words. SOA was blocked or mixed in Experiment 1. In addition, the ISI between color onsets was randomly variable in Experiment 2. Although RTs were affected, none of these manipulations influenced the typical shape of the time course of Stroop effects. Interference was about twice as large at zero SOA than at the other SOAs, and facilitation was present at preexposure SOAs, regardless of the constancy or variability of SOAs and ISIs. These findings provide evidence against the temporal predictability hypothesis and thereby against prominent models of the Stroop task.

8.1. Comparison with earlier findings

Schooler et al. (1997) argued that the time course of Stroop effects is different with mixed and blocked SOAs based on a comparison between their own study with mixed SOAs and the study of Glaser and Glaser (1982) with constant SOAs. The present Experiments 1 and 2 directly compared mixed and constant SOAs, and found no effect of SOA blocking or mixing on the specific Stroop interference and facilitation effects. Stroop interference peaked at zero SOA and facilitation was constant at preexposure SOAs. In contrast, Schooler et al. (1997) observed that interference peaked at SOA = 100 ms and facilitation at SOA = 200 ms. Different from what Schooler et al. (1997) observed, facilitation was constant at preexposure SOAs in the studies of Glaser and Glaser (1982, 1989) and Long and Lyman (1987). The present experiments do not replicate the peak of facilitation at SOA = 200 ms obtained by Schooler et al. (1997), but replicate the findings of Glaser and Glaser (1982, 1989) and Long and Lyman (1987). This suggests that the peak of facilitation at SOA = 200 ms obtained by Schooler et al. (1997) is an unusual finding. Whereas the pattern of facilitation obtained by Schooler et al. (1997) challenges the Stroop account by the WEAVER++ model of Roelofs (2003), the patterns obtained by Glaser and Glaser (1982, 1989), Long and Lyman (1987), and in the present Experiments 1 and 2 fully agree with WEAVER++.

8.2. Influence of temporal predictability

In Experiments 1 and 2, there was an interaction of SOA and block type, which suggests that temporal predictability plays a role in the Stroop task. However, the interaction between block type and SOA was independent of the Stroop condition. The blocking versus mixing of SOAs had a general non-specific effect. Similarly, Fan and colleagues (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005) and Shalev and Algom (2000) observed that presenting temporal cues and spatial cues before the targets in the Eriksen flanker and Stroop tasks affects RTs, but there were no interactions with the effects of target condition (i.e., incongruent vs. congruent). The preexposed temporal cues and spatial cues reduced the RTs in the studies of Fan et al. (2002, 2005) and Shalev and Algom (2000). In the present study, RTs were shorter in the variable- than the constant-SOA condition at SOA = −400 ms. It is possible that when the preexposure SOA of the word is sufficiently long, the appearance of the word has an alerting effect, just like temporal cues have. The present results would then suggest that such an alerting effect is more effective when the SOAs are variable than when they are constant.

However, such an alerting effect cannot explain why RTs were shorter rather than longer in the constant than the variable SOA condition at SOA = 200 ms. As discussed by Cohen and Huston (1994), it is likely that bottom-up effects of attentional capture play a role in the Stroop task. It may be that postexposure of the word on some trials (variable-SOA condition) captures attention more strongly than a postexposure on all trials within a block (constant-SOA condition). When the word unpredictably appears shortly after the color onset, its appearance may temporarily distract the participant, drawing attention away from the color and slowing the response. This would explain the slower responding in the variable- than the constant-SOA blocks at the postexposure SOA in the present experiments.

The reported experiments clearly show that temporal orienting of attention does not determine the time course of the specific Stroop interference and facilitation effects. The results leave open the possibility that the temporal separation of color and word is used by the participants to select the imperative stimulus (cf. La Heij, Van der Heijden, & Plooij, 2001). Glaser and Glaser (1989) instructed participants to respond to the first stimulus component that appeared on the screen, which could be either a color patch (requiring color naming) or a word (requiring reading). Glaser and Glaser demonstrated that participants are able to use the temporal separation of stimulus components as selection cue even at SOAs as short as 50 ms (see Roelofs, 2003, for simulations of these experiments using WEAVER++). In Broadbent's (1970, 1971) terms, the stimulus set may include temporal order. However, the present results indicate that if temporal separation of color and word is used by the participants to select the imperative stimulus, this is done regardless of the blocking condition, because the time course of the Stroop effects does not differ between constant and mixed SOAs and ISIs.

Moreover, previous research showed that stimulus *offset* asynchrony reduces Stroop interference, just as SOA does. When the color and word have the same presentation onset but the color is removed after 120 or 160 ms, this reduces interference (La Heij et al., 2001). Removing both color and word simultaneously reduces interference less than removing the color only (La Heij et al., 2001). If a color patch is not removed but only repositioned (<2°) after 100 ms, interference is also reduced (Lamers & Roelofs, 2007). And if the distractor is repositioned while the target remains stationary, interference is again reduced. These results indicate a role for Gestalt grouping in the Stroop task (Lamers & Roelofs, 2007). It is possible that a temporal proximity of color and word also yields such a Gestalt grouping. The present results do not rule out this possibility. However, the results indicate that if such temporal Gestalt grouping occurs, this should hold regardless of the blocking condition, because the time course of the Stroop effects does not differ between constant and mixed SOA and ISI conditions.

8.3. Theoretical Implications

The characteristic time course of the Stroop effects (e.g., Dyer, 1971; Glaser & Glaser, 1982, 1989; Long & Lyman, 1987; replicated by the present Experiments 1 and 2) and the pattern of absolute RTs challenge a number of important models of the Stroop phenomenon, namely the models of Cohen et al. (1990), Cohen and Huston (1994), and Phaf et al. (1990). The present experiments show that the typical time course of effects is obtained regardless of whether color and word are temporally predictable or not. This suggests that the models cannot be saved by assuming temporal input-modulation mechanisms. Note that this conclusion does not depend on acceptance of the null hypothesis (i.e., no effect of blocking or randomization of SOA and ISI on Stroop effects). Given that the models predict that absolute RTs and Stroop interference should be maximal at SOA = −400 ms (Cohen et al., 1990) or constant at preexposure SOAs (Cohen & Huston, 1994; Phaf et al., 1990) if there is no temporal predictability, then the observation of maximal RTs and interference at zero SOA with no predictability is sufficient to disconfirm the models. Elsewhere, I demonstrated that the WEAVER++ model of Stroop task performance accounts for the time course of Stroop interference and facilitation effects (Roelofs, 2003). In the model, distractor words are only processed for a limited period of time before they are actively blocked. Distractor impact will decrease with increasing SOA because activation decays over time. Stroop interference occurs when the activation of the target and distractor temporally overlaps, which happens when target and distractor are presented close together in time. Facilitation is constant at preexposure SOAs in the model, due to a floor effect in speeding up responses, which also makes the magnitude of the effect less dependent on the decay. This holds for both color–word Stroop and picture-word interference tasks (Roelofs, 2003).

The model of Starreveld and La Heij (1996) also accounts for the time course of picture-word interference effects by assuming that distractor words provide perceptual input for a limited period of time and that distractor activation decays, although the model assumes no active blocking. However, the active blocking in WEAVER++ explains a number of findings that remain unexplained in the model of Starreveld and La Heij (1996). The findings include the effect of fixed versus variable stimulus locations (Roelofs, 2003), the observation of Miozzo and Caramazza (2003) that high-frequency distractor words cause less interference in object naming than low-frequency distractor words (Roelofs, 2005b), and the negative relation between the magnitude of Stroop interference and reading ability (Protopapas, Archonti, & Skaloumbakas, 2007).

It is possible that other models will be able to account for the time course of the Stroop effects by making assumptions about distractor processing and activation decay that are similar to those implemented in WEAVER++ and the model of Starreveld and La Heij (1996). For example, Phaf et al. (1990) assume that distractor processing continues throughout a trial. Consequently, build-up of distractor activation is maximal at preexposure SOAs. It is possible that by limiting the duration of distractor processing in the model of Phaf et al., distractor activation will be much less at long preexposure SOAs, as in WEAVER++. However, this raises the question what mechanism in the model of Phaf et al. might cause that distractor words are only processed for a limited duration. This issue is also not addressed by the model of Starreveld and La Heij (1996). The model of Phaf et al. has implemented a mechanism for input filtering (stimulus set) based on lateral inhibition, but it apparently does not reduce the impact of preexposed distractors in the way suggested by the empirical data (Glaser and Glaser, 1982, 1989; Long and Lyman, 1987; the present Experiments 1 and 2). Moreover, it seems unlikely that limiting the distractor processing duration in the model is sufficient to account for the empirically observed increase of Stroop interference with decreasing SOA. In the model of Phaf et al., the amount of interference does not differ much between SOA = −400 ms and zero SOA. However, the distractor is processed 400 ms longer at SOA = −400 ms than at zero SOA. This suggests that the magnitude of Stroop interference in the model of Phaf et al. does not depend much on distractor processing duration, so that implementing a mechanism that limits the distractor processing in the model is unlikely to save the model.

9. Conclusion

The reported experiments demonstrate that although the constancy or variability of SOAs influences RTs, the magnitude of specific Stroop interference and facilitation effects remains unaffected. These results disconfirm the temporal predictability hypothesis of the time course of the Stroop phenomenon. Thus, the characteristic time course of Stroop effects remains a challenge for prominent models of attention and context effects in naming performance (i.e., Cohen et al., 1990; Cohen and Huston, 1994; Phaf et al., 1990).

Acknowledgements

The author thanks Marianne Severens for her help in running the experiments, and two reviewers for helpful comments. The preparation of the article was supported by a VICI grant from the Netherlands Organisation for Scientific Research.

References

Broadbent, D. E. (1970). Stimulus set and response set: Two kinds of selective attention. In D. I. Mostofsky (Ed.), *Attention: Contemporary theory and analysis* (pp. 51–60). New York: Appleton-Century-Crofts.

Broadbent, D. E. (1971). *Decision and stress*. London: Academic Press.

Broadbent, D. E., & Gregory, M. (1964). Stimulus set and response set: The alternation of attention. *Quarterly Journal of Experimental Psychology, 16*, 309–317.

Cohen, J. D., Dunbar, K. O., Barch, D. M., & Braver, T. S. (1997). Issues concerning relative speed of processing hypotheses, schizophrenic performance deficits, and prefrontal function: Comment on Schooler et al. (1997). *Journal of Experimental Psychology: General, 126*, 37–41.

Cohen, J., Dunbar, K., & McClelland, J. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97*, 332–361.

Cohen, J. D., & Huston, T. A. (1994). Progress in the use of interactive models for understanding attention and performance. In C. Umiltà & M. Moscovitch (Eds.), *Conscious and nonconscious information processing: Attention and performance XV* (pp. 453–476). Cambridge, MA: MIT Press.

Dyer, F. N. (1971). The duration of word meaning responses: Stroop interference for different preexposures of the word. *Psychonomic Science, 25*, 229–231.

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage, 26*, 471–479.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*, 340–347.

Glaser, W. R., & Düngelhoff, F.-J. (1984). The time course of picture–word interference. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 640–654.

Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 875–894.

Glaser, W. R., & Glaser, M. O. (1989). Context effects in Stroop-like word and picture processing. *Journal of Experimental Psychology: General, 118*, 13–42.

Goolkasian, P. (1981). Retinal location and its effect on the processing of target and distractor information. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1247–1257.

La Heij, W., Van der Heijden, A. H. C., & Plooij, P. (2001). A paradoxical exposure-duration effect in the Stroop task: Temporal segregation between stimulus attributes facilitates selection. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 622–632.

Lamers, M., & Roelofs, A. (2007). Role of Gestalt grouping in selective attention: Evidence from the Stroop task. *Perception & Psychophysics, 69*, 1305–1314.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22*, 1–38.

Long, G. M., & Lyman, B. J. (1987). Foveal and parafoveal processing of asynchronous Stroop stimuli. *British Journal of Psychology, 78*, 151–162.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*, 163–203.

MacLeod, C. M. (1992). The Stroop task: The "gold standard" of attentional measures. *Journal of Experimental Psychology: General, 121*, 12–14.

Miozzo, M., & Caramazza, A. (2003). When more is less: A counterintuitive effect of distractor frequency in the picture-word interference paradigm. *Journal of Experimental Psychology: General, 132*, 228–252.

Naccache, L., Blandin, E., & Dehaene, S. (2002). Unconscious masked priming depends on temporal attention. *Psychological Science, 13*, 416–424.

Nobre, A. C. (2001). Orienting attention to instants in time. *Neuropsychologia, 39*, 1317–1328.

Phaf, R. H., Van der Heijden, A. H. C., & Hudson, P. T. W. (1990). SLAM: A connectionist model for attention in visual selection tasks. *Cognitive Psychology, 22*, 273–341.

Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York: W.H. Freeman.

Protopapas, A., Archonti, A., & Skaloumbakas, C. (2007). Reading ability is negatively related to Stroop interference. *Cognitive Psychology, 54*, 251–282.

Rayner, K., & Springer, C. J. (1986). Graphemic and semantic similarity effects in the picture–word interference task. *British Journal of Psychology, 77*, 207–222.

Roelofs, A. (1992). A spreading-activation theory of lemma retrieval in speaking. *Cognition, 42*, 107–142.

Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. *Cognition, 64*, 249–284.

Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review, 110*, 88–125.

Roelofs, A. (2005a). The visual-auditory color–word Stroop asymmetry and its time course. *Memory & Cognition, 33*, 1325–1336.

Roelofs, A. (2005b). From Popper to Lakatos: A case for cumulative computational modeling. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 313–330). Hillsdale, NJ: LEA.

Roelofs, A. (2006). Context effects of pictures and words in naming objects, reading words, and generating simple phrases. *Quarterly Journal of Experimental Psychology, 59*, 1764–1784.

Roelofs, A. (2008a). Tracing attention and the activation flow in spoken word planning using eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 353–368.

Roelofs, A. (2008b). Dynamics of the attentional control of word retrieval: Analyses of response time distributions. *Journal of Experimental Psychology: General, 137*, 303–323.

Roelofs, A. (2008c). Attention, gaze shifting, and dual-task interference from phonological encoding in spoken word planning. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 1580–1598.

Roelofs, A. (2008d). Attention to spoken word planning: Chronometric and neuroimaging evidence. *Language and Linguistics Compass, 2*, 389–405.

Roelofs, A. (in press). Attention and facilitation: Converging information versus inadvertent reading in Stroop task performance. Journal of Experimental Psychology: Learning, Memory, and Cognition.

Roelofs, A., & Hagoort, P. (2002). Control of language use: Cognitive modeling of the hemodynamics of Stroop task performance. *Cognitive Brain Research, 15*, 85–97.

Schooler, C., Neumann, E., Caplan, L. J., & Roberts, B. R. (1997). A time course analysis of Stroop interference and facilitation: Comparing normal individuals and individuals with schizophrenia. *Journal of Experimental Psychology: General, 126*, 19–36.

Shalev, L., & Algom, D. (2000). Stroop and Garner effects in and out of Posner's beam: Reconciling two conceptions of selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 997–1017.

Starreveld, P. A., & La Heij, W. (1996). Time course analysis of semantic and orthographic context effects in picture naming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 896–918.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

Wright, R. D., & Ward, L. M. (2008). *Orienting of attention*. Oxford: Oxford University Press.

Yu, Y., & Choe, Y. (2006). Selective attention in time: An extended model of stimulus onset asynchrony (SOA) in Stroop effect. In *Proceedings of the fifth international conference on development and learning, IN University, Indiana, Bloomington*.