

Time Course Analysis of the Stroop Phenomenon

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Dyer (1971) investigated the response competition hypothesis of the Stroop phenomenon by temporally separating the color and word components of single stimuli (incongruent, control, and congruent). This line of research was continued in a series of five experiments that generalized Dyer's study: (a) In addition to the color-naming task, a reading task was included; (b) the irrelevant stimulus component was presented before and after the relevant one; (c) the probabilities of congruent and incongruent stimuli were varied; (d) besides color-word/color stimuli, color-color and word-word stimuli were used; and (e) the functional discrimination (color naming or reading) was compared with a sequential discrimination task. The data suggest the following temporal relations: (a) a slow facilitation due to response bias; (b) its inhibitory counterpart; and (c) a fast, strong inhibition with no facilitatory complement that seems to correspond to the usual Stroop conflict but that seems to occur earlier than the response execution stage.

Generally, Stroop stimuli consist of two dimensions. One dimension is a word and the other is a physical attribute such as color, form, pitch of voice, and so forth. Frequently, the physical dimension is a necessary attribute of the word, for example, the color of the ink used to print the name of a color as in the standard Stroop (1935) task. The essential variable is the degree of congruency between word and color. In the congruent condition both dimensions match (e.g., the word *red* printed in red); in the incongruent condition they mismatch (e.g., the word *red* printed in green). The subject's task is to name the color or to read the word while ignoring the other dimension. The reaction times (RTs) to congruent and incongruent stimuli are usually evaluated by comparing

them with a control condition that lacks one dimension.

The complete crossing of the factors, "stimulus condition" (incongruent, control, congruent) and "task" (color naming and reading), results in a characteristic pattern of mean data points (heavy lines in Figure 1).

The RT for reading is not influenced by stimulus variation and is faster than is the color-naming control by the amount b in Figure 1. In the literature, a range of values are reported: $b = 22$ msec (Gholson & Hohle, 1968), $b = 200$ msec (Duncan-Johnson, 1981), and $b = 213$ msec (Glaser & Dolt, 1977). The lower values are more often observed when using homogeneous control blocks, the higher values when using heterogeneous blocks where the control trials are interspersed among the congruent and incongruent trials. The basic reading time (see a in Figure 1) reported is between 400 msec and 550 msec.

Traditionally, the difference between the RTs for naming incongruent stimuli and for naming control stimuli (see c in Figure 1) is called the Stroop phenomenon. However, we prefer to define the Stroop phenomenon as the complete data pattern as displayed in Figure 1, because c cannot be explained without reference to all data points. In the literature, reported values for c range from 70 msec up to 200 msec; values between 100

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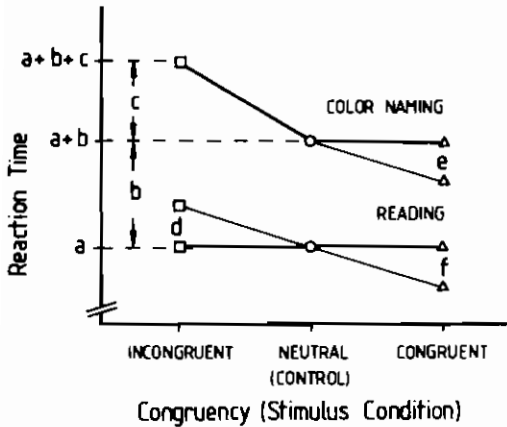


Figure 1. Idealized data pattern of the Stroop task with single stimuli and reaction time measurements. (a = basic reading time; b = difference between naming and reading control stimuli; c = Stroop conflict; d = reversed Stroop conflict; e = color-naming facilitation; f = reading facilitation.)

msec and 130 msec are frequent. Experimental manipulations—foremost, spatial separation of word and color (Dyer & Severance, 1973), reduced semantic similarity between the two dimensions (Klein, 1964), or the use of key pressing instead of vocal response (Keele, 1972; Pritchatt, 1968)—reduce c below 70 msec, but usually do not remove the difference completely. The time for naming the color of a congruent stimulus differs at least randomly from the control RT, but we will further discuss whether the congruent irrelevant word facilitates color naming (see e in Figure 1). In the literature, significant facilitations are frequently reported (Dyer, 1971, 1972, 1973; Hintzman et al., 1972; Neumann, 1980; Regan, 1978), but there are contradictory reports as well (Schulz, 1979; Sichel & Chandler, 1969; Stirling, 1979).

The central questions for an adequate theoretical explanation of the Stroop phenomenon are: Why is the time needed to name a color so prolonged when the stimulus consists of a word semantically related to this color? Why does the effect reach its maximum if the semantic distance between stimulus components is minimal (Klein, 1964) but disappear if the distance is zero, as in the congruent condition? Finally, why is the phenomenon asymmetrical; that is, why does

reading the word component of an incongruent stimulus usually not show any prolonged RT ($d = 0$ in Figure 1)?

Depending on the hypothesized locus of the Stroop effect, three classes of explanations can be distinguished. Hock and Egeth (1970) suggest that the color word disrupts the identification of the color by diverting attention from it. This "distraction effect" is largest for words semantically related to the color-naming task because the subjects are sensitized to them. The most important objection against this *perceptual-encoding* hypothesis is that it cannot explain why the congruent stimuli do not cause interference although the semantic similarity between word and color is maximal (Dalrymple-Alford & Azkoul, 1972; Seymour, 1977; Stirling, 1979).

The *response competition* hypothesis of the Stroop phenomenon (Keele, 1972; Morton, 1969; Posner & Snyder, 1975; Warren, 1972) states that word and color are processed in a parallel manner until their motor programs are activated. Because only the program that corresponds to the relevant stimulus dimension is admitted to response execution, the program that corresponds to the irrelevant stimulus dimension must be prevented from getting control over the overt response. There is no conflict when congruent stimuli are to be named or read, because both stimulus components activate the same response program. Reading incongruent stimuli provides no problem either because the relevant motor program reaches the execution stage before the irrelevant one does. If, on the other hand, incongruent stimuli have to be named, the irrelevant motor code arrives at the response execution stage before the relevant one does. The delay in RT (see c in Figure 1) and the other behavioral signs of a conflict (cf. Jensen & Rohwer, 1966, p. 58) are explained as a consequence of the subject's difficulty in suppressing the first and executing the second of two articulatory codes that arrive at the response execution stage in close succession. There have only been a few attempts to render the properties of this process more precise: Glaser and Dolt (1977) suggest a temporal discrimination model; Neumann (1980) models a race between both signals competing to gain en-

trance to a single-channel response buffer as in Morton's (1970) logogen model.

The response competition hypothesis not only explains the basic pattern of Stroop data but is also supported by further experimental evidence: Manipulations that reduce the difference in speed between naming and reading control stimuli (see *b* in Figure 1), such as practicing the naming response extensively or reducing the legibility of the word, decrease the Stroop delay. Occasionally, such manipulations also result in a small reversed Stroop effect, that is, a delay in reading incongruent stimuli (see *d* in Figure 1; Dyer & Severance, 1972; Gumenik & Glass, 1970; Liu, 1973; Stroop, 1935).

Contradicting this view, however, are experimental findings that suggest that the main conflict occurs at an earlier stage when the color information makes contact with semantic memory after perceptual encoding. These results support a *semantic-encoding* hypothesis as proposed by Seymour (1974, 1977). In his 1974 study, subjects matched the spatial location of a sign (above or below a square) to the meaning of a locational adverb (*above* or *below*) presented inside the square. Their vocal response was "yes" or "no." The sign itself was either neutral (*XXX*), identical to one of the response words (*yes* or *no*), semantically related to the response (*right* or *wrong*), or semantically related to the locational adverb (*up* or *down*). Only the last condition yielded a Stroop conflict that was tied to a mismatch of words; that is, the Stroop conflict occurred if the meaning of the distractor word differed from the meaning of the locational adverb. A consistent locational mismatch effect, that is, a response delay caused by incongruent distractor meaning and distractor location as predicted by the perceptual-encoding hypothesis, did not occur. Also, a response competition, that is, a response delay caused by incongruent distractor word and response word, was not observed. The most reasonable explanation of these data seems to be that there is a competition between two semantically related words that are used as input in the spatial word-picture comparison task. In an experiment more similar to the standard Stroop task, Seymour (1977) found further evidence for his hypothesis that the con-

flict is located between perceptual encoding and response activation at the level of semantic representation of the relevant and the irrelevant stimulus attribute: The simultaneous activation of two distinct semantic codes that are closely related leads to an ambiguity that must be resolved before further processing. The Stroop phenomenon is an indication of the extra processing time needed to delete the irrelevant code. Processing congruent stimuli causes no response delay because both components of the stimulus activate the same semantic code.

In Experiment 1, we tested a prediction that follows from the response competition hypothesis: If the relevant and the irrelevant components of Stroop stimuli are processed in a parallel manner and the arrival time at the response execution stage is the only determinant of the conflict (Dyer & Severance, 1972; Gumenik & Glass, 1970; Palef & Olson, 1975), then the temporal separation of both components should permit us to find a stimulus onset asynchrony (SOA) that compensates for slower processing of color (cf. Neumann, 1980). In this case, word and color should arrive at the response execution stage simultaneously or with a small temporal lead for color. The RT for reading an incongruent stimulus should now be prolonged by the same amount as is the RT for naming the color in the ordinary Stroop task. The conflict should become symmetrical (e.g., $d = c$ in Figure 1).

However, it could be argued that the association between a color stimulus and a color-word response, despite lifelong practice and overlearning (at least for primary colors), is not as strong as the association between a word stimulus and a reading response (Smith & Magee, 1980). Therefore, even with an adequate SOA, the color component of a Stroop stimulus could interfere only to a small degree with the reading task. Nevertheless, most formulations of the response competition hypothesis at least implicitly support the prediction that an adequately preexposed color component of a Stroop stimulus should markedly interfere with a reading response (cf. Posner, 1978, pp. 91-92; Posner & Snyder, 1975, pp. 57, 63).

Experiment 2 concerned itself with the role of voluntary and involuntary compo-

nents in the naming and reading processes. In Experiment 3 we further traced the naming-reading asymmetry as obtained in the data of Experiments 1 and 2. Instead of Stroop stimuli, color-color and word-word stimuli were used. The main question was whether these stimuli would produce time courses similar to those in the color-naming or similar to those in the reading Stroop task.

As an interpretation frame, the "method of specific effects" suggested by Taylor (1977) was used. Its central idea is as follows: In a double stimulation experiment with a relevant and an irrelevant stimulus separated by a systematically varied SOA, "specific effects" can be computed in each SOA cell as differences between the mean RTs in the experimental conditions and a mean control RT. If a delay of processing, caused by the irrelevant stimulus, is expected as it was in our incongruent condition, the mean control RT is subtracted from the mean experimental RT. This specific effect is called inhibition, because an experimental RT that is longer than a control RT renders this difference positive. Conversely, subtracting a mean experimental RT from the mean control RT, as in our congruent condition, yields a difference that can be called facilitation. The processing of the relevant and the irrelevant stimuli is modeled by Taylor (1977) using the assumption that the cognitive representations of both pass through the same sequence of processing stages. For the irrelevant stimulus, this sequence ends before an overt response occurs, whereas the relevant stimulus activates the response execution stage. If the data show a specific effect as defined above, the processing of the irrelevant stimulus must have interacted with the processing of the relevant stimulus in at least one stage. Taylor distinguishes two kinds of possible interactions. The ongoing processing of one stimulus can influence the ongoing processing of another stimulus. This interaction, due to a temporal overlap at the same stage regardless of which stimulus is first, is called the *primary* effect. On the other hand, the completed processing of one stimulus can leave a stage in an altered state, thus affecting processing of an immediately succeeding stimulus. This influence is called the *secondary* effect.

The facilitation and inhibition data as functions of SOA make it possible to discriminate between these two kinds of cognitive processes. If both stimuli have the same modality, as in our Experiment 3, their cognitive representations should pass the processing stages with constant internal SOA. Now, if the data show a specific effect at a postexposure of the irrelevant stimulus, a primary effect must have occurred. Furthermore, a primary effect should result in a facilitation or inhibition function symmetrical with regard to the SOA level of 0 as it is of no importance whether the irrelevant stimulus precedes or follows the relevant one. In contrast, a secondary effect results in an asymmetrical time course because it occurs only if the irrelevant stimulus precedes the relevant one. Given these definitions, we deduce from Seymour's (1974, 1977) semantic-encoding hypothesis that the effects must be primary because the time-consuming ambiguity depends only on a temporal overlap of two codes, regardless of which one is first. A response competition hypothesis would suggest secondary effects because a conflict depends on a temporal lead of the irrelevant stimulus component.

Experiments 4 and 5 examined alternative interpretations of Experiment 3.

Experiment 1

Temporal separation of the color and word components of Stroop stimuli was in part already investigated by Dyer (1971) who preexposed the word before the color in a color-naming task. However, his technique for displaying the components of the stimulus allowed no preexposure of the color before the word. Kamlet and Egeth (1969) and Egeth, Blecker, and Kamlet (1969) achieved the full Stroop effect by having their subjects name the background color on which white characters were printed. We generated similar stimuli by superposing a projection of a white word on a black background (using one slide projector) onto a somewhat larger, homogeneously colored rectangle (projected using a second slide projector). If an adequate intensity relation is chosen, the white letters contrast well against the colored background and do not show a residual coloration. This

display technique permits any SOA level (including SOA = 0) regardless of whether the word or the color is preexposed.

Method

Subjects. In all five experiments, subjects were undergraduate psychology students at the University of Tuebingen; they were native speakers of German and varied in age from 19 to 45 years. No subject took part in more than one experiment. Participation was voluntary and was credited as partial fulfillment of curriculum requirements. Subjects were questioned for sufficient color vision. In Experiment 1, subjects were nine females and seven males.

Materials. The components of the stimuli were four German color words, *rot, gelb, grün, and blau* (red, yellow, green, and blue), and their respective colors. The neutral color "word" consisted of seven capital *Is*. Because this letter was represented by a narrow vertical rectangle, the control "word" was perceived as a series of vertical bars rather than as the word "iiiiiii," which would elicit a reading tendency. The stimulus words, including the neutral one, were black Letraset capitals (Helvetica extrabold, 10.0 mm) affixed to white index cards and photographed on a high contrast black and white 35-mm film. The negatives, white characters on dark background, were mounted in 5- \times -5-cm slide frames and used to project the words. For the colors, film with white horizontal rectangles on a dark background was mounted, together with red, yellow, green, or blue acetate foil, into the slide frames. For the neutral control "color," the rectangle was a homogeneous, medium grey.

Instrumentation. The slides were displayed by a projection tachistoscope consisting of three optically identical Kodak Carousel projectors. Exposure was controlled by solenoid-operated Compur shutters mounted in front of the projection lenses. One projector (Kodak S-RA 2000) permitted random access; it was used to project the colors. The words and a steady grey background slide were each projected by sequential access projectors (Kodak S-AV 2000). The experiment was conducted in a sound-proof, dimly illuminated room. The subject was seated 1.9 m in front of the projection screen; the tachistoscope was placed behind her or him. The 24- \times -36-mm film field was projected at 640 \times 970 mm; the colors produced a horizontal rectangle of 315 \times 875 mm, subtending a visual angle of 9 $^{\circ}$ \times 26 $^{\circ}$. The words were 160 mm high (4 $^{\circ}$); the three-letter word *rot* was 550 mm long (16 $^{\circ}$); and the mean length of the four-letter words was 735 mm (22 $^{\circ}$). The large visual angles were chosen for technical reasons only: The projection of two superposed components requires small relative location tolerances, which were obtained by reproducing the stimuli as large as possible on film. Thus, with the given geometrical relations of our tachistoscope, the visual angles were determined. As preliminary studies yielded the usual Stroop data, we did not reduce the visual angles of our stimuli. The brightness of a complete stimulus, measured at the projection screen, was 550 lx for the white characters. The color fields had a brightness of 70 lx (grey), 140 lx (red), 250 lx (yellow), 55 lx (green),

and 70 lx (blue). The background surrounding the color field had a brightness of 17.5 lx.

The subjects spoke the response into a high-fidelity microphone whose amplified signal, digitalized by a Schmitt trigger, controlled a Hewlett-Packard electronic timer. The RTs were automatically recorded on paper tape. The program for the experiment was controlled by a Massey Dickinson system.

Design. Half the subjects were instructed to name the color component of the stimulus while ignoring the word (color-naming task); the other half had to read the word while ignoring the color (reading task). The irrelevant component, word or color depending on the task, was either preexposed before the relevant component by an SOA level of -400, -300, -200, or -100 msec, exposed simultaneously (SOA = 0 msec), or postexposed by an SOA level of +100, +200, +300, or +400 msec. Throughout this article, preexposure of an irrelevant component is indicated by a minus sign, postexposure by a plus sign.

The stimuli were presented to each subject in nine homogeneous SOA blocks that were distributed on two sessions on different days with four or five blocks each. The sequence of the blocks was randomized for each subject. All blocks consisted of 24 incongruent, 8 control, and 16 congruent trials in pseudorandom order, preceded by 6 warm-up trials.

Procedure. Subjects were familiarized with the properties of the stimuli and of the voice-operated choice RT task. They were instructed to name the relevant component of each stimulus as fast as they could but to avoid errors as far as possible. Subjects received feedback on errors only, not on RTs. In case of a false response or a technically faulty reaction (equipment or voice key failure), the stimulus was repeated in a new trial randomly inserted some trials later. All blocks were separated by short rest periods. One session lasted about 40 min.

A single trial consisted of the following: After the subject's response, the experimenter typed the slot number of the next color component and the right-wrong evaluation of the response into a keyboard to record the RT and the accuracy of the response. The timer was set at zero, and both slides of the stimulus for the next trial were programmed. Trial onset was subject-paced: A signal light below the projection screen indicated to the subject that she or he could start the next trial by pressing a key. The first component of the stimulus, whether relevant or irrelevant, appeared 500 msec after key pressing and was followed after the SOA interval by the second component. The reaction timer started counting at the onset of the relevant component and stopped at the onset of the vocal response. Both components disappeared 200 msec after the reaction. Each experimenter- and subject-paced trial cycle lasted about 10 sec.

Results and Discussion

For each of the 16 subjects, mean RT of the correct responses was computed in the Task \times SOA \times Stimulus Condition cells and used as a raw score in the statistical analyses. Figure 2 shows the means of these RT values

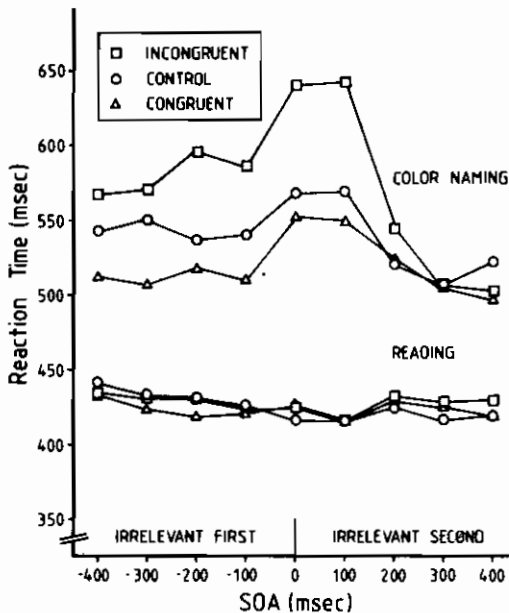


Figure 2. Mean reaction times in the Task \times SOA \times Stimulus Condition cells of Experiment 1. (SOA = stimulus onset asynchrony.)

over subjects. Each point in the incongruent conditions represents 192 single RT measures; in the control conditions, 64; and in the congruent conditions, 128. The respective standard errors of these means were 9.44, 14.10, and 9.09 msec in the color-naming task and 3.68, 6.05, and 4.55 msec in the reading task, averaged across the SOAs. Because records of false responses and of technically faulty reactions were confounded in the protocols, error data unfortunately cannot be reported.

Consistent with our predictions, Figure 2 displays the basic pattern of Figure 1 (heavy lines) at the 0 level of SOA. The variation of the pattern as a function of SOA is discussed below. The control reading time (see *a* in Figure 1) was 425 msec, and the difference between control color naming and reading time (see *b* in Figure 1) was 115 msec, $t(42) = 3.62$, $p < .01$, averaged over all SOAs. This difference varied from 91 to 154 msec, SOA = +300 msec, $t(378) = 2.64$, $p < .01$; and SOA = +100 msec, $t(378) = 4.48$, $p < .01$, respectively.

For general statistical evaluation, a 2 (task, between subjects) \times 9 (SOA, within subjects) \times 3 (stimulus condition, within sub-

jects) split-plot analysis of variance (ANOVA) was conducted on the RT data. The three main effects proved to be significant. In general, RTs (a) were longer in the color-naming task than in the reading task, $F(1, 14) = 14.18$, $p < .01$; (b) increased from congruent through control to incongruent conditions, $F(2, 28) = 33.95$, $p < .01$; and (c) varied with SOA, $F(8, 112) = 5.08$, $p < .01$. Also significant were the three two-way interactions and the three-way interaction. Additional analyses were conducted to examine these interactions.

Specifically, separate two-way ANOVAs with repeated measurements were conducted on the color-naming and the reading data. The stimulus conditions interacted with SOA for both the color-naming task, $F(16, 112) = 7.83$, $p < .01$, $MS_e = 430$,¹ and the reading task, $F(16, 112) = 2.06$, $p = .015$, $MS_e = 85$. The simple main effect of SOA at the control stimuli level was significant, $F(8, 56) = 2.81$, $p < .05$, $MS_e = 1,256$ in the color-naming task and $F(8, 56) = 2.32$, $p < .05$, $MS_e = 268$ in the reading task. In a subsequent Newman-Keuls analysis of the control conditions, only the differences in the color-naming task between the SOA points of 0 and +100 msec on the one hand and the +300-msec point on the other hand reached the significance limit ($p < .05$). These results corroborated the trends apparent in Figure 2.

We next consider the two principal theoretical concerns: facilitation (see *e* and *f* in Figure 1) and inhibition (see *c* and *d* in Figure 1) effects and their variations as a function of SOA. A facilitation score was computed for each subject in each task and SOA by subtracting the mean correct RT for congruent stimuli from the mean correct RT for control stimuli. The corresponding inhibition score was obtained by subtracting the mean correct RT for the control stimuli from the mean correct RT for the incongruent stimuli. Table 1 contains the means of these scores across subjects. Because the error terms of the SOA cells proved homogeneous for the color-naming task as well as for the reading task, the pooled error variances ($MS_e = 569$ for color naming, $MS_e = 88$ for reading, $df = 126$ each) were used for the single *t* tests of Table 1. Furthermore, two

¹ All MS_e s given herein are in squared milliseconds.

separate 9 (SOA) \times 2 (facilitation/inhibition) ANOVAS with repeated measurements were conducted on these scores. In the color-naming task, the mean of facilitation and inhibition varied with SOA, $F(8, 56) = 13.14$, $p < .01$, $MS_e = 389$. SOA and facilitation/inhibition interacted due to the increased inhibition at the SOA points of 0 and +100 msec, $F(8, 56) = 3.44$, $p < .01$, $MS_e = 1,415$, but there was no reliable overall facilitation/inhibition difference. In the reading task analysis, only the interaction reached the significance level, $F(8, 56) = 2.58$, $p = .018$, $MS_e = 299$. The simple main effect of SOA was significant for facilitation in the color-naming task, $F(8, 56) = 2.59$, $p = .018$, $MS_e = 658$, and in the reading task, $F(8, 56) = 2.41$, $p = .026$, $MS_e = 211$, as well as for inhibition in the color-naming task $F(8, 56) = 7.23$, $p < .01$, $MS_e = 1,146$, and in the reading task, $F(8, 56) = 2.25$, $p = .037$, $MS_e = 159$. The results of subsequent Newman-Keuls analyses are presented in Table 1. Finally, the amounts of facilitation and inhibition were compared within each Task \times SOA cell. For color naming, the SOA levels of 0 and +100 msec yielded significant results, $t(63) = 2.81$, $p < .01$; and 2.67 , $p < .01$, respectively; for the reading task, the +300-msec point of SOA was reliable, $t(63) = 2.29$, $p < .05$.

The 0 cell of SOA that corresponds closely to the standard Stroop task with simultaneous presentation of color and word showed

the known pattern of means as given in Figure 1 (heavy lines). In the color-naming task, there was a large Stroop inhibition, *c*, but no significant facilitation, *e*. Somewhat surprising was the negative facilitation, that is, the inhibition in the congruent reading condition. However, though statistically significant in the more sensitive analysis for the reading task, these 10 msec were a small effect compared with the significant effects in the color-naming task.

At the +100-msec point of SOA, this data pattern changed very little. The small negative facilitation for reading now disappeared. In the color-naming task, the irrelevant word maintained its full power to disturb color naming though the temporal lead of the word processing was reduced by 100 msec. If the difference between color-naming and reading (115 msec on the average, 154 msec at the +100-msec level of SOA) of the control stimuli is taken as a measure of faster processing for word than for color, this result is consistent with the response competition hypothesis: Even a 100-msec postexposed word generally arrives at the response execution stage soon enough to disturb the color-naming response.

As expected, at the SOA level of +200 msec, the inhibition effect is markedly reduced. One could hypothesize that this inhibition is a probabilistic mixture of a majority of undisturbed naming responses and a few that were fully disturbed by extremely

Table 1
Mean Facilitation and Inhibition (in msec) as a Function of Stimulus Onset Asynchrony (SOA) in Experiment 1

Task	SOA (in msec)								
	-400	-300	-200	-100	0	+100	+200	+300	+400
Color naming									
Facilitation	31 _{a,b} **	44 _b **	19 _{a,b}	30 _{a,b} *	16 _{a,b}	20 _{a,b}	-4 _a	3 _a	25 _{a,b} *
Inhibition	25 _{a,b,c} *	20 _{a,b}	59 _{b,c} **	45 _{b,c} **	72 _c **	73 _c **	24 _{a,b,c} *	-3 _a	-19 _a
Reading									
Facilitation	7	9*	13**	6	-10*	-1	-4	-9	1
Inhibition	-6	-2	-1	-3	8	0	7	12*	11*

Note. Scores (reading horizontally) that share a common subscript do not differ significantly ($p > .05$) in the Newman-Keuls analysis. For SOA msec values, a minus sign indicates preexposure, a plus sign postexposure of the irrelevant stimulus component. For facilitation and inhibition in the reading task, there was no significant Newman-Keuls result ($p > .05$).

* $p < .05$. ** $p < .01$ (*t* test).

rapidly processed words (Neumann, 1980; Warren & Lasher, 1974). An inspection of the RT distribution does not support this hypothesis (cf. Glaser, 1981).

At the SOA level of +300 msec, there were no longer facilitatory or inhibitory color-naming effects. At this SOA and at the SOA of +400 msec, the irrelevant stimulus is presented too late to influence substantially the processing of the relevant stimulus. Therefore, the color-naming facilitation at +400 msec, though statistically significant, empirically makes no sense. Because this color-naming facilitation is accompanied by a negative inhibition, we are inclined to explain the facilitation as a random variation of the control mean, which also has the largest standard error in this experiment.

At the negative SOAs (preexposure of the irrelevant component of the stimulus), the color-naming inhibition decreased, but it remained significant up to the level of -400 msec, -300 msec excepted. The color-naming facilitation increased up to significant amounts with a flat maximum at -300 msec. These data essentially replicated Dyer's (1971) results. His data also showed a small Stroop conflict even with long word preexposures. This result contradicts some interpretations of the response competition hypothesis (e.g., Klein, 1964) that assume complete fading out of the reading tendency within a time interval that corresponds to the reading RT. Therefore, Dyer (1971) hypothesized "that the additional flash when the word is colored serves to reinstate the 'meaning'" (p. 230). But if that were the case, the effect should not appear in our data because we colored the background, not the word itself.

The results of the reading task were substantially different from the color-naming time courses and clearly opposite to our expectations. There was no SOA at which the temporal lead of the color-naming process resulted in interference with the reading process. This finding obviously contradicts any theory that proposes a balanced, parallel processing of both components up to the response execution stage and explains the Stroop phenomenon only by temporal relations between inner responses. The facilitation by a preceding congruent stimulus, however, was shown by the reading data, also,

but with a markedly reduced amount compared with the color-naming data.

Experiment 2

In Experiment 1, the color did not compete with the word in a race to be the first response in the reading task. This result means that the temporal lead of a semantically related irrelevant internal code could be a necessary, but not sufficient, condition to obtain the Stroop inhibition. There could be another, necessary condition that was fulfilled in the color-naming task but was violated in the reading task. Palef (1978) supports this view and formulates such an additional, necessary condition:

Stroop-like effects seem to arise only when the nature of the interfering material corresponds to one of the codes used in the processing of the relevant information. This may be either the initial code for the stimulus or some translation that is necessary for a certain type of response to be made. (p. 74)

Suppose color encoding was only nonverbal in the reading task of Experiment 1. Then the condition of a corresponding code was violated, and a modified response competition hypothesis may survive its negative results: If subjects could be induced to translate the irrelevant color component into a verbal code in the reading task, and if the SOA is adequate, covert color naming should now interfere with overt word reading. Therefore, the probabilities of stimulus conditions were considerably changed in Experiment 2 in order to induce such a translation in the reading task with color preexposure. The congruent stimuli occurred with a probability level of .8, whereas control and incongruent stimuli each occurred with a probability level of .1. As a consequence of the high predictive validity of the first stimulus component, the subjects were expected to translate internally the color into a verbal code. A time course of facilitation and inhibition similar to the one in the naming task of Experiment 1 should occur in the reading task as well. Tversky (1969) and Taylor (1977), among others, reported data that give strong evidence for internal coding caused by an 80% probability condition. For reasons of comparison, the color-naming task was changed in the same way.

Method

Subjects. Subjects were seven females and five males.

Materials and instrumentation. Stimuli and apparatus were the same as in Experiment 1 except that the tachistoscope consisted of one sequential- and two random-access projectors. Besides this, the whole experiment was run under on-line program control by a Hewlett-Packard Type 1000 minicomputer. A complete protocol including the results of some data preprocessing was recorded on magnetic tape.

Design. As in Experiment 1, half the subjects were run under the color-naming instruction, half under the reading instruction. For both groups, the SOAs ranged from -500 up to 0 msec with 100-msec increments and were held constant within blocks. Contrary to Experiment 1, there was no postexposure of the irrelevant stimulus. Each SOA block was administered once to each subject. One block of 120 trials consisted of 12 incongruent, 12 control, and 96 congruent trials. Therefore, an incongruent or control stimulus occurred with a probability of .1 each, a congruent stimulus with a probability of .8. Stimulus sequence within the blocks was pseudorandom without replacement and with the further restriction that in each partial sequence of 20 trials, starting at Trials 1, 21, and so on, there were exactly two control stimuli and two incongruent stimuli. The experiment was divided into two sessions on different days, with 60 trials of each block per session. The six SOA blocks followed one another according to a sequentially balanced Latin square across subjects, mirrored between the first and second session.

Procedure. On the whole, the procedure was the same as in Experiment 1, except that now the probabilities of the stimulus conditions were explained to the subjects. They were instructed to try to take advantage of the predictive validity of the prestimulus to achieve as short a reaction time as possible while avoiding errors.

Results and Discussion

As before, for each of the 12 subjects mean RT of the correct responses was computed in the Task \times SOA \times Stimulus Condition cells and used as a raw score in the statistical analyses. Figure 3 shows the means of these RT scores across subjects. In the incongruent and control conditions, each point represents 72 single RT measures, in the congruent condition, 576. On the average over the SOAs, the standard errors of the color-naming task entries were 17.23 msec (incongruent), 10.95 msec (control), and 3.12 msec (congruent). The respective standard errors of the reading points were 10.36, 7.94, and 2.90 msec.

There were 56 (1.27%) false responses in the color-naming task, 49 of them in the incongruent condition. In the reading task, 50 (1.14%) false responses were given, 49 of them, too, in the incongruent condition.

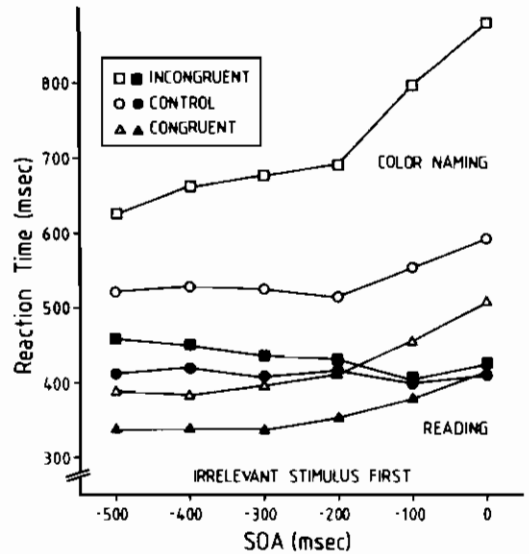


Figure 3. Mean reaction times in the Task \times SOA \times Stimulus Condition cells of Experiment 2. (SOA = stimulus onset asynchrony.)

Within the incongruent conditions, the errors were most frequent at the SOAs that produced the slowest reactions (cf. Table 2).

All main and interaction effects in the 2 (task, between subjects) \times 6 (SOA, within subjects) \times 3 (stimulus condition, within subjects) split-plot ANOVA on the RT data proved significant. Color-naming times exceeded reading times, $F(1, 10) = 30.91$, $p < .01$; times increased as SOA approached 0, $F(5, 50) = 41.61$, $p < .01$; and congruent conditions yielded faster times than control or incongruent conditions, $F(2, 20) = 130.55$, $p < .01$. As before, the reliable interactions were evaluated by separate analyses. Overall, the mean control reading time was 412 msec and the mean difference between control color-naming and reading across the SOAs was 127 msec, $t(30) = 4.04$, $p < .01$. This difference varied from 97 to 181 msec, SOA = -200 msec, $t(180) = 2.86$, $p < .01$; and SOA = 0, $t(180) = 5.33$, $p < .01$, respectively.

Paralleling the results of the overall ANOVA, the color-naming data increased as SOA approached 0, $F(5, 25) = 46.08$, $p < .01$, $MS_e = 1,310$, and as the stimulus conditions varied from congruent to incongruent, $F(2, 10) = 93.21$, $p < .01$, $MS_e =$

8,729. The interaction between SOA and stimulus condition, $F(10, 50) = 10.39$, $p < .01$, $MS_e = 761$, arose mainly from the more rapid increase in RTs as SOAs approached 0 for the incongruent instead of for the other conditions. The simple main effect of SOA at the control stimuli level was significant, too, $F(5, 25) = 6.73$, $p < .01$, $MS_e = 764$. The Newman-Keuls analysis yielded no significant differences at the .05 level between the color-naming control RTs at the SOAs from -400 up to -100 msec. The control RT at the 0 value of SOA significantly differed from all other color-naming control RTs (the smallest difference was significant only at the .05 level).

The reading times also increased with the incongruency of the components, $F(2, 10) = 59.28$, $p < .01$, $MS_e = 880$, and interacted with SOA, $F(10, 50) = 16.43$, $p < .01$, $MS_e = 215$. The main effect for SOA failed to reach the .01 significance level, $F(5, 25) = 3.05$, $p < .05$, $MS_e = 400$. The simple main effect of SOA at the control stimuli level did not reach the .05 significance level.

As in Experiment 1, for each subject in each SOA cell, a facilitation and an inhibition score were computed. Their means over subjects, together with the results of the respective t tests, are given in Table 2. Again, the error terms for the single t tests proved homogeneous for the color-naming task

($MS_e = 2,089$) as well as for the reading task ($MS_e = 326$) and therefore were pooled across the SOAs ($df = 60$ for each). In the color-naming task, the decrease of facilitation, together with the increase of inhibition as SOAs approached 0, led to an SOA main effect, $F(5, 25) = 7.53$, $p < .01$, $MS_e = 956$, and an SOA \times Facilitation/Inhibition interaction, $F(5, 25) = 15.23$, $p < .01$, $MS_e = 1,697$. The overall facilitation/inhibition difference was not significant. In the reading task, there were two significant main effects: SOA, $F(5, 25) = 18.28$, $p < .01$, $MS_e = 348$; and facilitation/inhibition, $F(1, 5) = 22.69$, $p < .01$, $MS_e = 615$. There was also a significant interaction, $F(5, 25) = 8.58$, $p < .01$, $MS_e = 247$. In both tasks, the simple main effects of SOA at the facilitation and the inhibition levels were significant. The color-naming test statistics for facilitation were $F(5, 25) = 4.77$, $p < .01$, $MS_e = 725$ and for inhibition, $F(5, 25) = 15.34$, $p < .01$, $MS_e = 1,928$. The respective reading statistics were $F(5, 50) = 23.99$, $p < .01$, and $F(5, 50) = 4.52$, $p < .01$, pooled $MS_e = 298$. Table 2 contains the results of subsequent Newman-Keuls analyses for the single means.

The comparison of facilitation and inhibition for single SOAs yielded the following results. In the color-naming task, the comparison between facilitation and inhibition showed significant differences at the SOA lev-

Table 2
Mean Facilitation and Inhibition (in msec) as a Function of Stimulus Onset Asynchrony (SOA) in Experiment 2

Task	SOA (in msec)					
	-500	-400	-300	-200	-100	0
Color naming						
Facilitation	135 _a **	146 _a **	130 _a **	105 _{a,b} **	98 _b **	84 _b **
Inhibition	102 _a **	133 _{a,b} **	150 _{a,b} **	176 _b **	243 _c **	287 _c **
(% false responses to incongruent stimuli)	6	6	8	3	12	23
Reading						
Facilitation	74 _a **	82 _a **	70 _a **	63 _a **	21 _b *	-4 _c
Inhibition	47 _a **	29 _{a,b} **	28 _{a,b} **	15 _b	5 _b	15 _b
(% false responses to incongruent stimuli)	19	11	12	9	5	1

Note. Scores (reading horizontally) that share a common subscript do not differ significantly ($p > .05$) in the Newman-Keuls analysis. For SOA msec values, the minus sign indicates preexposure of the irrelevant stimulus component.

* $p < .05$. ** $p < .01$ (t test).

els of -100 and 0 msec, $t(30) = 4.06$, $p < .01$ and $t(30) = 5.70$, $p < .01$. In the reading task, facilitation and inhibition differed significantly from the -500 -msec point up to the -200 -msec point. The respective statistics were $t(30) = 2.63$, $p < .05$; 5.16 , $p < .01$; 4.15 , $p < .01$; and 4.76 , $p < .01$.

In the color-naming task, the facilitation and inhibition time courses were essentially the same as in Experiment 1 within the SOA range common to both experiments, but now the numerical values were about four times as large. Obviously, the redundancy structure of the trial sequence in Experiment 2 very effectively raised the facilitation and inhibition effects.

The reading task, too, produced marked facilitation and inhibition effects. The subjects indeed translated the irrelevant color prestimulus into an internal code that interacted with the reading process. The facilitation shows essentially the same time course as in the color-naming tasks of both experiments: minimal or near zero at the 0 -msec level of SOA and slowly increasing with increasingly negative SOAs up to a flat maximum between -200 and -400 msec. The numerical values are about half those of the color-naming facilitation in this experiment and twice those in Experiment 1. If the word is to be read, processing seems to be aided by a congruent word code generated by translation of a congruent color prestimulus in the same manner that color naming is aided by a preexposed congruent word.

Most surprising was the reading inhibition. Though clearly significant, it was the smallest effect in this experiment. Its time course is rather similar to the facilitation time courses in both experiments with their flat maxima at SOAs below -200 msec and sharply contrasts with the color-naming inhibitions with their steep maxima near 0 . We conclude from this time course difference that the cognitive process underlying this reading inhibition is substantially different from the usual color-naming Stroop effect. The error statistics for the incongruent stimuli, as given in Table 2, further support this view. In the color-naming task, the errors cumulate at the short and the 0 SOAs; in the reading task, they cumulate at the other end of the SOA range. For these reasons, it seems inadequate

to interpret these data simply as a reversed Stroop effect. Because our SOA range certainly included the time relation between relevant and irrelevant stimuli which should cause a reversed Stroop conflict and because Palef's (1978) additional condition (a translation of both components of the stimulus into corresponding internal codes) was surely fulfilled, the necessary circumstances to obtain Stroop-like conflicts must be further differentiated.

Experiment 3

The main question in Experiment 3 was whether the asymmetry in inhibition is due to the different characteristics in processing words and in processing colors or due to the consequence of a specific interaction that occurs only if a word and a color component are processed in temporal contiguity. In particular, the two different inhibition time courses in Experiment 2 could depend only on the modality of the interfering stimulus (word or color) without any effect of the relevant stimulus modality. Or the reverse might be true: The relevant modality alone could be the important variable. To decide this question, we attempted to generate facilitatory and inhibitory effects with color-color and word-word stimuli, where relevant and irrelevant components of the stimulus were in the same modality. Moreover, for the new stimulus material Taylor's (1977) assumption of a constant internal SOA should hold. Therefore, the time course functions should answer the question of whether primary or secondary specific effects, as defined above, occurred, and so further characterize the nature of the Stroop phenomenon. Because the response competition hypothesis implies secondary effects, and the semantic-encoding hypothesis, primary effects, further evidence in favor of, or against, these hypotheses should be provided.

One problem that had to be solved when using color-color and word-word stimuli was that, contrary to standard Stroop stimuli, the two color patches or color words are spatially separated. A second problem was that under standard Stroop conditions the task defines the relevant component because it is impossible to "read" the color or to "name"

the word. With the new material, this task-related *functional discrimination* is excluded because both components can be either named or read. We supposed that a spatial definition of the relevant and irrelevant component would only produce weak residual Stroop effects due to input selection (Treisman, 1969) and that an additional instruction stimulus (cf. Proctor, 1981, Experiments 3B and 4) would change the structure of the underlying cognitive processes. Therefore, we chose a *sequential discrimination* task. The components of the stimulus were successively presented one above the other. For negative SOAs, the subjects had to name or to read the second of the two components; for positive SOAs, they had to react to the first one. The location of the relevant component, above or below the irrelevant one, varied randomly from trial to trial. This uncertainty of location should prevent input selection as in the usual Stroop task. The SOA base of 0 msec was replaced by ± 50 msec, which seemed sufficiently above the onset discrimination threshold for our stimuli.

Method

Subjects. Subjects were nine females and seven males.

Materials and instrumentation. Stimuli and apparatus were the same as in Experiment 2, except that the projectors of the components either both contained word slides or both contained color slides. Their optical axes

were inclined reciprocally, so that the two components appeared one above the other, each centered in the upper or lower half of the display field.

Design. Again, half the subjects were run in the color-naming task, half in the reading task. The eight SOA levels, ± 300 , ± 200 , ± 100 , and ± 50 msec, were varied between and held constant within the blocks; each SOA block was given once to each subject. To spare the subjects from frequent switching between the reaction to the first and the reaction to the second stimulus component, the four positive and the four negative SOAs succeeded one another. The subjects started with the positive or negative SOAs in alternating order. The first four SOAs followed one another according to a sequentially balanced Latin square across subjects whose rows were reversed for the second four SOAs. Each SOA block consisted of 12 incongruent, 12 control, and 12 congruent stimuli, preceded by six warm-up trials. Thus, each stimulus condition had the probability of .33.

Procedure. On the whole, the procedure was the same as in the former experiments. The subjects were now instructed to perform the sequential discrimination task, that is, to name or to read the first (or the second) of two components presented with locational uncertainty while disregarding the other one. Unlike Experiment 2, the experimenter did not mention the probability structure of the stimulus sequence.

Results and Discussion

Scoring followed the previous pattern. The results appear in Figure 4. Each point in the drawing represents 96 single RT measures. On the average over the SOAs, the standard errors of the color-naming task entries were 9.37 msec (incongruent), 7.52 msec (control), and 7.61 msec (congruent). The respective standard errors of the reading points were 9.33, 5.40, and 6.39 msec.

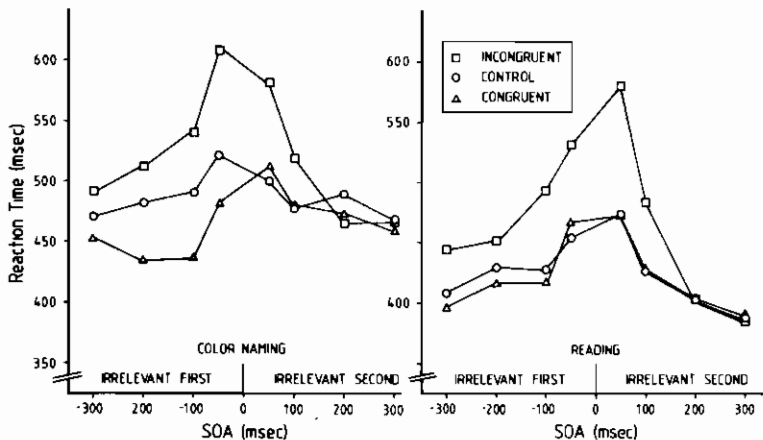


Figure 4. Mean reaction times in the Task \times SOA \times Stimulus Condition cells of Experiment 3. (SOA = stimulus onset asynchrony.)

There were 61 (2.58%) false responses in the color-naming task, most of them about equally distributed on the incongruent (23) and the control (26) conditions. In the reading task, 50 (2.12%) false responses were given, 44 of them in the incongruent condition. Within the incongruent condition, the errors were most frequent at the SOAs that produced the slowest responses.

Once again, the overall ANOVA showed that all main effects and interactions were reliable, except the Task \times SOA interaction, $F(7, 98) = 1.88, p > .05$. The main effect of task and the other two-way interaction involving this factor reached only the .05 significance level. The other significances reached the .01 level. The mean control reading time across the SOAs was 425 msec; the mean difference between control color-naming and reading was 62 msec, $t(42) = 3.36, p < .01$. This difference varied from 28 to 88 msec, SOA = +50 msec, $t(336) = 1.16, p > .05$; and SOA = +200 msec, $t(336) = 3.68, p < .01$, respectively.

The ANOVA on the color-naming data alone showed significant main effects and an interaction: SOA, $F(7, 49) = 8.86, p < .01, MS_e = 2,058$; stimulus condition, $F(2, 14) = 74.67, p < .01, MS_e = 710$; and SOA \times Stimulus Condition, $F(14, 98) = 7.93, p < .01, MS_e = 700$. The simple main effect of SOA

at the control stimuli level was just significant, $F(7, 49) = 2.48, p < .05, MS_e = 981$. In the Newman-Keuls analysis, only the largest color-naming control mean at -50 msec differed significantly ($p < .05$) from the two smallest means at ± 300 msec.

In the reading-only ANOVA, too, main effects and interaction were significant: SOA, $F(7, 49) = 20.53, p < .01, MS_e = 1,932$; stimulus condition, $F(2, 14) = 61.85, p < .01, MS_e = 727$; and SOA \times Stimulus Condition, $F(14, 98) = 10.75, p < .01, MS_e = 379$. The simple main effect of SOA at the control stimuli level was significant, $F(7, 49) = 13.82, p < .01, MS_e = 453$. In the Newman-Keuls analysis on the control means as function of SOA, the three smallest means at the SOAs of -300, +200, and +300 msec were not significantly different from each other, as were not the two largest means at SOAs of ± 50 msec. A third group of means not significantly different from each other was found at the SOAs of -200, ± 100 , and -50 msec.

As in the preceding experiments, facilitation and inhibition scores were computed. Their means over subjects, together with the results of the respective t tests, are given in Table 3. The error terms for the single t tests proved homogeneous only for the color-naming task; the pooled error term was a MS_e of 701 with df of 112. In the reading

Table 3
Mean Facilitation and Inhibition (in msec) as a Function of Stimulus Onset Asynchrony (SOA) in Experiment 3

Task	SOA (in msec)							
	-300	-200	-100	-50	+50	+100	+200	+300
Color naming								
Facilitation	19 _{a,b,c}	49 _{b,c} **	54 _c **	40 _{b,c} **	-12 _a	-4 _a	15 _{a,b,c}	10 _{a,b}
Inhibition	21 _{a,d}	30 _{a,d} *	50 _{a,b} **	87 _b **	81 _b **	42 _{a,b,d} **	-24 _c	-2 _{a,d}
(% false responses to incongruent stimuli)	1	3	4	7	3	2	2	1
Reading								
Facilitation	12	13	10	-12	1	-3	-2	-4
Inhibition	35 _{a,b,c} **	22 _{a,b} *	66 _{c,d} **	77 _{d,e} **	107 _e **	56 _{b,c,d} **	-1 _a	-2 _a
(% false responses to incongruent stimuli)	5	1	5	7	14	8	2	1

Note. Scores (reading horizontally) that share a common subscript do not differ significantly ($p > .05$) in the Newman-Keuls analysis. For SOA msec values, a minus sign indicates preexposure, a plus sign postexposure of the irrelevant stimulus component. For facilitation in the reading task, simple main effect of SOA was not significant ($p > .05$).

* $p < .05$. ** $p < .01$ (t test).

task, the single error terms were heterogeneous because of very small values in the SOA cells of +200 and +300 msec, $MS_e = 134$ and 82 , in contrast with an average $MS_e = 528$ across the other six SOAs. Therefore, the single error terms were used with dfs of 14 each.

The SOA \times Facilitation/Inhibition ANOVA yielded a significant main effect of SOA, $F(7, 49) = 8.78$, $p < .01$, $MS_e = 976$, and a significant interaction, $F(7, 49) = 5.97$, $p < .01$, $MS_e = 1,271$, in the color-naming task. In the reading task, two significant main effects—SOA, $F(7, 49) = 12.09$, $p < .01$, $MS_e = 492$; and facilitation/inhibition, $F(1, 7) = 40.68$, $p < .01$, $MS_e = 1,458$ —and a significant interaction, $F(7, 49) = 8.27$, $p < .01$, $MS_e = 800$, were obtained. In both tasks, the simple main effects for inhibition proved significant, $F(7, 49) = 8.55$, $p < .01$, $MS_e = 1,345$ (color naming) and $F(7, 49) = 12.59$, $p < .01$, $MS_e = 945$ (reading). The simple main effect for color-naming facilitation produced $F(7, 49) = 5.16$, $p < .01$, $MS_e = 902$; only the reading facilitation, $F(7, 49) = 1.91$, $MS_e = 347$, failed to reach the .05 significance limit. Table 3 contains the results of subsequent Newman-Keuls analyses, too, for the single means.

In the color-naming task, the facilitation/inhibition difference was significant at the SOAs of ± 50 , +100, and +200 msec. The respective test statistics were $t(56) = 2.52$, $p < .05$; 4.96 , $p < .01$; 2.46 , $p < .05$; and 2.09 , $p < .05$. In the reading task, the facilitation/inhibition difference was significant from SOAs of -100 up to +100 msec, $t(56) = 3.76$, $p < .01$; 6.04 , $p < .01$; 7.11 , $p < .01$; and 3.99 , $p < .01$.

In both tasks, the time course of the control conditions shows its maxima at the smallest SOAs, its minima at the largest. It is very similar to the control time course in the color-naming task of Experiment 1 and, within the common SOA range, of Experiment 2. This similarity indicates that a sequential discrimination at the ± 50 -msec SOA is more difficult than at the remaining SOAs by about the same amount as the color-naming control in Experiment 1 at 0- and +100-msec SOAs. Furthermore, the rise of the control RTs at the smallest SOAs demonstrates that the subjects have really per-

formed the sequential discrimination, though from a logical point of view, the correct response to control and congruent stimuli can be given without any discrimination between relevant and irrelevant components, just as in the usual Stroop task.

The inhibition time courses are not only very similar to one another in the color-naming task and in the reading task, but they are also of the same type as the inhibition time courses of the color-naming tasks in Experiments 1 and 2. Therefore, we hypothesize that the same cognitive process underlies word-word, color-color, and word-color conflicts (color component relevant) that does not work in color-word conflicts (word component relevant). Processing of a word seems to override processing of color even if the color is translated into a word code and is timed to cause a response conflict. But, when paired with an irrelevant word, processing of a relevant word is delayed in the usual manner.

The facilitation time course in the color-naming task matches the one in the color-naming task of Experiment 1 and in both tasks of Experiment 2. The reading process in Experiment 3, on the other hand, does not seem to be considerably accelerated by a preceding congruent word. The data show only a small nonsignificant facilitation.

Because a sequential discrimination task is rather unusual in Stroop research, two control experiments are reported before we attempt a further interpretation of these results. Experiment 4 examined whether the data of Experiment 3 really depended on uncertainty of location. Experiment 5 questioned whether the rise in mean control RTs at SOAs of ± 50 msec was, as supposed, a measure of the basic difficulty of the sequential discrimination task.

Experiment 4

Experiment 4 was an exact replication of Experiment 3 in all but one respect. The spatial uncertainty of the relevant and irrelevant stimulus components was replaced by spatial certainty.

Method

Subjects. Subjects were 11 females and 5 males.
Materials, instrumentation, and design. Materials,

instrumentation, and design were identical to those of Experiment 3.

Procedure. The computer program from Experiment 3 was modified to present the relevant stimulus component at the same location in all trials of all SOA blocks for one subject. Half the subjects saw the relevant stimulus component above the irrelevant one, half viewed the reversed location. The subjects were made aware of this redundancy and were instructed to take advantage of it as far as possible.

Results and Discussion

Figure 5 shows the means of the RT scores across subjects; each point represents 96 single RT measures. On the average over the SOAs, the standard errors of the color-naming task entries were 7.41 msec (incongruent), 7.12 msec (control), and 7.42 msec (congruent). The respective standard errors of the reading points were 5.12, 4.81, and 4.91 msec. Errors did not exceed 1.79%.

As before, color-naming times exceeded reading times, $F(1, 14) = 18.00, p < .01$, and the times increased with incongruency, $F(2, 28) = 72.01, p < .01$. The mean control reading time across the SOAs was 394 msec, the mean difference between control color-naming and reading was 72 msec, $t(42) = 3.92, p < .01$. This difference varied from 57 to 82 msec, SOA = -50 msec, $t(336) = 2.76, p < .01$; and SOA = -300 msec, $t(336) = 3.98, p < .01$, respectively.

The separate ANOVAs to probe the reliable interactions of stimulus conditions with task and with SOA showed that both color-naming times and reading times decreased with congruency, $F(2, 14) = 58.22, p < .01, MS_e = 245$ and $F(2, 14) = 21.58, p < .01, MS_e = 183$, respectively, and interacted with SOA. SOA showed a reliable main effect for the color-naming data only, $F(7, 49) = 3.06, p < .01, MS_e = 598$. The simple main effect of SOA at the control stimuli level was not significant in the color naming nor in the reading data.

The facilitation and inhibition scores resulted in the means presented in Table 4. As in Experiment 3, the error terms for the single t tests proved homogeneous only for the color-naming task. Its pooled error was $MS_e = 300$ with a df of 112. In the reading task, there were two very small single error terms in the SOA cells of +50 and +300 msec ($MS_e = 42$ and 67) in contrast with an av-

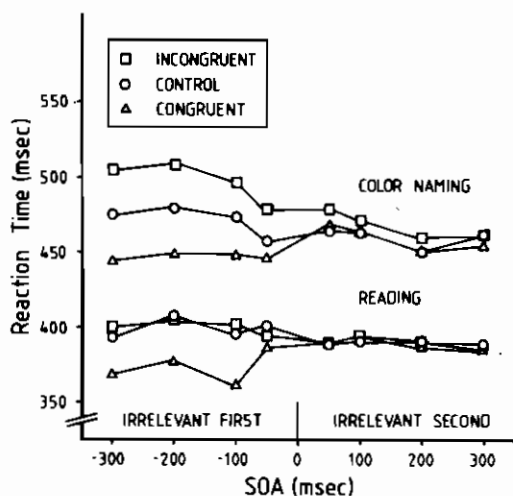


Figure 5. Mean reaction times in the Task \times SOA \times Stimulus Condition cells of Experiment 4. (SOA = stimulus onset asynchrony.)

erage MS_e of 180 across the other SOAs. Because the error-term differences proved significant, $F_{\max}(8, 14) = 6.22, p < .05$, the single error terms were used with dfs of 14 each.

In the color-naming task, the SOA \times Facilitation/Inhibition ANOVA yielded a significant main effect for SOA, $F(7, 49) = 6.42, p < .01, MS_e = 368$, but not for facilitation/inhibition, $F(1, 7) = 1.19, p > .05, MS_e = 341$, nor for the interaction, $F(7, 49) < 1, p > .05, MS_e = 742$. The two simple main effects were significant, $F(7, 49) = 2.48, p < .05, MS_e = 673$ for facilitation and $F(7, 49) = 2.27, p < .05, MS_e = 437$ for inhibition. In the reading task, both main effects—SOA, $F(7, 49) = 5.50, p < .01, MS_e = 190$; and facilitation/inhibition, $F(1, 7) = 9.04, p < .05, MS_e = 555$ —and the interaction, $F(7, 49) = 2.81, p < .05, MS_e = 292$, proved significant. The simple main effect of SOA was significant only on the facilitation means, $F(7, 49) = 7.76, p < .01, MS_e = 220$. The Newman-Keuls analysis yielded single significances only for the reading facilitation. They are presented in Table 4.

Significant single facilitation/inhibition differences were not obtained in the color-naming task. In the reading task, the facilitation/inhibition differences were significant from SOAs of -300 to -50 msec. The respective test statistics were $t(56) = 2.06, p <$

Table 4
Mean Facilitation and Inhibition (in msec) as a Function of Stimulus Onset Asynchrony (SOA) in Experiment 4

Task	SOA (in msec)							
	-300	-200	-100	-50	+50	+100	+200	+300
Color naming								
Facilitation	31**	31**	26**	12	-4	0	1	8
Inhibition	30**	30**	23**	21*	14	7	9	-1
(% false responses to incongruent stimuli)	1	0	0	5	2	1	3	3
Reading								
Facilitation	25 _a **	29 _a **	34 _a **	15 _{a,b}	-2 _b	-2 _b	3 _b	3 _b
Inhibition	6	-2	6	-7	1	4	0	-3
(% false responses to incongruent stimuli)	2	3	4	4	1	2	0	2

Note. Scores (reading horizontally) that share a common subscript do not differ significantly ($p > .05$) in the Newman-Keuls analysis. For SOA msec values, a minus sign indicates preexposure, a plus sign postexposure of the irrelevant stimulus component. For facilitation in the color-naming task and inhibition in both tasks, simple main effect of SOA or largest difference in the Newman-Keuls test was not significant ($p > .05$).

* $p < .05$. ** $p < .01$ (t test).

.05; 3.46, $p < .01$; 3.19, $p > .01$; and 2.37 $p < .05$.

The most salient result is that the steep maxima of the inhibition time courses at the SOAs of -100 msec up to +100 msec, as obtained in Experiment 3, completely disappeared under locational certainty of the stimulus components. The reading task did not show any inhibition at all by an incongruent irrelevant stimulus, as in Experiment 1. The color-naming inhibition time course, on the other hand, is now similar to the facilitation time courses, which are all very similar throughout our experiments. Obviously, the context effects in our double stimulation task worked very differently depending on the kind of discrimination between the relevant and irrelevant stimulus. Before a further comparison and interpretation of the results of Experiments 1-4, Experiment 5 will be reported. Its aim was to evaluate the basic difficulty of the sequential discrimination task of Experiment 3.

Experiment 5

Experiment 5 was as similar as possible to Experiment 3. Again, each subject was given a sequential discrimination task with the same incongruent, control, and congruent color-color and word-word stimuli under

spatial uncertainty, but the required verbal response was semantically neutral with respect to colors and color words. Therefore, in all three stimulus conditions, the subjects had to perform a sequential discrimination for correct responding. Thus, Experiment 5 provided a direct measure of the basic sequential discrimination difficulty.

Method

Subjects. Subjects were six females and six males.

Materials and instrumentation. Materials and instrumentation were identical to those of Experiments 3 and 4.

Design and procedure. As in Experiment 3, the spatial location of the relevant stimulus component was random. Only the three SOA levels of +50, +100, and +200 msec were chosen. The subjects had to name the spatial position of the first stimulus component by responding "oben" (above) or "unten" (below). Each SOA block consisted of 12 incongruent, 12 control, and 12 congruent stimuli, preceded by six warm-up trials. Each Stimulus Kind (colors, words) \times SOA cell was assigned to one block and run with each subject.

Results and Discussion

Figure 6 shows the means across the subjects for each Stimulus Kind \times Stimulus Condition cell as a function of the three SOA levels. Each point in the drawing represents 144 single RT measures. On the average over

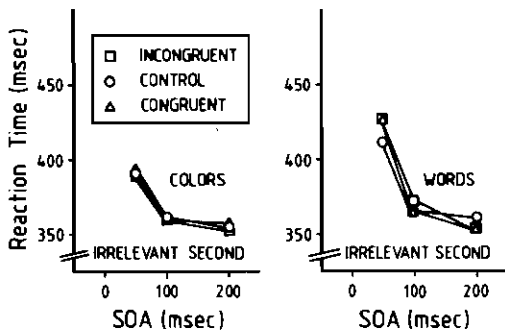


Figure 6. Mean reaction times in the Stimulus Kind (color, word) \times SOA \times Stimulus Condition cells of Experiment 5. (SOA = stimulus onset asynchrony.)

the SOAs, the standard error of these entries for the color stimuli were 7.41 msec (incongruent), 7.77 msec (control), and 7.71 msec (congruent). The respective standard errors of the word points were 8.61, 8.26, and 8.53 msec. The maximum error rate was 2.19%.

Significant were the main effects of SOA, $F(2, 187) = 35.82$, $p < .01$, $MS_e = 1,552$ (pooled), and of stimulus kind, $F(1, 187) = 4.86$, $p < .05$. The third main effect and the interactions were not significant. At the SOAs of 50, 100, and 200 msec, the mean RTs across stimulus conditions were 391, 359, and 354 msec for the color stimuli; 420, 365, and 353 msec for the word stimuli. For both stimulus kinds, the mean RT at SOA of 50 msec was significantly different from both other mean RTs in the Newman-Keuls analysis. The mean color-word difference was 12 msec.

Obviously, the task of naming the location of the first of two stimulus components displayed with a short but easily noticeable SOA is not at all influenced by the semantic relations between the stimulus components. Regarding the Stroop literature discussed earlier, this result is certainly not surprising. More important is that between SOA levels of +50 and +100 msec, RTs for control stimuli have increased by about the same amounts as in Experiment 3, where the mean differences between SOA levels of ± 50 and ± 100 msec were 27 msec in the color-naming task and 37 msec in the reading task. This increase confirms our assumption that the subjects performed a sequential discrimination in all stimulus conditions of Experiment 3.

Therefore, the inhibition effects that were found there cannot be attributed, wholly or partially, to an inadequate control condition.

General Discussion

For the theoretical interpretation of our experiments, a comparison of the results with those of Taylor (1977) seems useful. In his double stimulation experiments, Taylor used three-letter stimuli. The subjects had to respond by pressing a key to the middle letter in a choice reaction time task. The left and the right letters were always identical to one another and served as context; they could be incongruent, neutral, or congruent with the relevant middle letter. In the neutral condition, letters to which no response was assigned were used as context. There were, in our terms, two congruent conditions. In the stimulus repetition condition, the context matched the relevant stimulus as in our Experiments 3–5, where the congruent stimuli consisted of two identical colors or color words. In the congruent response-bias condition, context and relevant letters were different, but were associated with the same response as in the congruent conditions of our Experiments 1 and 2 with color-word/color stimuli. In the incongruent condition, relevant letter and context differed from one another and were associated with different responses. Besides SOA, a further independent variable was the probability of congruent stimuli. In the no-validity condition they occurred with a probability level of .5; in the high-validity condition, with a probability level of .75 among the noncontrol stimuli. By using this variation, Taylor separated involuntary ($p = .5$) and voluntary ($p = .75$) stimulus processing. He isolated three types of influences of the irrelevant stimulus component: a fast, involuntary inhibition effect; a fast, involuntary facilitation by stimulus repetition; and a slow, voluntary response facilitation. As "fast" we characterize a facilitation or inhibition time course with a steep maximum at short SOAs; "slow" means the opposite, a flat maximum at long negative SOAs. All of Taylor's effects were secondary in nature.

In our data, there are three characteristic time courses, too. First, we obtained a *slow*

secondary facilitation time course in all color-naming tasks in Experiments 1-4. It is a secondary effect because it only appears if the irrelevant stimulus component precedes the relevant one. We interpret this time course in agreement with Taylor, assuming that the subject generates the response code associated with the first, irrelevant stimulus component and only has to release it if the response to the second, relevant stimulus component matches it. This effect occurred in the reading tasks of Experiments 1, 2, and 4 as well. However, there are two clear differences to Taylor's results. None of our experiments yielded his fast stimulus-repetition effect, and our slow facilitation functions did not depend on encouraging the subjects to process the first, irrelevant stimulus component. A comparison of Experiment 1 (processing of the irrelevant stimulus not specifically encouraged) with Experiment 2 (processing of the irrelevant stimulus encouraged) suggests that encouraging the subjects to translate the irrelevant first stimulus into the code of the relevant second stimulus increases the facilitation effects without a substantial change in their time course.

Second, we obtained *slow secondary inhibition time courses* in the reading task of Experiment 2 and in the color-naming task of Experiment 4. We interpret these functions as the inhibitory counterpart of the slow response preparation underlying our facilitation functions. Taylor, however, does not interpret his data with regard to a slow inhibitory component, though the inhibition he obtained in his Experiments 2 and 3 at SOAs of 200 up to 500 msec could be explained in this way. Greenwald (1972), on the other hand, demonstrated response conflicts resulting from the slow preparation of an irrelevant response.

Third, in the color-naming task as well as in the reading task of Experiment 3, there are strong *fast primary inhibition time courses* in the -100-msec to +100-msec SOA range with no facilitatory complement. In the color-naming task of Experiment 1, it is plausible to assume that the temporal symmetry axis is displaced from the SOA level of 0 msec in the direction of word postexposure to compensate for faster word processing. Therefore, this inhibition time course can be

regarded as a fast primary one, too. In his Experiment 1, Taylor did not obtain even a hint of such an effect. The reading task in our Experiment 4 is the one most similar to Taylor's experimental series, and it lacks a primary effect, also. Obviously, stimuli of this kind, presented with locational certainty, do not yield the effect in question.

With the three types of time courses we have found, there is no inhibitory time course in our results that cannot be described as a secondary effect or as a superposition of a secondary and a primary effect. Considering the results of all five experiments, as summarized in Table 5, the following picture arises:

1. With color-word/color stimuli, a marked secondary facilitation effect is easily obtained in the color-naming task with adequate word preexposure. The same is true for color-color stimuli.

2. With color-word/color stimuli, reading is difficult to accelerate. In Experiment 1, there is a small but significant facilitation. In Experiment 2, the reading facilitation is only half of the color-naming facilitation, and in Experiment 3 (word-word stimuli), it does not reach statistical significance. Only in Experiment 4 is there a marked effect.

3. In all color-naming, but only in two reading tasks (Experiments 2 and 3), the slow secondary facilitation is accompanied by a slow secondary inhibition. In the reading task of Experiment 2, it was only half its facilitation complement. Thus, the cognitive pathway to read a word aloud seems especially protected against additional distracting stimulus words or internal codes even if the time requirements for a conflict are fulfilled.

4. The usual Stroop conflict seems to be the fast primary inhibition effect observed only within a SOA window about 200 msec wide and nearly symmetrical around the 0 level of SOA, with a steep maximum of at least 70 msec. Undoubtedly, the high-validity condition of Experiment 2 could not generate this effect in the reading task. This result contradicts the hypothesis that, under adequate temporal conditions, Stroop-like effects can always be caused by translating the distractor into the code of the relevant stimulus or response.

5. The sequential discrimination task of

Table 5
Facilitation and Inhibition Effects in Experiments 1-5

Experiment	Stimuli	Discrimination	Color naming		Reading	
			Facilitation	Inhibition	Facilitation	Inhibition
1	Color-word/ color	Functional	Secondary	Primary + secondary	Secondary	None
2	Color-word/ color	Functional (80% congruent stimuli)	Secondary (strong)	Primary + secondary (strong)	Secondary	Secondary
3	Color-color and word-word	Sequential (location uncertain)	Secondary	Primary + secondary	None	Primary + secondary
4	Color-color and word-word	Sequential (location certain)	Secondary	Secondary	Secondary	None
5	Color-color and word-word	Sequential (location uncertain, location naming)	None	None	None	None

Experiment 3 produced primary inhibitory effects with spatially separated stimulus components. This fact seems to be important for further research. Whereas the application of the Stroop technique as a tool in experimental cognitive psychology is limited to spatially integrated stimuli (cf. Rayner & Posnansky, 1978; Smith & Magee, 1980), the sequential discrimination task yields the full Stroop conflict without this restriction. Perhaps the sequential discrimination task overcomes an input selection that is very effective in everyday selective attention. It is remarkable that now even a simple overt reading response is fully disturbed by a distractor word.

6. Experiment 4 demonstrates that under locational certainty, the primary inhibition effect of the sequential discrimination task completely disappears, whereas the secondary facilitation and, at least for color naming, the secondary inhibition are maintained. The narrow input-selection window, bypassed only by spatially integrated stimuli or by spatially separated stimuli in the sequential discrimination task, does not seem to prevent slow secondary effects.

7. Experiment 5 shows that the facilitation and inhibition effects disappear if the response in the sequential discrimination task is semantically neutral with regard to the stimulus content. Because the same result is found in standard Stroop research, it confirms the assumption that the semantic ef-

fects in the sequential discrimination task are essentially the same as those in the usual Stroop task.

8. Finally, we come to the question of the locus of Stroop effects. It seems plausible, according to Greenwald (1972), Taylor (1977), Posner (1978), and others, to interpret the slow secondary facilitation and inhibition functions as produced by response priming or response generating. Therefore, the secondary inhibition effect indicates a response conflict according to the response competition hypothesis. On the other hand, the secondary inhibition is only weak at the most interesting small SOAs. The strong primary inhibitory effects at SOAs near 0, as found in Experiments 1-3, contradict the response competition hypothesis if it is operationalized so that it predicts only secondary effects as defined according to Taylor (1977) in our introduction. Hence, it is plausible to assume that the Stroop conflict is located at an earlier processing stage, where the stimulus components are semantically evaluated.

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