Colour-Word-Interference: Why we should measure it with coloured keys

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Running title: **CWI with colour keys**

Summary

Colours of coloured words and word patterns of coloured words (integral Stroop stimuli) were given time advantages up to 600 ms against each other. Ss had either to determine the relevant dimension colour or word by four keys which were unpredictably coloured in each trial. Results of two experiments showed symmetrical relations between the word and the colour task. Thus, the word can influence the highly compatible colour key response as can the colour in word naming (‘reading’). This first sort of interference cannot be translational and can be regarded as proper colour-word interference while the second one must be translational. Thus, neither ‘horse-race’ nor ‘translational’ explanations of the Stroop effect can be correct. A ‘word dominance’ account as a variant of the automaticity explanation is preferred.

Key words: Stroop-, colour-word interference, translational models, word dominance

Introduction

The phenomenon of colour-word interference (CWI) is widely known as Stroop effect (Stroop, 1935; for history and accounts see Dyer, 1973; Schulz, 1978; MacLeod, 1991). In short the effect is described for reminder: it is difficult to name the colour of a colour-word (“colour-naming” = CN), if the word denotes a colour different from the colour in which the word is coloured; whereas (almost) no disturbance is found with a differing (incongruent) colour, if the word is to be named (“word reading” = WR). The difference in RT of incongruent/congruent words (stimuli) in comparison to a single valued control condition (coloured x's or spots in CN, black or neutral words in WR) is called interference/priming or inhibition/facilitation respectively (cf. Dalrymple-Alford & Budayr, 1966; Glaser & Glaser, 1982; Schulz, 1979 a).

According to an earlier widespread explanation of the Stroop effect the word wins the 'horse race' (Dunbar & MacLeod, 1984) because the word is faster than the colour.[1] The race hypothesis could not explain why word reading (WR) virtually shows no dependency on stimulus onset asynchrony (SOA) between colour and word - especially when given the colour an advantage - while in condition CN interference disappeared when such conditions were realised (Glaser & Glaser, 1982). Moreover, the hypothesis failed to sufficiently account for results like those of Dunbar & MacLeod (1984) with rotated words which did not diminish interference.

More recent accounts of Stroop interference have accentuated either failures of the automaticity account to explain aspects of the effect (Besner & Stolz, 1999; Besner, Stolz & Boutilier, 1997) or have tried to produce symmetrical relations between colour and word with the claimed result that symmetry lets vanish the Stroop effect (Algom, Dekel & Pansky, 1996; Melara & Mounts, 1993; Sabri, Melara & Algom, 2001). Furthermore some recent studies have used coloured keys but fixed assignments to measure Stroop interference (Besner & Stolz, 1999; Henik, Ro, Merril, Rafal & Safadi, 1999; Kuhl & Kazén, 1999; Kazén & Kuhl, 2005).

I argue that both new developments do not meet the core of the effect and that fixed assignments do not meet the requirements to measure colour and word processing separately (cf. Schulz & Liebing, 1991; Sugg & McDonald, 1994). To reach this aim I propose to pick up the concept of compatibility again (Fitts & Seeger, 1953). Here I describe two of our first experiments in which we used coloured keys which show that interference is observed under conditions of high compatibility (colour naming with coloured keys) as well as under conditions of low compatibility (word reading with coloured keys).

The argument is that colour-naming (CN) interference under conditions of high compatibility (in short: CN-colour-key interference) is proper interference due to conceptual activation of colour and colour-words. CN-colour-key interference cannot be destroyed by symmetrical conditions (Algom et al., 1996; Melara & Mounts, 1993; Sabri et al., 2001), rather it is the result of symmetrical compatibility relations which are obtained if coloured keys are used in the CN and in the word-reading (WR) task. The latter authors have argued that Stroop effects might result from unequal baseline discriminabilities. But they did not discuss the role of compatibility, so they missed the point that is put forward here that the word task in a vocal reaction time setting will be always easier than the colour task.

According to Schulz & Liebing (1991) traditional Stroop interference consists of at least two separate sources. One source is the low compatibility of colours (colour naming) to vocal responses, the other one is the influence of the word as a conceptual unit for itself (cf. Anderson, 1983; Seymour, 1977). Schulz & Liebing (1991) had hypothesised that colour naming (CN) interference is still obtained with coloured keys, because such a high compatibility condition will measure interference without confounding effects from the spoken response as in the conventional task setting. We called the interference obtained in the colour task with coloured keys of about 70 ms "encoding" interference and proposed that it is due to the effect of the word ("word dominance").

Dominance of the word means that the word code has the power to influence the colour response even under unfavourable conditions. In addition, dominance could be seen as amount of activation, as is the case in network simulations of the Stroop effect (Cohen, Dunbar & McClelland, 1990; Cohen, Servan-Schreiber & McClelland, 1992; Kanne, Balota, Spieler & Faust, 1998).

More recently Sugg & McDonald (1994) published a study with computer coloured stimuli varying the stimulus asynchrony (SOA) between colour and word, and using coloured as well as worded keys to test the race hypothesis more properly again. They obtained no (8 ms at zero SOA. Exp.1) interference with coloured keys in the CN task. However, Sugg & McDonald (1994) used a two alternative task which may obscure encoding effects: with only two alternatives the S needs to encode only one (stimulus) aspect in order to decide for the remaining alternative, and even more important, the authors used non-integral stimuli, because their words had only coloured contours, instead of fully coloured words, thus probably decreasing the words influence. Similar arguments apply to the setup and the null results with zero and 50 ms SOAs of Kornblum, Stevens, Whipple & Requin (1999) as they also used only two alternatives, this time with half-integral stimuli.

Different sorts of interference?

In contrast to the naming-reading asymmetry under the vocal response mode, 'reading' a word (condition WR), irrespective of its colour, becomes difficult under a coloured response key condition because of the low compatibility between colour response mode and word meaning stimulus. With colour keys, it is necessary to 'translate' a word into a colour (Virzi & Egeth, 1985), because the meaning of the word is to be responded to (see also below).

The comparison of interference under these two colour label conditions (CN and WR with colour labels) with the same task conditions (CN and WR) under word label conditions, suggested to Schulz & Liebing (1991) that conventional vocally measured Stroop interference consists of both types of interference, because approximate additivity of CN and WR interference (65 + 120 ms) with colour keys adding to about 180 ms under CN with word label conditions showed up. Irtel (1995) reported a replication of the Schulz & Liebing (1991) results in an unpublished study using a touch-screen similarly to Sugg & McDonald (1994).

In the terms of Sugg & McDonald (1994), our argument is that the "translated word response" [verbal CN] consists of both an untranslated colour (CN with coloured keys) and a translated colour response (WR with coloured keys). That is, verbal CN which defines the traditional Stroop task is a hybrid, unnecessary complex condition to measure interference (cf. Schulz & Liebing, 1991). Verbal CN yields an overestimation of interference, because the influence of the word is amplified by the need to give a vocal response. Therefore, no word response, but only an untranslated colour response and a translated colour response will be investigated here.

So far, it can be concluded that the interference observed in all traditional Stroop investigations which used the vocal response mode will contain strong recoding parts of interference (see also Henik et al., 1999).

Recoding explanations of Stroop interference

The "translational" model of Virzi & Egeth (1985) like that of Glaser & Glaser (1989) can be regarded as a recoding model. Recoding models explain Stroop interference by the amount of necessary coding/translational steps or necessary module contacts where each step or contact is an opportunity for "cross-talk".

Thus, the translational models of Glaser & Glaser (1989) and Virzi & Egeth (1985) predict no interference in the untranslated colour response condition (CN with colour keys), because the response can be given without contact to a verbal lexicon, viz. without translation.

However, early (Glaser & Dolt, 1977; McClain, 1983 a, b) and earlier studies (Pritchatt, 1968; Treisman & Fearnly, 1969; for still further precursors see Schulz & Liebing, 1991) showed some remaining interference under conditions of hypothetically zero translational interference while more recently Mascolo & Hirtle (1990) sought again to support translational models of Stroop interference - but again their data seem equivocal. In contrast, Baldo, Shimamura & Prinzmetal (1998) reported small, though significant amounts of interference (about 10 ms) under conditions which according to their opinion did not call for a translation, namely responding direction of arrows with a right and a left key, and responding vocally to the words ‘right’ and ‘left’. Similar results were reported by the author (Schulz, 1991). Thus, it seems possible to obtain interference under conditions of high compatibility.

To summarise, the task to answer a colour with a colour (cf. Treisman & Fearnley, 1969) by using colour(ed) keys is an encoding task without recoding components. Note that the setting includes the varying, unpredictable change of colour/word assignment of the response keys in order to prevent Ss from developing spatially based schemata which save processing of the colours/words (see also Sugg & McDonald, 1994, p. 653). According to the translational models in this setting no interference should be observed. However, as will be shown, there will be encoding interference as has been already shown in our previous work (Schulz & Liebing, 1991).

Conclusions for the time course in a colour-key task

In general, translational models predict the same time course (SOA) curves for the same translation condition (Sugg & McDonald, 1994). This means that we should not expect the same time course with an untranslated colour and a translated colour condition which are to be investigated here.

Essential Compatibility Predictions for Coloured Keys

I argue that the compatibility relations of the primary as of the secondary stimulus aspect as well work against one another in the CN case while they add in the WR case. In CN, the primary task colour naming is highly compatible with the coloured keys while in WR the primary task is low compatible and therefore more difficult. However, in CN the word as secondary aspect is low compatible to the colour and should therefore not easily intrude into the easy response whereas in WR the secondary aspect colour is highly compatible to the response mode and can thus easily intrude into the difficult response. Therefore, CN with colour keys is twofold easy and WR with colour keys is twofold difficult. One part of the difficulty differences will be represented in the absolute reaction time, CN being easier than WR, another part of the difficulty differences will be represented in the interference or impact (difference between congruent and incongruent condition): low compatible [difficult] word in easy CN, high compatible colour [easy] in difficult WR. Thus, given that colour and word codes are equally strong the relation WR to CN in impact should be at least 2:1 even irrespective of absolute speed (RT). However, the more the word is dominant the more the SOA functions and their impact should become equivalent with both response conditions, because the difficulty of the translational WR-condition where the distractor is high compatible is matched by the difficulty caused by the dominant, but low compatible word disturbing in the easy CN-condition. In fact, Schulz & Liebing (1991) found a relation of between 2:1 and 1:1 (122 ms interference in WR and about 100 ms general RT-increase in comparison to CN with 67 ms interference; the difference 122 to 67, however, was not reliable according to strict criterions, but see later the results of Exp. 1).

Further predictions: *Should the SOA-function be symmetrical?*

Under the validity of the race hypothesis interference in a conventional colour-word (SOA = 0) stems from the word having won the race already. Thus, contrary to simple expectations often encountered the maximum of conflict should show up when both attributes reach the response control gate at the same time. But this will only be the case if the colour is given some advantage to compensate exactly for its assumed slow speed. The horse race model therefore predicts an asymmetrical SOA-function with the peak of interference on the positive SOA side.

Furthermore, one may derive predictions concerning the difference between the influence of a 'fast' and a 'dominant' word (colour) as distractor. However, in my opinion it is not clear whether the ‘fast word’ predicts rather increasing interference with increasing negative SOA or decreasing difficulty, as many of the variables important are not known (see Sugg & McDonald, 1994, p. 655).

Turning to the reading condition, remember that word reading (WR) with colour keys is a low compatibility condition, because the word has to be translated ('recoded') into a colour(ed) label. The S reads a coloured word and has to answer with a key which bears the colour that is denoted by the word read. This task must be strongly interference prone and response dependent, because the colour is necessary for coding the response. Independently, the SOA function could reflect the early availability of the (irrelevant) colour (see Note 1). Therefore, the influence of the incongruent colour on reading could be expected immediately with the onset of the incongruent irrelevant colour.

Thus, under colour key conditions, rather similar time courses for CN and WR seem possible though an untranslated and a translated condition are compared, especially under the hypothesis of a dominant word. A dominant word should produce interference independent of control (point in time) level whereas a 'fast' word should be more dependent on the absolute speed.

In sum, we expect a time course for encoding interference, describing the true conceptual interaction of dimensions (semantic inhibition), and one for recoding interference describing more of the response inhibition time course. The word dominance account predicts stable interference under CN and rather similar time courses for naming and reading and at least the same impact for both tasks.

Experiment 1

Method

Apparatus

Stimuli were controlled by a Schneider CPC 664 computer and shown in the colour screen (CTM 644) of this computer. With the start of a trial the upper band of the screen was filled by four coloured rectangles of equal size (59 [length] x 32 [height] mm)(see Fig. 1).[3] Possible colours were yellow, green, red and blue corresponding to the colour numbers 6, 9, 1, 24 of the computer corresponding to the colour description: (bright) red, green, blue and (bright) yellow, corresponding to luminance values of 30 (red), 23 (green), 17 (blue) and 22.5 (yellow) cd/m^2 on a bright grey screen (65 cd/m^2). The sequence of these colours (from left to right) changed with each trial randomly. The stimulus (colour word, row of 'xxxx' or colour spots) was presented immediately after in the centre of the screen, 49 mm below the row of colours. The magnitude of such a (target) stimulus was 8 (length) x 1 (height) mm +/- 2 mm for one letter more or less corresponding to about 4° x 0.5° of visual angle in a viewing distance of 0,65 m. The sequence of colour rectangles defined the response keys (micro-switches; 12 x 15 mm) arranged in front of the screen where the S had the middle and forefinger of the left and right hand prepared to press. (This response definition appeared to be self-evident for all Ss).

Fig. 1 about here

Stimuli and general experimental conditions

There were two tasks: Determine colour, in short, colour naming (CN) and determine meaning of the word, in short, word reading (WR), three types of stimulus: Congruent, control and incongruent, and five SOAs: Two negative, two positive and zero. All combinations of these conditions were realised as follows:

In the condition CN and *Word before colour* [= *colour after word*] (SOA < 0) a black colour word changed into a congruent one (CON) by changing from black into the colour denoted by the word or changed into an incongruent one (INC) by changing into a colour different from the word, or a row of black X's changed into one of the four colours (C = control). In the condition *Word after colour [= colour before word*] (SOA > 0) colour spots changed into CON- or INC-words or into four 'X's (C), in all cases the colour remaining constant (cf. Fig. 2).

In WR and the condition *Colour before word* [= *word after colour]* (SOA < 0) colour spots changed into CON- or INC-words, or black spots changed into a black word (C). In the condition *Colour after word [= word before colour] (SOA > 0)* a white colour-word changed into a CON- or INC-coloured-word or into a black word (C).

Note that these conditions (especially white words in WR for SOA > 0; black spots changing to black words) were chosen to avoid predictability of stimulus and stimulus type as much as possible in a given task; the first criterion was predictability of the response and the second equivalence of the different conditions. For example, in the colour before word condition in WR spots had to be black when a black control word was to appear, because a patch randomly coloured would possibly have confused the S. Such a control stimulus would have meant to introduce a stimulus not used anywhere in the experiment though the 'black colour' allowed to predict the appearance of a control word. Fig. 3 gives an overview on the possible stimulus changes and a picture of the conditions.

CWI with colour keys

Fig. 2 about here

The signs of SOA were chosen as it has become usual in the priming paradigm (irrelevant aspect first = negative). SOA = 0 meant that a conventional Stroop colour word or control stimulus appeared on the screen without any change. RT was measured from the onset of the relevant stimulus with a special routine bound into the computer program (cf. Schulz & Liebing, 1991).

Design and procedure

There were five SOAs (-400, -200, 0, 200, 400 ms) and the two tasks, i.e. ten conditions and the three types of stimulus. The tasks were blocked. Stimulus type and SOAs were randomly mixed in blocks of 150 trials. The very first block was regarded as training and discarded from data analysis. Each block contained additional 20 warm up trials which were also excluded from analysis. The task (naming, reading) was changed after each block, and Ss began either with naming or reading in a balanced sequence.

Nine Ss (six female, three male, except for one non-psychologist) were run with a total of six blocks of reading and naming each in two sessions (five blocks remaining for the analysed data yielding 750 trials in total for each task per S). They were paid with 20 DM for both sessions.

Results

Reaction times (RTs) longer than 1500 ms and below 150 ms were discarded from further analysis (only some single trials out of 5 x 2 x 150 x 9 = 13500 in total). First, an analysis of variance was computed over the whole set of reaction time data (mean RT over blocks and both sessions per condition [Stimulus type, SOA, task, subject]). Note, concerning the SOA effects that negative SOA in CN means word first, but in WR means colour first. Naming vs. reading (CN vs. WR) yielded $F(1,8) = 27.08$, $p < .01$, $MS_e = 18103$, relative onset (SOA) $F(4,32) = 13.47$, $p_{adj} < .01$, $MS_e = 2457$ (linear, quadratic and quartic trends become significant with $p < .01$) and stimulus type (CON, INC, C[ontrol]) $F(2,16) = 94.99$, $p < .001$, $MS_e = 3490.3$ (linear and quadratic trends are significant with $p < .01$). One interaction is significant: SOA x stimulus type [$F(8,64) = 46.4$, $p < 0.001$, $MS_e = 1015.5$]. Here, the interaction trends quadratic in stimulus type and cubic in SOA, are significant with $p < .01$. Task x SOA x stimulus type misses significance with $p_{adj} > .15$ ($F(8,64) = 2.19$, $MS_e = 1026.6$), all other interactions miss significance with $p > .20$.

The main effect for SOA is reflected in the means 610, 653, 651, 677 and 662 ms for the two negative SOA, zero SOA and the two positive SOA conditions. These means (cf. lowest row of table 1) reflect a structure which will be better understood when the results are split for CN and WR.

CWI with colour keys

Table 1 about here

In contrast to data from conventional Stroop experiments, but in accordance with Schulz & Liebing's (1991) results the main effect of task shows CN to be faster than WR (608 vs 693 ms).

The strong main effect of stimulus type consists of interference as facilitation as well (715 [INC] vs. 642 [C] vs. 595 [CON] ms) similarly to Schulz & Liebing (1991), but note that these means are task mixed, and that our old data refer to SOA = 0 only, so that a direct comparison should be restricted to SOA = 0 in the colour naming condition (see below). In the SOA main effect the differences indicated by the SOA x stimulus type interaction are intermixed. The means of the interaction SOA x stimulus type are given in Table 1.

The interaction of stimulus type x SOA reflects on one side the dynamics of constant interference when the irrelevant aspect precedes the relevant one, or is given simultaneously, decreasing then with delay of the irrelevant one, and on the other side the monotonously decreasing facilitation. It should be noted as soon as here that it seems surprising that these trends emerge clearly though colour naming and reading task are mixed. Thus, both tasks have a rather similar time course, as the non-significant triple interaction tells as well.

However, for the sake of better understanding the results are described now separated for tasks [naming (CN) vs. reading (WR)]; but remember that both, the interaction SOA x task x stimulus type, as well as the interaction SOA x task missed significance (the former with $.20 > p > .10$ [adjusted in degrees of freedom], the latter with $p < .20$).

Fig. 3 shows the means for colour naming (CN) from Exp. 1.

Figure 3 about here

In the separate analysis of variance the main effect of SOA is significant with $F(4,32)= 5.28$, $p_{adj} < .05$ (with a significant quadratic and quartic component), similarly the main effect of stimulus type ($F(2,16)= 31.72$, $p > .001$). Most interestingly the interaction SOA x stimulus type is significant with $F(8,64) = 18.62$, $p < .001$, $MS_e = 1197.4$. Fig. 4 clearly shows that there is almost no variation in the control RTs; however interference is immediate and remains significant up to 200 ms (word after colour) [97, 99, 88, 41 ms] while there is a surprising development in the congruent condition: The word given before the colour helps the colour response [gain 58 ms], especially strong when given with 400 ms advantage [148 ms].

In word reading (see Fig. 4) the SOA main effect is significant again with $F(4,32)= 9.80$ $p < .01$ (with a strong quadratic [$p < .001$] and quartic [$p < .01$] component), stimulus type with $F(2,16)$

= 168.4, $p < .001$ and again SOA x stimulus type with $F(8,64) = 32.03$, $p < .001$, $MS_e = 844.9$. Here again several interaction trend components become significant (double linear, quadratic stimulus type x SOA, quadratic and cubic SOA x stimulus type with $p < .01$). It can be seen in the figure why the effects seem a bit more pronounced in WR than in CN: it is because of a strong almost linear priming development [132, 120, 58 ms gain] in addition to some dynamics in the course of interference [87, 113, 115, 43 ms] while the control stimuli again do not show substantial variation (a separate analysis of variance on control stimuli (for both tasks) yielded a main effect of SOA with $.10 > p > .05$ while task x SOA interaction yielded $F < 1$).

Fig. 4 about here

Error rates for CN and for WR are 6.73 and 5.86 % respectively. An analysis of variance on the error rates showed some effects of modest positive covariation with the RT effects as usual when task difficulty is reflected in both the RT and the error rates. The rates are 2.1 % for CON, 2.6 % for C and 14.2 % for the INC condition (stimulus type was not quasi-randomised, i.e. not completely balanced so that some low frequencies occurred which render the error percentage estimates not very reliable and let appear the incongruent condition higher in error rate than usual).

Summarising so far, the following effects can be noted, first for CN (see Fig. 3) and then for WR (Fig. 4):

1.1 In CN a nearly constant function for control stimuli is found.
1.2 Interference is zero, if the colour precedes the word by 400 ms, that is the word is delayed by 400 ms, but it does not increase much (9-11 ms, not significant) in comparison to zero SOA (88 ms) when the word precedes (cf. Fig. 3).
1.3 Strong facilitation occurs when the word precedes the colour. When the word follows a meaningless blob of colour spots, the response is no more fastened, in contrast, rather delayed (not significant).

2.1 In WR the picture is very similar to that of CN, but the RT level is significantly increased by nearly 100 ms (85 ms).
2.2 Again there is pronounced interference (115 ms at SOA = 0), and again, it is only zero, when the relevant part precedes the irrelevant part by 400 ms; it is maximal (as interpolated) between -200 ms (colour before word) and zero SOA. Note that a particular test between CN and WR interference at SOA = 0 is not allowed because of the above reported non-significant triple interaction. However the difference of 28 ms increased interference in WR as compared with CN is in accordance with other results where about 20 ms difference were obtained repeatedly in our laboratory (Breker, 1996; Hoeschen, 1996) and in a modest contrast to even 49 ms in Schulz & Liebing (1991).

CWI with colour keys

2.3 Facilitation of the word response by the colour decreases almost linearly up to +200 ms SOA (i.e. colour after word/word before colour).

Summarising, CN and WR differ minimally (not significantly) in the time course of interference and facilitation. Thus, Table 1 presents a not too misleading picture of the time course of facilitation and inhibition besides the absolute RT values though the results of both tasks are mixed in this picture.

Discussion

The results seem to fit the word dominance hypothesis and contradict the translational account. First, interference in CN remains constant, neither decreases nor increases though an even faster word should either increase its disturbing effect or, alternatively, should be easier to handle (cf. Sugg & McDonald, 1994, p. 655). Second, the prediction of the dominance hypothesis that both dynamics approach in amount and tend to be equal is supported, but not the difference prediction of the translational account.

Especially the data at SOA = 0 corroborate the results of Schulz & Liebing (1991) that reliable interference is obtained even under conditions of high compatibility. The stable interference of nearly 90 ms at zero SOA in CN contradicts the Glaser & Glaser

(1989) account of picture (colour)-word interference which predicts zero interference as well as other translational accounts. Our result is in sharp contrast to that of Sugg & McDonald (1994) who presumably did not found it because their non-integral stimuli with only two alternatives rendered their Stroop task too easy to obtain interference in the colour-key task at SOA = 0.

In addition, going into other details, a 'fast' word should let disappear interference immediately if presented later, especially, if it is taken into account that at the same time (SOA) it does not longer prime the colour (cf. Fig. 4). Specifically, the lead of the fast word should be compensated by some advantage of the colour thus causing an interference peak shifted to the right (cf. Table 2 b). But the peak is found symmetrically as in most other SOA studies before.

According to the missing task interaction the colour can disturb with about the same power (speed) as can the word, given the response code is low compatible (because of coloured keys) as the word can disturb when the answer code is highly compatible (CN). Fig. 5 shows the 'impact' equivalence visually by depicting the difference scores (facilitation/inhibition). However, to succeed in overcoming the distraction in the CN case should be much more difficult than in the former (cf. Predictions section). Only the race model would assume that the high speed of the word can compensate for high compatibility (of the relevant aspect); however, the data yield no hint on a time shift between CN and WR in this direction. If there is a shift, it is in the other direction: as in Schulz & Liebings's data there is only insignificant facilitation at SOA = 0 in CN, but it is in WR (58 ms) suggesting that the word is not fast enough to prime significantly the highly compatible colour answer in CN while the colour is fast enough to prime the low compatible word answer in WR (the problem that the word answer is given about 100 ms later than the colour response will be discussed in the General Discussion, cf. also Note 1). In sum, according to the logic presented in the introduction, the word is not 'fair'. It dominates the colour, because it is as potent in the incongruent colour condition as is the colour in the incongruent word condition. However, the prediction was that the colour should be much more potent in the word condition because of the double unfair compatibility relations for reading.

Fig. 5 about here

These would be strong conclusions changing much of our traditional views on Stroop interference which is still likely to be seen as response bound output conflict effect though the idea of the horse race won by the word no longer gets much credit (MacLeod, 1991). Therefore, a replication appeared to be necessary. Not only should it control for balanced frequencies of occurrence of all conditions to improve the estimation of error rates, but also examine whether a point of stabilisation with the 400 ms SOA has really been arrived by exchanging the 200 ms point against a 600 ms SOA. Only one session was planned for this experiment.

Experiment 2

There were five SOAs: -600, -400, 0, 400, 600 ms and three blocks for CN and WR respectively. Each of the nine fresh Ss (again six female and three male) were given one block training. This time all subconditions (SOA x stimulus type) were exactly balanced within each block, i.e. 30 trials per SOA and stimulus type were given. All other conditions remained the same as in Exp. 1.

Results

In this experiment the analysis of variance on the total data yielded a strong task effect (CN vs. WR: $F(1,8) = 165.4$, $p < .001$), a significant SOA effect ($F(4,52) = 59.6$, $p < .001$) and stimulus type effect ($F(2,16) = 99.2$, $p < .001$). This time the interaction task x SOA is significant with $F(4,32) = 5.3$, $p_{adj} < .02$, $MS_e = 1508.3$ and again SOA x stimulus type with $F(8,64)= 19.3$, $p < .001$, $MS_e = 1124.9$. Table 2 shows the means of this interaction. Again the task x SOA x stimulus type interaction touches significance rather marginally ($F(8,64) = 1.8$, $p_{adj} < .19$).

CWI with colour keys

Therefore and because of the significant task x SOA interaction the results are again shown as in Exp. 1 split for tasks.

Table 2 about here

The separate analysis of variance for CN yields significant effects for SOA ($F(4,32) = 59.6.$, $p < .001$), type of stimulus ($F(2,16) = 73.1$, $p < .001$ and stimulus type x SOA ($F(8,64) = 9.99$, $p_{adj} < .01$), $MS_e = 1731.1$. Fig. 6 shows the means of condition CN.

Fig. 6 about here

As can be seen from the figure encoding interference [66, 57 ms] as well as facilitation [66, 87, 19 ms (n.s.)] appear to be lower than in Exp. 1 except for the peak of interference at zero SOA [138 ms], but the remaining dynamics of SOA look not as pronounced. Again, an end of interference at SOA = -600 (word before colour) is not clear; facilitation dynamics look like that of Exp. 1.

Fig. 7 shows the SOA functions for WR. This picture looks also similar to that of Exp. 1 [124, 74, 63 ms significant facilitation; 30 (n.s.), 67, 62 ms interference]. The analysis of variance yields $F(4,32) = 13.4$, $p_{adj} < .01$ for the effect of SOA, $F(2,16) = 41.6$, $p < .001$ for the stimulus type effect and $F(8,64)$

= 15.4., $p < .001$ for the interaction (SOA x stimulus type), MS_e = 902.6.

Fig. 7 about here

Fig. 8 shows again facilitation/inhibition, this time in Exp. 2. This figure accentuates that encoding interference in this experiment appears to be increased (138 ms vs. 88 ms in Exp. 1) and recoding interference somewhat lowered (62 vs. 115 ms at SOA = 0 in Exp. 1) and possibly finds an end with insignificant 30 ms at -600 ms SOA (colour before word).

Fig. 8 about here

The mean error rates are 5.8 for CN and 4.7 % for WR respectively (M = 5,3%). Again there are effects in the error rates which again covary positively with the RT effects and do not vanish if the rates are arcsin transformed (3.5, 4.4, 7.9% for CON, C, and INC conditions respectively).

Discussion

The second experiment has essentially replicated the results of the first one. The main results of the first experiment, encoding interference at zero SOA and almost identical impacts on encoding and recoding task have been obtained again though, first, encoding interference this time was found to be higher (138 ms) than recoding interference (62 ms) at SOA = 0, and second, facilitation by the word in the encoding task does not appear as extreme as in the first experiment.

I regard the somewhat curious relation of 138 ms CN interference vs. 62 ms WR interference under SOA =0 in Exp. 2 as extreme values caused by random factors. But note that the direction of this extreme variation is very probable if word dominance decreases the difficulty relation on the whole from 2:1 to 1:1. In fact, we never have observed again this reversal of the interference relation. In most of our subsequent colour-key Stroop experiments the interference obtained in WR amounted to 20-40 ms more than interference in CN.

Finally, it should be noted that almost no end of interference (with negative SOAs) and priming can be seen even with the long SOAs realised in Exp.2. This may mean that irrelevant activation persists for 400 ms as well as for 600 ms, this phenomenon possibly depending on the mode of stimulus control (the irrelevant aspect did not disappear but change after the SOA into the complete stimulus). Summarising, Exp. 2 replicates Exp. 1 in the essentials and does not show much change with SOA -/+ 600 ms in comparison to 400 ms.

Thus, there can be no doubt that the results of the first experiment can be replicated in the essentials, so that my suggestion is to explain the zero result of Sugg & McDonald (1994) at SOA = 0 by their specific experimental setting (as described in the introduction).

General Discussion

The reliability of the general results of both experiments (symmetrical facilitation and inhibition for both tasks, interference peak at SOA= 0, no end of interference with long SOAs) is underlined by the fact that similar experiments have been run also with IBM-compatible PCs controlled by another program with slightly changed stimuli presented on a standard colour screens. A greater number of SOAs especially in the short-time range (30, 60, 90 ms) has been used, but the results were very similar to those presented here (Hoeschen, 1996). In his unpublished study he obtained (significant) 56 ms interference with CN at SOA = 0 in an experiment with several SOA values realised, but no facilitation (+16 ms [i.e. inhibition], n.s.). In a second experiment the corresponding values were 85 and –5 ms, respectively. In line with the results presented here especially in Exp. 1 he obtained a slightly contrasting pattern under the WR condition (for SOA = 0). Here interference amounted to 118 ms (Exp. 1) and 91 ms (Exp. 2) while facilitation by the colour was pronounced (-59 ms in both experiments). Irtel (1995) in his unpublished study obtained similar results (for SOA = 0).

The differences between the two experiments presented here seem to be in the range of extreme values: concerning maximal facilitation especially in priming by the colour (WR), Exp. 2 shows smaller effects. The same is true for interference except of the zero SOA in CN. However, this value as others in the positive SOA range seem to reveal rather some instability of the measures, possibly because of the lower reliability of the data in comparison to Exp. 1.

Concerning the time courses, it must be first noted that they are almost the same for both tasks in both experiments though the translational accounts would not predict that. Second that the peak in interference in both experiments showed up for SOA = 0 which is a clear case against the race explanation. Third, the simple idea which has been put forward in Note 1, that the colour is processed about 50 ms earlier than the word can be seen as supported if we look at the facilitation/inhibition courses of both experiments together. They show a small effect in SOA -600, -200 and 0, but unfortunately not in SOA –400. Facilitation by colour in WR seems to emerge earlier by at least 25 ms than facilitation by the word in CN. If colour processing is faster than word processing, the most parsimonious explanation would assume that the same advantage is again reflected in the facilitation gain in word reading. The other way round, if words take longer to be processed they cannot much facilitate the colour identification process in the encoding stage while they can disturb on a later stage which is nearer to the response selection stage – especially if they are strong (dominant).

One problem with this account is the apparent identity of facilitation values at SOA= 400 ms for CN and WR. But it seems mainly due to the extreme value of 148 ms facilitation in Exp. 1, a value which Hoeschen (1996) could not replicate. So I take it for granted that a real difference of 25-50 ms between the two time courses of facilitation exists.

The same explanation would be valid for the lack of facilitation in the conventional colour-word task. When the colour is processed in the traditional vocal task, the words processing is not finished; but while searching for the verbal colour name the meanwhile processed word can intrude. So the word does not prime because of being too late, but it produces interference by just coming a bit later (25 - 50 ms) at the moment of verbal response preparation. And the word would do so because of its strength though coming late. In the colour-key task used here, interference would be reduced, because no verbal word response must be searched for. The word would intrude only because of its dominance though neither a word response nor a verbal response has to be prepared (see below the concept of the pseudotranslated word response).

CWI with colour keys

Yet, our conclusions might not be warranted. Figs. 5 and 9 combine relative timings which cover the fact that WR takes about 100 ms longer than CN - the colour identification response with colour keys is given earlier than the word response with words (Schulz & Liebing, 1991; Sugg & McDonald, 1994). Again, the lack of facilitation by the word at SOA = 0 seems to be the critical point. If the word gets an advantage by preexposition it can prime with some influence; if it gets no advantage as in SOA = 0 it cannot prime but can only block (interfere) by its dominance after having been processed while the correct colour key response is searched for. Of course there is no problem for the colour to prime a translated word response about 100 ms later (in WR); however, if this were the whole story the priming 100 ms later should be much stronger.

Finally – given a ‘fast word’ - interference and facilitation should have decreased with a SOA of -600 ms. Realising that even with this SOA interference is of almost the same amount and facilitation has not decreased, we should conclude that the idea of the ‘fast word’ is again refuted by our data.

It could still be argued that Ss used a verbal code though they had no benefit of this (cf. Schulz & Liebing, 1991). This means that I see no reason why the S should use a verbal code for solving the main task to respond to the colour when he/she is shown a colour in the same format as that of a coloured key except for the strange possibility that activating a word code through showing a word forbids the usage of any other code, so that the colour keys would be of no use. This, indeed, would mean even more word dominance to exist than I am inclined to assume (but cf. the concept of a pseudo-translated word response of Sugg & McDonald, 1994, p. 653).

So the results of both experiments presented here demonstrate pronouncedly that the hypothesis of the word's dominance wins the conflict, not to say the race, between race and dominance models. First, the dominance hypothesis predicts the less dynamic curves (dependency) on SOA in contrast to the 'fast word' hypothesis. Second, the other way round, the hypothesis assuming fair relations between colour and word which assumption should be the base for a race model predicts greater impact of the recoding condition (determining the words meaning with colour keys). Neither the first result nor the second could be observed in both experiments. In both experiments interference showed up immediately without almost any variation up to the positive SOA range while priming by the irrelevant part occurred also immediately revealing that the colour rather seems to exert its influence earlier than the word by 25 to 50 ms. Extreme (especially in Exp. 2) time advantage of the word or the colour did virtually not change the picture. However, under real race conditions this should occur: of course, the unfair beginner should win the race. If extreme time advantage does not change the picture more, the traditional simultaneous (zero SOA) condition cannot be explained with either a somewhat intermediate advantage of the word or of the colour.

Last not least it should be remembered that high compatibility was realised by coloured keys, i.e. microswitch keys which were spatially congruent with colour patches shown in the computer screen - in unpredictable sequence/assignment. It is only with such an arrangement that processing of the colour and word can be taken for granted - given more than two alternatives (see also Lavie, 2000). In this setting we obtain symmetrical SOA courses for colour and word identification tasks. This result on one hand supports the word dominance assumption (possibly ‘reading’ dominance, cf. Algom et al., 1996; Schulz, 1978), but practically more important, it underlines the view that the Stroop task mechanisms should not be investigated but with coloured keys and not with verbal responses.

Finally, it should be understood that the separation of encoding and recoding contributions to the Stroop effect is meant as to locate the word dominance on the encoding stage. This stage is 'early' in the sense that it means before recoding, but it does not necessarily mean 'early selection' in the traditional sense because separation of colour against word can be understood as a conceptual separation (cf. Anderson, 1983; Seymour, 1977). In extreme, the possibility should not be excluded that interference on an earlier level could be the necessary condition for the development of response bound interference on a later level. Vice versa, the undeniable existence of the latter should not tempt to assume that it is the only sort of interference which exists.

CWI with colour keys

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Notes

1 It is essential to note here that there can be no doubt that it is the colour which is faster processed as a feature, not the word. This is shown as well on the grounds of old data on visual search of colours vs. words (cf. Lund, 1927) as on the grounds of more recent ones (Uleman & Reeves, 1971; Schulz, 1979 b). Especially, detection or matching answers are faster with colours as targets than with words as targets (cf. in another context, e.g. Treisman, 1982; Treisman & Gormican, 1988). In an attempt to replicate the older data I obtained in two experiments mean reaction times of 349/342 ms for the ‘yes’ (Go) response in the task to detect one target colour out of four possible colours and 407/405 ms in the task to detect a distinct colour word out of a set of four words (stimuli were the same integral Stroop colour words as used here). The experiments were run as a Go-NoGo task with 75% NoGo trials. In both experiments the difference of well above 50 ms in favour of the colour was highly significant. Thus, the data say that the colour is about 50 ms earlier in processing than the word. Besides, they suggest that a necessary though not sufficient condition for interference to occur is to be represented, because there was, similarly to Uleman & Reeves (1971), no interference by the slow word in the colour detection task (3 ms in the first study, 0 in the second), but 34 ms (first study) and 23 ms (second study) by the fast colour in the word

detection task (for similar more recent results with a ‘word search task’ see Brown, 1996).

2 In this context it may be noted that Neumann (1980, Exp. 1) obtained symmetric interference peaks in contrast to Glaser & Glaser where the peak was shifted to the right corresponding to the prediction of the race model for some artificial advantage of the colour in comparison to the word. Interestingly Sugg & McDonald (1994) obtained an interference peak with SOA +100 in the translated word response (Sugg & McDonald, 1994, Table 3, p. 358).

3 In fact, it does not matter much as far as we know from our experiments whether the row of colour patches is shown on the top or on the bottom of the screen. This result might surprise, but can be easier understood if the assumption is made that with the start of a trial the subject tries to comprise a gaze from the band and the stimulus together; thus it makes only the difference that he/she starts with an attentional movement at the top or at the bottom.

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CWI with colour keys

Table 1
Interaction SOA x Stimulus type in Exp. 1

	SOA (ms)				
Stimulus type	-400	-200	0	200	400
Incongruent	717	753	733	703	671
Control	627	647	631	661	646
Congruent	488	558	591	669	668
Main effect SOA	610	653	651	677	661

Table 2
Interaction SOA x Stimulus type in Exp. 2

	SOA (ms)				
Stimulus type	-600	-400	0	400	600
Incongruent	656	678	781	663	659
Control	608	616	681	677	635
Congruent	512	535	640	656	657
Main effect SOA	592	610	701	665	650

Captions

Figure 1

Stimulus and response key display as used in Exp. 1 and 2

The colour fields in the top define response assignment for middle finger (MF) and forefinger (FF) of the left hand (LH) and right hand (RH) (with the colours red, green, blue and yellow from left to right). In the figure, the word blue ['blau'] is shown in the colour red. In the colour naming task the 'red' key is the correct response, in the reading task the 'blue' key as shown by the arrows (keys themselves are not coloured).

Figure 2

Stimulus types for naming and reading tasks and negative and positive SOAs

Time goes from left to right; the bars are filled of (coloured) dots, they form the control stimuli in the conditions 'colour before word'; subscripts denote the actual colour of the colour dots (patch) stimulus or the colour word; INC means an incongruent, C control and CON a congruent stimulus. CN means colour naming, WR word reading, and the sign means positive (+) or negative (-) SOA depending on the task.

Figure 3

Exp. 1: Condition CN: Mean RTs in the colour naming task with coloured keys. Negative SOAs mean word appeared before colour; positive SOAs mean colour appeared before word.

Figure 4

Exp. 1: Condition WR: Mean RTs in the word reading task with coloured keys. Negative SOAs mean colour appeared before word; positive SOAs mean word appeared before colour.

Figure 5

Exp. 1: Means of interference (inhibition) and priming (facilitation) for CN and WR. Negative SOAs mean irrelevant aspect appeared before the relevant one; positive SOAs mean relevant appeared before the irrelevant one.

Figure 6

Exp. 2: Condition CN: Mean RTs in the colour naming task with coloured keys. Negative SOAs mean word appeared before colour; positive SOAs mean colour appeared before word.

CWI with colour keys

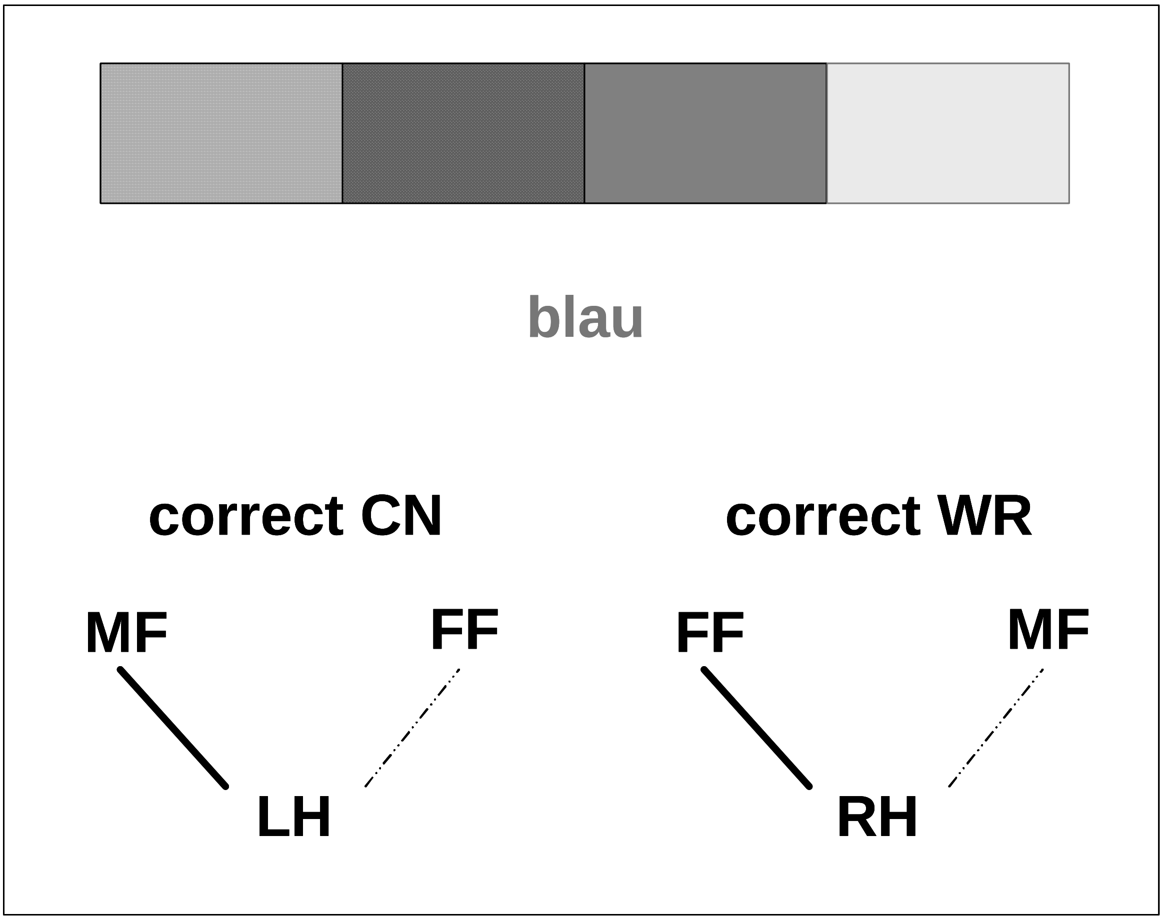
Figure 7

Exp. 2: Condition WR: Mean RTs in the word reading task with coloured keys. Negative SOAs mean colour appeared before word; positive SOAs mean word appeared before colour.

Figure 8

Exp. 2: Means of interference (inhibition) and priming (facilitiation) for CN and WR. Negative SOAs mean irrelevant aspect appeared before the relevant one; positive SOAs mean relevant appeared before the irrelevant one.

Fig. 1



CWI with colour keys

Fig. 2

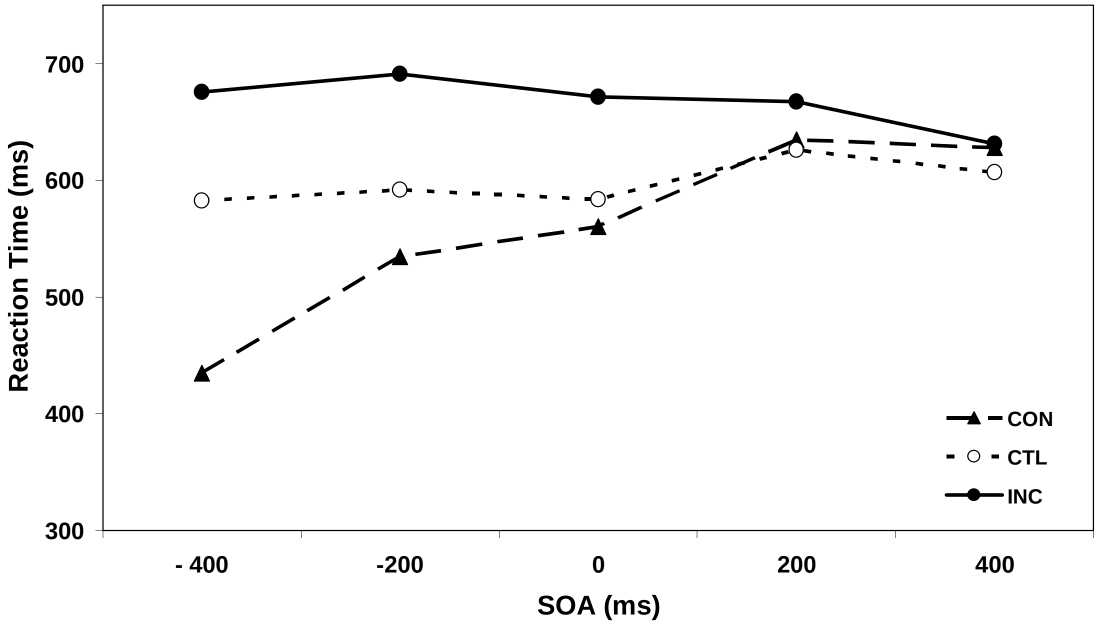
Colour before word → **t** — Condition (+/- for SOA <> 0)

[colour patch] red	**blau** red	**INC**	**CN+, WR-**
[colour patch] red	**xxxx** red	**C**	**CN+**
[colour patch] red	**rot** red	**CON**	**CN+, WR-**
[colour patch] red	**rot** red	**C**	**WR-**

Word before colour → **t** — Condition (+/- for SOA <> 0)

blau black	**blau** red	**INC**	**CN-**
xxxx black	**xxxx** red	**C**	**CN-**
blau black	**blau** blue	**CON**	**CN-**
blau white	**blau** red	**INC**	**WR+**
blau white	**blau** black	**C**	**WR+**
blau white	**blau** blue	**CON**	**WR+**

Fig. 3



Word first (-) / Colour First (+)

CWI with colour keys

Fig. 4

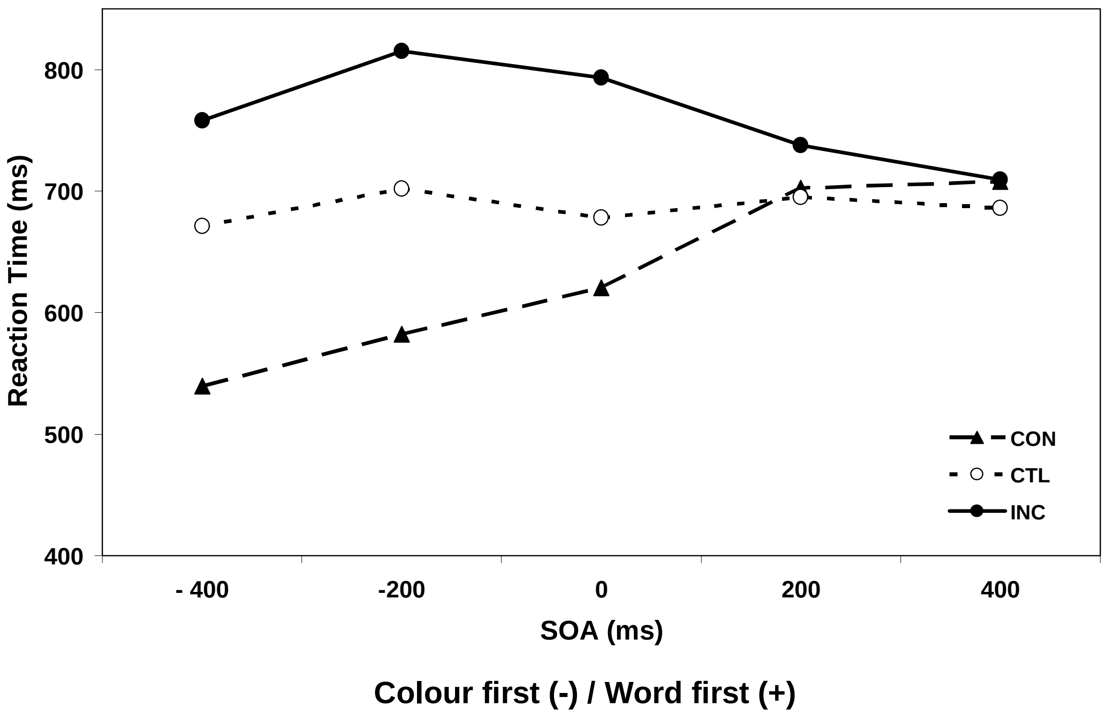
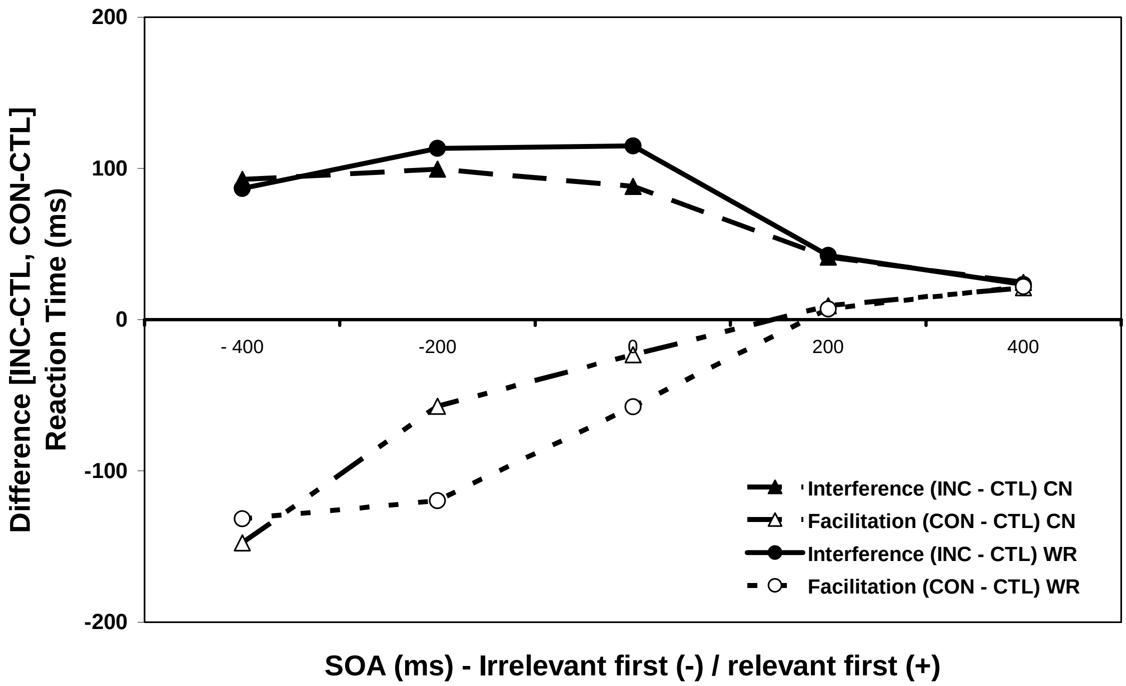


Fig. 5



Interference / Facilitation Exp. 1

CWI with colour keys

Fig. 6

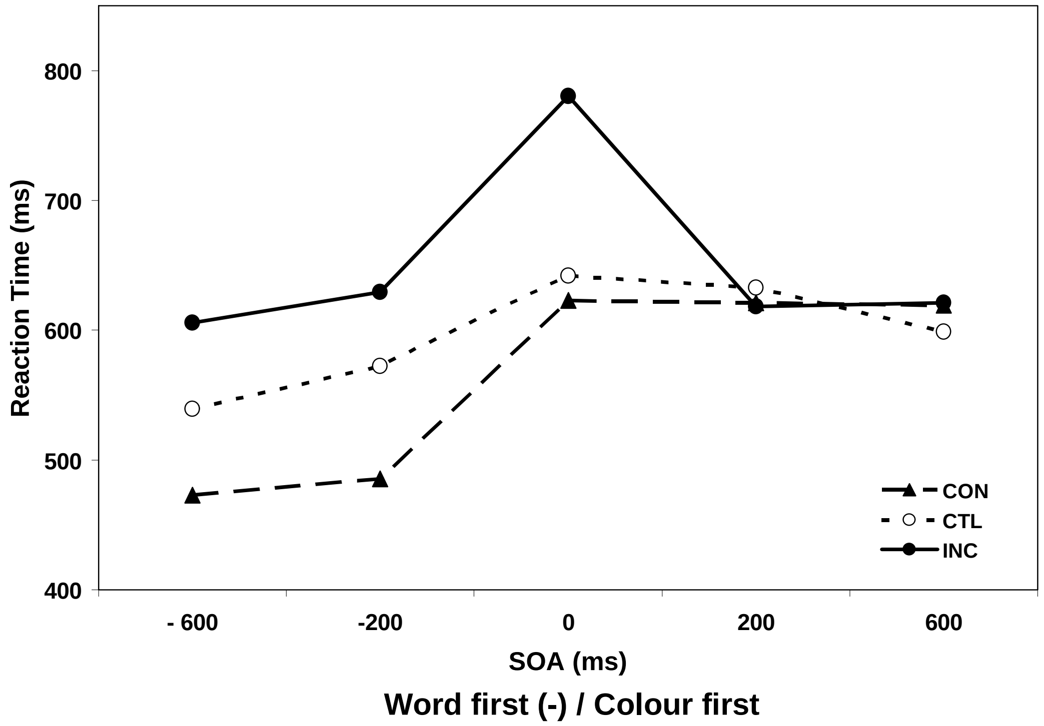
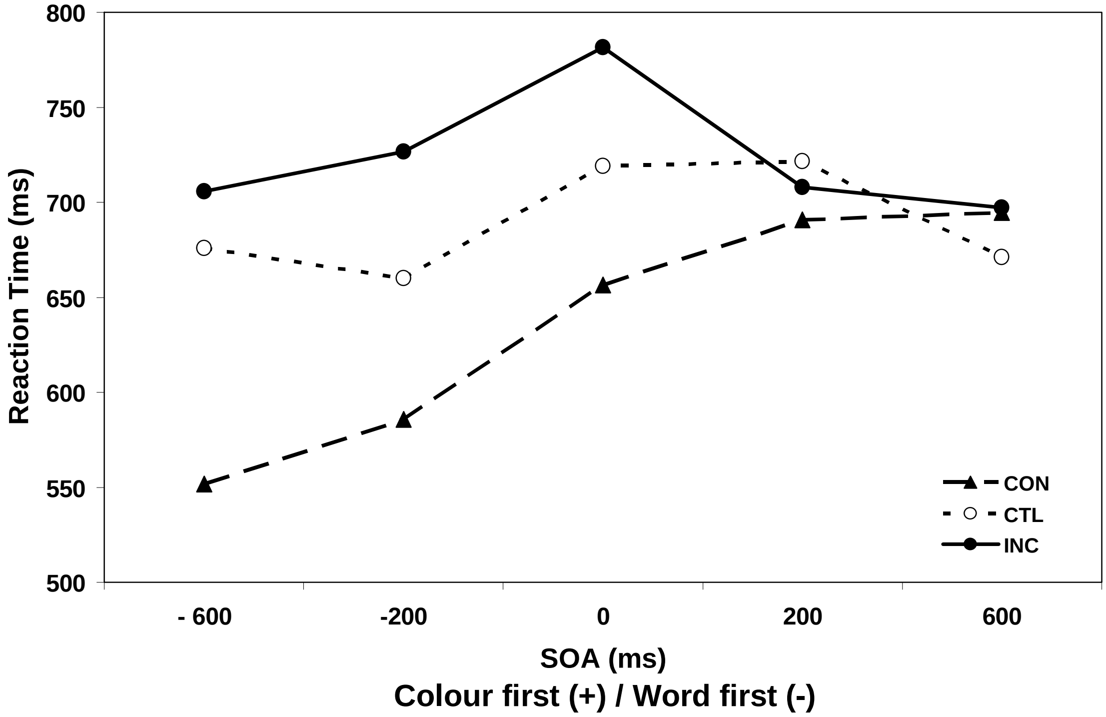
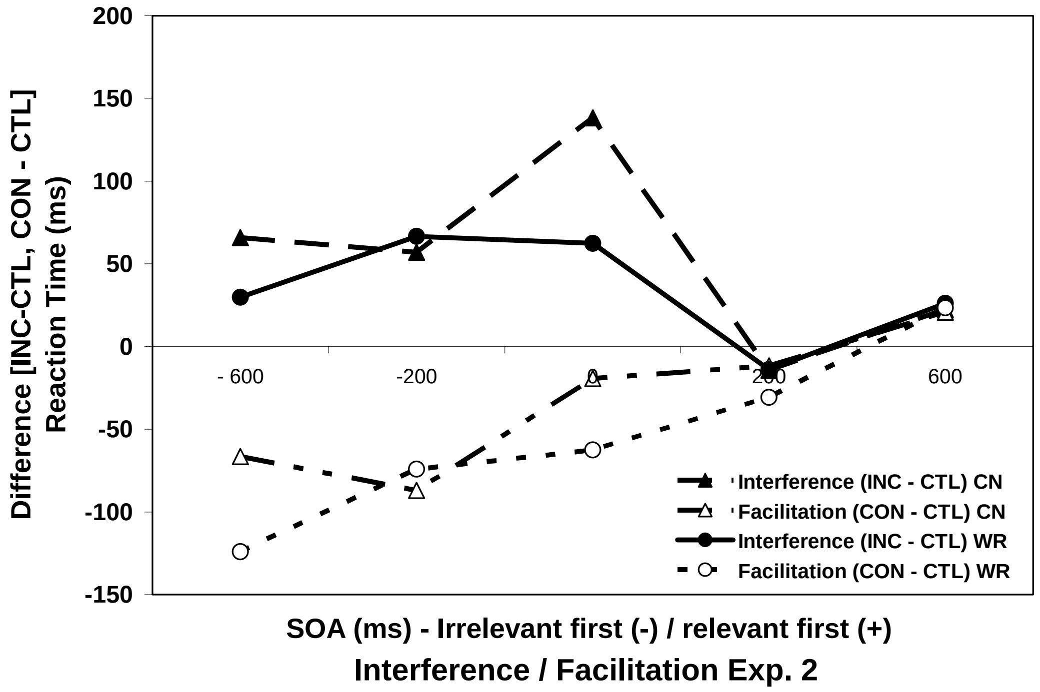


Fig. 7


800
750
700
650
600
550
500
Reaction Time (ms)
- 600
-200
0
200
600
SOA (ms)
Colour first (+) / Word first (-)
CON
CTL
INC

CWI with colour keys

Fig. 8



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