

Attention, spatial integration, and the tail of response time distributions in Stroop task performance

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A few studies have examined selective attention in Stroop task performance through ex-Gaussian analyses of response time (RT) distributions. It has remained unclear whether the tail of the RT distribution in vocal responding reflects spatial integration of relevant and irrelevant attributes, as suggested by Spieler, Balota, and Faust (2000). Here, two colour–word Stroop experiments with vocal responding are reported in which the spatial relation between colour and word was manipulated. Participants named colours (e.g., green; say “green”) while trying to ignore distractors that were incongruent or congruent words (e.g., *red* or *green*), or neutral series of Xs. The vocal RT was measured. Colour words in colour, white words superimposed onto colour rectangles (Experiment 1), and colour rectangles combined with auditory words (Experiment 2) yielded Stroop effects in both the leading edge and the tail of the RT distributions. These results indicate that spatial integration is not necessary for effects in the tail to occur in vocal responding. It is argued that the findings are compatible with an association of the tail effects with task conflict.

Keywords: Attention; Response time distribution; Spatial integration; Stroop task; Vocal responding.

Attention includes the ability to formulate goals and plans of action and to follow these while facing distraction. This ability is critical to normal human functioning, and it is a hallmark of general intelligence (e.g., Duncan, 2010; Wundt, 1904). Attention plays a central role in human performance generally and language performance specifically (e.g., Roelofs, 2003, 2008). For example, in naming attributes of perceived objects, individuals typically have to focus attention

and respond discretely to one attribute of an object (e.g., colour) while ignoring other attributes (e.g., shape). This often involves resolving competition among responses activated by the different attributes of an object. A classic example of a laboratory task that engages this kind of selective attention is the colour–word Stroop task (Stroop, 1935). In modern versions of this task, individuals are instructed to vocally name the presentation colour of printed congruent or incongruent colour words

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This research was supported by a Vici grant from the Netherlands Organisation for Scientific Research. The author thanks Marianne Severens for her help in running the experiments and two reviewers and the members of the Attention and Language Performance Lab at the Donders Centre for Cognition for helpful comments.

(e.g., the words *green* or *red* printed in green ink; say “green”) or neutral series of Xs. Mean response time (RT) is typically longer in the incongruent than the neutral condition, descriptively called *interference*, and often shorter in the congruent than the neutral condition, descriptively called *facilitation* (see MacLeod, 1991, for a review).

Whereas researchers have relied heavily on mean RT as the primary measure in behavioural studies of Stroop task performance, a few studies have performed ex-Gaussian analyses to formally characterize entire RT distributions. The ex-Gaussian function consists of a convolution of a Gaussian (i.e., normal) and an exponential distribution, which generally provides good fits to empirical RT distributions (e.g., Luce, 1986; Ratcliff, 1979). The analyses provide three parameters characterizing a distribution, called μ (mu), σ (sigma), and τ (tau). The μ and σ parameters reflect the mean and standard deviation of the Gaussian portion, and τ reflects the mean and standard deviation of the exponential portion. The mean of the whole distribution equals the sum of μ and τ . Thus, ex-Gaussian analyses decompose mean RTs into two additive components, which characterize the leading edge (μ) and the tail (τ) of the underlying RT distribution.

In a seminal Stroop colour-naming study using ex-Gaussian analyses, Heathcote, Popiel, and Mewhort (1991) observed that the RT effect of Stroop condition (congruent, incongruent, neutral) may be different for the condition means and the three ex-Gaussian parameters. Participants had to vocally name the ink colour of congruent or incongruent colour words (e.g., the words *green* or *red* printed in green) or a neutral series of Xs. Mean RTs were longer for the incongruent than the congruent and neutral conditions, which did not differ. In contrast to the analysis of the mean RTs, analysis of μ showed both interference (i.e., μ was larger for incongruent than neutral stimuli) and facilitation (i.e., μ was smaller for congruent than neutral stimuli). Moreover, τ was greater for the congruent and incongruent conditions than for the neutral condition, whereas the congruent and incongruent conditions did not differ. Thus, in the ex-Gaussian analysis, the congruent condition

showed both facilitation in μ and interference in τ . Given that the mean of an RT distribution is equal to the sum of μ and τ , and the interference and facilitation effects of congruent stimuli in μ and τ had about the same magnitude, no difference between the congruent and neutral conditions was obtained in the mean RTs. These patterns of results have been replicated for Stroop colour naming with vocal responding by Mewhort, Braun, and Heathcote (1992) and Spieler, Balota, and Faust (1996, 2000). Although the effects of Stroop condition on the ex-Gaussian parameters are robust, the underlying mechanisms that give rise to the effects have remained unclear.

To constrain formal modelling of these mechanisms, subsequent research has examined under what condition the τ effects occur in performing Stroop-like tasks. An important variable that influences Stroop task performance is whether colour and word are spatially integrated or separated (see MacLeod, 1998, for a review). Spieler et al. (2000) examined the effect of spatial integration on τ in vocal responding. They observed that effects of Stroop condition are reflected in τ only if the colour and word are spatially integrated, as in the classic Stroop task, but not if the word appears above or below the colour information. Similarly, they found that effects on τ are absent in a local/global figures task, in which participants respond to a large letter (e.g., H or S) made up of a number of congruent or incongruent smaller letters (e.g., an H consisting of Ss). The identity of the large letter was indicated by pressing a left or right button. Effects on τ were also found to be absent in the Eriksen flanker task, in which participants respond to a central letter (e.g., H or S) surrounded by two congruent or incongruent letters on each side (e.g., SSHSS). The identity of the central letter was indicated by pressing a left or right button. According to Spieler et al. (2000), spatial separation of stimulus attributes influences the RT distribution differently from spatial integration. In particular, only interference from spatially integrated target and distractor attributes is evidenced as a change in τ . Thus, according to this view, the critical factor eliminating effects of distractor condition on τ is the separation of target

and distractor attributes, either in Euclidian space, as in the Eriksen flanker and spatially separated Stroop tasks, or in “hierarchical space”, as Spieler et al. (2000) assumed for the local/global task. With separation, effects on τ are not obtained.

Later studies by Aarts, Roelofs, and Van Turennout (2009) and Steinhauser and Hübner (2009) suggested that τ is sensitive to manipulations of task conflict in performing Stroop-like tasks, even in the absence of spatial integration of target and distractor. In a task-switching situation, Aarts et al. presented participants with incongruent and congruent combinations of left- or right-pointing arrows and the words *left* or *right*, or with arrows and words only (the neutral condition). The words were superimposed onto the arrows. Because incongruent and congruent stimuli afford both tasks, they are called “bivalent”, whereas neutral stimuli are called “univalent” (e.g., Monsell, 2005). Participants had to respond to the arrow or word by pressing a left or right button. On each trial, a cue indicated whether the task was to respond to the arrow or word. Mean RT was longer on incongruent than congruent trials, but also longer on congruent than neutral trials, henceforth the “bivalency effect” (Steinhauser & Hübner, 2009). Because incongruent and congruent stimuli are equally associated with the two tasks, slower responding to incongruent than to congruent stimuli must reflect response conflict. Congruent stimuli create no conflict at the response level but are associated with both tasks, whereas neutral stimuli are associated with only one task. Therefore, slower responding to congruent than to neutral stimuli can only reflect conflict at the task level (Aron, Monsell, Sahakian, & Robbins, 2004; Monsell, 2005; Rogers & Monsell, 1995). This bivalency effect in task switching (i.e., the positive congruent–neutral RT difference) invites the interpretation that interference in τ for congruent relative to neutral trials in single-task Stroop colour naming (Heathcote et al., 1991; Mewhort et al., 1992; Spieler et al., 1996, 2000) also reflects task conflict.

Direct support for a link between the bivalency effect and τ was obtained from ex-Gaussian analyses performed by Aarts et al. (2009). These

analyses revealed that the positive RT difference between the incongruent and congruent conditions (i.e., RT incongruent > RT congruent) was uniquely associated with the μ and σ parameters of the ex-Gaussian distribution. In contrast, the positive RT difference between the congruent and neutral conditions (i.e., RT congruent > RT neutral, the bivalency effect) was uniquely associated with the τ parameter. These findings suggest that RT effects at the level of task set are reflected in the exponential portion of the ex-Gaussian curve. Moreover, functional magnetic resonance data obtained by Aarts et al. showed that brain activity in dorsolateral prefrontal cortex was higher in the congruent than in the neutral condition, whereas the incongruent and congruent conditions revealed no differential activity in this area. This agrees with prior studies, which associated activity in dorsolateral prefrontal cortex with processes at the level of task set (see Kane & Engle, 2002, for a review). Dorsolateral prefrontal cortex is part of a frontoparietal brain system that plays a central role in task control during goal-directed behaviour. This system is engaged by simple Stroop-like tasks as well as by complex tasks requiring fluid intelligence, the ability to solve novel problems (e.g., Duncan, 2010).

Steinhauser and Hübner (2009) observed a similar link between μ and response conflict, on the one hand, and τ and task conflict, on the other, in a manual task-switching version of the colour-word Stroop task. The link between τ and task conflict was obtained regardless of whether colour and word were spatially integrated (Experiment 1) or spatially separated (Experiment 2). Participants indicated the identity of the colour or word by pressing corresponding buttons. The effect of task conflict (the bivalency effect) in τ was only obtained when participants switched between responding to the colour and responding to the word in a block of trials, but not when only one task (i.e., responding to the colour or responding to the word) was performed in a trial block. In contrast, Mewhort et al. (1992) and Spieler et al. (1996, 2000) obtained a τ effect in Stroop colour naming without task switching. Steinhauser and Hübner (2009) argued that whether task conflict occurs in the Stroop task may

depend on the extent that the distractor attribute activates the competing task. According to them, the magnitude of interference effects is typically smaller in manual versions of the Stroop task (as they used) than in versions requiring vocal responding (used by Mewhort et al. and Spieler et al.). It may be that the Stroop conflict induced by the manual responding in the pure task blocks of Steinhauser and Hübner was too small to yield enough task conflict to be reflected in τ .

Spieler et al. (2000) argued against a link between the magnitude of conflict and τ effects in vocal responding by demonstrating that distractor effects on τ with spatially separated colours and words were absent for participants showing large (52-ms) interference effects as well as participants showing small (19-ms) interference effects. This suggests that the presence of τ effects in vocal responding does not depend on the magnitude of the distractor effects. Rather, spatial integration seems to be the crucial factor with vocal responding. However, this argument concerning effect sizes may not be conclusive, because distractor attribute activation was presumably much less with the 52-ms effect for spatial separation than the 152-ms effect obtained by Spieler et al. (2000) for spatially integrated colours and words. The 152-ms effect was associated with a τ effect, whereas the 52-ms effect was not. Thus, it remains possible that with the 52-ms effect the distractor was processed insufficiently to evoke task conflict. Similarly, the distractor attribute activation in the Eriksen flanker and local/global tasks of Spieler et al. (2000) may have been too weak to evoke sufficient task conflict in manual responding. The interference effects in the Eriksen flanker task (33 ms) and the local/global task (28 ms) were smaller than the effect with spatially separated Stroop stimuli (45 ms) and much smaller than the effect with integrated Stroop stimuli (152 ms). Thus, it is possible that Spieler et al. (2000) did not obtain τ effects in the spatially separated conditions because the magnitude of interference was too small. However, this possibility is speculative and needs to be explicitly tested.

To summarize, researchers have found no agreement on exactly what experimental manipulations

yield τ effects in Stroop task performance. Yet, understanding the circumstances under which τ effects occur is important for constraining formal models of the underlying mechanisms. Evidence from vocal responding suggests that spatial integration of target and distractor causes effects of Stroop condition in τ (Spieler et al., 2000). Evidence from manual responding in combination with task switching suggests that task conflict causes τ effects even in the absence of spatial integration (Aarts et al., 2009; Steinhauser & Hübner, 2009). The data of these two lines of research are not necessarily in disagreement. It may be that τ is sensitive to manipulations of spatial integration with vocal responding and sensitive to task conflict with manual responding and task switching. Alternatively, it may be that the presence of effects in τ depends on the magnitude of the Stroop conflict induced by the stimuli, which is typically larger with vocal than manual responding (e.g., Sugg & MacDonald, 1994). The latter would explain why Steinhauser and Hübner (2009) did not obtain a bivalency effect in τ in single-task performance, whereas Spieler et al. (2000) did. Still, Spieler et al. (2000) did not obtain τ effects in vocal responding to separated stimuli, suggesting that spatial integration is crucial for obtaining τ effects in the vocal modality. If nevertheless the magnitude of interference matters, it should be possible to induce τ effects in vocal responding using stimuli that induce large Stroop effects, even in the absence of spatial integration (unlike what Spieler et al., 2000, observed). This was examined in the experiments reported in the present article.

Plan of the present study

Below, two experiments are reported that examined the role of spatial integration in inducing effects in τ in the colour–word Stroop task with *vocal* responding (the classic response modality in Stroop task performance). In Experiment 1, Stroop task performance was assessed with spatially integrated stimuli (classic Stroop stimuli) and with stimuli consisting of written words in neutral white colour that were superimposed onto colour

rectangles. That is, the words were displayed inside the boundaries of colour rectangles (i.e., the colour was not an attribute of the word). Words superimposed onto colour rectangles have in common with the local/global figures of Spieler et al. (2000) a kind of hierarchical relation that exists between target and distractor. Moreover, whereas it is not possible to visually fixate the colour but not the word of integrated stimuli, participants may, in principle, gaze at part of the colour rectangle (e.g., one of the corners) without fixating the word. The superimposed presentation mode is commonly used when investigating the time course of the Stroop phenomenon (e.g., Glaser & Glaser, 1982, 1989; Long & Lyman, 1987) and in variants of the Stroop task, such as picture-word interference (e.g., Glaser & Dünghoff, 1984; Roelofs, 2008). Earlier research (e.g., Roelofs, 2003) suggested that the magnitude of Stroop interference with superimposed distractors is of the order of 80–100 ms, which should be large enough to induce effects of task conflict in τ , according to the suggestions above. In contrast, if full spatial integration rather than the magnitude of conflict is important, τ effects should be reduced or eliminated, as in the Eriksen flanker and local/global tasks (Spieler et al., 2000).

Spieler et al. (2000) argued that in classic integrated Stroop stimuli, the colour and word dimensions are integrated into a single object, and selection is between attributes of this object. For the local/global task, the local and global dimensions overlap in terms of their spatial position, but the two dimensions are less obviously integrated than in classic colour-word Stroop stimuli. “Hierarchical forms as in the local/global task might be similar to spatially separated stimuli except that instead of being distributed across Euclidean space, the forms are distributed across hierarchical space” (Spieler et al., 2000, p. 513). Spieler et al. (2000) suggested that the perceptual system may process the distracting information in the Stroop task as an attribute of the selected object, whereas distracting information in the local/global task is treated as information from a different object. In case of words superimposed onto colour patches, the colour and word are also

less obviously integrated than in classic colour-word Stroop stimuli. As a consequence, it is possible that the perceptual system processes the distracting information in superimposed stimuli differently from in classic integrated stimuli. This is examined in Experiment 1.

In Experiment 2, Stroop task performance with superimposed and auditory distractors was assessed. Earlier research (e.g., Roelofs, 2005) suggested that the magnitude of Stroop interference with auditory distractors is of the order of 80–90 ms, which should be sufficient to induce effects of task conflict in τ . In contrast, because the auditory words and colour rectangles are spatially separated (i.e., headphones and computer screen), τ effects should be eliminated if spatial integration is crucial.

EXPERIMENT 1

In the first experiment, participants vocally named ink colours or colour rectangles while trying to ignore congruent or incongruent colour words or neutral distractors. Trials were blocked by the presentation mode of the target and distractor attributes (i.e., integrated, superimposed). The RTs were examined using ex-Gaussian analyses.

Method

Participants

The experiment was carried out with 20 paid participants, who were students at Radboud University Nijmegen. All were young adults and native speakers of Dutch.

Materials and design

The stimuli consisted of red, green, and blue colour rectangles and the corresponding written Dutch colour words *rood*, *groen*, and *blauw* in neutral white colour (for the superimposed condition), or the words in one of the three ink colours red, green, or blue (for the integrated condition). The colour rectangles were 1.5 cm high and 4.5 cm wide. The written words were presented in 36-point lower-case Arial font. A row of 5 Xs served as stimulus in the control condition

(cf. Heathcote et al., 1991; Spieler et al., 2000, Experiment 1).

There were two independent variables, which were varied within participants. The first independent variable was *Stroop condition*. There were three congruent pairings of the word and colour attributes (*rood*–red, *groen*–green, *blauw*–blue), three incongruent pairings (*rood*–blue, *groen*–red, *blauw*–green), and three neutral stimuli (the row of Xs in an ink colour or superimposed onto colour rectangles). With three colours, three colour words, and a series of Xs, there are six possible colour–word combinations in the incongruent condition, but only three combinations in the congruent condition and three in the neutral condition. In order to have an equal number of stimuli in each of the Stroop conditions, incongruent trials were therefore constructed by repeatedly pairing one colour word with one colour (i.e., *rood*–blue, *groen*–red, *blauw*–green). Roelofs (2010) observed that the yoking of colours with words does not affect Stroop effects compared with fully crossing colours and words. The second independent variable was *presentation mode*: The colour and word attributes were integrated or superimposed. Trials were blocked by presentation mode. Half the participants first received a block of trials with all the integrated stimuli and then a block of trials with all the superimposed stimuli, and vice versa for the other half of the participants. Thus, the order of the presentation modes was counterbalanced across participants. Each of the congruent, incongruent, and control stimuli occurred 16 times within a presentation mode. There were 48 trials per condition per presentation mode. The stimuli were presented in random order.

Procedure and apparatus

The experiment was run under the NESU software developed at the Max Planck Institute for Psycholinguistics in Nijmegen. The participants were tested individually. They were seated in front of a computer monitor (NEC Multisync) and a Sennheiser microphone connected to an electronic voice key. The distance between participant and screen was approximately 50 cm. The participants were asked to name the ink colour or colour

rectangles as quickly as possible while trying to make no mistakes.

The structure of a trial was as follows. A trial started with the presentation of the Stroop stimulus. The stimuli remained visible for 1.5 s after stimulus presentation onset. Following stimulus presentation, the screen was blank for 2 s, after which the next trial began. A desktop computer controlled the stimulus presentation and data collection, including the voice key.

Analyses

Five types of incorrect response were distinguished: wrong response word, wrong pronunciation of the word, a disfluency, triggering of the voice key by a nonspeech sound, and failure to respond within 2.5 s after target presentation onset. Incorrect responses were excluded from the statistical analyses of the RTs. The RTs and errors were submitted to repeated measures analyses of variance with the crossed variables Stroop condition and presentation mode. Both variables were tested within participants. Interactions between variables were statistically explored through paired *t* tests. In particular, pairwise comparisons tested for Stroop facilitation (i.e., congruent minus neutral) and interference (i.e., incongruent minus neutral) within each presentation mode.

The RTs were examined at the level of distributional characteristics by performing ex-Gaussian and Vincentile analyses. Whereas ex-Gaussian analyses characterize an RT distribution by assuming an explicit function for the shape of the distribution, Vincentile analyses do not depend on prior distributional assumptions and examine the raw RT distributions directly (Ratcliff, 1979). To obtain the distributions, the rank-ordered RTs for each participant were divided into deciles (10% quantiles), and mean RTs were computed for each decile, separately for each Stroop condition in each presentation mode. By averaging these decile means across participants for each condition and presentation mode, Vincentized cumulative distribution curves were obtained. For RTs, Vincentizing the data across individual participants provides a way of averaging data to obtain group

distributions while preserving the shapes of the individual participant distributions.

The ex-Gaussian parameters μ , σ , and τ were estimated from the data using the quantile maximum likelihood estimation method proposed by Brown and Heathcote (2003). The parameters were estimated per Stroop condition and presentation mode for each participant individually using the QMPE software using ten quantiles (Brown & Heathcote, 2003). All estimations converged within 66 iterations in both experiments. The ex-Gaussian parameters were then submitted to analyses of variance with the crossed variables Stroop condition and presentation mode (cf. Spieler et al., 1996, 2000).

Following the recommendations of Heathcote et al. (1991) and Ulrich and Miller (1994), the RT data were not trimmed. Data are usually trimmed to eliminate extreme RTs and, thereby, create a distribution closer to the normal (Gaussian) form. Often, researchers trim trials with an RT longer than a fixed number of standard deviations from the mean (e.g., Steinhäuser & Hübner, 2009). However, using trimming to correct a skewed distribution may discard valuable information, especially if the skew itself is the topic of investigation, as is the case in the present experiments.

Results and discussion

Analyses of means

Table 1 gives the mean colour naming RTs and error rates for Stroop condition and presentation mode. The table shows that responding was slower in the incongruent condition than in the congruent and neutral conditions, which did not differ much. This held for both presentation modes. Error rates were highest for the incongruent condition and slightly higher for the congruent than the neutral condition in both presentation modes.

The statistical analysis of the errors yielded effects of Stroop condition, $F(2, 38) = 6.68$, $p < .003$, $\eta_p^2 = .26$, but not of presentation mode, $F(1, 19) = 1.60$, $p = .22$, $\eta_p^2 = .08$. Stroop condition and presentation mode did not interact,

$F(2, 38) < 1$, $p = .42$, $\eta_p^2 = .04$. Most errors were made in the slowest condition, excluding a speed-accuracy trade-off in the data.

The statistical analysis of the RTs yielded effects of Stroop condition, $F(2, 38) = 142.54$, $p < .001$, $\eta_p^2 = .88$, and presentation mode, $F(1, 19) = 25.72$, $p < .001$, $\eta_p^2 = .58$. Stroop condition and presentation mode interacted, $F(2, 38) = 3.93$, $p < .03$, $\eta_p^2 = .17$. The integrated distractors yielded a Stroop condition effect, $F(2, 38) = 91.36$, $p < .001$, $\eta_p^2 = .83$. Planned comparisons revealed that responding was slower on incongruent than neutral trials, $t(19) = 10.8$, $p < .001$, whereas responding on congruent and neutral trials did not differ, $t(19) = 1.8$, $p = .09$. The superimposed distractors also yielded a Stroop condition effect, $F(2, 38) = 116.26$, $p < .001$, $\eta_p^2 = .86$. Planned comparisons revealed that responding was slower on incongruent than neutral trials, $t(19) = 12.3$, $p < .001$, whereas responding on congruent and neutral trials did not differ, $t(19) = 1.4$, $p = .19$. The magnitude of interference was greater with the integrated stimuli (127 ms) than the superimposed stimuli (101 ms), $t(19) = 4.67$, $p < .04$.

Distributional analyses

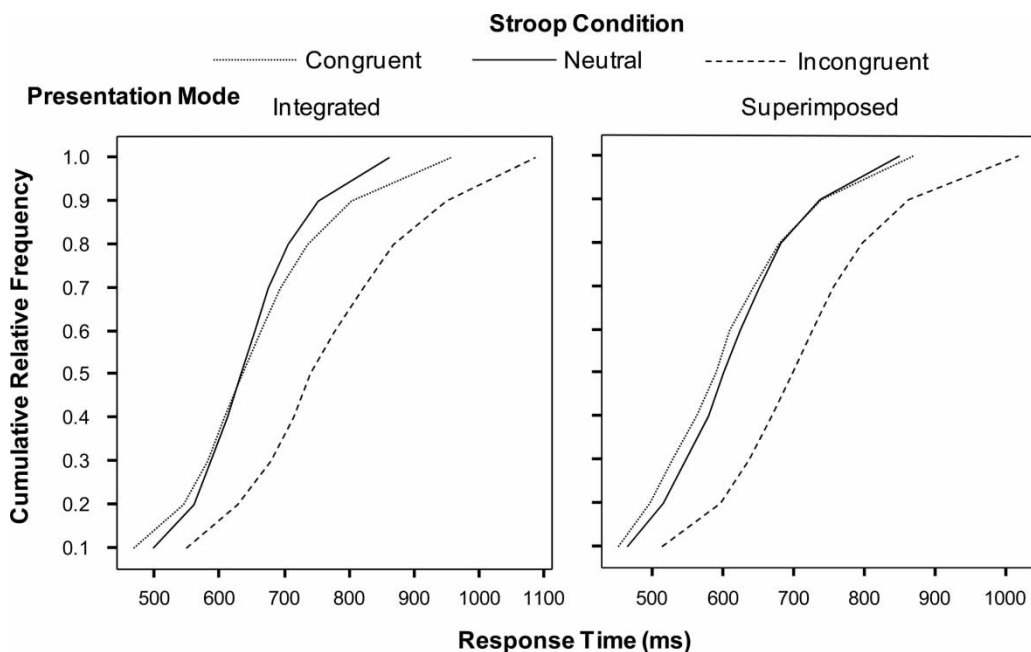
Figure 1 gives the Vincentized cumulative distribution curves per Stroop condition and presentation mode. The figure shows that the incongruent condition is much slower than the neutral condition throughout the latency range in both presentation modes. The magnitude of the interference seems to increase with increasing RT. The curves for the congruent condition show a different pattern. In both presentation modes, the congruent condition shows facilitation for the relatively fast responses, but interference or a lack of an effect for the relatively slow responses.

Table 1 gives the ex-Gaussian parameter estimates per Stroop condition and presentation mode. The table reveals that the Stroop effects on the Gaussian parameters (μ and σ) are similar to the pattern observed in the mean RTs, except that the congruent stimuli yield facilitation in μ but not in the means. However, for the exponential parameter τ the patterns are different. Here, congruent and incongruent stimuli yield interference

Table 1. Mean naming time, percentage error, and mean ex-Gaussian parameter estimates as a function of presentation mode and Stroop condition in Experiment 1.

Presentation mode	Stroop condition	M	PE	μ	σ	τ
Integrated	Incongruent	781	3.1	672	90	114
	Congruent	669	2.3	575	72	94
	Neutral	654	1.3	600	67	52
Superimposed	Incongruent	726	2.2	652	93	72
	Congruent	616	1.5	520	63	95
	Neutral	625	1.2	559	68	66

Note: M = mean naming time; PE = percentage error. Mean ex-Gaussian parameter estimates: μ , σ , τ . Mean naming times and ex-Gaussian parameter estimates are given in milliseconds.

**Figure 1.** Vincitized cumulative distribution curves per Stroop condition and presentation mode in Experiment 1.

relative to the neutral condition in both presentation modes.

Statistical analyses revealed that for μ , there were main effects of Stroop condition, $F(2, 38) = 69.09$, $p < .001$, $\eta_p^2 = .78$, and presentation mode, $F(1, 19) = 9.78$, $p < .006$, $\eta_p^2 = .34$. Stroop condition and presentation mode did not interact, $F(2, 38) = 1.20$, $p = .31$, $\eta_p^2 = .06$. Planned comparisons revealed that μ was larger on incongruent than on neutral trials, $t(19) = 7.1$, $p < .001$, and smaller on

congruent than on neutral trials, $t(19) = 4.4$, $p < .001$. Thus, incongruent stimuli yielded interference, whereas congruent stimuli yielded facilitation. For σ , there was a main effect of Stroop condition, $F(2, 38) = 6.26$, $p < .004$, $\eta_p^2 = .25$, but not of presentation mode, $F(1, 19) < 1$, $p = .70$, $\eta_p^2 = .008$. Stroop condition and presentation mode did not interact, $F(2, 38) < 1$, $p = .53$, $\eta_p^2 = .03$. Planned comparisons revealed that σ was larger on incongruent than on neutral trials,

$t(19) = 2.48, p < .02$, whereas the congruent and neutral conditions did not differ, $t(19) < 1, p = .99$. For τ , there was again a main effect of Stroop condition, $F(2, 38) = 7.60, p < .002, \eta_p^2 = .29$, but not of presentation mode, $F(1, 19) < 1, p = .38, \eta_p^2 = .04$. There was a marginally significant interaction between Stroop condition and presentation mode, $F(2, 38) = 2.73, p = .08, \eta_p^2 = .13$. Planned comparisons revealed that τ was larger on incongruent than on neutral trials, $t(19) = 2.86, p < .01$, which was dependent on presentation mode, $F(1, 19) = 4.72, p = .043, \eta_p^2 = .20$, indicating that the interference was most prominent for the integrated distractors. The value of τ was also larger on congruent than on neutral trials, $t(19) = 4.55, p < .001$, regardless of presentation mode, $F(1, 19) < 1, p = .58, \eta_p^2 = .02$. Thus, incongruent and congruent stimuli yielded interference in τ in both presentation modes.

To summarize, relative to neutral trials, incongruent stimuli yielded interference in both the Gaussian (μ and σ) and exponential (τ) portions of the RT distribution. In contrast, congruent distractors yielded facilitation in μ and interference in τ . These patterns of effects were obtained independent of attribute presentation mode.

The patterns of results in μ and τ obtained with the integrated stimuli replicate earlier findings on Stroop colour naming in the literature (i.e., Mewhort et al., 1992; Heathcote et al., 1991; Spieler et al., 1996, 2000). The present data show that the same pattern of results is obtained with superimposed distractors. This suggests that colour and word do not need to be fully integrated for τ effects to emerge in vocal responding.

EXPERIMENT 2

In the second experiment, Stroop task performance with superimposed and auditory distractors was assessed. Participants vocally named colour rectangles while trying to ignore congruent or incongruent colour words or neutral distractors. The distractor words were presented in white colour superimposed onto the colour rectangles, as in Experiment 1, or they were presented auditorily.

Trials were blocked by presentation mode (i.e., superimposed, auditory). Earlier research (e.g., Roelofs, 2005) has suggested that the magnitude of Stroop interference with auditory distractors is of the order of 80–90 ms, which should be sufficient to induce effects of task conflict in τ . In contrast, because the auditory words and colour rectangles are spatially separated (i.e., headphones and computer screen), τ effects should be eliminated if spatial integration is crucial. The RTs were again examined using ex-Gaussian and Vincentile analyses.

Method

Participants

The experiment was carried out with 20 paid participants, who were students at Radboud University Nijmegen. All were young adults and native speakers of Dutch. None of them had participated in Experiment 1.

Materials, design, procedure, apparatus, and analyses

These were the same as those in Experiment 1, except that the integrated stimuli were replaced by colour rectangles combined with auditory distractors. The auditory word stimuli were spoken by a native Dutch female speaker and recorded using a DAT recorder. They were digitalized and stored on the hard disk of the experimental computer as WAV files. The durations of the spoken words *rood*, *groen*, and *blauw* were 763, 719, and 710 ms, respectively. The control stimulus consisted of a stretch of white noise of 730 ms long, which corresponded to the mean duration of the auditory word stimuli. The auditory stimuli were presented over closed Sennheiser headphones. The onset of the auditory stimuli corresponded to the onset of colour rectangle presentation.

Results and discussion

Analyses of means

Table 2 gives the mean colour naming latencies and error rates for Stroop condition and presentation mode. The table shows that responding was slower in the incongruent condition than in the congruent and neutral conditions, which did not

Table 2. Mean naming time, percentage error, and mean ex-Gaussian parameter estimates as a function of presentation mode and Stroop condition in Experiment 2.

Presentation mode	Stroop condition	M	PE	μ	σ	τ
Auditory	Incongruent	602	5.0	520	79	81
	Congruent	537	1.3	449	55	89
	Neutral	524	2.6	453	52	70
Superimposed	Incongruent	714	5.0	620	81	96
	Congruent	578	1.7	499	64	79
	Neutral	588	2.1	527	65	61

Note: M = mean naming time; PE = percentage error. Mean ex-Gaussian parameter estimates: μ , σ , τ . Mean naming times and ex-Gaussian parameter estimates are given in milliseconds.

differ much. This held for both presentation modes. Error rates were highest for the incongruent condition and smaller for the congruent than the neutral condition in both presentation modes.

The statistical analysis of the errors yielded an effect of Stroop condition, $F(2, 38) = 12.50$, $p < .001$, $\eta_p^2 = .40$, but not of presentation mode, $F(1, 19) < 1$, $p = .94$, $\eta_p^2 = .00$. Stroop condition and presentation mode did not interact, $F(2, 38) < 1$, $p = .75$, $\eta_p^2 = .02$. Most errors were made in the slowest condition, excluding a speed-accuracy trade-off in the data.

The statistical analysis of the response times yielded effects of Stroop condition, $F(2, 38) = 85.38$, $p < .001$, $\eta_p^2 = .82$, and presentation mode, $F(1, 19) = 26.88$, $p < .001$, $\eta_p^2 = .59$. Stroop condition and presentation mode interacted, $F(2, 38) = 18.64$, $p < .001$, $\eta_p^2 = .50$. As in Experiment 1, the superimposed distractors yielded a Stroop condition effect, $F(2, 38) = 93.86$, $p < .001$, $\eta_p^2 = .83$. Planned comparisons revealed that responding was slower on incongruent than neutral trials, $t(19) = 9.82$, $p < .001$, whereas responding on congruent and neutral trials did not differ, $t(19) = 1.61$, $p = .12$. The auditory distractors also yielded a Stroop condition effect, $F(2, 38) = 31.84$, $p < .001$, $\eta_p^2 = .63$. Planned comparisons revealed that responding was slower on incongruent than neutral trials, $t(19) = 7.10$, $p < .001$, whereas responding on congruent and neutral trials did not differ, $t(19) = 1.06$, $p = .30$. The magnitude of interference was greater with the superimposed distractors (126 ms) than the auditory distractors (78 ms), $t(19) = 4.17$, $p < .001$.

Distributional analyses

Figure 2 gives the Vincentized cumulative distribution curves per Stroop condition and presentation mode. The figure shows that the incongruent condition is much slower than the neutral condition throughout the latency range in both presentation modes. The magnitude of the interference seems to increase with increasing RT. The curves for the congruent condition show a different pattern. The superimposed distractors yield facilitation except for the slowest responses, which replicates the pattern for the superimposed distractors in Experiment 1. The auditory distractors yield interference except for the fastest responses, which resembles the pattern obtained for the integrated distractors in Experiment 1.

Table 2 gives the ex-Gaussian parameter estimates per Stroop condition and presentation mode. The table reveals that the Stroop effects on the Gaussian parameters (μ and σ) are similar to the pattern observed in the mean RTs, except that the congruent stimuli tend to yield facilitation in μ but not in the means. However, for the exponential parameter τ the patterns are different. Here, congruent stimuli yield interference relative to the neutral condition in both presentation modes.

Statistical analyses revealed that for μ , there were main effects of Stroop condition, $F(2, 38) = 41.81$, $p < .001$, $\eta_p^2 = .69$, and presentation mode, $F(1, 19) = 23.12$, $p < .001$, $\eta_p^2 = .55$. There was a marginally significant interaction between Stroop condition and presentation mode, $F(2, 38) = 2.84$, $p = .07$, $\eta_p^2 = .13$. Planned comparisons revealed that μ was larger on incongruent than on neutral

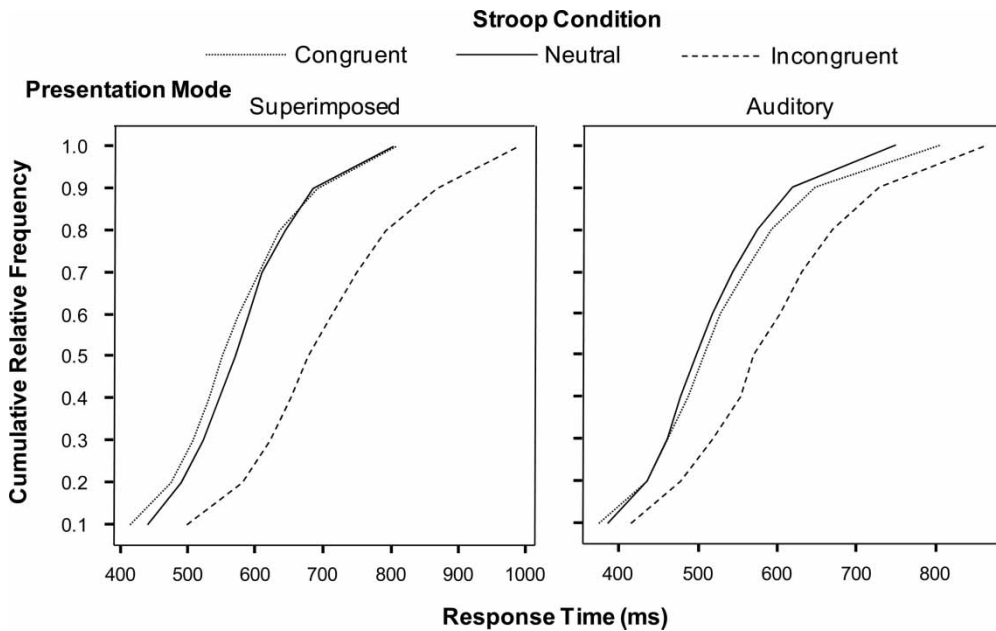


Figure 2. Vincitized cumulative distribution curves per Stroop condition and presentation mode in Experiment 2.

trials, $t(19) = 6.53$, $p < .001$, regardless of presentation mode, $F(1, 19) = 1.43$, $p = .25$, $\eta_p^2 = .07$, and smaller on congruent than on neutral trials, $t(19) = 2.15$, $p < .04$, regardless of presentation mode, $F(1, 19) = 1.64$, $p = .22$, $\eta_p^2 = .08$. Thus, incongruent stimuli yielded interference, whereas congruent stimuli yielded facilitation. For σ , there was a main effect of Stroop condition, $F(2, 38) = 7.87$, $p < .001$, $\eta_p^2 = .29$, but not of presentation mode, $F(1, 19) = 1.23$, $p = .28$, $\eta_p^2 = .06$. Stroop condition and presentation mode did not interact, $F(2, 38) < 1$, $p = .62$, $\eta_p^2 = .03$. Planned comparisons revealed that σ was larger on incongruent than on neutral trials, $t(19) = 4.26$, $p < .001$, whereas the congruent and neutral conditions did not differ, $t(19) < 1$, $p = .85$. For τ , there was a marginally significant main effect of Stroop condition, $F(2, 38) = 3.02$, $p < .06$, $\eta_p^2 = .14$, but there was no effect of presentation mode, $F(1, 19) < 1$, $p = .91$, $\eta_p^2 = .001$. Stroop condition and presentation mode did not interact, $F(2, 38) = 1.38$, $p = .26$, $\eta_p^2 = .07$. Planned comparisons revealed that τ was larger on incongruent than on neutral trials, $t(19) = 2.44$, $p < .03$, and also

larger on congruent than on neutral trials, $t(19) = 2.14$, $p < .05$. Thus, both incongruent and congruent stimuli yielded interference in τ .

To summarize, relative to neutral trials, incongruent stimuli yielded interference in both the Gaussian (μ and σ) and exponential (τ) portions of the RT distribution. In contrast, congruent stimuli yielded facilitation in μ and interference in τ . These patterns of effects were obtained independent of presentation mode.

The patterns of results in μ and τ replicate the results of Experiment 1 and earlier findings in the literature obtained with integrated distractors (i.e., Heathcote et al., 1991; Mewhort et al., 1992; Spieler et al., 1996, 2000). The results indicate that spatial integration is not necessary for τ effects to occur in vocal responding.

GENERAL DISCUSSION

Previous research assessed selective attention in Stroop task performance through ex-Gaussian analyses of RT distributions. It has remained unclear

whether the tail of the distribution in vocal responding reflects spatial integration of relevant and irrelevant attributes. This was suggested by Spieler et al. (2000) but contested by Steinhauser and Hübner (2009). In the present article, two colour–word Stroop experiments with vocal responding were reported in which target and distractor attributes were spatially integrated or they were not. In Experiment 1, Stroop task performance with spatially integrated and superimposed distractors was assessed. In Experiment 2, Stroop task performance with visually superimposed and auditory distractors was assessed. Participants named ink colours or colour rectangles while trying to ignore congruent or incongruent colour words or neutral distractors.

The magnitude of the interference effects in previous experiments failing to obtain τ effects with spatially separated targets and distractors was some 50 ms or less in the mean RTs (Spieler et al., 2000). In contrast, the interference effects in the present Experiments 1 and 2 were over 75 ms regardless of presentation mode. Relative to neutral trials, incongruent distractors yielded interference in both the Gaussian (μ and σ) and exponential (τ) portions of the RT distribution. In contrast, congruent distractors yielded facilitation in the Gaussian portion (μ) and interference in the exponential portion (τ). These patterns of effects on Stroop colour naming replicate earlier findings (i.e., Heathcote et al., 1991; Mewhort et al., 1992; Spieler et al., 1996, 2000). Importantly, the data patterns were obtained in the present experiments independent of the presentation mode of the colour and word attributes. The results indicate that full spatial integration is not necessary for τ effects to occur in vocal responding, contrary to what Spieler et al. (2000) suggested.

The results from the present experiments confirm and extend the findings of Aarts et al. (2009) and Steinhauser and Hübner (2009). The present results indicate that Stroop effects on τ in vocal responding may be obtained regardless of whether target and distractor are spatially integrated, which agrees with what Steinhauser and Hübner observed using a manual version of the colour–word Stroop task. Moreover, the present

results indicate that Stroop effects on τ in vocal responding may be obtained in single-task performance, without task switching. In contrast, Aarts et al. and Steinhauser and Hübner used task-switching procedures in combination with manual responding. Taken together, the results of the present study and those of Aarts et al. and Steinhauser and Hübner suggest that Stroop effects on τ need not reflect spatial integration of target and distractor.

The positive congruent–neutral latency difference observed in τ in the present experiments and in the studies by Heathcote et al. (1991), Mewhort et al. (1992), and Spieler et al. (1996, 2000) corresponds to the bivalency effect observed in mean RTs and τ in task switching (Aarts et al., 2009; Steinhauser & Hübner, 2009). Because incongruent and congruent stimuli are equally associated with the two tasks in task switching, longer RTs on incongruent than congruent trials must reflect response conflict. Congruent stimuli create no conflict at the response level but are associated with both tasks, whereas neutral stimuli are associated with only one task. Therefore, longer RTs on congruent than neutral trials (the bivalency effect) must reflect task conflict. This invites the interpretation that interference in τ for congruent relative to neutral trials in single-task Stroop colour naming also reflects task conflict.

Assessment of task conflict

In the present study, longer latencies on congruent than neutral trials were taken to reflect task conflict, following Monsell and colleagues (Aron et al., 2004; Monsell, 2005; Rogers & Monsell, 1995). However, slower responding on congruent than neutral trials may underestimate the magnitude of task conflict. This is because the converging information provided by the colour and word dimensions of a congruent stimulus (e.g., *red* in red ink) may facilitate response selection (e.g., Roelofs, 2010), whereas such facilitation is absent for neutral stimuli. A positive congruent–neutral latency difference indicates that the response facilitation from congruent stimuli is insufficiently large to compensate for the effect of task conflict, so that

the net effect is slower responding on congruent than neutral trials. Thus, if response facilitation is present, the positive latency difference between congruent and neutral stimuli underestimates the magnitude of task conflict. Nevertheless, despite this possible underestimation, Experiments 1 and 2 provide clear evidence for task conflict in the τ parameter.

Steinhauser and Hübner (2009) used another estimate of task conflict—namely, the mean latency of incongruent and congruent trials minus that of neutral trials. By taking the mean of incongruent and congruent trials, facilitation from congruent stimuli is somewhat offset by interference from incongruent stimuli. However, this will provide a pure measure of task conflict only if the magnitude of interference equals that of facilitation. But interference is typically larger than facilitation relative to both neutral Xs and colour-unrelated words (e.g., Roelofs, 2003). Thus, it is likely that the mean of incongruent and congruent trials minus that of neutral trials will overestimate the magnitude of task conflict, because the estimate includes some of the response conflict from incongruent stimuli.

Steinhauser and Hübner (2009) used task mixing and switching to increase task conflict in a manual version of the colour–word Stroop task. Participants responded to the colour or word in constant-task blocks or in blocks of trials where tasks were mixed. In the constant-task blocks, no effects on τ were obtained, whereas the mixed-task blocks yielded effects in τ . The absence of an effect on τ in the constant-task blocks differs from what was observed in the present Experiments 1 and 2, where effects on τ were obtained in colour naming without task switching. The difference in effects between studies may be related to the difference in response modality: manual responding (Steinhauser & Hübner, 2009) versus vocal responding (present experiments). Evidence suggests that manual responding may reduce the magnitude of Stroop effects relative to vocal responding (e.g., Sugg & McDonald, 1994). Apparently, the conflict effects from vocal responding in the present Experiments 1 and 2 were sufficiently large to yield both response and

task conflict, whereas the conflict effects from manual responding in the constant-task blocks of Steinhauser and Hübner were not sufficiently large to yield task conflict.

Monsell, Taylor, and Murphy (2001) provided independent RT evidence that task conflict contributes to Stroop interference in single-task performance. They had participants vocally name the colour of colour-unrelated high- and low-frequency words, pseudowords, and unpronounceable letter strings (e.g., a series of Xs). Unlike what is the case in a standard Stroop experiment, each stimulus was presented only once. Colour naming RTs were longer for the words and pseudowords than for the unpronounceable letter strings. The amount of interference was independent of word frequency. These results suggest that words and pseudowords delayed colour naming because they activated the reading task set, whereas unpronounceable letter strings did not because they lacked word-like properties. Monsell et al. (2001) stated that “when a stimulus affords multiple responses, as with a color word, there may be two sources of interference with the performance of the weaker task, color naming. The first is competition at the level of whole task sets. If the stimulus contains word-like perceptual properties, this activates the whole task set of reading, and competition from this irrelevant task set reduces the efficiency with which color naming is performed. The second is competition from a specific response tendency, the word’s name, activated in spite of the intended suppression of the reading task set” (p. 149). The correspondence between the positive congruent–neutral difference in τ in single-task Stroop performance, on the one hand, and in mean RTs and τ in task switching, on the other hand, suggests that competition at the level of whole task sets is reflected in the τ parameter of the ex-Gaussian distribution.

Accounting for the link between tail effects and task conflict

The ex-Gaussian is an ad hoc distribution that may be used to capture the influence of experimental manipulations on RT distributions (e.g., Luce,

1986). Ideally, analyses of RT distributions proceed from quantitative models of processing that make explicit predictions about distributions. The diffusion model of Ratcliff and colleagues (e.g., Ratcliff & Smith, 2004) would be a good example. However, this model has not been applied to the Stroop task yet. Spieler et al. (2000) implemented their spatial integration account using a random walk model, which shares much in common with Ratcliff's diffusion model. In the model of Spieler et al. (2000), the evidence provided by a stimulus increases a counter with a certain probability on each time step. The rate of evidence accumulation is called the drift rate. A correct response is selected when the counter exceeds a threshold. The model successfully simulated the observed effects of Stroop condition on the ex-Gaussian parameters under the assumption that the mean probability of increasing the counter was reduced for incongruent stimuli, and its variability was increased for congruent trials. Spieler et al. admitted that this model only provides a post hoc explanation for their data. More importantly, the model is challenged by the present evidence that spatial integration is not the sole critical factor in inducing τ effects in Stroop task performance with vocal responding. Also, the model does not explain why task conflict is reflected in τ . In an evidence accumulation model, τ effects may be a result of a decreased drift rate (e.g., Spieler, 2001), which results in condition differences increasing over the distribution (as lower drift rate leads to an increased right tail). Perhaps, decreased drift rate is the result of task conflict. This possibility may be further examined in future research.

Currently, there exists no formal model that explains the observation by Aarts et al. (2009) and Steinhauser and Hübner (2009) that task conflict is reflected in τ . In the absence of such a formal model, Steinhauser and Hübner (2009) speculated about how task conflict may lead to τ effects. They reasoned that effects occur in the tail of an RT distribution (i.e., the τ parameter) when an experimental factor selectively changes the probability of slow responses or more strongly influences slow than fast responses. This invites the

interpretation that the presence of task conflict mainly influences slow responses. In agreement with this, the bivalency effect was only present in the slowest quantiles in the experiments of Steinhauser and Hübner. Steinhauser and Hübner (2009) discussed two possible explanations for this observation. First, the detection of task conflict may trigger a conflict resolution process, which prolongs the processing time and leads to long RTs. Second, slow responses may occur particularly when task preparation was insufficient or failed, which increases task conflict. Whether a formal model that implements these suggestions may fit the τ effects obtained by Aarts et al., by Steinhauser and Hübner (2009), and in the present experiments remains to be demonstrated.

Another possible account of the link between task conflict and τ was discussed by Schmiedek, Oberauer, Wilhelm, Suss, and Wittmann (2007), based on an examination of individual differences in the magnitude of the three ex-Gaussian parameters. They identified latent factors for each of the three ex-Gaussian parameters using structural equation modelling for a battery of choice reaction tasks. These factors had differential relations to criterion constructs, such as working memory and fluid intelligence. Individual differences in τ , but not in μ and σ , predicted individual differences in working-memory span and fluid intelligence. Tse, Balota, Yap, Duchek, and McCabe (2010) also observed that τ , as opposed to μ and σ , was uniquely related to working memory measures. Schmiedek et al. (2007) and Wilhelm and Oberauer (2006) hypothesized that the link between τ and working memory exists because how well stimulus-response mappings (i.e., task sets) are maintained determines the rate of evidence accumulation in a task. The effect of Stroop condition on τ would then reflect the greater difficulty of maintaining the mapping of colours onto responses on incongruent and congruent trials than on neutral trials. Presumably, this is because incongruent and congruent stimuli evoke the competing word reading task set, whereas neutral stimuli do not. Unsworth, Redick, Lakey, and Young (2010) also observed a relation between τ and measures of working memory capacity and fluid intelligence, which they

attributed to lapses in sustained attention (i.e., temporary loss of the task goal from working memory or brief moments of disengagement). Again, the effect of Stroop condition on τ may reflect the greater difficulty of reloading or reengaging the task goal of colour naming on incongruent and congruent trials than on neutral trials, because of the presence of task conflict.

As with the theoretical possibilities discussed by Steinhauser and Hübner (2009), the proposals of Schmiedek et al. (2007) and Unsworth et al. (2010) remain speculative and need to be further examined in future research and formal modelling efforts. To constrain such modelling, it is important to examine under exactly what experimental conditions effects in τ occur in Stroop task performance, as was done by Spieler et al. (2000), Aarts et al. (2009), and Steinhauser and Hübner (2009), and in the present two experiments.

CONCLUSIONS

The present data show that spatial integration is not the sole crucial factor in inducing τ effects in Stroop task performance and may not have been the crucial factor in the seminal studies of Mewhort et al. (1992), Heathcote et al. (1991), and Spieler et al. (1996, 2000). Whereas the present data are compatible with an association of τ effects with task conflict, the mechanism underlying the association remains unclear and should be further examined in future research.

Original manuscript received 5 November 2010

Accepted revision received 26 April 2011

First published online 21 September 2011

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