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## Interactions between stimulus-stimulus congruence and stimulus-response compatibility

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**Abstract** According to a central claim of Kornblum's dimensional-overlap model, response-related processes do not start before stimulus-related processes have been completed, which implies an additive relationship between effects of stimulus-stimulus congruence and stimulus-response compatibility. Three experiments were conducted to test this prediction. In Exp. 1, additive effects of color-word congruence (Stroop effect) and irrelevant spatial S-R compatibility (Simon effect) were in fact obtained. However, interactions between congruence and compatibility were observed in Exp. 2, where flanker-target congruence was varied, and in Exp. 3, where inter-level congruence of multi-level letters was manipulated. It is argued that these findings are inconsistent with the seriality assumption of the dimensional-overlap model, but that they support models claiming a temporal overlap of stimulus and response processing instead.

### Introduction

Many tasks investigating human perceptual or motor performance are based on the use of conflicting information. Most prominently, attentional processes are commonly probed by presenting stimuli made up of several features that, in different trials, may call for the same or for opposing responses. If the subject is instructed to attend (and to respond) to only one critical stimulus feature but to ignore the others, effects of manipulating noncritical features can be taken as a measure of attentional failure. A classical example is the Stroop effect (Stroop, 1935). In the Stroop task, subjects respond to the ink color of color words. Typi-

cally, subjects are much better in terms of reaction times (RTs) and accuracy if the word's meaning is congruent with its color (e.g., the word "RED" in red ink) than if color and meaning are incongruent (e.g., the word "RED" in blue ink). Thus, the meaning of the word is encoded and processed even though it is completely irrelevant to the task.

The Stroop task with its special integrality of relevant and irrelevant stimulus aspects is not the only task to demonstrate attentional limitations. Another frequently used task was developed by Eriksen and Eriksen (1974). In the simplest version, the subject is presented with a central target, say the letter *H* or *S*, and responds by pressing the assigned response key. The target is flanked by either congruent flankers, such as with the string *HHHHH*, or with incongruent flankers, such as in *SSHSS*. Typically, subjects perform much better with congruent than with incongruent flankers, thus showing that they are unable to prevent attending to letters in close proximity to the target.

A third, similar task introduced by Navon (1977) has been used to investigate the ability to attend to one level of a stimulus but to ignore others. Typically, subjects are presented with a large (global) letter made up of small (local) letters and are instructed to respond only to the former or to the latter. The critical manipulation is that the letter on the relevant and the irrelevant level are either congruent (e.g., an *H* made up of *H*s) or incongruent (e.g., an *H* made up of *S*s). Usually, subjects do much better with congruence than with incongruence between relevant- and irrelevant-level information, especially if the local level is relevant. Thus, subjects seem to have difficulties ignoring information from an irrelevant level of an attended stimulus structure.

All these examples have in common that congruence among different aspects of a stimulus or stimulus compound allows for better performance than incongruence. The present study investigates whether and, if so, how effects of congruence between stimulus features are related to effects of compatibility between stimulus

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and response features. It is well known that similarity between stimuli and responses leads to improved performance, even if the similarity relation involves irrelevant features. For example, the spatial correspondence between stimulus and response (e.g., left-hand response to left-side stimulus) permits faster responding than noncorrespondence (e.g., left-hand response to right-side stimulus), whether stimulus position is the relevant stimulus feature (Fitts & Seeger, 1953) or not (Simon & Small, 1969). The former kind of effect has become known as the *spatial compatibility effect proper*, while the latter is often called the *Simon effect*.

Consistent with the widespread belief that stimulus-response (S-R) compatibility affects response selection while stimulus-stimulus (S-S) congruence influences a preceding stage (e.g., stimulus identification), most studies on the relationship between these two factors found additive effects (Kornblum, 1994; Simon & Berbaum, 1990; Simon, Paulin, Overmyer, & Berbaum, 1985; Stoffels & Van der Molen, 1988).<sup>1</sup> Along this line, the most comprehensive model of compatibility phenomena to date, suggested by Kornblum (1992, 1994; Kornblum et al., 1990), provides two different sites for congruence and compatibility effects: Conflicts arising from S-S incongruence occur and are solved at a stimulus-identification stage before any stimulus information is passed on to the succeeding response-production stage. In contrast, S-R compatibility effects are located at the response-production stage, where responses can be activated via two routes: a controlled one and an automatic one. The controlled route serves to translate the relevant stimulus code into the correct response code. This task is facilitated if both codes are similar, as with correspondence in a standard spatial compatibility task, or if a simple translation rule can be applied. The automatic route comes into play only if the stimulus shares some feature with one of the responses in the response set, which in this case is automatically activated to some degree. Because automatic activation takes place independent of the task-relevance of the respective stimulus feature, the model provides an explanation for effects of relevant as well as irrelevant S-R compatibility, such as the Simon effect.

<sup>1</sup> In trying to avoid any confusion between, and confounding of, (S-S) congruence and (S-R) correspondence (or compatibility), I only am considering studies combining pure S-S congruence (i.e., feature overlap between stimulus elements independent of any stimulus-response overlap) with pure S-R compatibility (i.e., feature overlap between stimulus and response independent of any stimulus-stimulus overlap). For the same reason, I use the terms *congruence* and *compatibility* (or correspondence) exclusively for referring to and describing S-S and S-R relationships, respectively, although other authors sometimes use one or the other term in referring to both kinds of relationship (e.g., Hasbroucq & Guiard, 1991; Kornblum, Hasbroucq, & Osman, 1990). Moreover, it should be emphasized that both terms are used in their descriptive, not explanatory, sense.

Only recently, two virtually identical models have been developed independently by Hommel (1993, 1994a, 1994b, 1995a) and by De Jong, Liang, and Lauber (1994) that share many features with the dimensional-overlap model, including its dual-route notion. Nevertheless, they make different predictions about the relationship between congruence and compatibility effects, and one of these was tested in the present study. Due to its strict seriality of stimulus identification and response-selection processes, the dimensional-overlap model predicts that congruity and compatibility effects should always combine additively (Kornblum, 1994). However, the seriality assumption is not shared by Hommel's temporal-overlap model or the dual-route conception of De Jong et al. Instead, these models claim that different features of a stimulus may be transmitted to response stages at different points in time, hence asynchronously (Miller, 1988), so that stimulus processing and response processing may overlap. From this follows that, under circumstances to be described below, congruence and compatibility effects should not add up but interact. Consequently, if an interaction could be demonstrated, there would be evidence for a temporal overlap between stimulus identification and response selection, which again would require major modifications of several existing compatibility models.

According to the temporal-overlap model of Hommel (1993), congruence and compatibility are likely to interact if the response-overlapping stimulus feature is task-irrelevant, as is the stimulus position in a Simon task. While codes of task-relevant stimulus information may be actively maintained (Hommel, 1996), irrelevant codes are assumed to decay rapidly (cf. Simon, Acosta, Mewaldt, & Speidel, 1976). As a consequence, their impact on response selection, hence the compatibility effect, should be smaller the later in time response selection takes place. Because the timepoint of response selection is determined by the duration of processing the relevant stimulus feature, any prolongation of this process should result in a decreased compatibility effect. Indeed, prolongations by hampering sensory coding (Hommel, 1993) or making identification more difficult (Hommel, 1994a, 1994b) have been shown to produce diminished compatibility effects and, hence, interactions between compatibility and stimulus-related factors. From the model, there is little reason to assume that S-S congruence has a different effect. On the contrary, congruence and irrelevant S-R compatibility should interact because incongruent stimuli are processed slower than congruent stimuli, this allowing for a more pronounced decay of spatial codes in the former than the latter case.

However, interactions need "operating space," as Sanders (1980) put it. That is, congruence-by-compatibility interactions can only be expected to show up if the factors involved produce substantial effects of their own. In fact, up to now spatial compatibility has only been found to interact with stimulus-related factors if

the latter produced main effects of at least 100 ms, while studies with smaller main effects were less successful (see Hommel, in press, for an overview). Therefore, the fact that most previous studies showed additive effects of congruence and compatibility does not necessarily invalidate the opposing prediction from the temporal-overlap model. As pointed out below, these studies often produced very small main effects of congruence, which might have worked against an interaction. Moreover, only mean RTs, but no RT distribution analyses, are available from these studies. Yet, as Grice, Boroughs, and Canham (1984) as well as De Jong et al. (1994) have shown, distribution analyses can be used to index the timecourse of response conflicts and, thus, to reveal effects that are bound to a certain part of a distribution only. That is, even with small main effects and in the absence of a statistically significant interaction between congruence and compatibility in mean RTs, decay effects and related interactions can be expected to show up in a more meticulous analysis of the data. Consequently, distribution analyses were carried out for all three experiments of the present study.

## Experiment 1

In a first attempt to investigate the relationship between congruence and compatibility effects more closely, a manual Stroop task was combined with a Simon task. Such a task combination was already run by Simon et al. (1985: Exp. 2), Simon and Berbaum (1990: ink-color group), and Kornblum (1994: Lag = 0). (Results of a related task of De Jong et al., 1994, will be discussed below.) The outcome was always the same: no interaction, but additivity of Stroop and Simon effects, hence of congruence and compatibility.

However, the congruence main effect was very small in the studies of Simon and colleagues (Simon et al., 1985; Simon & Berbaum, 1990), 27 ms and 30 ms, respectively, and even absent in the Kornblum (1994) experiment. Conversely, the compatibility effect was insignificant in all but the Kornblum study (11 ms, 11 ms, and 36 ms, respectively). As argued above, these were anything but favorable preconditions for obtaining a congruence by compatibility interaction. It would be more convincing to demonstrate such an interaction or the lack of it in the presence of substantial main effects of both factors involved. Moreover, especially small main effects call for a meticulous analysis of their temporal dynamics, which is, however, not available from the previous studies. Therefore, apart from hoping to find substantial main effects for both congruence and compatibility in mean RTs, the major result from the present experiment was expected from distribution analyses.

In the present task, subjects pressed a left or right key in response to the color of stimulus words. The

meaning of these words did or did not match their color, thus yielding conditions with S-S congruence and incongruence, respectively. S-R compatibility was manipulated by presenting the stimuli randomly on the left or right side, thus yielding spatially compatible and incompatible conditions. As in the Simon and Berbaum (1990) study, stimulus duration was also varied. The reason was that in the original study a three-way interaction of congruence, compatibility, and stimulus duration had occurred, albeit of borderline significance. Though Simon and Berbaum did not devote much attention to this effect, it could indicate a dependence of congruence by compatibility interactions on moderating conditions. This made it worthwhile to check whether it was replicable.

## Method

*Subjects.* Twenty-four adult volunteers served as paid subjects in single sessions of about 30 min. They had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

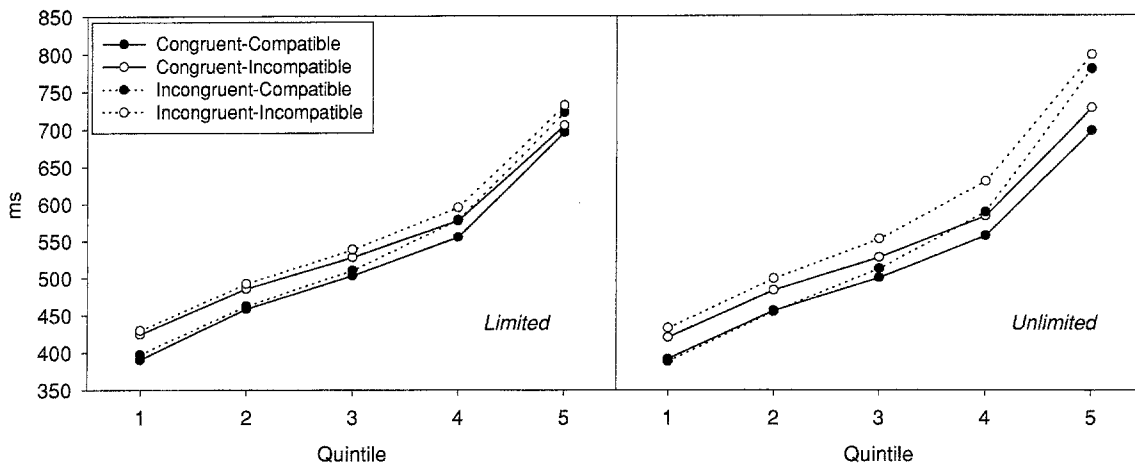
*Apparatus and stimuli.* Stimulus presentation and data collection were controlled by a Hewlett Packard Vectra QS20 computer, interfaced to an Eizo Flexscan 9070S monitor. Subjects responded by pressing the left- or right-hand shift key of the computer keyboard with the corresponding index finger. A white asterisk served as central fixation mark. The German words "Blau" and "Grün" ("blue" and "green") served as stimuli, each presented randomly in blue or green color (standard CGA colors). From a viewing distance of about 60 cm, the words measured about  $1.2^\circ \times 0.6^\circ$ , and they appeared adjacent to the left or right of the fixation point. A row of four yellow Xs was used as a stimulus mask.

*Procedure and design.* The experiment took place in a dimly lit room. After an intertrial interval of 1,500 ms, each trial started with a 1,000-ms presentation of the fixation mark, followed by a blank interval of 250 ms. Next, the stimulus appeared randomly on the left or right. In the limited-duration condition, the stimulus was masked after 100 ms. In the unlimited-duration condition, it remained visible until the response was made, but no longer than 1,500 ms. Subjects responded to the color of the stimulus by pressing the left or right key. In the case of an incorrect keypress or response omission (RT > 1,500 ms), the trial was recorded and then repeated at some random position in the remainder of the block.

Half of the subjects responded to the blue and green color with the left and right key, respectively, while the other half received the opposite mapping. A session was divided into two sections, according to the two stimulus durations (limited vs. unlimited). Section order was balanced across subjects. In each section, there were 2 warming-up blocks and 20 experimental blocks. Each block was composed of eight randomly mixed trials, whose type resulted from the factorial combination of stimulus color (or response location), stimulus location (left or right), and color-word congruence (i.e., "Blau" in blue and "Grün" in green vs. "Blau" in green and "Grün" in blue).

## Results

Trials including response omissions (< 0.2%) were discarded from analysis. Percentages of errors (PEs) were computed for each factorial combination of



**Fig. 1** Exp. 1: Means of individual reaction time quintiles (see Results section for calculation procedure) for limited (left panel) and unlimited (right panel) stimulus duration, as a function of color-word congruence (*straight lines*) or incongruence (*dotted lines*) and spatial S-R compatibility

Congruence (of color and word), Compatibility (of stimulus and response), and Stimulus Duration (limited vs. unlimited), and were analyzed by using a  $2 \times 2 \times 2$  ANOVA with repeated measures on all variables. RTs from correct trials were Vincentized according to the procedure suggested by Ratcliff (1979), that is, individual mean RT quintiles were calculated for the 1st to 5th fifth of the rank-ordered raw data for each combination of congruence, compatibility, and duration (see Fig. 1 for an overview). The obtained quintiles served as input into a  $2 \times 2 \times 2 \times 5$  (quintile) ANOVA. As long as the quintile factor is not involved in an interaction, all statistical effects of such an analysis are identical to that of a standard ANOVA of conventionally computed means, which are given in Table 1 together with mean PEs.

The RT analysis yielded highly significant main effects of congruence,  $F(1, 23) = 22.85$ ,  $p < .001$ , compatibility,  $F(1, 23) = 48.42$ ,  $p < .001$ , and quintile,  $F(4, 92) = 316.28$ ,  $p < .001$ . The three significant interactions all involved the quintile factor: Congruence  $\times$  Quintile,  $F(4, 92) = 14.96$ ,  $p < .001$ , Compatibility  $\times$  Quintile,  $F(4, 92) = 2.69$ ,  $p < .05$ , and Duration  $\times$  Congruence  $\times$  Quintile,  $F(4, 92) = 3.85$ ,  $p < .01$ . As Fig. 1 shows, the compatibility effect decreases with increasing RT level (or quintile), while the congruence effect increases, and the more so with unlimited than with limited stimulus duration. As with RTs, the PE analysis produced significant main effects of congruence,  $F(1, 23) = 7.44$ ,  $p < .05$ , and of compatibility,  $F(1, 23) = 6.32$ ,  $p < .05$ , and an additional main effect of duration,  $F(1, 23) = 15.36$ ,  $p < .001$ .

## Discussion

The presence of reliable main effects of both congruence and compatibility suggests that the present experi-

**Table 1** Mean reaction time (in ms) and percentage of errors (in parentheses) in Exp. 1 as a function of stimulus duration (limited vs. unlimited), stimulus-stimulus (color-word) congruence, and stimulus-response compatibility. Reaction-time compatibility-effect sizes ( $\Delta$ ) in the right-hand column

Stimulus-stimulus	Stimulus-response		$\Delta$
	Compatible	Incompatible	
	Limited		
Congruent	521 (6.3)	545 (8.7)	24
Incongruent	535 (7.8)	558 (11.2)	23
	Unlimited		
Congruent	504 (2.0)	529 (5.6)	25
Incongruent	526 (3.2)	560 (6.8)	34

ment provides better preconditions for an interaction between congruence and compatibility to occur than the previous studies did. However, though clearly significant, both effects are still small (20 ms and 27 ms, respectively), which raises doubts about whether they are potent enough to produce a significant interaction (Hommel, 1993). Indeed, there is no indication of a congruence-by-compatibility interaction nor of a three-way interaction involving stimulus duration. In other words, the present Exp. 1 fully replicates the major outcome of the studies of Simon et al. (1985), Simon and Berbaum (1990), and Kornblum (1994), at least as far as mean RTs are concerned. This result is consistent with the seriality assumption of Kornblum's dimensional-overlap model, but not with the temporal-overlap hypothesis of Hommel's (1993).

However, the picture changes somewhat if the RT distributions are considered. Two observations are important here. First, the size of both the congruence and the compatibility effect clearly depends on relative response speed. As far as compatibility is involved, this is exactly what the temporal-overlap model predicts and what has been repeatedly obtained in Simon tasks (see Hommel, in press, and Lu, in press, for an overview). Because the spatial code's activation level decreases

over time, fast responses should be affected more by spatial correspondence or noncorrespondence than slow responses.

As far as congruence is involved, the dependence on relative response speed suggests some role of a horse race between color and word in producing the Stroop effect. If color is translated into the response before the word's meaning is encoded, congruence or incongruence cannot affect RT. These cases would be represented by the lower quintiles, which in fact are associated with the smallest congruence effects. The three-way interaction involving stimulus duration fits well into this context. As masking is likely to hamper word identification more than color encoding, the word's meaning would often be determined later (or not at all) under limited rather than under unlimited exposure time. As a consequence, congruence effects are rather small, even with slow responses, if stimulus duration is limited.

A horse-race interpretation of the positive correlation between congruence effects and response speed is in good agreement with findings from studies using stimulus-onset asynchrony (SOA). For instance, with button-press responses to word color, Sugg and McDonald (1994) found larger congruence effects if the word preceded the color than vice versa. This fits with the present results insofar as delaying the word should reduce the word's chances to win the race against color and should thus produce a diminished congruence effect, just as a mask does. Thus, converging evidence from SOA and distribution analyses suggests that temporal factors are likely to determine the actual pattern of (at least the S-S congruence component of) Stroop effects as well as of Simon effects, even though a full-fledged model of the Stroop effect certainly requires more complex assumptions than a simple horse-race model provides (e.g., MacLeod, 1991; Sugg & McDonald, 1994).

The second important finding from the distribution analysis concerns the relationship between the interaction of congruence and quintile on the one hand and that between compatibility and quintile on the other. Although the effects of both congruence and compatibility depend on relative response speed, these dependencies run in opposite directions. While congruence exhibits a positive correlation with the RT level, compatibility is negatively correlated. This means that the larger one of the two effects is, the smaller the other one is, which of course renders it difficult to obtain a reliable interaction between them.

Interestingly, the same pattern of results has been observed in the study of De Jong et al. (1994: Exp. 3), which was published after completion of the present experiment. De Jong et al. used a modified Stroop task, where subjects responded to the spatial location of the words "high" and "low" that appeared above or below, and to the left or right, of a reference point. While the compatibility effect was smaller than in the present experiment, the (position-word) congruence effect was

much larger (62 ms). Probably due to this latter fact, a clear interaction of congruence and compatibility was obtained even in mean RTs. More important, RT distribution was very similar to the present one: positive correlations with RT level for congruence effects and negative correlations for compatibility effects. Thus, the pattern of opposing temporal dynamics of congruence and compatibility effects seems to be a stable and replicable finding.

From this perspective, it is not too surprising to find that previous studies were afflicted by a kind of trade-off between congruence and compatibility main effects: presence of congruence effects but absence of compatibility effects in the studies of Simon et al. (1985) or Simon and Berbaum (1990), and vice versa with Kornblum (1994). In fact, given the temporal dynamics obtained, the size of congruence and compatibility main effects – as well as the relationship between them – can be expected to depend mainly on particularities of the respective sample and the task. All other things being equal, any quickening of the color-related response (due to whatever sample characteristic or task feature) should decrease the Stroop effect and increase the compatibility effect at the same time, while the opposite would be true for any delay. That is, depending on which end a theoretical distribution is caught, one or the other effect may dominate.

In summary, at first look the outcome of Exp. 1 is consistent with the prediction from Kornblum et al.'s (1990) dimensional-overlap model, namely that effects of S-S congruence and S-R compatibility should combine additively. At second look, however, the distributions reveal that additivity may only be obtained because the Stroop effect and the correspondence effect have different – and, in fact, opposing – temporal dynamics, so that large congruence effects go together with small compatibility effects, and vice versa. Therefore, one may doubt whether the present results provide strong support for the dimensional-overlap model as opposed to the temporal-overlap model of Hommel (1993) or similar models. On the contrary, it may well be that using S-S congruence effects with different temporal characteristics does actually produce an interaction with S-R compatibility, just as predicted by the temporal-overlap hypothesis.

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## Experiment 2

The major outcome of Exp. 1 is that, due to the specific pattern of its temporal dynamics, the Stroop effect might not represent the best choice in demonstrating interactions between congruence and compatibility. In Exp. 2 a second attempt was made, using the flanker task of Eriksen and Eriksen (1974) that presented a to-be-responded-to central target stimulus among congruent or incongruent flankers.

Stoffels and Van der Molen (1988, Exp. 1) were the first to combine such a task with a compatibility task by presenting an irrelevant response-corresponding or noncorresponding tone together with the centrally appearing stimulus string. As with the Stroop studies, the result suggested additivity, hence no interaction of flanker-target congruence and tone-response compatibility. However, while the effect of congruence was substantial (56 ms), the compatibility effect was very small (14 ms). Thus, in the absence of a distribution analysis, it would be premature to exclude the possibility that this effect was simply too weak to be statistically modified by congruence.

In the present Exp. 2, it was attempted to maximize compatibility effects by presenting the whole stimulus string, rather than an irrelevant tone only, on the left or right side. That is, one group of subjects (the *horizontal* group) was presented with lateralized strings consisting of one letter target with two congruent or incongruent flankers on either side. However, there is one potential problem with using horizontally oriented letter strings in a left-right compatibility task. From flanker studies it is known that the impact of flanker-target congruence depends not only on the distance between flanker and target, but also on whether the critical flanker appears on the left or right side of the target. Left-side flankers produce larger effects than right-side flankers (Harms & Bundesen, 1983; Hell, 1987). Interestingly, this left-side bias only occurs with letters, not with symbols, and it tends to turn into a right-side bias with mirror-inverted letter material, suggesting that it reflects an automatic reading (or attentional scanning) tendency induced by word-like stimulus structures (Hommel, 1995b). Unfortunately, the presence of such a bias or tendency might complicate the interpretation of congruence-by-compatibility interactions (or their absence) in unpredictable ways, so I decided to run a second version of the flanker task that can be assumed to minimize scanning-related problems. Accordingly, a second group of subjects (the *vertical* group) was also presented with target-flanker strings on the left or right side, but here the stimulus string was vertically oriented, so that the flankers were located above and below the target letter.

There is, indeed, some reason to expect the Eriksen task to provide better preconditions for revealing congruence-compatibility interactions than the Stroop task. As Grice and Gwynne's (1985) distribution analyses have shown, the flanker-target congruence effect follows an inverted U-shaped function of relative RT level. That is, the effect is small – but not absent – with fast responses, large with intermediate RT levels, and virtually absent with very slow responses. Thus, although the flanker-target effect can be assumed to contribute its own dynamics to distribution analyses just as the Stroop effect does, the timecourse of the flanker effect does not seem to be a mirror-inverted copy of that of S-R compatibility, as in the case of the

Stroop effect. Consequently, I expected that the parts of the RT distribution where both reliable congruence and compatibility effects can be found would be larger than in Exp. 1, this providing a somewhat better basis for statistical interactions.

## Method

*Subjects.* Thirty-two adult volunteers served as paid subjects in single sessions of about 15 min. They fulfilled the same criteria as the subjects in Exp. 1. Sixteen subjects were randomly assigned to each of the two stimulus-orientation conditions.

*Apparatus and stimuli.* The apparatus was the same as in Exp. 1. In the horizontal group, subjects faced a white field of  $5.8^\circ \times 2.0^\circ$  in which the black stimuli appeared. A fixation asterisk was presented at field center and the target stimulus, the uppercase letter *H* or *S* was presented, 0.6 to the left or right of the fixation mark. Each target stimulus was flanked by four letters, two on either side. These were either congruent (i.e., identical to the target) or incongruent (i.e., identical to the alternative target). Letters measured  $0.3^\circ \times 0.4^\circ$ , so that the whole five-letter stimulus string extended over  $1.5^\circ \times 0.4^\circ$ . In the vertical group, conditions were the same except that the white field measured  $2.7^\circ \times 2.9^\circ$ , a small horizontal line was used as fixation mark, and the flankers appeared above and below the target, so that the stimulus string measured  $0.3^\circ \times 2.0^\circ$ .

*Procedure and design.* The procedure was identical to that in Exp. 1, except that the intertrial interval was 2,000 ms and stimulus duration was always unlimited. The design was also analogous to Exp. 1, but there was no second section.

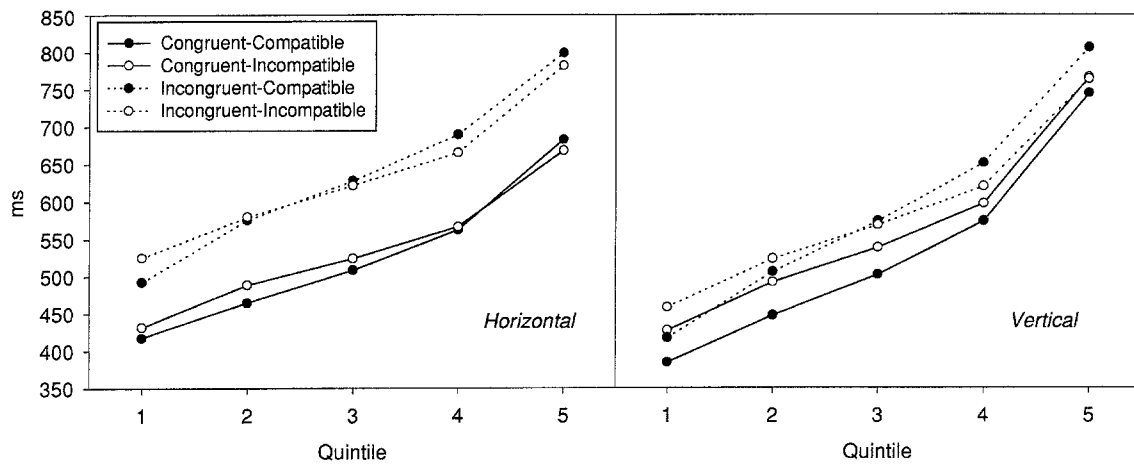
## Results

After the exclusion of trials with response omissions ( $< 0.1\%$ ), mean PEs and, analogous to Exp. 1, RT quintiles were calculated for each factorial combination of congruence (of flanker and target) and compatibility. (See Table 2 for RT and PE means.)

In a  $2 \times 2 \times 2 \times 5$  ANOVA of the RTs with Stimulus Orientation (horizontal or vertical) as between-subjects variable and Congruence, Compatibility, and Quintile as within-subjects factors, the main effects of congruence,  $F(1, 30) = 379.10$ ,  $p < .001$ , and quintile,

**Table 2** Mean reaction time (in ms) and percentage of errors (in parentheses) in Exp. 2 as a function of stimulus-stimulus (flanker-target) congruence and stimulus-response compatibility. Reaction-time compatibility-effect sizes ( $\Delta$ ) in the right-hand column

Stimulus-stimulus	Stimulus-response		
	Compatible	Incompatible	$\Delta$
	Horizontal		
Congruent	528 (2.3)	536 (4.3)	8
Incongruent	637 (9.6)	635 (9.8)	-2
	Vertical		
Congruent	495 (3.2)	522 (2.6)	27
Incongruent	543 (4.5)	540 (5.2)	-3



**Fig. 2** Exp. 2: Means of individual reaction time quintiles for horizontal (left panel) and vertical (right panel) stimulus orientation, as a function of flanker-target congruence (*straight lines*) or incongruence (*dotted lines*) and spatial S-R compatibility

$F(4, 120) = 243.94$ ,  $p < .001$ , were highly significant, while the effects of stimulus orientation and compatibility only approached the significance level ( $p < .06$  and  $p < .12$ , respectively). There were six significant interactions. The congruence effect is greater with horizontal than with vertical stimulus strings,  $F(1, 30) = 120.12$ ,  $p < .001$ . It also varies with quintile,  $F(4, 120) = 5.69$ ,  $p < .001$ , but, as indicated by a three-way interaction of congruence, quintile, and stimulus orientation,  $F(4, 120) = 3.33$ ,  $p < .05$ , more so with horizontal stimuli (mean effect sizes 84 ms, 101 ms, 108 ms, 113 ms, and 115 ms, for the first to fifth quintile, respectively) than with vertical stimuli (26 ms, 36 ms, 40 ms, 40 ms, and 23 ms). The effect of compatibility also varies as a function of quintile,  $F(4, 120) = 13.18$ ,  $p < .001$ , yet it not only decreases but even inverts at higher quintiles (see Fig. 2: mean effect sizes 28, 20, 9,  $-7$ , and  $-12$  ms, for the first to fifth quintile, respectively).

Most importantly, there is a clear interaction between congruence and compatibility,  $F(1, 30) = 11.98$ ,  $p < .005$ , which is modified by a three-way interaction with quintile,  $F(4, 120) = 4.45$ ,  $p < .005$ . As indicated by separate ANOVAs and as is obvious from Fig. 2, congruence and compatibility effects combine additively with the first and the last quintile, but interact underadditively in between. Positive compatibility effects occur across all five relative RT levels with congruence (24 ms, 30 ms, 23 ms, 12 ms, and 1 ms, respectively), but not with incongruence, where the compatibility effect is inverted in the slower responses (33, 9,  $-5$ ,  $-25$ , and  $-25$ , respectively). Planned comparisons (two-tailed) revealed significant positive compatibility effects for the first to third quintile with congruent stimuli, and for the first to second quintile with incongruent stimuli ( $p < .05$ , at least), while there was a negative effect for the fourth to fifth quintile with incongruent stimuli ( $p < .05$ , at least).

In the PE analysis with congruence and compatibility as within-subject and stimulus orientation as between-subject variables, the only significant effects obtained were a main effect of congruence,  $F(1, 30) = 24.46$ ,  $p < .001$ , and a Congruence  $\times$  Orientation interaction,  $F(1, 30) = 6.79$ ,  $p < .05$ . Although incongruent conditions produced more errors than congruent ones with both stimulus orientations, this effect was larger with horizontal (3.3% vs. 9.7%) than with vertical stimulus strings (2.9% vs. 4.9%).

## Discussion

The experiment produced several noteworthy results. First, as shown in Fig. 2, there is a substantial compatibility effect, but only with fast responses of up to about 550 ms. With slower RTs, it tends to invert into a negative compatibility effect; yet once inverted, the negativity does not increase any further (cf. quintile 4 and 5 in incongruent conditions). Such a pattern is clearly expected from the automatic-decay notion of temporal-overlap models.

Second, the congruence effect also depends on relative response speed. Consistent with the findings of Grice and Gwynne (1985), it starts at a relatively small scale and grows with increasing RT. The following decrease with very large RTs observed with vertical stimulus orientation also fits well with the inverted U-shaped pattern reported by Grice and Gwynne. Why the same pattern did not occur with horizontal orientation is not so clear, though it should be noted that even in this condition at least the growth rate of the congruence effect decreased with the quintile.

Third, and most important, there was a clear interaction of congruence and compatibility, which was further modified by quintile. Consistent with predictions from the temporal-overlap hypothesis, compatibility effects are diminished if the response is delayed due to incongruence. True, the overall pattern of the results does not indicate a direct interaction between processes having to do with (or leading to) congruence

and those producing compatibility effects. Actually, the general form of the Compatibility  $\times$  Quintile function is virtually identical in both congruence conditions, at least with horizontal stimulus orientation. The effect decreases continuously with increasing RT, starts to invert at an average RT level of about 600 ms, and remains slightly inverted to a possibly constant degree. The constancy of this shape suggests that, in agreement with the dimensional-overlap model of Kornblum (1992, 1994), congruence or incongruence may not have a direct impact on compatibility or response-related processes. However, inconsistent with this model, congruence does determine the size of compatibility effects in an indirect way, presumably by delaying the final response selection process and thus allowing for more progressed decay of automatic response code activation. This indicates that response-related processes are not delayed until stimulus-related conflicts are resolved, just as predicted by the temporal-overlap model.

Finally, it should be noted that stimulus orientation played a greater role than one might have expected from such a simple experimental manipulation. The finding that congruence effects are smaller with vertical than with horizontal orientation is rather easy to explain. With horizontal, but not with vertical, orientation half of the flankers are projected to less peripheral retinal locations than the target and thus enjoy a better retinal resolution, so they should be identified better and/or earlier than the target stimulus. However, although not statistically reliable, there was also some indication that the interaction between congruence and compatibility was less pronounced with horizontal than with vertical orientations (three-way interaction  $p < .12$ ; cf. Fig. 2). As already pointed out, one reason for this may be the presence of spatial biases or attentional scanning tendencies with letter stimuli, or interactions of these biases or tendencies with spatial S-R compatibility. At any rate, it is clear that interactions of congruence and compatibility can be successfully demonstrated in an Eriksen flanker task.

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### Experiment 3

Experiment 2 yielded first evidence that S-S congruence and S-R compatibility can be shown to interact, provided the temporal dynamics of the effects involved do not work against such an interaction. Experiment 3 was carried out to gather further, converging evidence. Compatibility was varied analogously to Exps. 1 and 2, while congruence was manipulated by using Navon-type letter compounds (Navon, 1977). These consist of one large (global) letter that is composed of a number of small (local) letters with global and local letters being the same (congruence) or different (incongruent). In different blocks, subjects responded either to

the global level of these stimulus compounds, ignoring the local one, or to the local level, ignoring the global one.

Such a task is known to produce two typical outcomes (Miller, 1981; Navon, 1977). First, there is *global precedence*, that is, it usually takes more time to identify the local than the global level. Second, between-level congruence produces asymmetric effects. While the speed of identifying the global level is not or is only mildly affected by the congruence between global and local letter(s), congruence has a strong impact on identifying the local letter(s). According to the temporal-overlap model, both congruence and level effects can be expected to modulate the impact of irrelevant spatial S-R compatibility. Insofar as local-letter identification takes longer than global identification, the decay of the irrelevant spatial code should be more pronounced under local than under global identification. Likewise, if identifying the relevant stimulus is delayed by between-level incongruence, spatial code decay should be more pronounced than with congruence. Thus, compatibility effects were expected to decrease from global to local identification and from between-level congruence to incongruence.

As with Exps. 1 and 2, Exp. 3 is not without its predecessor. In an earlier investigation of the global precedence phenomenon, Boer and Keuss (1982) presented their subjects with congruent and incongruent letter compounds appearing on the same or the opposite side of the response key. Although substantial congruence and compatibility effects were obtained, there was no significant interaction between the two. However, Boer and Keuss did not perform their analyses on RTs or RT distributions, but on slopes and intercepts of speed-accuracy functions obtained by employing a deadline method. As it is far from clear how these kinds of data can be translated into conventional RTs and their associated (and usually correlated) error rates or RT distributions, Boer and Keuss's null effect can hardly be counted as strong evidence against the predictions from the temporal-overlap model.

### Method

*Subjects.* Ten adult volunteers served as paid subjects in single sessions of about 25 min. They fulfilled the same criteria as the subjects in Exp. 1.

*Apparatus and stimuli.* Stimulus presentation and data collection were controlled by a Rhotron VME system, connected to an Atari SM124 monochrome monitor. Responses were made by pressing the right or left shift key of the computer keyboard with the corresponding index finger. Stimuli appeared in black on a white background. A small cross served as central fixation mark. The reaction stimuli were a large single *H* and *O* ( $1.2^\circ \times 2.3^\circ$ ), made up of a number of small *H*s or *O*s ( $0.2^\circ \times 0.3^\circ$  each), depending on the congruence condition. The number of local letters was virtually the same for the two global stimuli (17 and 16 for *H* and *O*, respectively). Reaction stimuli were centered  $1.5^\circ$  to the left or right of the fixation mark.



**Procedure and design.** The intertrial interval of 2,500 ms was followed by a 500-ms presentation of the fixation mark and a blank interval of 50 ms. The stimulus appeared randomly on the left or right side and stayed until response, but no longer than 2,000 ms. Subjects responded to the letter *H* or *O* by pressing the right or left key, respectively. The remaining procedure was as in Exp. 1. A session consisted of a global- and a local-identification section, in balanced order. Analogous to Exp. 1, each section consisted of 2 warm-up and 20 experimental 8-trial blocks (stimulus location  $\times$  response location  $\times$  between-level congruence).

## Results

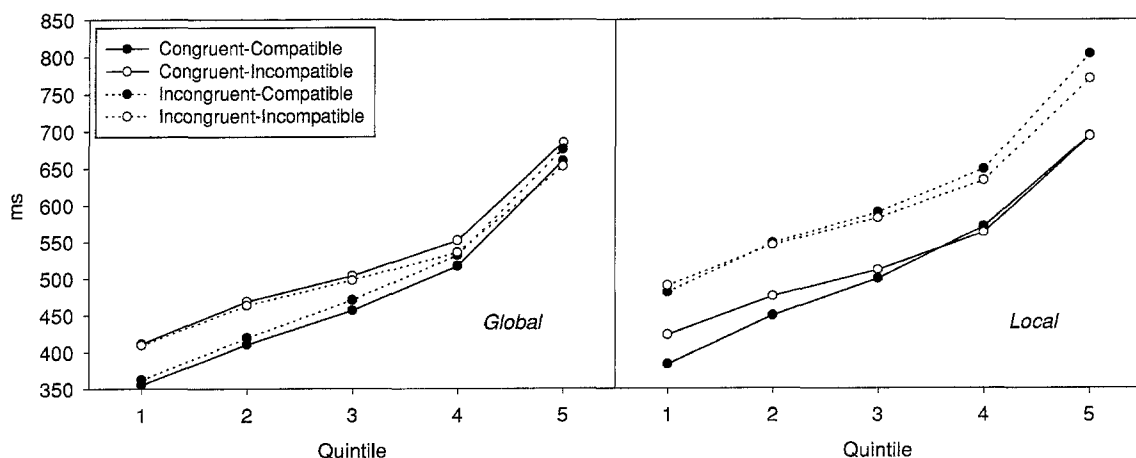
There were no response omissions and a total of five anticipations (i.e., RT < 150 ms) was excluded. Mean PEs and RT quintiles were calculated for each factorial combination of congruence (between stimulus levels), compatibility, and level of identification (see Table 3 for means).

In the  $2 \times 2 \times 2 \times 5$  ANOVA of RTs, all main effects were significant: congruence,  $F(1,9) = 96.45$ ,  $p < .001$ ,

**Table 3** Mean reaction time (in ms) and percentage of errors (in parentheses) in Exp. 3 as a function of level of identification (global vs. local), stimulus-stimulus (global-local) congruence, and stimulus-response compatibility. Reaction-time compatibility-effect sizes ( $\Delta$ ) in the right-hand column

Stimulus-stimulus	Stimulus-response		$\Delta$
	Compatible	Incompatible	
Global			
Congruent	480 (2.4)	525 (3.6)	44
Incongruent	492 (2.9)	512 (3.6)	20
Local			
Congruent	552 (0.5)	565 (2.1)	13
Incongruent	638 (4.1)	629 (2.8)	-9

**Fig. 3.** Exp. 3: Means of individual reaction time quintiles for global (left panel) and local (right panel) stimulus identification, as a function of between-level congruence (straight lines) or incongruence (dotted lines) and spatial S-R compatibility.



compatibility,  $F(1,9) = 5.33$ ,  $p < .05$ , level,  $F(1,9) = 58.85$ ,  $p < .001$ , and quintile,  $F(4,36) = 134.84$ ,  $p < .001$ . Responses were faster with congruence than with incongruence between levels (531 ms vs. 568 ms, respectively), to compatible than to incompatible stimuli (541 ms vs. 558 ms), and to global than to local levels (502 ms vs. 596 ms).

More important, compatibility interacted with congruence,  $F(1,9) = 10.18$ ,  $p < .05$ , with level,  $F(1,9) = 19.12$ ,  $p < .005$ , and with quintile,  $F(4,36) = 9.97$ ,  $p < .001$ . As shown in Fig. 3, the compatibility effect was greater for congruent than for incongruent conditions, greater for global- than for local-level responses, and greater for lower than for higher quintiles. Planned comparisons yielded significant positive compatibility effects ( $p < .05$ , at least) for the lower quintiles in all conditions (quintiles 1-4, 1-3, and 1-2, for global/congruence, global/incongruence, and local/congruence, respectively) except for the combination of local level and incongruence, which produced a negative effect with borderline significance instead ( $p < .07$ ).

Finally, there was an interaction of level and congruence,  $F(1,9) = 43.50$ ,  $p < .001$ , showing that congruence had an effect with local- but not with global-level responding (75 ms vs. 0 ms, respectively). A similar effect was found in the PE analysis,  $F(1,9) = 5.50$ ,  $p < .05$ , which, however, did not reveal any further effect.

## Discussion

As compared to the two preceding experiments, the preconditions for an interaction between congruence and compatibility to occur were now quite favorable. Not only were there substantial main effects of both congruence and compatibility, but the typical results of global-local tasks – global precedence and asymmetric between-level interference – were also clearly replicated. Therefore, it comes with little surprise that congruence and compatibility were again found to

interact. As expected from the temporal-overlap model, the size of the compatibility effect was greater with congruence than with incongruence and, as also predicted, greater with global than with local identification.

The Compatibility  $\times$  Quintile functions exhibit the usual decay pattern, that is, a negative correlation between effect size and relative RT level. Interestingly, the overall pattern is very much like that obtained in Exp. 2. After continuously decreasing to zero with increasing RT, the compatibility effect starts to invert at an average RT level of about 600 ms and then remains slightly inverted at a seemingly constant degree. One can only speculate why this pattern is more pronounced with incongruent than with congruent conditions. It may be that perceiving stimulus incongruence as such leads to the inhibition of the currently prevalent response or to the preparation of its alternative. In either case, both the facilitative effect of spatial correspondence and the interfering effect of noncorrespondence would be diminished. If such an effect added to the spontaneous decay of spatial codes over time, negative correspondence effects would be expected with incongruence, but not with congruence – just as obtained here. Interestingly, a very similar pattern occurred in the vertical group of Exp. 2 (see Fig. 2, right panel). Although reliable compatibility effects disappeared at about the same time under congruence and incongruence (i.e., with RT levels of about 550–600 ms), an inversion was only observed with incongruence, not with congruence.

A further interesting finding is that, in contrast to the flanker task in Exp. 2, there was no hint of a dependence of congruence effects on relative response speed. This finding fits the observation of Boer and Keuss (1982) and Grice, Canham, and Boroughs (1983) that between-level congruence affects the whole RT distribution, not only later parts. Importantly, this rules out explanations of global dominance phenomena in terms of differential temporal availability of global and local information (e.g., Navon, 1977). If responses based on local features are slow merely because it takes longer to compute local than global information, an overadditive relationship between congruence and quintile would be expected in the global condition. While global judgments should be unaffected by the congruence or incongruence of local information with fast responses—because local information is not yet available—an impact of the local level should become more likely the slower responding gets, hence the higher the quintile. As the results do not show this pattern, it seems rather that local information is available at about the same time as global information, but focusing attention on it or making use of it for response decisions is more difficult than attending or using global information (Miller, 1981; Stoffer, 1994), at least if spatial stimulus uncertainty is given (Grice et al., 1983).

## General discussion

Three experiments investigated the relationship between S-S congruence and S-R compatibility and, in particular, whether both effects do interact, as predicted by both the temporal-overlap model suggested by Hommel (1993) and the dual-route model of De Jong et al. (1994). Experiment 1 showed no evidence of an interaction of color-word congruence with irrelevant spatial S-R correspondence, that is, the Simon effect. However, the distribution analysis revealed that color-word congruence and the Simon effect have different temporal characteristics: While the former grows with increasing reaction time, the latter decreases. That is, the lack of an interaction may well be attributable to the mirror-image relationship between the two effects involved.

Experiment 2 combined the Simon task with Eriksen and Eriksen's (1974) flanker task. This time, a clear interaction was obtained as well as a three-way interaction with relative response speed. Fortunately, although the effect of flanker-target congruence also increased with response speed, it was substantial even with fast responses. Consequently, even fast responses were delayed by incongruence to a considerable degree, so that there was sufficient time for the hypothesized decay of spatial codes, which again were expected to produce a decreased compatibility effect. Indeed, the compatibility effect was greater with congruence than with incongruence, and even tended to invert after about 600 ms.

Experiment 3 replaced the flanker task with a global-local task introduced by Navon (1977). Again, there was a marked interaction of congruence and compatibility, with compatibility effects decreasing from between-level congruence to incongruence. Moreover, compatibility effects also decreased from global to local identification, exactly as predicted from the temporal-overlap model. As in Exp. 2, compatibility effects tended to invert after about 600 ms.

Taken together, these results are a major challenge for the dimensional-overlap model of Kornblum (1992, 1994). While the model's first version (Kornblum et al., 1990) focused on the distinction of a voluntary and an automatic route from stimulus to response codes – a distinction shared by Hommel's (1993) temporal-overlap model and De Jong et al.'s (1994) dual-route conception, the later version (Kornblum, 1992, 1994) includes the assumption of seriality between stimulus processing and response selection – which is not shared by the competing models. As Kornblum (1994) pointed out, the seriality assumption clearly predicts additive effects between S-S congruence and S-R compatibility – a prediction that is not consistent with the outcome of the present Exps. 2 and 3, or of the De Jong et al. (1994) study.

One way to save the seriality assumption of the dimensional-overlap model would be to allow for the

decay of spatial codes, but to restrict it to the stimulus domain. Assume that, say, in a flanker task all critical stimulus features – target, flanker, and string location – were encoded after stimulus onset. With congruence, all stimulus information would be transferred to the response stage immediately after letter identification. At this time, the spatial stimulus code is still strong and thus produces a pronounced activation of the corresponding response. With incongruence, however, stimulus identification or stimulus selection would be considerably prolonged, this leading to a pronounced decay of the spatial stimulus code. When stimulus information is then transmitted to the response stage, the spatial code would only weakly activate the corresponding response, or even not at all. The prediction would be that congruence and compatibility interact underadditively, just as found here.

Put this way, the seriality assumption may be upheld even in the face of the present data. However, there are several empirical problems with this story. First, decay effects can be shown to extend beyond the stimulus identification stage. In the study of Hommel (1995a), the effect of irrelevant spatial S-R compatibility was shown to decrease from a small to a large memory-set size. As set-size manipulations can be expected to affect post-identification processes, its interaction with compatibility can hardly be accounted for by decay restricted to a stimulus identification stage.

Second, in incompatible trials of the Simon task, the stimulus activates the spatially corresponding (hence, incorrect) response to a considerable degree, which is reflected in the lateralized readiness potential (LRP; De Jong et al., 1994; Sommer, Leuthold, & Hermanutz, 1993), a measure of hand-specific response activation, and sub-threshold motor activity in the wrong hand (Zachay, 1991). The finding that this activation is temporally stimulus-locked, not response-locked, implies that the point in time when irrelevant spatial information is transmitted to response stages does not depend on the duration of stimulus-identification processes and, thus, not on the point in time when the relevant information is transmitted.

Third, besides indicating the mere presence of automatic response activation, LRPs also mirror the hypothesized temporal dynamics of irrelevant spatial codes as inferred from distribution analyses (Eimer, Hommel, & Prinz, 1995). By presenting arrow stimuli in a situation that did not require immediate responding, Eimer (1995) confirmed that automatic, stimulus-induced response activation is stimulus-locked and independent from processing relevant information or from the need to select a response at this time. Interestingly, he also found that it peaks at about 300 ms after stimulus onset and then quickly decays until, after about 500 ms to 600 ms, the activity level returns to baseline. Although Eimer used a different task, these temporal characteristics are remarkably similar to the

temporal dynamics of the compatibility effect observed in Exps. 2 and 3.

These findings strongly suggest that irrelevant spatial stimulus information is not kept from entering response stages before stimulus identification or stimulus selection is completed. That is, prolonging identification or stimulus selection processes, as in the case of incongruence, does not affect the point in time when spatial information activates its corresponding response, but only the point in time when the correct response is selected. Therefore, it is response activation that decays, not (only) stimulus activation, as far as this distinction makes sense at all. (For opposing views, see Bekkering, 1995; Deubel & Schneider, 1996; Hommel, *in press*.) Accordingly, the outcome of the present study does not support the central claim of Kornblum's (1992, 1994) extended dimensional-overlap model that response-related processes can only begin after the completion of stimulus-related processes. Instead, the data provide evidence for the assumption of asynchronous transmission of stimulus information to response stages (Miller, 1988), as incorporated in Hommel's (1993) temporal-overlap model and the dual-route conception of De Jong et al. (1994).

In view of the interactions between S-S congruence and S-R compatibility demonstrated in this study, one may be tempted to conclude that congruence and compatibility effects must be located on the same processing stage and thus have a common origin. In fact, the additive factor method proposed by Sternberg (1969) would suggest exactly this conclusion. Moreover, there are several observations that have been taken to support the idea that congruence effects are produced by response-selection processes—especially in the case of Eriksen effects. For instance, interference from a perceptually incongruent flanker is drastically decreased, or even eliminated, if flanker and target are mapped onto the same response (Eriksen & Eriksen, 1974; Miller, 1991). This implies that it is not visual dissimilarity *per se* that is responsible for the flanker effect, but the fact that flanker and target imply alternative, conflicting responses. There is also evidence that more than one response alternative can be activated during a single trial. Both LRPs and electromyographic measurements show that in incongruent trials the flanker-related, and thus incorrect, response is prepared to a very large degree, even if eventually the correct response is emitted (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen, Coles, Morris, & O'Hara, 1985; Smid, Mulder, & Mulder, 1990). This suggests that response priming takes place before stimulus-related conflicts are resolved, which is consistent with Hommel's (1993) temporal-overlap view but inconsistent with the extended dimensional-overlap of Kornblum (1992, 1994).

However, although the available evidence clearly points to multiple response activation in incongruent trials, it does not require the assumption that

congruence effects are located at a response-related stage – at least, not all of the effect. As Smid, Lamain, Hogeboom, Mulder, & Mulder (1991) have pointed out, the studies that so far employed electrophysiological measures of the duration of stimulus-related processes (i.e., the so-called P3 component) uniformly revealed delays in that measure with incongruent flankers, which strongly suggests that at least part of the flanker effect is of perceptual origin. A similar conclusion can be drawn in the case of Navon's global-local task, where incongruence between different levels of the same stimulus has also been demonstrated to produce delays in the P3 (Ridderinkhof, 1993; Ridderinkhof & Van der Molen, 1995). Ironically, only the Stroop task that Kornblum (1994) used for his S-S congruence manipulation has failed to show identification-related effects (Duncan-Johnson & Kopell, 1981).

Altogether, these electrophysiological findings clearly imply that congruence manipulations – at least of the type employed in the present Exps. 2 and 3 – do produce RT effects by putting increased demands on perceptual or attentional processes, just as the extended dimensional-overlap model maintains. However, given the evidence that response priming does not wait for the completion of those processes, in no way does a perceptual location of congruence effects exclude the possibility that response conflict plays a causal role in their emergence. Actually, it is quite plausible that it is the very presence of response-related indecision (i.e., multiple response activation) that calls for additional perceptual or attentional work, the duration of which then contributes to RT. Yet, as Van der Heijden (1981) has emphasized, the evidence required to decide which of several competing responses should eventually be performed must be based on perceptual information and thus be acquired through perceptual processes. From this perspective, continuous transmission of information from stimulus to response stages may allow not only for stimulus-related responding with the least possible delay, but also for providing perceptual stages with feedback from response stages regarding the amount of evidence required for optimal performance.

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