Limits on the application of additive factors logic: Violations of stage robustness suggest a dual-process architecture to explain flanker effects on target processing

K. Richard Ridderinkhof [a,*], Maurits W. van der Molen [a], Theodore R. Bashore [b]

[a] *Department of Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands*
[b] *Department of Psychology, University of Northern Colorado, Greeley, CO 80639, USA*

Abstract

This study aimed to establish whether the logic of the AFM applies when multielement stimuli contain relevant and irrelevant elements. Target Size (TS) and symbolic S-R Compatibility (SRC) were manipulated in three reaction time (RT) experiments. TS and SRC are assumed in the AFM literature to selectively influence the independent stages of feature extraction and S-R translation, respectively. Experiment 1 showed that the effects of TS and SRC on RT were additive when the target was presented in isolation and this additive relation was not changed when the target was flanked by stimuli that contained no information relevant to the response. In Experiment 2, this additivity changed into a superadditive interaction when flankers signaled the same response as the target: The effect of SRC was larger when targets were small rather than large. The overall pattern of findings violated the AFM stage robustness criterion. Neither a discrete stage model nor a continuous flow conception account for the results. To explain flanker effects on target processing a dual-process architecture was formulated that assumes that perceptual information is processed along concurrently engaged routes: An attentive processing route and a direct priming route. Experiment 3 confirmed the prediction of the dual-process model that the relation between TS and SRC would be subadditive when flankers signal the response opposite to that designated by the target.

1. Introduction

Within the past 25 years there has been an explosion of research designed to characterize the structure and timing of mental processing, the impetus for which

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* E-mail: op_ridderinkhof@macmail.psy.uva.nl.

was provided in large measure by the work of Sternberg (1969). In his centennial tribute to the seminal work on mental chronometry by Donders (1868), Sternberg articulated a model of information processing and an experimental method to test that model. The model assumes that information is processed via a series of nonoverlapping stages in which the processing in one stage must be completed before its output is transmitted to the next stage. The experimental method, the additive factors method (AFM; Sternberg, 1969), has proven to be a powerful tool in the analysis of the structure of mental processing. Sternberg derived the method from a set of assumptions concerning this structure that are embodied in the stages of processing model. The model assumes that (a) the time consumed from the presentation of a stimulus to the execution of the response it signifies is the sum of the durations of a finite set of processing stages that are organized in a linear sequence and engaged in a serial fashion (i.e., a stage does not begin its processing until its predecessors have finished theirs), (b) the output from one stage to its successor is constant, and (c) the time necessary to complete processing in a given stage is independent of the duration of processing in any preceding stage. Violations of these assumptions undermine the reasoning on which the AFM is based. If its assumptions are met, the AFM can be used to infer the existence of new processing stages or the locus of an experimental effect in the chain of information processing.

These ends are made possible in principle by additional statistical assumptions that derive from the serial model: (a) If two experimental factors have additive effects on mean RT, they are assumed to have a selective influence on the rate of processing of different stages; and (b) if two experimental factors have interactive effects, they are thought to influence the same stage. Hence, the discovery of a new stage is based on additivity of factor effects, whereas identification of a previously unknown locus of a factor effect is revealed by its interaction with another factor thought to influence a particular stage of processing.

Evidence in support of the discrete transmission of information has been derived traditionally from studies in which the subject is presented a single stimulus, and the response it signifies is based on one invariant property of the stimulus (for reviews see Sanders, 1980, 1990). For example, in Sternberg's (1969) memory scanning task subjects are shown a sequence of digits, one at a time, and must indicate if each digit is or is not selected from a previously memorized set of digits. Under these circumstances, the single invariant property of the functional stimulus is its name.

However, when stimulus configurations include distractor elements that are sufficiently salient to engage the information processing system, their identity may interact with the processing of the target stimulus. For example, Eriksen and Schultz (1979) demonstrated that RT to a target letter (e.g., H) is prolonged when it is flanked by instances of another letter (e.g., SSHSS; an incongruent array) that signal the alternative response but are to be ignored, as compared to when the target letter is flanked by itself (e.g., HHHHH; a congruent array). This raises the fundamental issue examined in the present study: Does the processing of multielement stimulus arrays entail the engagement of processing mechanisms that violate the assumptions on which the discrete stage model rests?

Use of multielement stimuli, such as the letter arrays employed in the Eriksen task, raises important questions about how the stimulus is processed. Are the elements of the array processed as a unit or is each element processed separately? Advocates of stage models of processing have reasoned that the effects of flankers challenge the discrete stage model only if it is assumed that the multielement stimulus array is analyzed as a unitary whole with a perceptual code for the central target as the constant stage output of stimulus identification (e.g., Miller, 1988; Sanders, 1990). To explain the typical findings from the Eriksen task, Miller (1988) invoked a model that allows parallel processing without abandoning the requirement of discrete outputs from one stage to another. This model assumes that the target stimulus and flankers are encoded in parallel as separate units rather than as one integrated stimulus array, and each code is then transmitted via an S-R translation stage to a response preparation stage, where response activation can grow continuously. Thus, whereas the target evokes activation of the correct response, incongruent flankers evoke activation of the incorrect response so that close temporal activation of both response channels may take place, thereby impeding the execution of the correct response. This model has received partial support in a simulation study by Molenaar (1990), who showed that a neural network representation of Miller's model can, to some extent, simulate the typical flanker effect, although it generated slow errors rather than the fast incorrect responses observed in empirical studies (e.g., Coles et al., 1985).

As alternatives to the serial discrete stage conception, a variety of models have been offered that assume varying degrees of temporal overlap in the transmission process. At the theoretical extreme of the discrete stage model is the continuous flow model of Eriksen and Schultz (1979). These authors hypothesized that presentation of the critical stimulus initiates the gradual accumulation of information in the visual system about the properties of the stimulus array. As it accumulates, stimulus information is continuously transmitted to the response system where responses are likewise gradually primed or partially activated without waiting for stimulus processing to be completed. Thus, if an array contains conflicting information, both the correct and the incorrect responses are activated concurrently, a process that produces response competition or mutual inhibition of the activation of each response channel. This process slows response speed and increases the likelihood of an incorrect response. On the other hand, if an array contains congruent information the correct response channel will be activated earlier or to a greater extent so that the correct response is facilitated. Inferences drawn from the continuous flow model have gained support from psychophysiological evidence for continuous transmission of partial information (e.g., Gratton et al., 1988; Smid et al., 1991). Smid et al. (1991) argued that such findings challenge the general validity of the AFM when multielement stimulus displays are used. The goal of the present study was to investigate the applicability of additive factors logic to the case of flanker effects on target processing.

Sternberg (1969) advocated selection of experimental factors on the basis of a thorough review of the literature to identify those factors that produced consistent effects and, therefore, could be assumed to influence a single stage of processing.

Gopher and Sanders (1984) formulated a tool by which to make a reasoned selection of these experimental factors, as well as to infer stage structure from factor effects. This tool, the stage robustness criterion, requires that the relations among experimental factors, and hence the inferred stage structure, remains invariant when additional experimental factors are included in the design. If these relations are unchanged, then the logic of the AFM is affirmed and extended, and support is provided for the model of processing on which it is based. If these relations are changed, however, the serial stages of processing architecture may be challenged for the task at hand. In particular, as argued by Sternberg (1969), if any pair of factors influence no stage in common, then their effects should be additive not only when averaged over levels of a third factor, but also at each level of that third factor. Sternberg (1984) later demonstrated that this particular pattern of factor effects comprises an inconsistency that precludes an appropriate assignment of factors to an appropriate set of stages, thus rendering the AFM falsifiable. Gopher and Sanders' (1984) formulation of stage robustness further extends this property: The sign of low-order interactions (zero, positive, or negative) involving two or more factors should remain invariant in higher-order interaction involving the same factors with one or more others.

In additive factors studies, Target Quality and symbolic Stimulus-Response (S-R) Compatibility have consistently been observed to produce additive effects on RT (see reviews in Sanders, 1980, 1990). This additivity has led to the inference that variations in S-R Compatibility affect the duration of processing in the S-R translation stage, whereas variations in Target Quality selectively influence the rate of stimulus encoding in the feature extraction stage (Sanders, 1990). According to the stage robustness criterion, Target Quality and S-R Compatibility are expected to produce additive effects on choice RT invariantly whenever they appear in a factorial design.

Under conditions in which the target stimulus is one member of a multielement stimulus array and is flanked by stimulus elements designated as irrelevant, stage robustness may be violated. In the Eriksen task, the effects of both Target Quality and symbolic S-R Compatibility differ as a function of variations in the congruence of the stimulus array. Eriksen and Schultz (1979) manipulated Target Quality by varying the size of the target stimulus and observed that the prolongation of RT to small compared to large target stimuli was most pronounced when they were flanked by incongruent stimulus elements. Bashore and Osman (1987, cited in Bashore, 1990) observed that the increase in RT produced by the need to make an incompatible response was reduced when the target element was flanked by incongruent flankers. If congruence influences the effects of both Target Quality and S-R Compatibility, then, it is conceivable that the additive relation between the effects of Target Quality and S-R Compatibility can be transformed into an interaction when the target is accompanied by flankers. Such a transformation would indicate a violation of stage robustness.

In the present study, we attempted to develop conditions to test stage robustness in this sense. First, we used single-element stimuli as well as multielement stimuli composed of a target flanked by elements that provided no information

pertinent to the response signaled by the target (i.e., neutral flankers). Target Quality and S-R Compatibility were manipulated parametrically using this stimulus set. Based on the AFM literature, we expected these two factors to exert additive effects on RT. The use of multielement stimulus arrays permits a test of the prediction that variations in Target Quality and S-R Compatibility will also produce additive effects when the target stimulus is flanked by neutral flankers. Next, we flanked the target stimulus with stimuli that provided response-signifying information consistent with that given by the target and, once again, manipulated Target Quality and S-R Compatibility parametrically. The stage robustness citerion prescribes that variations in Target Quality and S-R Compatibility should again produce additive effects, whether stimuli contain neutral flankers or congruent flankers. Any departure from this additive pattern would comprise an inconsistency that violates the logical assumptions formulated by Sternberg (1969, 1984) and extended by Gopher and Sanders (1984), so that both the application of additive factors logic and the serial stage model may be disputed for this particular paradigm. Examination of the precise pattern of divergence may provide insight into both the limitations of the AFM and the nature of processing when multielement stimulus displays are being used.

2. Experiment 1

2.1. Method

Subjects

Ten undergraduate Psychology students at the University of Amsterdam participated in this experiment and received course credits for their participation. They all had normal or corrected-to-normal vision, and were right-handed according to self-report. No subject took part in more than one experiment reported in this study.

Design and procedure

The experimental design comprised 3 within-subject factors, each with 2 levels, that were varied blockwise: Flanker Presence (absent, neutral), Target Size (large, small), and S-R Compatibility (compatible, incompatible). Flanker Presence refers to the composition of the stimulus display. The imperative stimulus was an arrow that pointed to the left or right. In "flanker absent" blocks, the target arrow was presented in isolation; in "neutral flanker" blocks, target arrows were flanked by neutral elements (see Fig. 1). In the latter condition, the two flankers on both sides of the target arrow consisted of one diamond and one arrow pointing upward or downward, each covering 0.28° horizontally and vertically. All elements were separated from each other by 0.06°. The position of the diamond and the arrow within the two flanker locations to the left of the target varied randomly but equiprobably. Independent of this variation, the position of the diamond and the arrow to the right of the target also varied pseudorandomly. If the target arrow
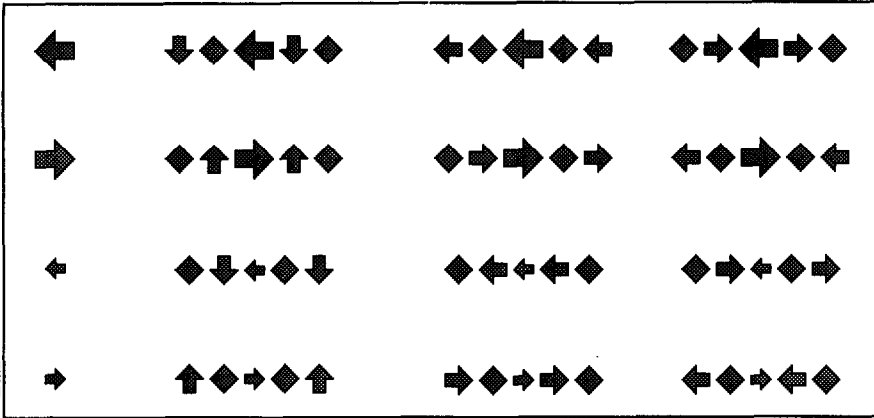
Fig. 1. The stimuli used in the present experiments. Central targets could be large (upper two rows) or small (lower two rows). Flankers are absent (left panel), neutral (left middle panel), congruent (right middle panel), or incongruent (right panel).

pointed to the left, the flanker arrows pointed downward; right-pointing target arrows were associated with upward-pointing flanker arrows. This correlation between the direction of the flanker arrows and the direction of the target arrow was established to minimize differences with the "congruent flanker" condition of Experiment 2.

Subjects were instructed to make their response choice on the basis of the direction in which the center arrow pointed, and to ignore flankers when they were present. Thus, the center arrow was defined as the target. Target quality was varied such that the target was either small or large; when present, flankers were of intermediate size. Hence, this manipulation is denoted as Target Size. The target arrow subtended 0.38° (both horizontally and vertically) in large-target conditions and 0.20° in small-target conditions. S-R compatibility was varied by requiring subjects to respond either by pressing the response key on the side corresponding to the direction indicated by the target arrow (a compatible response, e.g., target pointing left, left key press) or by pressing the key on the opposite side (an incompatible response; e.g., target pointing left, right key press).

The subjects were seated in a dimly lit, sound attenuated chamber, approximately 100 cm in front of a Macintosh Plus ED computer, with a high resolution (8.7 pixels/mm²) monitor, that was used for stimulus presentation and data acquisition. Subjects indicated their choices by pressing the left ("z") or right ("/") response key of the computer keyboard with their left or right index finger, respectively.

Each trial block began with the presentation of a rectangular contour presented at the center of the computer screen that remained visible throughout the block and served to fixate the eyes. The contour subtended visual angles of 3.03° and 0.77° in the horizontal and vertical planes. Presentation of the first stimulus array occurred 750 ms after the onset of the rectangular contour. Stimulus arrays were

shown in the center of the rectangle and remained on the screen until the subject responded (with a maximum duration of 1000 ms). The interval between the offset of the stimulus array in one trial and the onset of the array in the subsequent trial was fixed at 750 ms.

An experimental session included two phases, practice and test. Subjects first completed 8 practice blocks of 32 trials. During this practice phase, they were trained to balance speed with accuracy (i.e., to respond as quickly as possible to the target while keeping errors to a range of 5–10%). Each practice block represented one of the eight combinations of absent/neutral flankers, small/large targets, and compatible/incompatible S-R mappings. Thus, Target Size, S-R Compatibility, and Flanker Presence were fixed within a block of trials. Left- and right-pointing target arrows were varied pseudorandomly within a block of trials, such that equal numbers of each occurred within a block of trials. In the test phase, each subject completed 8 blocks of 122 trials structured as were the practice trials. The first 2 trials in each block were used as warm-ups and were excluded from data analysis. The order of trial blocks was determined randomly per subject. Blocks of trials were separated by a rest period of 1–2 minutes that was extended to 5 minutes following completion of the 4th block. The practice and test phases were separated by a 10 minute break.

2.2. Results and discussion

Mean RTs were submitted to a three-way analysis of variance with repeated measures on Flanker Presence (FP; absent, neutral), Target Size (TS; large, small), and S-R Compatibility (SRC; compatible, incompatible). All three factors exerted main effects on response latency (see Table 1): RTs were faster when targets were presented in isolation compared to when they were surrounded by flankers ($F(1,9) = 41.88$; $p < 0.001$); large targets were associated with faster responses than small targets ($F(1,9) = 71.67$; $p < 0.001$); and responses were slower when incompatible rather than compatible responses were required ($F(1,9) = 34.03$; $p < 0.001$). Flanker Presence influenced the Target Size effect such that RTs were prolonged to small targets compared to large targets by 19 ms when no flankers were present and by 39 ms when neutral flankers were present (TS × FP: $F(1,9) = 7.87$; $p = 0.021$). Flanker Presence did not influence the effect of S-R Compatibil-

Table 1
Mean RTs and error rates for the flanker presence, target size, and S-R compatibility factors in Experiment 1

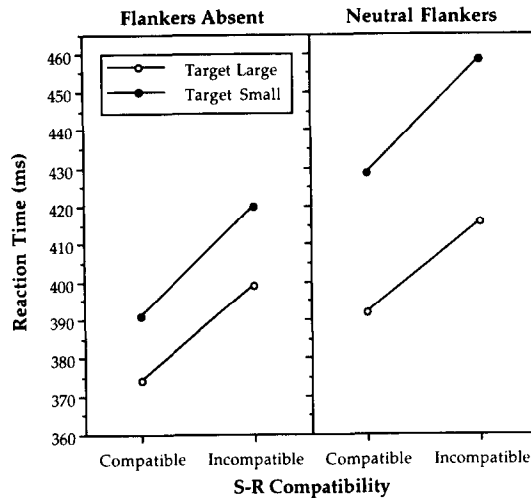| Factor	Flanker presence		Target size		S-R compatibility	
	Absent	Neutral	Large	Small	Comp.	Incomp.
RT	396	423	395	424	396	423
% err	5.3	5.5	5.3	5.5	5.2	5.6

Fig. 2. Effects on response latencies of S-R Compatibility and Target Size in flanker-absent (left panel) and neutral-flanker (right panel) conditions. Open markers represent large-target conditions whereas closed markers represent small-target conditions. S-R Compatibility conditions are on the abscissa.

ity (FP × SRC: $F(1,9) = 0.01$). Importantly, Target Size and S-R Compatibility did not interact in their effects on response speed (TS × SRC: $F(1,9) = 0.57$). Moreover, this pattern was not influenced by the presence or absence of flankers (TS × SRC × FP: $F(1,9) = 0.02$). As shown in Fig. 2, additivity between Target Size and S-R Compatibility obtained both when targets were presented by themselves and when they were flanked by neutral flankers.

Flanker Presence, Target Size, and S-R Compatibility failed to produce significant effects on error rate (see Table 1; FP: $F(1,9) = 0.29$; TS: $F(1,9) = 0.29$; SRC: $F(1,9) = 1.82$). None of the interactions reached significance. In general, however, increases in response speed were associated with increases in accuracy. Thus, explanations in terms of speed/accuracy trade-off can be ruled out.

According to the logic of the AFM, the additive relation between the effects of Target Size and S-R Compatibility implies that at least two stages of processing exist: What we infer to be stimulus identification (influenced by variations in Target Size) and response selection (influenced by variations in S-R Compatibility). The finding that the observed additivity was not modulated by the presence or absence of flankers suggests that the introduction of neutral flankers did not alter the stage structure mediating the response to these stimuli; hence, the stage robustness criterion was satisfied. The neutral flanker condition can then serve as a reference to the congruent flanker condition in Experiment 2. The only difference between these two conditions was in the direction of the flanker arrows relative to the direction of the target arrow. To meet the stage robustness criterion, additivity must also be maintained with congruent flankers.

3. Experiment 2

3.1. Method

Subjects

Eleven undergraduate Psychology students at the University of Amsterdam served as subjects in this experiment, receiving course credits for their participation. They all had normal or corrected-to-normal vision, and were right-handed according to self-report.

Design and procedure

The experimental apparatus was the same as that used in the first experiment; the stimuli differed only in that the nature of the flankers was changed. In Experiment 1, flankers were either absent or neutral; in the present experiment, the flankers were either neutral or congruent. Stimuli in the "neutral flanker" condition were identical to those used un Experiment 1. In the "congruent flanker" condition, the upward- or downward-pointing arrows were replaced by right- or left-pointing arrows, respectively. The flanker arrows always pointed in the same direction as the target arrow (see Fig. 1). In both flanker conditions, the direction of the flanker arrows was correlated with the direction of the target arrow. Hence, the only difference between the two conditions was in the direction of the flanker arrows relative to the direction of the target arrow: Same (in congruent flanker conditions) as opposed to orthogonal (in neutral flanker conditions).

3.2. Results and Discussion

Mean RTs were submitted to a three-way analysis of variance with repeated measures on Flanker Congruence (FC; neutral, congruent), Target Size (large, small), and S-R Compatibility (compatible, incompatible). All three factors exerted main effects on response latency (see Table 2): RTs were faster when targets were surrounded by congruent compared to neutral flankers ($F(1,10) = 61.67$; $p < 0.001$); large targets were associated with faster responses than small targets ($F(1,10) = 98.72$; $p < 0.001$); and RTs were slower when the S-R mapping assignment was incompatible rather than when it was compatible ($F(1,10) = 114.80$; $p < 0.001$). Flanker Congruence influenced the effect of Target Size such that RTs to small

Table 2
Mean RTs and error rates for the flanker congruence, target size, and S-R compatibility factors in Experiment 2

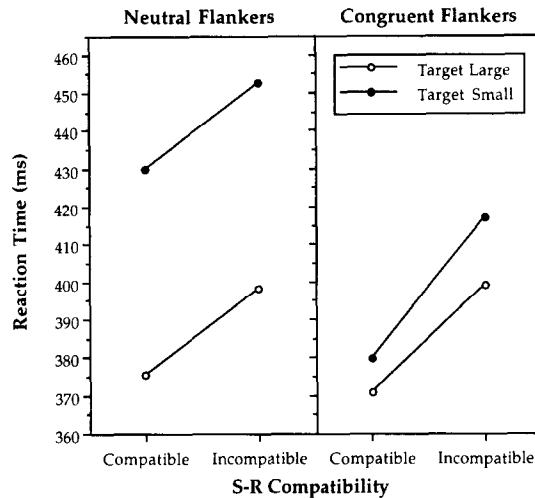| Factor	Flanker congruence		Target size		S-R compatibility	
	Neutral	Congr.	Large	Small	Comp.	Incomp.
RT	414	389	384	420	389	414
% err	8.5	7.7	7.5	8.7	8.1	8.1

Fig. 3. Effects on response latencies of S-R Compatibility and Target Size in neutral (left panel) and congruent (right panel) flanker conditions. Open markers represent large-target conditions whereas closed markers represent small-target conditions. S-R Compatibility conditions are on the abscissa.

targets compared to large targets were prolonged by 54 ms in neutral flanker conditions and by 18 ms in congruent flanker conditions (TS × FC: $F(1,10) = 50.26$; $p < 0.001$). In addition, Flanker Congruence influenced the S-R Compatibility effect such that the cost of making an incompatible response was greater when the flankers were congruent than when they were neutral (28 msec vs. 22 msec; SRC × FC: $F(1,10) = 5.11$; $p = 0.047$).

The cost of making an incompatible response was 21 msec when the target was easy to discriminate, but 30 msec when it was difficult to discriminate. This interaction failed to reach statistical significance (TS × SRC: $F(1,10) = 3.14$). Importantly, however, this pattern was mediated by Flanker Congruence (TS × SRC × FC: $F(1,10) = 8.23$, $p = 0.017$), as can be seen in Fig. 3. With *neutral* flankers, the cost of incompatibility was not influenced by Target Size (23 ms in both large- and small-target conditions; TS × SRC: $F(1,10) = 0.00$). Thus, the finding of Experiment 1 that Target Size and S-R Compatibility produced additive effects when targets were accompanied by neutral flankers was replicated here. In contrast, when flankers were *congruent*, the cost of incompatibility was smaller when the target was large than when it was small (19 vs. 37 ms, respectively; TS × SRC: $F(1,10) = 6.37$, $p = 0.030$). Thus, the additive relation between the effects of Target Size and S-R Compatibility, observed when flankers were absent or neutral, changed into a superadditive interaction when flankers were congruent to the target.

Again, Flanker Congruence, Target Size, and S-R Compatibility failed to produce significant effects on error rate (see Table 2; FC: $F(1,10) = 0.90$; TS:

$F(1,10) = 2.68$; SRC: $F(1,10) = 0.02$). None of the interactions reached significance. Accuracy results largely parallelled RT results, rendering explanations in terms of speed/accuracy trade-off unlikely.

The result that Target Size and S-R Compatibility produced additive effects when flankers were absent or neutral suggests that these factors selectively influence separate stages. The stage robustness criterion of the AFM asserts that the selective and independent influence of Target Size and S-R Compatibility on processing time, and hence the underlying stage structure inferred from these additive effects, must remain unchanged when examined in the presence of other experimental factors. The interactive pattern observed in the congruent flanker condition is a clear violation of this criterion. This result provides a serious challenge to the general applicability of discrete stage models to the processing of stimulus displays that contain response-signifying (albeit defined as irrelevant) elements in addition to the target element.

According to the continuous flow model, developed originally to account for effects of irrelevant stimulus elements on target processing, flanker effects suggest that the conflicting information provided by the stimuli on the flanks is processed through the level of response execution. Note that the response activated by congruent flankers is always the same as that designated by the target, irrespective of the S-R mapping assignment: If in incompatible conditions a left-pointing target signals a right-hand response, then a left-pointing flanker also signals a right-hand response. Large flankers may induce earlier and/or stronger partial response activation, but they will do so both in compatible and incompatible conditions, thereby producing additivity between Target Size and S-R Compatibility effects.

The superadditive relation observed in Experiment 2 might be predicted if it is assumed that the incompatible S-R rule is not applied to the flankers. That is, whereas the response to the target is designated by the S-R rule, flankers activate the response signaled by the direction of the arrow, regardless of the S-R rule. Hence, congruent flankers activate the *correct* response in compatible conditions, but the *incorrect* response in incompatible conditions, thus enhancing the effect of S-R Compatibility. However, the continous flow model lacks an S-R translation mechanism to mediate these effects. In fact, Eriksen and Schultz (1979) considered the absence of such a translation mechanism as an essential postulate of their model (p. 252).

In Miller's (1988) model of flanker effects, asynchronous parallel processing of target and flankers may result in stronger partial response activation when flankers are relatively large rather than small, but, as in the continuous flow model, they will do so in both compatible and incompatible conditions. To predict interactions between the effects of Target Size and S-R Compatibility, the model would have to assume either that the incompatible S-R rule is not applied to the flankers, or, alternatively, that the assigned S-R rule is applied to the flankers but the S-R translation stage emits additional output codes that represent the response signified by the "original" arrow direction before the S-R rule has been applied. As Miller's model postulates that all stimulus elements are processed through the same S-R translation stage with a single discrete output code for each of these
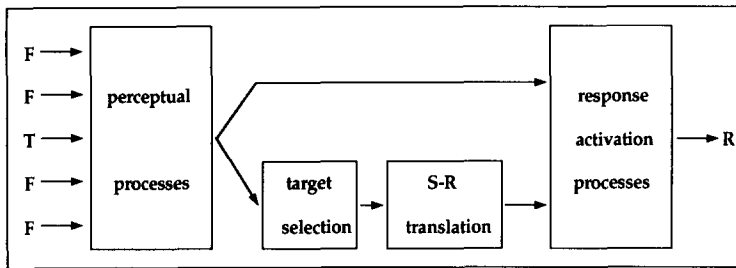
Fig. 4. Diagram of the dual-process model. *T* represents the target stimulus, *Fs* represent flankers, and *R* represents the response. Subsequent to perceptual processing, stimulus information is processed along two concurrent routes: A direct priming route (the upper route) and an attentive route (the lower route). The two processing routes converge on the level of response activation.

elements, strong additional assumptions would be required to allow the application of different S-R rules to target and flanker elements.

To accommodate the additive relations among Target Size and S-R Compatibility when flankers were neutral and the superadditive relation when flankers were congruent, we propose a dual-process architecture for target processing and flanker effects (diagrammed in Fig. 4). Perceptual processes are activated with the presentation of the stimulus array. The perceptual information is then envisioned to be processed along two routes that are engaged concurrently. Over an attentive processing route, the perceptual information enters a target selection process that comprises a controlled search to locate the target stimulus (e.g., Treisman and Gelade, 1980). Once selected, the code for the target undergoes an S-R translation process that determines the response appropriate to the target, and then sends this output code to subsequent response activation processes. The activation and initiation of the imminent response is contingent upon the outcome of these attentive processes. Concurrent with processing in this route, however, the perceptual information is processed over a second route. In this direct priming route, the attentive target selection and S-R translation processes are disregarded or bypassed, so that response activation processes are primed directly by both the target and flanker information. The operation of these priming processes does not follow the assigned S-R rule and is not confined to target information; initially, it may be dominated by flanker information (e.g., Coles et al., 1985; Smid et al., 1991).

At the level of response activation, there is a confluence and integration of the response priming that has occurred over the direct priming route and the output of the S-R translation stage in the attentive processing route. So, when flankers signify a response that is different from the response appropriate for the target, response competition will occur, as both response channels have been primed. This assumption receives support from the present observation of a subadditive interaction between Flanker Congruence and S-R Compatibility. Under compatible S-R mapping instructions, congruent flankers will elicit direct priming of the correct response, thus facilitating its activation and execution (as contingent upon the attentive processing of the central target). Under incompatible S-R mapping

instructions, congruent flankers will elicit direct priming of the incorrect response. The correct response is then delayed by the need to resolve the competitive conflict produced by the simultaneous activation of both the correct and the incorrect response. Hence, the time needed to preferentially activate the correct response depends on the duration of processing in the S-R translation stage. The nature (positive/negative) and extent of this dependence are determined by the direction (correct/incorrect) and intensity of direct priming effects.

When flankers are relatively large, it may take longer to extract the identity of the relatively small target, so that it takes longer for attentive processes to "assume control" at the level of response activation. If relatively large flankers have relatively large direct priming effects, then congruent flankers prime responses (the correct response in compatible conditions and the incorrect response in incompatible conditions) to a larger extent when they are relatively large rather than small. Thus, Target Size and S-R Compatibility would be expected to produce superadditive effects on RT when flankers are congruent. Target Size and S-R Compatibility produce additive effects on RT when flankers are neutral, or absent, as no direct priming of any response is elicited, regardless of the Target Size and of the S-R mapping assignment.

This dual-process model makes precise predictions about the relation between the effects of Target Size and S-R Compatibility when flankers are *incongruent* (that is, when target and flanker arrows point in opposite directions). Under compatible S-R instructions, incongruent flankers will elicit direct priming of the *incorrect* response. The correct response, contingent upon attentive target processing, is then delayed by the need to resolve the competitive conflict produced by the simultaneous activation of both responses. Under incompatible S-R instructions, incongruent flankers will elicit direct priming of the *correct* response, thus facilitating response execution.

If relatively large flankers have relatively large direct priming effects, then incongruent flankers prime responses to a larger extent when they are relatively large rather than small (the incorrect response in compatible conditions and the correct response in incompatible conditions). Thus, Target Size and S-R Compatibility are predicted to produce *subadditive* effects on RT when flankers are incongruent. This prediction was tested in a third experiment, described below.

Coles et al. (1985) argued that with blockwise variation of Flanker Congruence, subjects may adopt a less conservative speed/accuracy strategy in congruent conditions. Although the stimulus displays used in the present experiments were designed to prevent the strategy to focus on flanker positions, subjects still may have inferred that in congruent blocks any recognized arrow always points in the same direction as the target. The finding that the large effect of Target Size with neutral flankers was almost cancelled with congruent flankers (see Fig. 2) might be explained in part by such a strategy: The costs of small targets might be reduced if subjects used the relatively large congruent flankers to help identify the target. Hence, Target Size effects might be more balanced between Flanker Congruence conditions if the latter factor were varied in mixed rather than pure blocks. Within-block variation of Flanker Congruence further provides the opportunity to

replicate the factor effects observed in Experiment 2 under conditions where any possible influence of blocked presentations is eliminated. Thus, in Experiment 3 the Flanker Congruence factor was varied within blocks, and was extended to include an incongruent flanker condition to test the prediction that Target Size and S-R Compatibility interact subadditively when flankers are incongruent.

4. Experiment 3

4.1. Method

Subjects

Eleven undergraduate Psychology students at the University of Amsterdam served as subjects in this experiment. They received course credits for their participation. All subjects had normal or corrected-to-normal vision, and were right-handed according to self-report.

Design and procedure

The details concerning stimulus material were identical to those reported for Experiment 2, with the exception that incongruent stimulus arrays were added to the stimulus set. Flanking arrows in incongruent stimulus arrays were identical to those in congruent arrays, except that they pointed in the direction opposite to that indicated by the center arrow (see Fig. 1). Thus, the experimental design comprised 3 within-subject factors: Flanker Congruence (neutral, congruent, incongruent), Target Size (large, small), and S-R Compatibility (compatible, incompatible). Flanker Congruence refers to the composition of the stimulus display: The target arrow was surrounded by neutral, congruent, or incongruent flankers. Unlike Experiment 2, Flanker Congruence conditions were varied randomly within a block of trials, with the restriction that equal numbers of each occurred in every trial block. As in Experiment 2, Target Size and S-R Compatibility were fixed within a block of trials. Subjects first completed 4 practice blocks of 48 trials, in which they were trained to respond as quickly as possible to the target arrow, while at the same time keeping errors to a range of 5–10%. Each practice block represented one of the four combinations of small/large targets and compatible/incompatible S-R mappings. Each subject then completed 12 blocks of 122 trials, the first 2 trials

Table 3
Mean RTs and error rates for the flanker congruence, target size, and S-R compatibility factors in Experiment 3

Factor	Flanker congruence			Target size		S-R compatibility	
	Neutral	Congr.	Incongr.	Large	Small	Comp.	Incomp.
RT	443	425	467	405	486	436	455
% err	5.6	3.5	13.1	6.1	8.8	7.5	7.4

of which in each block were used as warm-ups and were discarded from data analysis. The order of trial blocks was determined randomly per subject. Further procedural details were identical to those of Experiments 1 and 2. Subjects were instructed to base their response choice on the direction of the target arrow, and to ignore the flankers.

4.2. Results and discussion

Mean RTs were submitted to a three-way analysis of variance with repeated measures on Flanker Congruence (neutral, congruent, incongruent), Target Size (large, small), and S-R Compatibility (compatible, incompatible). All three factors exerted main effects on response speed (see Table 3): responses were fastest when targets were surrounded by congruent flankers, slowest when flankers were incongruent, and intermediate when flankers were neutral ($F(2,20) = 91.99$, $p < 0.001$); large targets were associated with shorter response latencies than small targets ($F(1,10) = 196.74$, $p < 0.001$); and incompatible responses were slower than compatible responses ($F(1,10) = 18.41$, $p = 0.002$). Moreover, Flanker Congruence influenced the effect of Target Size such that RTs to small targets compared to large targets were prolonged by 54 ms when flankers were congruent, by 80 ms when flankers were neutral, and by 108 ms when flankers were incongruent (TS × FC: $F(2,20) = 123.05$, $p < 0.001$). Furthermore, variations in Flanker Congruence also influenced the effect of S-R Compatibility such that the increase in RT associated with making an incompatible compared to a compatible response was 27, 18, and 11 msec in congruent, neutral, and incongruent flanker conditions, respectively (SRC × FC: $F(2,20) = 16.88$, $p < 0.001$). That is, the processing penalty imposed by the need to produce an incompatible response was increased when the target was flanked by congruent arrows, but reduced when it was flanked by incongruent arrows.

Target Size and S-R Compatibility did not interact in their effects on response speed (TS × SRC: $F(1,10 = 0.65$). These two factors were part of a second-order interaction, however, with Flanker Congruence (TS × SRC × FC: $F(2,20) = 20.59$, $p < 0.001$). It is evident in Fig. 5 that Flanker Congruence plays a crucial role in the relation between Target Size and S-R Compatibility. With neutral flankers, Target Size did not influence the cost of incompatibility (15 vs. 20 ms in large and small target conditions; TS × SRC: $F(1,10) = 1.59$; see Fig. 5, left panel). Thus, the findings of Experiments 1 and 2 that Target Size and S-R Compatibility produced additive effects when targets were surrounded by neutral flankers was replicated here. When flankers were congruent, the cost of incompatibility was larger when Target Size was small rather than large (37 vs. 17 ms, respectively; TS × SRC: $F(1,10) = 6.98$, $p = 0.025$; see Fig. 5, middle panel). Thus, the finding from Experiment 2 that Target Size and S-R Compatibility produced superadditive effects when targets were surrounded by congruent flankers was also replicated here. In contrast to this finding, when flankers were incongruent the cost of incompatibility was *smaller* when Target Size was small rather than large (4 vs. 18 ms, respectively; TS × SRC: $F(1,10) = 8.83$, $p = 0.014$; see Fig. 5, right panel). Thus, the
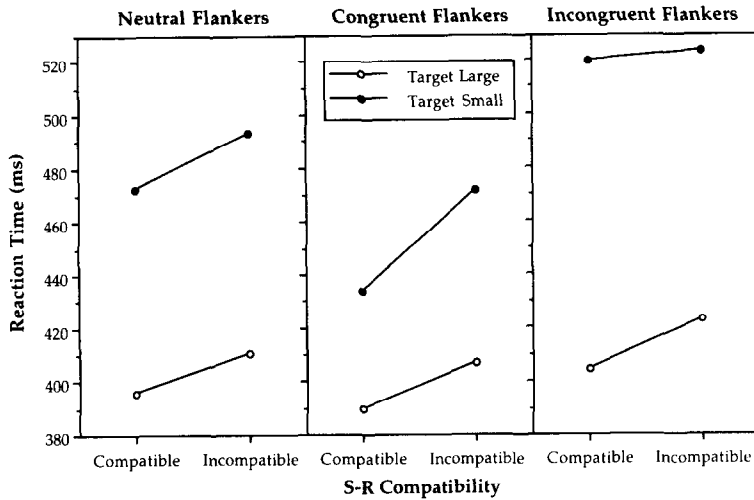
Fig. 5. Effects on response latencies of S-R Compatibility and Target Size in neutral (left panel), congruent (middle panel), and incongruent (right panel) flanker conditions. Open markers represent large-target conditions whereas closed markers represent small-target conditions. S-R Compatibility conditions are on the abscissa.

additive relation between the effects of Target Size and S-R Compatibility, observed when flankers were neutral, was transformed into an interaction by flankers that contained response-signifying information and the direction of the interaction varied with the congruence of the flankers (congruent-superadditive; incongruent-subadditive).

Accuracy results largely corroborated RT results (see Table 3), again rendering explanations in terms of speed/accuracy trade-off unlikely. Error incidence was lowest when targets were surrounded by congruent flankers, highest when flankers were incongruent, and intermediate when flankers were neutral ($F(2,20) = 52.40$, $p < 0.001$). Large targets were associated with fewer errors than small targets ($F(1,10) = 31.79$, $p < 0.001$). Error rates did not differ between compatible and incompatible responses ($F(1,10) = 0.03$). When flankers were neutral or congruent, responses to small targets were slightly more accurate than to large targets, whereas when flankers were incongruent, responses to small targets were less accurate (FC × TS: $F(2,20) = 46.87$, $p < 0.001$). Importantly, the three-way interaction between the effects of Flanker Congruence, Target Size, and S-R Compatibility (TS × SRC × FC: $F(2,20) = 4.48$, $p = 0.025$) appeared to parallel the corresponding interaction effect on response speed, although contrast analyses failed to reach statistical significance: With neutral flankers, Target Size did not influence the cost of incompatibility (0.2 vs. 0.8% in large and small target conditions); when flankers were congruent, small targets but not large targets were associated with a cost of incompatibility (1.3 vs. −0.2%, respectively); by contrast, when flankers were incongruent small targets but not large targets were associated with a *benefit* of incompatibility (−2.8 vs. 0.0%, respectively).

5. General discussion

This study was motivated by our interest in determining if the stage robustness criterion of the AFM would be met when target stimuli are flanked by irrelevant stimulus elements that the subject is instructed to ignore. Satisfaction of the stage robustness criterion requires preservation of the additive relations between Target Size and S-R Compatibility when these factors are combined systematically with variations in Flanker Congruence. The experiments yielded a pattern of results containing elements that suggest straightforward interpretations within the context of the additive factors logic as well as other elements that defy this interpretive logic. The former have arisen from the first experiment in which the effects on performance of combined variations in Target Size and S-R Compatibility were assessed when flankers were absent or neutral. Response latencies were found to increase when targets were small and when incompatible responses were required; these effects were additive, suggesting that these factors selectively influence separate stages.

This pattern of additive factor effects was transformed into the pattern of interactions revealed in Experiments 2 and 3 when variations in the congruence of the stimulus display were added to the factor array, suggesting (according to AFM logic) the inference that Target Size and S-R Compatibility influence one and the same stage. Hence, the stage robustness criterion was violated. This violation provides an important challenge to the general applicability of the AFM as a procedure for studying the processing of stimulus displays that contain irrelevant but response-signifying elements in addition to a target element. It therefore supports similar conclusions arrived at on the basis of psychophysiological evidence for continuous transmission between perceptual and response processes (Smid et al., 1991).

This failure should not be taken to imply that these findings may be reconciled easily with the basic postulates of the continuous flow conception in its present form. According to this model, relatively large flankers may induce earlier and/or stronger partial response activation than relatively small flankers, but will do so in both compatible and incompatible conditions, due to the lack of an S-R translation mechanism. This would result in additivity between Target Size and S-R Compatibility effects in all Flanker Congruence conditions, a prediction that was clearly not confirmed by the current findings.

Miller (1988) formulated a discrete stage model that allows asynchronous parallel processing of target and flankers. The model postulates that all stimulus elements are processed separately through the same S-R translation stage with a single discrete output code for each of these elements. Thus, flankers produce stronger partial response activation when they are relatively large rather than small, in both compatible and incompatible conditions. However, to predict interactions between the effects of Target Size and S-R Compatibility, strong additional assumptions would be necessary to allow different S-R rules to be applied to target and flanker elements.

We formulated a dual-process architecture in an attempt to integrate the

additive and interactive relations among Target Size and S-R Compatibility under different conditions of Flanker Congruence. To summarize, perceptual processes are activated with the presentation of the stimulus array. Over an attentive processing route, the perceptual information enters a target selection process; the code for the target undergoes an S-R translation process. Concurrently, the perceptual information is processed along a direct priming route that by-passes the attentive target selection and S-R translation processes. Via this route, response activation processes are primed directly both by target and flanker information. At the level of response activation, the processing routes are assumed to converge.

Under compatible S-R instructions, congruent flankers elicit direct priming of the correct response. The correct response, as contingent upon the attentive processing of the central target, is then facilitated. With incompatible S-R assignments, congruent flankers elicit direct priming of the incorrect response. The resulting response competition delays execution of the correct response. Relatively large flankers impede the extraction of the identity of the relatively small target, and thus have more time to directly prime the response activation system (for the correct response in compatible conditions and for the incorrect response in incompatible conditions). Hence, with congruent flankers, Target Size and S-R Compatibility are expected to produce superadditive effects on response speed, as was observed in Experiment 2. When flankers are neutral or absent, no direct response priming is thought to occur; hence, these factors are expected to produce additive effects in these conditions, as was observed in each of the experiments in the present study.

Specific predictions were derived from the dual-process model about the relation between Target Size and S-R Compatibility effects when flankers are incongruent. In compatible conditions, incongruent flankers will elicit direct priming of the incorrect response. Under incompatible S-R instructions, incongruent flankers will elicit direct priming of the correct response. As incongruent flankers prime responses (the incorrect response in compatible conditions and the correct response in incompatible conditions) to a larger extent when they are relatively large rather than small, Target Size and S-R Compatibility were predicted to produce subadditive effects on response speed. This hypothesis was supported in Experiment 3.

Some reports in the literature (e.g., Eimer, 1993) point to the special status of arrow stimuli with respect to their potential to directly prime or activate the response on the side to which they point. Whereas a left-pointing arrow can prime a left-hand response even when it is explicitly assigned to a right-hand response, a specific letter identity can only prime the response to which it has been assigned by instruction. Still, one might easily imagine a task where congruent flanking letter identities could potentially prime the incorrect response (e.g., if the response were to be based on the letter that alphabetically precedes the target letter, and if that preceding letter were associated with the opposite response), just as the congruent arrows in incompatible conditions did in this study. Thus, it remains to be seen whether central processes (such as S-R translation) can be by-passed by direct response priming effects of flankers whose dimensions have less natural or over-

learned associations with specific responses, such as the letter identities usually invoked in the Eriksen task.

In conclusion, the current pattern of findings indicate that the logic of the AFM does not extend to the set of multielement stimuli used in this study. The results were found to conform to a dual-process model for target processing and flanker effects. This scheme is in accordance with other dual-process models that propose direct response priming effecs of distractors or directional cues in parallel to concurrent central response selection or memory search processes (e.g., De Jong et al., 1994; Eriksen et al., 1986; Smid et al., 1991). The elements and dynamics of this model may be validated and articulated with more precision by supplementing the RT analysis of the current task with psychophysiological procedures that provide on-line measures of stimulus and response processing (e.g., Van der Molen et al., 1991), by developing a wider variety of RT tasks to test the model, and by performing neural network simulations of the proposed processing architecture. This work is now in progress.

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