

## ORIGINAL ARTICLE

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## The dimensionality of the flanker compatibility effect: A psychophysiological analysis

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**Abstract** The psychophysiological approach was used to evaluate the effects of feature similarity and “intrinsic response mapping” on the flanker compatibility effect. Symbol (e.g., < > < and </<) and letter arrays (e.g., *HCH* and *SCS*) were used. Results showed that delays in stimulus evaluation and both peripheral and central response competition contributed to the compatibility effect, with the contribution of these processes depending on feature similarity and the intrinsic response mapping of the stimuli. For letter stimuli, the difference in the size of the compatibility effect for similar and dissimilar arrays could be accounted for in terms of stimulus evaluation. For symbol arrays, differences in size of the compatibility effect could be accounted for by response competition. Thus, symbol and letter arrays do not appear to be processed differently; what is different is the degree to which stimulus and response-related processes are affected by incompatibility.

### Introduction

People appear to be unable to focus attention exclusively on particular locations in their visual world. They cannot always exclude information from irrelevant locations and attend only to relevant information, even when the locations of the relevant information are specified in advance (see Van der Heijden, 1992, and Fournier, 1994, for a review).

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The Eriksen flankers paradigm has often been used to investigate this phenomenon (Eriksen & Eriksen, 1974). In this paradigm, three or five letters are presented in a horizontally oriented array. The center letter in the array is always the target (to be attended and responded to), while the flanking letters are irrelevant (noise, to be ignored). When noise letters flanking a visual target are mapped to a different response than the target (response-incompatible arrays), reaction times (RTs) are slower and responses are less accurate than when the target and flankers are mapped to the same response (response-compatible arrays). This effect of compatibility on performance (termed the “compatibility effect”) suggests that subjects are unable to ignore the irrelevant information. In other words, the response-incompatible noise letters interfere in some way with the processing of the target (Eriksen & Eriksen, 1974; 1979).

Eriksen and Schultz (1979) proposed that this interference occurs at the level of response processing. They argued that feature information is available before location information. Thus, early in the processing of the array, perceptual information may be dominated by the flanking letters (because there are more of them), and only later does perceptual information about the centrally located letter become dominant. In addition, they argued that if information from the perceptual system is passed on continuously to the response system, the response associated with the features of the flankers will be activated first, while activation of the response associated with the target letter features will follow later. In short, when the array is response-incompatible, incorrect response activity associated with processing of the flankers will have to be overridden or inhibited by the correct response activity associated with the processing of the target (see also Grice, Nullmeyer, & Spiker, 1982). In turn, this will delay the correct response and increase the probability of response errors. The delay in correct response execution due to incorrect response activity has been termed the “response-competition” effect.

The concept of “response competition” implies a particular view of the causal relationship between the

dynamics of the correct response and those of the incorrect response. That is, the activation of the incorrect response "causes" the correct response to be delayed. Research in which response activation was manipulated directly (e.g., Marteniuk & Mackenzie, 1980) supports the claim that there is a competitive (causal) relationship between the two response systems. However, it is important to note that much of the data adduced in support of the response-competition concept are correlational in nature. The degree of incorrect response activation is (cor)related with the delay in execution of the correct response and with other aspects of the correct response dynamics (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985). Of course, it is possible that this relationship between incorrect and correct response activation is the result of some third factor and does not reflect a direct competitive relationship between the two response systems. In this regard, it is important to note that the relationship was predicted from the continuous flow theory of Eriksen and Schultz (1979), which features a response-competitive mechanism. The data cited and reported are consistent with these predictions.

Several attempts to identify the locus of the compatibility effect have employed the psychophysiological approach (for a review, see Coles, Smid, Scheffers, & Otten, 1995). This approach utilizes different psychophysiological and response measures as markers of the activities of different parts of the information-processing system. Two components of the event-related brain potential are featured in our approach, the P300 and the lateralized readiness potential (LRP). Both measures are derived from scalp recordings of electrical brain activity. The P300 is a positive component with a maximum amplitude over central and parietal brain regions. Its amplitude is influenced by stimulus probability, implying that, by the time the P300 has occurred, the stimulus must have been categorized. Furthermore, its latency increases with the difficulty of stimulus categorization. This and other evidence (for a review, see Donchin & Coles, 1988) supports its use as a measure of stimulus-evaluation time. The LRP represents the asymmetry in electrical activity between electrodes located over left and right motor cortices. Because of the way that the LRP is derived, deviations from zero in the value of the LRP only occur when there is preferential activation of left or right motor responses. These kinds of deviations are observed before unimanual motor responses are executed. Furthermore, reaction time tasks involving a choice between left or right hands have shown that LRPs develop during the warning intervals when subjects know in advance which hand they will have to use in response to the imperative stimulus. This and other evidence reviewed by Coles (1989) supports the claim that the LRP is a sign of response activation.

Other measures of response activation are derived from more peripheral measures (e.g., Coles et al., 1985). Recordings of electromyographic activity (EMG) in the responding limbs are used to determine when peripheral response activation occurs, while measures of the force

associated with the response itself are used to describe even more peripheral signs of response activation. (subjects are required to squeeze one of two dynamometers to indicate the identity of a target.) Partial error activity can be identified using these three response measures (see Coles, Scheffers, & Fournier, 1995), and the possible effect of response competition between correct and incorrect responses can be evaluated by measuring the latency of the correct response on trials with partial error activity.

This kind of approach was used by Coles and colleagues (Coles et al., 1985) to evaluate the locus of interference in the Eriksen flanker paradigm. A center target letter (*H* or *S*) was surrounded by noise letters that were either response compatible (i.e., *SSSSS* and *HHHHH*) or response incompatible (i.e., *HSSHH* and *SSHSS*). As expected, Coles et al. found a compatibility effect: RTs for response-incompatible arrays were 47 ms slower than for response-compatible arrays. To evaluate the contribution of response conflict to this effect, Coles et al. included in their analysis a classification of trials according to the degree of error activity. Trial categories included: no error, EMG error, partial squeeze error, and criterion squeeze error. Coles et al. found significant delays in activation and execution of the correct squeeze response when partial squeeze errors occurred. More specifically, on partial squeeze error trials, the latency of the correct squeeze response was delayed, and the interval between correct EMG and squeeze onset was longer relative to the latency for EMG error trials or no error trials (peripheral response competition). In addition, partial squeeze errors occurred more often when the array was incompatible than compatible. These findings are consistent with the principle of response competition. Furthermore, it appears that the irrelevant flankers can influence response activation at the stage of EMG and squeeze (peripheral motor execution). This idea is consistent with continuous flow models (Eriksen & Schultz, 1979; see also Smid, Mulder & Mulder, 1990; Miller, 1982).

Out of the overall 47-ms compatibility effect found by Coles et al. (1985) 10 ms were accounted for by the peripheral response competition evident in partial squeeze errors. In addition, a more central kind of response delay accounted for 12 ms of the compatibility effect (measured by LRP). The remaining 25 ms were explained by perceptual conflict; P300 latency for response-incompatible arrays was 25 ms longer than that for response-compatible arrays. On the basis of these data, Coles et al. concluded that delays in both stimulus evaluation and response-related processes (both at central and peripheral motor processing levels) are responsible for the compatibility effect (see also Smid et al., 1990). It appears that incompatible noise leads both to conflict in the evaluative process (slowing stimulus evaluation) and to the activation of the two response channels (leading to response competition).

Unlike Coles et al. (1985), Rösler and Finger (1993) failed to find response-competition effects at the pe-

ripheral response level when symbols (<, >, \, /) rather than letters were used in the Eriksen flanker paradigm. Using three-element arrays, Rösler and Finger found a significant effect of compatibility with longer RTs (45 ms) for incompatible arrays (e.g., < > < and \ / \) than for compatible arrays (e.g., > > > and / / /). However, they claimed that this effect was not associated with any increases in the correct EMG-squeeze interval when incorrect squeeze activity was present. This led them to conclude that response competition for their symbol arrays only occurred at a central level of response activation that precedes the release of a particular motor program. Once this motor program is released, responses are assumed to be executed in a ballistic fashion. Thus, according to Rösler and Finger, the compatibility effect for these symbol arrays must be caused by processes that precede the release of a particular motor program. This account does not fit with the continuous flow model's assumption that information present in the input channel is transferred continuously up to the very last output stage. Rösler and Finger argued that the symbol stimuli they used may be processed differently than letter stimuli because they have a more intrinsic response mapping than letter stimuli (see also Stoffels & van der Molen, 1988). The symbols have a natural directionality, with / and > being associated with a right-hand response, and \ and < with a left-hand response.

There are several factors that complicate the comparison between the Coles et al. (1985) and the Rösler and Finger (1993) studies. First, these two studies used different definitions of "squeeze" activity. Rösler and Finger's definition of squeeze activity does not differentiate between partial and criterion squeeze responses, while Coles et al. evaluated partial and criterion squeeze responses separately. Thus, Rösler and Finger's method does not allow an evaluation of partial squeeze error responses on the correct EMG-squeeze interval (that is, correct EMG-criterion squeeze interval). It is unclear whether this method would underestimate or overestimate the influence of incorrect response activity on the correct EMG-squeeze interval relative to the Coles et al. method. In addition, the differences in definition make it impossible to compare the probability of partial squeeze errors for the response-compatible and response-incompatible arrays in the two studies. Thus, the results of these two studies are not directly comparable with respect to the issue of response competition at the peripheral, motor activation stage. Secondly, Rösler and Finger did not directly measure central motor activation (LRP) or the duration of stimulus evaluation processes (P300). This makes it impossible to determine whether their compatibility effect is primarily due to central response competition or perceptual competition.

Perhaps a more important difference concerns the fact that Coles et al. (1985) used letter stimuli in which the target and flankers were perceptually distinct from each other (e.g., the targets *S* and *H* formed incompatible arrays of *HSSH* and *SSHSS*), while Rösler and

Finger (1993) used symbol arrays in which target and flankers shared very similar features and were not perceptually distinct from each other (e.g., the arrowhead and slash targets formed incompatible arrays < > < and \ / \). Increased feature similarity between the target and irrelevant flankers will lengthen the time necessary to perceptually segregate the target from the flankers (Duncan & Humphreys, 1989; Watt, 1988), even if the target location is known in advance of the array presentation (Fournier, 1994). When an array contains all the same elements, segregation may not be necessary. However, when an array contains different elements, they must be segregated and this segregation will take a longer time when the elements are similar (as with the incompatible arrays used by Rösler and Finger). Increasing the time required for target-flanker segregation would delay the time by which the target and flankers can be evaluated as individual elements mapped to different responses. In turn, this should increase the time required for the target and flankers to prime their corresponding responses. In this case, segregation rather than response competition would play the major role in producing a compatibility effect.

The present study was designed to investigate the contributions of stimulus evaluation and response competition to the compatibility effect when feature similarity between the target and noise stimuli varies. Recall that Coles et al. (1985) accounted for approximately half of the compatibility effect found for their letter stimuli in terms of a delay in stimulus evaluation. Based on our earlier review, we were interested in the possibility that increasing feature similarity would result in an increase in the time required for target-flanker segregation. In turn, this would result in an increase in the contribution of stimulus evaluation (relative to response competition) to the compatibility effect. We were also interested in whether symbols with more intrinsic response mappings are processed differently than letter stimuli, as was suggested by Rösler and Finger (1993).

Both letter and symbol arrays were used, the symbols being similar to the arrowheads and slashes (<, >, \, /) that Rösler and Finger (1993) used. The left-pointing symbols (< and \) were mapped to the left-hand response, and the right-pointing symbols (> and /) were mapped to the right-hand response.<sup>1</sup> The letter stimuli were *S* and *C*, which share curved features, and *H* and *N*, which share straight features. Each of two responses was assigned to two letters, one with curved features and one with straight features. For example, the curved letter *S* and the straight letter *H* were mapped to a right-hand response, and the other curved letter *C* and straight letter *N* were mapped to a left-hand response.

Unlike the Coles et al. (1985) and Rösler and Finger (1993) studies, we varied arrays not only by response compatibility, but also by perceptual similarity (see

<sup>1</sup> For slash targets, subjects were told to respond with the hand towards which the top part of the slash pointed.

**Table 1** Example of stimulus arrays for each target and condition. *PsRc* is perceptually similar, response compatible; *PsRi* is perceptually similar, response incompatible; *PdRc* is perceptually different, response compatible; *PdRi* is perceptually different, response incompatible; *Neutral* is no response assigned to flanker. Only symbol arrays requiring a right-hand response are represented

Condition	Letter targets		Symbol targets	
	Curved	Straight	Slash	Arrowhead
<i>PsRc</i>	S S S	H H H	/ / /	> > >
<i>PsRi</i>	C S C	N H N	/ / /	> > >
<i>PdRc</i>	H S H	S H S	> / >	/ > /
<i>PdRi</i>	N S N	C H C	< / <	/ > /
<i>Neutral</i>	+ S +	+ H +	O / O	O > O

Table 1). For example, perceptually similar arrays (e.g., arrowheads or curved letters) could contain targets and flankers that were response incompatible (where target and flankers indicated different responses, e.g., > < > or *CSC*) or response compatible (where target and flankers were identical, e.g., < < < or *SSS*). In addition, perceptually different arrays (e.g., arrowheads and slashes or straight and curved letters) could contain target and flankers that were response incompatible (where target and flankers indicated different responses, e.g., / < / or *NSN*) or response compatible (where target and flankers were mapped to the same response, e.g., \ < \ or *HSH*).

We predicted that response-incompatible arrays would be associated with slower responses and more errors than would response-compatible arrays. This compatibility effect should result from both response competition and effects on stimulus evaluation, and the contributions of each of these processes will depend on the perceptual characteristics of the displays. When the target and noise elements share similar features, increased latency for response-incompatible displays should be accounted for by delays in stimulus evaluation (P300 latency) as well as by response competition. This is because time to segregate the display into individual elements should increase, delaying the time at which the flankers and the target can prime their corresponding responses. When the target and noise elements have distinctly different features, increased latency for response-incompatible displays should also be accounted for by both delays in stimulus evaluation (P300 latency) and by response competition, but delays in stimulus evaluation should be less than those found when target and noise share similar features. This is because, when target and noise elements are dissimilar, the display should be segregated more quickly into individual elements, and this should allow the flankers and target to prime their corresponding responses with less of a delay.

The symbol stimuli were included to enable us to evaluate the effects of the intrinsic response mapping between stimuli and their associated responses. For flanking stimuli that "naturally" lead to particular re-

sponses (e.g. a > symbol leads to a right-hand response), effects of compatibility should be more evident in response related processes. In particular, response competition should be a particular problem when flanking symbols are incompatible with the target.

## Method

**Subjects.** Five male and three female University of Illinois students served as paid volunteers. All were right-handed (by self-report) and had normal or corrected-to-normal vision (also by self-report).

**Apparatus and procedure.** Subjects were required to perform a choice reaction time task by responding with their left or right hands as a function of a visual stimulus. Stimuli were presented on a Hewlett Packard display (model HP 1310B). A white fixation dot appeared continuously in the center of the display, except when an array was presented. Arrays contained three symbols or three letters, arranged horizontally, with the center symbol or letter (the target) appearing 1° above the fixation dot. Symbol arrays could contain slashes (/ and \), arrowheads (> and <), and the character O. Letter arrays could contain the letters S, C, H, N, and the character +. The O and + only appeared in the outer locations in the array. The slashes, arrowheads, and letters appeared in the central and/or outer array locations. The characters in the outer array locations (flankers) were always identical to each other. The characters were approximately .4° of visual angle in height and width, arrays subtended 1.5° of visual angle in width, and stimuli were separated by .1° of visual angle.

Subjects responded to the targets by squeezing one of two zero-displacement dynamometers mounted on the left and right armrests of the chair in which subjects were seated. The dynamometers were connected to an amplifier system (Daytronic Linear Velocity Force Transducers, Model 152A, with Conditioner Amplifiers, Model 830A; see Kutas & Donchin, 1977), whose voltage output was a linear function of the force applied to the dynamometers. This provided a continuous measure of overt response activation. The squeeze threshold for an overt response was set at 25% of the subject's maximum voluntary squeeze force, which was assessed before the experiment began. On practice trials only, auditory feedback (a "click") was presented when the force exerted on the dynamometers exceeded the criterion force level. During all sessions, the latency and accuracy of criterion squeezes were recorded, with the latency measure being used to define reaction time (RT).

Subjects participated in four experimental sessions. Half of the subjects were presented with symbol arrays in the first two sessions and letter arrays in the third and fourth session, while the converse was the case for the other half of the subjects. Subjects were instructed to attend and respond to the target in the center of the array and to ignore the flankers. In the symbol condition, subjects squeezed the left dynamometer when the center symbol was a left-pointing arrowhead (<) or a left-pointing slash (\) and squeezed the right dynamometer when the center symbol was a right-pointing arrowhead (>) or a right-pointing slash (/). In the letter condition, half the subjects squeezed the left dynamometer when the center letter was an H or an S and squeezed the right dynamometer when the center letter was an N or a C. The other half of the subjects squeezed the left dynamometer when the center letter was an N or a C and squeezed the right dynamometer if the center letter was an H or an S.

At the start of each trial, a warning tone (440 Hz, 68 dB) was presented for 100 ms over a speaker located approximately 14 inches above the subject's head. Then, 900 ms later, the stimulus array was presented for 100 ms. Subjects had to respond within 1000 ms of array onset. The next trial began after a random delay of between 1150–2150 ms (in steps of 100 ms) after the response interval elapsed. Subjects were instructed to respond as quickly and

accurately as possible. Bonus points were earned (which later translated into money) for fast and correct responses (criterion squeezes) and were subtracted for slow correct responses and for incorrect responses. More bonus points were subtracted for slow correct responses than for incorrect responses in order to maintain a slight bias of speed over accuracy.

Symbol and letter arrays were defined in terms of perceptual similarity and response compatibility. In the symbol condition, an array was defined as perceptually similar if both target and noise were the same symbol type, independent of the direction in which the symbols were pointed. In the letter condition, an array was defined as perceptually similar if the target and noise shared curved features or shared straight features. For both the symbol and letter arrays, an array was defined as response compatible if both the target and noise were mapped to the same squeeze response; an array was defined as response incompatible if target and noise were mapped to different squeeze responses; and an array was defined as neutral if the noise stimuli did not have a defined response (i.e., if noise stimuli was an *O* or *+*). Thus, there were five conditions defined by the two levels of perceptual similarity and three levels of response compatibility (see Table 1):

1. The perceptually similar, response-compatible condition (PsRc), in which the target and noise stimuli shared similar features and were mapped to the same response (for symbol arrays: < < <, \\\, > > >, ///, and for letter arrays: SSS, HHH, CCC, NNN).
2. The perceptually different, response-compatible condition (PdRc), in which the target and noise differed in features and were mapped to the same response (for symbol arrays: \ < \, / > /, < \ <, > / > and for letter arrays: HSH, SHS, NCN, CNC).
3. The neutral condition in which noise stimuli were not mapped to a response (for symbol arrays: *O*\ *O*, *O* < *O*, *O*/ *O*, *O* > *O* and letter arrays: +*S*+, +*H*+, +*N*+, +*C*+).
4. The perceptually similar, response-incompatible condition (PsRi), in which the target and noise shared similar features and were mapped to different responses (for symbol arrays: \ \ /, > < >, \ / \, < > < and letter arrays: CSC, NHN, SCS, HNH).
5. The perceptually different, response-incompatible condition (PdRi), in which the target and noise differed in features and were mapped to different responses (for symbol arrays: > \ >, / < /, < / <, \ > \ and letter arrays: NSN, CHC, SNS, HCH).

Subjects completed four sessions: two sessions with symbol arrays and two sessions with letter arrays. Half of the subjects completed the two symbol sessions first and the other half of the subjects completed the letter sessions first. The symbol and letter sessions contained 25 blocks of 60 trials. Each block contained 12 trials of each of the five conditions, which were presented in a random order. Subjects completed 10 blocks of practice trials in the first and third experimental sessions. The purpose of the practice trials was to familiarize subjects with the symbol and letter discrimination tasks and to adjust the bonus system. The data for practice trials were not included in the analyses. Each session lasted from two to three hours.

**Physiological recording.** The electroencephalogram (EEG) was recorded with disposable Ag/AgCl electrodes from Fz, Cz, Pz, Oz, and the right mastoid (the international 10/20 system, Jasper, 1958), and C3' and C4' (placed 4 cm to the left and right of Cz, respectively). Each of these electrodes was referenced to a left mastoid electrode. The electrooculogram (EOG) was recorded from electrodes placed above and below the right eye to monitor vertical eye movements and from electrodes placed on the outer canthus of the left and right eye to monitor horizontal eye movements. The impedance for EEG and EOG electrodes was less than 5 Kohm. EOG and EEG amplifiers (Grass model 7P122) were set to a high-frequency cut-off of 35 Hz (3 dB/octave roll-off) and a time-constant of 8 s. The electromyogram (EMG) was recorded from electrodes placed on the flexors of both the left and right forearm (Lippold, 1967). EMG signals (electrode impedance < 10

Kohm) were rectified using Grass Model 7P3B preamplifiers (1/2 amplitude low-frequency cut-off at 1 Hz) and then integrated (full-wave rectification and a time-constant of .05 s). All signals (EEG, EOG, EMG, and output from the force transducers) were sampled at 100 Hz. The recording epoch (duration: 2700 ms) began 1,350 ms before the onset of the stimulus array. Eye-movement artifacts were corrected using the procedure described by Gratton, Coles and Donchin (1983) and extended by Miller, Gratton, and Yee (1988).

#### Data analysis

**EMG and squeeze measures.** A computer algorithm measured the latencies of EMG onset and squeeze onset on each trial. The procedure used was similar to that described by Scheffers, Coles, Bernstein, Gehring, and Donchin (1996). First, the algorithm determined the amount of variability in both EMG and squeeze force channels for the interval 100 ms prior to stimulus presentation for the current trial as well as the five preceding and succeeding trials. Pilot work suggested that a noise criterion equal to ten times the 80th percentile of these standard deviations provided an acceptable cut-off between signal and noise. Second, the algorithm determined the maximum amplitude in the post-stimulus interval between 70 ms and 1000 ms that exceeded the noise criterion. Third, the algorithm searched backward until it encountered the first sample point below the noise criterion. From this point on, the backward search was continued to the last point before the slope changed direction. The latency of this point was considered the onset latency for both EMG and squeeze force measures. Trials were discarded if the interval between onset and peak latency was larger than 400 ms, if a squeeze onset preceded an EMG onset, or if the EMG-squeeze onset interval was 150 ms or longer.<sup>2</sup> As noted earlier, RT was defined as the latency at which a complete squeeze response occurred (i.e., the time at which squeeze force exceeded the force criterion). Also, correct and incorrect response classification was based on the same criterion squeeze responses.

Following Coles et al. (1985), both correct and incorrect response channels were evaluated using the algorithm described above. The resulting data allowed the determination of the degree of error present for each trial and these trials were then classified as follows:

1. *No error* – a correct criterion squeeze was present, but there was no evidence of incorrect activity at the levels of either the squeeze or EMG.
2. *EMG error* – a correct criterion squeeze was present, and there was evidence of incorrect activity at the level of EMG (but not squeeze).
3. *Partial squeeze error* – a correct criterion squeeze was present, and there was evidence of incorrect activity at the levels of both EMG and squeeze.
4. *Incorrect criterion squeeze or RT error* – a criterion incorrect squeeze was present.

**P300 Latency.** P300 latency was measured on the single-trial ERP waveforms recorded at the Pz electrode site. The ERPs were filtered using a low-pass digital filter with 99 points and a transition-band from 4–6 Hz (see Farwell, Martinerie, Bashore, Rapp, & Goddard, 1993). P300 latency was defined as the latency of the most positive point in a window from 250–700 ms after stimulus onset.

**Lateralized readiness potential.** Measures of the lateralized readiness potential (LRP) for correct response trials were derived separately for each condition using the standard formula (see Coles,

<sup>2</sup> Gratton, Coles, Sirevaag, Eriksen & Donchin (1988) show a typical mean interval duration of about 50 ms between EMG and squeeze onset.

1989). In the context of this analysis, correct response trials were defined as those for which (a) there was a squeeze response with the correct hand whose force exceeded the criterion, and (b) there was either no activity or only EMG activity on the incorrect side. The logic underlying the derivation of the LRP implies that when the incorrect response hand is activated, the resulting LRP will show a positive deflection, while correct response activation is associated with negativity in the LRP. The larger the positive "dip" of the LRP, the stronger the incorrect response activation. To quantify LRP data in the present study, the amplitude of the LRP waveform averaged over a 100-ms interval immediately prior to stimulus onset was subtracted from the average value of the LRP for a 100-ms interval that preceded the "upswing" representing the final phase of correct response activation.

## Results and discussion

### Overt behavior

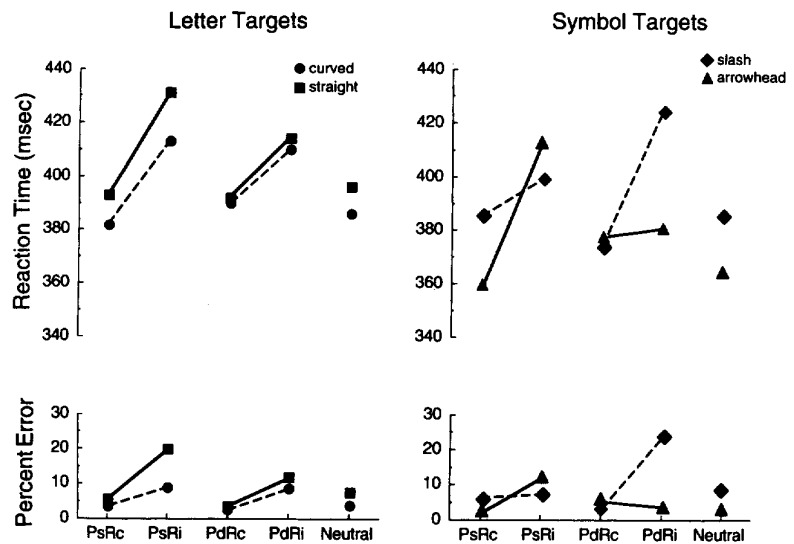
To evaluate perceptual similarity and intrinsic response mapping effects on overt performance measures, a repeated-measures ANOVA [Target type (4)  $\times$  Condition (5)] was conducted on mean latency of correct criterion squeezes (RT) and accuracy. Figure 1 shows these values for the letter and symbol target types, respectively, across the different conditions. There was a main effect of target for RT and accuracy,  $F(3, 21) = 4.79$  and  $8.13$ ,  $p = .01$ , respectively. Overall, responses to the arrowhead targets were significantly faster and more accurate than responses to the slash and letter targets, Tukey,  $p = .05$ . In addition, there was a main effect of condition, for RTs and accuracy  $F(4, 28) = 61.00$  and  $67.43$ ,  $p < .001$ , respectively. As expected, for both symbol and letter arrays, mean correct RT was longer and responses were less accurate for response-incompatible (PsRi and PdRi) than for response-compatible arrays (PsRc and PdRc), planned comparisons,  $p < .05$ . The speed and accuracy of responses in the neutral condition were

similar to those for the response-compatible arrays, planned comparisons,  $p > .05$ .

These observations were complicated by a significant interaction between target type and condition for RT and accuracy,  $F(12, 84) = 8.18$  and  $15.99$ ,  $p < .001$ , respectively. Since our primary interest is in the modulation of the compatibility effect for different kinds of targets, we shall focus separately on the data for letters and symbols. As shown in Fig. 1, the compatibility effect for letter targets was larger for perceptually similar arrays than for perceptually different arrays, planned comparisons,  $p < .05$ . This finding supports our prediction that perceptual similarity modulates the compatibility effect for the letters, since segregation is a particular problem when target and incompatible noise letters are similar.

For symbol targets a different picture emerged. For arrowheads, a large compatibility effect (53 ms) is seen for perceptually similar arrays, while only a small effect (3 ms) was evident for perceptually different arrays (planned comparisons,  $p < .001$ ). In contrast, for slash targets, the compatibility effect was smaller for similar (14 ms) than for different (50 ms) arrays (planned comparisons,  $p < .001$ ). These symbol effects appear to be attributable to a difference in the effectiveness of the symbols in priming a response (i.e., in what we have referred to as "intrinsic response mapping"). This inference is supported by the following observations. First, arrays with arrowhead targets were generally associated with the faster and more accurate responses than were arrays with slash targets. Second, in those conditions for which the arrowheads were incompatible flankers (i.e., PsRi for arrowhead targets and PdRi for slash targets), responses were slow and inaccurate. On the other hand, when arrowheads were compatible flankers (PsRc for arrowheads and PdRc for slashes), responses were fast and accurate. Third, the compatibility of flanking

**Fig. 1** Mean correct RTs and percent errors for each of the five different array conditions for the letter arrays (left panel) and symbol arrays (right panel). The slope of the lines connecting compatible and incompatible conditions provide a visual representation of the magnitude of the compatibility effect. *Ps* = perceptually similar array; *Pd* = perceptually different array; *Rc* = response-compatible array; *Ri* = response-incompatible array



slashes had little or no effect on response latency or accuracy.

Taken together, the letter and symbol data indicate that both perceptual similarity and intrinsic response mapping affect overt behavioral responses to compatible and incompatible arrays. For letter arrays, increasing perceptual similarity increases the compatibility effect, while, for symbol arrays, the degree of intrinsic mapping of the flankers moderates the compatibility effect. We proposed that these variables (similarity and response mapping) influence the processing system in different ways (via stimulus-related and response-related factors, respectively). In subsequent sections, we shall review the psychophysiological data that is relevant to this proposal.

### Stimulus evaluation

We measured P300 latency to evaluate the influence of array condition (perceptual similarity and response compatibility) on stimulus-evaluation processes (see Fig. 2). In general, the pattern of main effects and interactions for P300 latency was the same as those for RT. There was a main effect of target,  $F(3, 21) = 5.09$ ,  $p < .01$ . The symbol targets had significantly shorter P300 latencies than the letter targets, with the arrowhead targets having the shortest latencies of all, Tukey,  $p < .05$ . There was also a significant main effect of condition for P300 latency,  $F(4, 28) = 15.02$ ,  $p < .001$ . P300 latency was 17 ms longer for incompatible than for compatible arrays (planned comparisons,  $p < .01$ ).

A significant interaction between target type and condition was also evident,  $F(12, 84) = 2.45$ ,  $p < .01$  (see Fig. 2). For letter arrays, the compatibility effect on

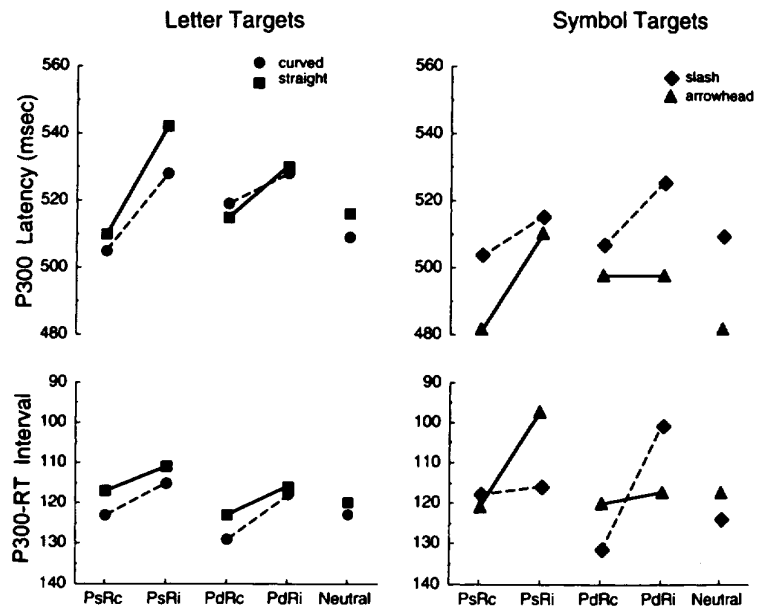
P300 was longer when the arrays contained perceptually similar elements. Consistent with our predictions, the segregation problems present in the PsRi condition apparently led to a delay in stimulus evaluation, as reflected in the delay in P300 latency. However, it is evident that segregation problems are not completely responsible for the P300 delay. For perceptually different arrays, the effect of response compatibility was smaller but still significant. Since the PdRc and PdRi arrays should be equally easy to segregate, the enduring difference between them in P300 latency suggests that this measure is also influenced by the response compatibility manipulation. A similar argument can be made on the basis of the slash target data, where a large effect of incompatibility on P300 is observed when the arrowheads are flankers. It appears that response incompatibility can affect evaluative processes, presumably by contributing to decisional conflict (cf., Botella, 1996).

Although these P300 effects are similar to those observed for RT, it remains to be seen whether differences in stimulus evaluation time (P300 latency) are entirely responsible for the RT effects found across the different stimulus arrays. To evaluate this issue, we now consider the P300 latency-RT relationship.

### The P300 latency-RT relationship

If the relationship between P300 latency and RT remains constant across all experimental conditions, then we infer that the experimental variables exert their effect on RT by changing the duration of the evaluative process. On the other hand, if the relationship between P300 and RT varies, then any differential effects on RT must be

**Fig. 2** P300 latencies and P300-RT intervals for each of the five different array conditions for the letter arrays (left panel) and symbol arrays (right panel). The slope of the lines connecting compatible and incompatible conditions provide a visual representation of the magnitude of the compatibility effect. Note that the scale for the P300-RT interval is inverted. As RT is delayed more, relative to P300, this interval becomes shorter. Ps = perceptually similar array; Pd = perceptually different array; Rc = response-compatible array; Ri = response-incompatible array



attributed to some process other than the P300 process (such as response competition). To explore these ideas, we measured the interval between the RT response and the P300 by subtracting the value of RT from the value for P300 latency for each combination of target and condition separately (see Fig. 2). A repeated-measures ANOVA [Target type (4)  $\times$  Condition (5)] on these derived values revealed a significant main effect of condition,  $F(4, 28) = 7.80, p < .001$ . The interval between the RT response and the P300 was 11 ms shorter for response-incompatible arrays (PsRi and PdRi), planned comparisons,  $p < .05$ . RTs were delayed relatively more than P300 latency for the response-incompatible conditions. This suggests that response incompatibility has an effect both on evaluation processes (given the effects on P300 latency described earlier) and on response-related processes (cf. Coles et al., 1985).

To determine how feature similarity and intrinsic response mapping moderated the compatibility effect, we analyzed the target type  $\times$  condition interaction [ $F(12, 84) = 2.23, p < .05$ ]. For letter stimuli, the interval between P300 and RT was smaller for incompatible arrays, but the reduction was not influenced by feature similarity (see lower left panel of Fig. 2). This means that the difference between similar and dissimilar feature conditions can be explained entirely in terms of stimulus-related processes. In contrast, for symbol arrays, the moderating effect of the type of flanking symbol (arrowhead or slash) is attributable to response processes. As can be seen in the lower right panel of Fig. 2, for both arrowhead and slash targets, the smallest P300-RT intervals were observed when the incompatible flankers were arrowheads (the PsRi condition for arrowhead targets and the PdRi conditions for slash targets, Tukey,  $p < .05$ , respectively). This indicates that RT was delayed more (relative to P300) when the symbol with the strongest intrinsic response mapping was the incompatible flanker.

To summarize, compatibility effects are attributable, at least in part, to delays in stimulus evaluation associated with incompatible arrays. However, since the influence of incompatibility on RT was not always precisely paralleled by its influence on P300, we infer that, in these cases, compatibility effects are also attributable to response processes. Furthermore, the role of response processes appears to be emphasized when incompatible arrowhead flankers were used. In the next sections, we shall consider more direct evidence for the role of response processes.

### Response competition

To evaluate the contribution of response competition to the compatibility effect, trials were classified according to the degree of error present. Following Coles et al. (1985), response categories were: no error, EMG error, partial squeeze error, and criterion squeeze error (RT Error).

### Peripheral response effects

The relationship between correct response latencies (correct squeeze onset and EMG onset) and the degree of error (no error, EMG error, and partial squeeze error categories) are shown in Table 2. Repeated-measures ANOVAs indicated that correct squeeze onset latency significantly increased with increases in the degree of error,  $F(2, 14) = 45.57, p < .001$ . Similar effects were observed for correct EMG onset latency,  $F(2, 14) = 35.78, p < .001$ . These findings are consistent with the notion of response competition (Coles et al., 1985).

In addition, the degree of error activity present was related to the dynamics of response execution as reflected in the interval between correct EMG and squeeze onset. The interval between correct EMG and correct squeeze onset was slightly longer when partial squeeze errors occurred (37 ms) compared to when no error activity (34 ms) and EMG error activity (33 ms) occurred,  $F(2, 14) = 3.45, p = .061$ . This result suggests that the presence of incorrect squeeze activity may interfere (very modestly) with the execution of the correct response. This trend is consistent with those found by Coles et al. (1985). However, the effect reported here is smaller (3–4 ms vs. 10–11 ms).

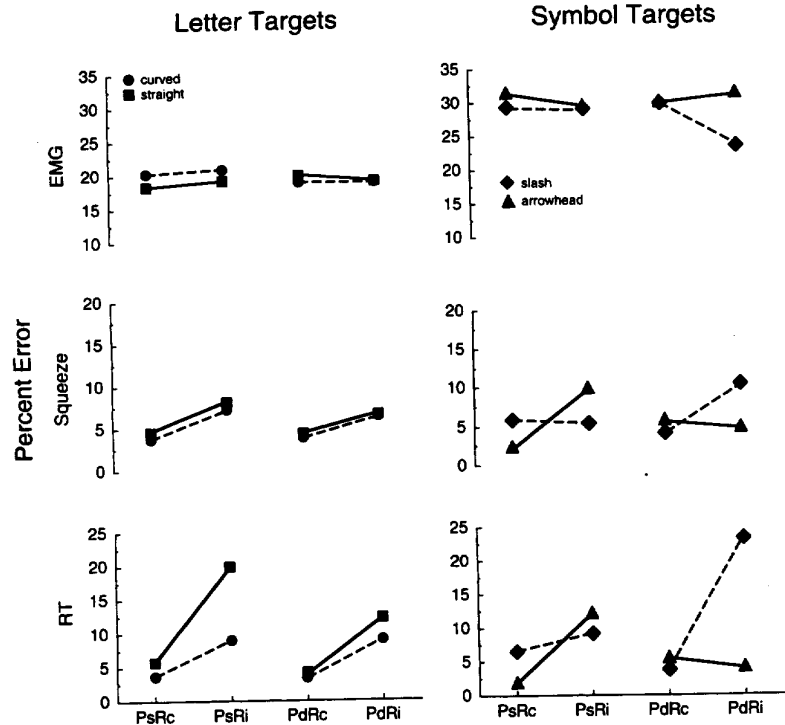
To evaluate the contribution of response competition to the compatibility effects evident in RT, we examined the effect of the type of target and array condition on the proportion of trials in each of the four response categories (no error, EMG error, partial squeeze error, criterion squeeze error). The relevant data are shown in Fig. 3. A repeated-measures ANOVA was performed on these proportion data after they had been transformed using the arc sine transformation (Neter, Wasserman, & Kutner, 1985). A significant interaction between condition and degree of error suggested that complete squeeze errors and partial squeeze errors occurred more frequently for response-incompatible arrays,  $F(12, 84) = 42.73, p < .001$ , (cf. Coles et al., 1985). The source of this interaction lies mainly in the greater frequency of complete errors for response-incompatible arrays, although the frequency of partial squeeze errors was also greater for these arrays (7.7% vs. 4.1%). A significant three-way interaction of target type  $\times$  condition  $\times$  degree of error,  $F(36, 252) = 11.21, p < .001$ , indicated that the effect of compatibility on the error profiles depended

**Table 2** Effects of the degree of response error on correct EMG and correct squeeze onset latencies

	Degree of error		
	None	EMG	Squeeze
Correct onset latency			
EMG	293	312	351
Squeeze	327	345	388



**Fig. 3** Percentages of different kinds of errors (EMG error, Squeeze error, RT error) as a function of target type and array condition. The slope of the lines connecting compatible and incompatible conditions provide a visual representation of the magnitude of the compatibility effect. *Ps* = perceptually similar array; *Pd* = perceptually different array; *Rc* = response-compatible array; *Ri* = response-incompatible array



on the target (see Fig. 3). For letters, there is an effect of compatibility on the frequencies of partial and complete squeeze errors, but this effect is the same for similar and dissimilar arrays (Tukey,  $p > .05$ , respectively). (Note, however, that similar arrays with straight letters had a higher frequency of complete errors relative to different arrays, Tukey,  $p < .05$ ). Thus, the modulating effect of feature similarity on the compatibility effect is not mediated by response-related processes. In contrast, for symbol targets, the effect of compatibility on the frequencies of partial and complete squeeze errors is modulated by the nature of flankers. Whenever arrowheads appeared as incompatible flankers, the incidence of partial and complete errors was much higher than for flanking slashes (Tukey,  $p < .01$ , respectively). This suggests that the larger compatibility effect observed with arrowhead flankers is due to their effectiveness in eliciting their response and to the response competition that ensues when the flankers are incompatible with the target.

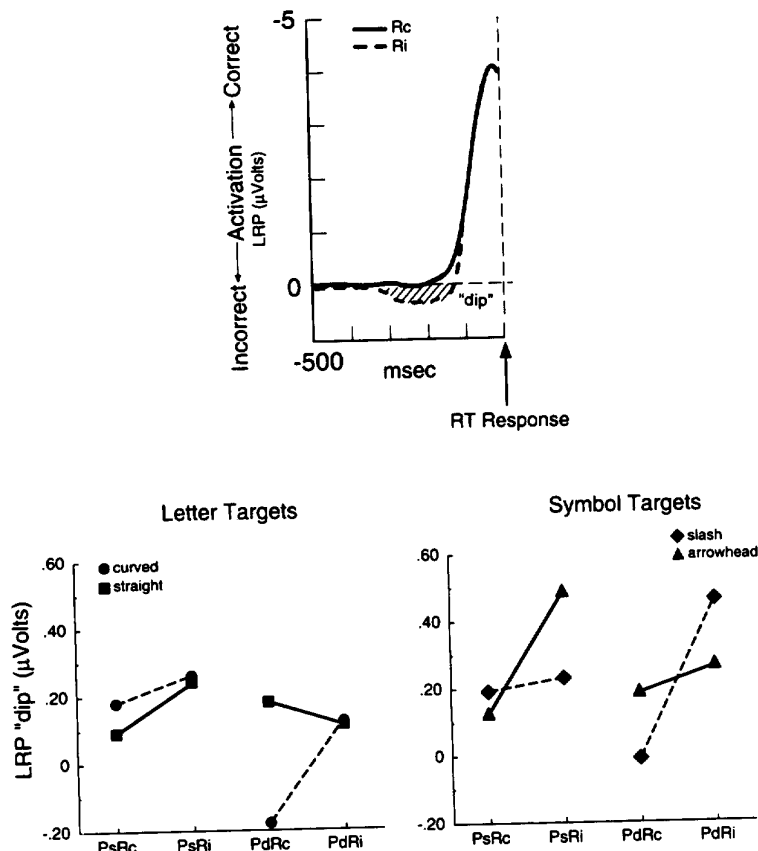
In short, data trends for both letter and symbol arrays show that partial squeeze and complete squeeze errors occur more frequently for arrays containing incompatible flankers, especially when stimuli with the greatest intrinsic response mapping are the flankers. Since correct response latency and, to a lesser extent, the EMG-to-squeeze interval increased when incorrect squeeze activity was present, the longer RTs observed for incompatible conditions can be attributed, at least in part, to response-related processes.

#### Central response effects

Finally, the LRP was used to evaluate the effects of "central" response competition on correct response trials (with either no error or only EMG error activity). We focused on the amplitude of the LRP for the 100-ms epoch immediately preceding the final upswing in the LRP function that is associated with response execution. In prior research (Gratton et al., 1988), we have shown that this aspect of the LRP can be sensitive to response compatibility. A repeated-measures ANOVA [Error activity (2)  $\times$  Target type (4)  $\times$  Condition (5)] performed on the LRP amplitude over this epoch revealed a main effect of array condition,  $F(4, 28) = 3.45$ ,  $p < .01$ . The insert in Fig. 4 shows the LRP waveforms for the response-incompatible arrays and response-compatible arrays, while the rest of Fig. 4 gives the amplitude measures for the different experimental conditions. There was a larger "dip" when the array was response-incompatible (planned comparisons,  $p < .01$ ). This indicates that the incorrect response was activated prior to correct response execution in these conditions. Although the interaction between compatibility condition and target was not significant, it is interesting to note that the largest "dips" (see Fig. 4) were observed in those conditions where the arrow head flankers were incompatible with either arrowhead or slash targets.

These LRP data indicate that even when subjects responded correctly to incompatible arrays (and showed no evidence of incorrect squeeze activity), the incorrect response was activated before the correct response was

**Fig. 4** Amplitude of the "dip" of the lateralized readiness potential (LRP) for the 100-ms-epoch just prior to the final upswing in the LRP. Values are given for each target type and array condition. The upper panel shows the average LRP waveforms for response-compatible and response-incompatible areas, with the area highlighted indicating the place where the dip amplitude was measured. *Ps* = perceptually similar array; *Pd* = perceptually different array; *Rc* = response-compatible array; *Ri* = response-incompatible array



executed. This incorrect response activation delays correct response execution by moving the activation function away from the correct response threshold (Gratton et al., 1988).

## Conclusion

In general, we found compatibility effects for both letter and symbol arrays, replicating the findings of Coles et al. (1985) and Rösler and Finger (1993), respectively. Reaction times were slower and responses were less accurate when arrays were incompatible. As predicted, the effect of incompatibility was moderated by perceptual similarity. For letter stimuli, the greater the similarity in the features of the target and noise letters, the larger the effect of incompatible noise. For symbol stimuli, we found a marked difference in the effectiveness of the slash and arrow stimuli. While this difference masked any effects of similarity for these kinds of stimuli, the difference did enable us to focus on the effects of intrinsic response mapping.

Several lines of evidence suggested that arrow stimuli were more effective in eliciting their associated responses because of their intrinsic response mapping (see especially Eimer, 1995). Slash stimuli appeared to be as effective as the letter stimuli, for which the intrinsic

response mapping was arbitrary. Thus, comparisons between the two symbol conditions (rather than between symbol and letter conditions) provided a good test of the role of intrinsic response mapping. In fact, compatibility effects were largest whenever arrowheads were flankers.

In line with previous research (e.g., Coles et al., 1985; Gratton et al., 1988), the effects of compatibility appear to be attributable to both stimulus and response-related processes. For all kinds of arrays, P300 latency was longer when the array was incompatible, suggesting that evaluation processes are prolonged under these conditions. Furthermore, whenever an array contained incompatible noise, a variety of response measures suggests that the incorrect response is activated more frequently and with more "vigor" than when the noise is compatible. In turn, this incorrect response activation was associated with a delay in the execution of the correct response (consistent with the notion of "response competition").

As we noted above, the magnitude of the compatibility effect depended on two variables: perceptual similarity among the elements in the arrays, and the effectiveness of the stimuli in eliciting their associated responses. The locus of these moderating effects was revealed by the analysis of the various dependent variables. For letter stimuli, the moderating effect of perceptual similarity could be explained in terms of

stimulus-related processing. This inference was based on the effects of this manipulation on P300 latency, the invariance of the P300 latency-RT interval, and the absence of similarity effects on degree of error profiles and the LRP. The greater the similarity among the elements in the display, the more time was needed for the array to be segregated into its component parts. In contrast, for symbol stimuli, the moderating effect of intrinsic response mapping could be explained in terms of response-related processes. The P300-RT interval, degree of error profiles, and the LRP were all affected by the type of symbol, with arrowheads being associated with greater incorrect response activity when they occurred as incompatible flankers. These latter findings are consistent with those found by Eimer (1995), who showed that single arrow cues caused early response activation, evident in the LRP, that corresponded to the side of the response hand to which the arrow pointed. Furthermore, this LRP activity was present even when the arrow direction did not always correctly predict the response hand.

Based on the data reviewed above, it is reasonable to propose that the same processes are affected by the presence of incompatible flankers in all arrays, and that symbol and letter arrays are not processed differently, as was suggested by Rösler and Finger (1993). What is different is the degree to which stimulus and response-related processes are affected by incompatibility. Similarly, when the present results for letter stimuli are compared to those reported by Coles et al. (1985), differences in the relative contribution of the two processes are also evident. In the present study, peripheral response competition was found to play a more minor role in contributing to the compatibility effect. For example, the frequency of partial squeeze errors for incompatible arrays was much lower in the present experiment (6% vs. 16%, respectively). This discrepancy may be attributed to several important differences between our letter arrays and the letter arrays used by Coles et al. First, Coles et al. used five letters in the arrays, while the present study used three letters in the arrays. Thus, there were only two flankers (rather than four) to activate the competing response. Second, in the Coles et al. study, the individual letters (*H* and *S*) that were assigned to two different responses had clearly distinguishable features (curved vs. straight). Thus, subjects could respond accurately on the basis of crude, preliminary feature analysis. In the present study, two stimuli were mapped to each of the two responses, and these two stimuli contained both curved or straight features. The letters *H* and *S* were mapped to one response, while the letters *N* and *C* were mapped to the other response. Thus, subjects could not respond accurately on the basis of a crude analysis of the straight vs. curved features of the letters. The arrays used in the present study may have required a more detailed (and longer) perceptual analysis compared to those used in the Coles et al. study. The need for a longer perceptual analysis would

reduce the time period within which incompatible flankers (even those that are perceptually distinct from the target) could activate their responses before the central target activated its response. In turn, this shorter interval would limit the opportunity for response competition to occur (see Fournier, 1994).

To summarize: we sought to determine the locus of the compatibility effect for stimuli that vary in feature similarity and intrinsic response mappings. We found the compatibility effect to result from a combination of stimulus evaluation delays, central response competition, and peripheral response competition. The relative contributions of these processes depend on feature similarity and intrinsic response mapping.

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