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Attentional Scanning in the Selection of Central Targets from Multi-symbol Strings

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Subjects responded to five-symbol strings consisting of a central target, one or two compatible or incompatible flankers, and neutral symbols in the remaining positions. Performance strongly depended on the position of compatible or incompatible flankers. With normal letters, left-side flankers had a much larger impact than right-side flankers. This left-side asymmetry of the flanker compatibility effect disappeared with strings composed of spaced letters or of tiny pictures and tended to turn into a right-side asymmetry with vertically mirrored letters. These results seem to indicate the operation of attentional scanning processes. Flankers may be scanned either automatically, due to a reading-like habit, or strategically, in attempting to localize the target.

The human ability to attend selectively to an object among others is rather limited. This is strikingly demonstrated in a task introduced by B. A. Eriksen and C. W. Eriksen (1974) that has become a very popular tool for investigating attentional mechanisms. Basically, the subject is presented with a target, say the letter *S* or *H*, to which a certain response is assigned, such as pressing a left- or right-hand key, respectively. The crucial manipulation is that the target is flanked by members of the target set, so that, in a given trial, target and flankers may be mapped onto either the same response (e.g. *SSSSS*) or onto different responses (e.g. *HHSHH*). Although subjects know the location of the target in advance and

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are instructed to ignore the flankers, they respond faster when the targets are accompanied by compatible than by incompatible flankers (B. A. Eriksen & C. W. Eriksen, 1974; C. W. Eriksen & Schultz, 1979; Miller, 1991). Moreover, flanker-related activation of the incorrect response can be measured both electromyographically (Coles, Gratton, Bashore, C. W. Eriksen, & Donchin, 1985; C. W. Eriksen, Coles, Morris, & O'Hara, 1985) and behaviourally (St. James, 1990) even in correct trials, this indicating that flankers are processed up to a level of incipient response activation.

Usually the impact of flankers on performance is viewed as a problem of the limited resolution of spatial attention. It is proposed that stimuli are selected by employing a precategorial filtering mechanism, such as a "zoom-lens" or an "attentional spotlight" (e.g. C.W. Eriksen & Yeh, 1985; LaBerge, 1983; Posner, 1980) that restricts stimulus processing to a certain area in space. This filter is assumed to have a limited resolution, so that flankers too close to the target may fall into the attended area, thereby producing the flanker-compatibility effect (FCE). Spotlight approaches predict that the FCE should vary with the distance between target and flankers. In fact, it has been shown repeatedly that the FCE decreases with increasing distance, whether the space between target and flanker is empty (e.g. B.A. Eriksen & C.W. Eriksen, 1974; Miller, 1991; St. James, 1990) or contains response-compatible letters (e.g. C.W. Eriksen & Hoffman, 1973). More important for the present study, spotlight approaches do not predict any spatial asymmetries of the FCE—that is, the FCE should not depend on the side or the relative position of the compatible or incompatible flankers. In other words: spotlight approaches predict a spatial distribution of the FCE that is symmetrical around the target.

There is, however, evidence for an asymmetrical distribution: Harms and Bundesen (1983) found that, overall, flankers to the left of the target had a stronger impact on performance than flankers to the right. Thus, the likelihood of processing a flanker seems to depend on its relative position in the stimulus string or on some correlated property. Further support for this idea comes from a study of Hell (1987, Experiment 17), where the subjects named either one or all elements of a row of digits. When two or three different digits were presented, the one to the left was reported or named first more often than any other. A left-side advantage could also be shown in a somewhat more traditional flanker compatibility design (Experiment 18), where, in different blocks, the left, the central, or the right digit of a row of digits was named. With rows of three digits, responses were faster to left targets than to central or right targets. In a further study (Experiment 20), Hell found that in order to be chosen more often than digits at the left position, right digits need to be preexposed about 20 msec. Finally, Pashler (1984) found that in several bar probe tasks and under different stimulus onset asynchronies, leftmost stimuli were consistently responded to faster than rightmost stimuli. In sum, then, these results indicate that attention is not distributed symmetrically in the processing of letter strings such as those used in the flanker-compatibility task.

The aim of the present study was to investigate the FCE's spatial distribution around the target. In standard flanker tasks, the flankers are identical. For example, the target *S* may be flanked by incompatible *H* flankers in a string such as *HHSHH*. If the flankers yielded an interference effect as compared to a neutral or compatible condition, we would not be able to determine whether all flankers have the same impact or whether there is a certain spatial distribution of the FCE. Therefore, I used five-letter stimulus strings that consisted of a central target and either one or two critical (i.e. compatible or incompatible) flankers. The remaining flanker positions were filled with replications of a neutral stimulus. The relevant question was whether the position(s) of the critical flanker(s) matter(s)—that is, whether the FCE is larger with this flanker in a certain position. If so, this would demonstrate that this position was attended to more often or was more likely to be attended to than other flanker positions.

Experiment 1 was an attempt to replicate the left-side advantage as found in the studies mentioned above in a standard flanker-compatibility task. In Experiment 2, the effects of target–flanker distance and flanker side were compared. Experiments 3–5 investigated whether the spatial distribution of attention depends on the stimulus material.

EXPERIMENT 1

Experiment 1 was conducted to test the general idea that attention may be asymmetrically distributed in the flanker compatibility task. A standard flanker task was employed, with a central letter target (an *S* or an *H*) and four letter flankers, two on each side of the target. The flankers on one side were either compatible or incompatible with the target—that is, identical with the current or the alternative target; the side of these critical flankers was randomly determined from trial to trial. The two remaining flanker positions on the opposite side contained neutral letters (*D*s). It was expected that critical flankers on the left side of the target would produce a larger FCE than flankers on the right.

Method

Subjects

Eight female and seven male adults were paid to participate in single sessions of about 30 min. They reported having normal or corrected-to-normal vision and being right-handed. Subjects were not familiar with the purpose of the experiment.

Apparatus and Stimuli

Stimulus presentation and data acquisition were controlled by a Hewlett Packard Vectra QS20 computer, interfaced with an Eizo MD-B11 graphics adaptor and attached to an Eizo 9070S (or 9080i) monitor. All stimuli were taken from the CGA text mode font. Responses were given by pressing the left or right shift key of the computer keyboard with the corresponding index finger.

From a viewing distance of approximately 60 cm, the subject saw a white rectangular field 5.8° in width and 3.3° in height. The *y* position of the stimuli was continuously marked by two arrows, 1.2° to the left and right of the centre. The fixation point, an asterisk, and the target stimulus appeared black-on-white at the geometrical centre of the screen. The uppercase letters *S* and *H* served as targets that were assigned to the left and right response key, respectively. Each target was flanked by four distractor letters, two on either side. The flankers on one side were either compatible (identical to the target) or incompatible (identical to the alternative target). The remaining two flanker positions were filled with the neutral letter *D*. Uppercase letters measured 0.3° × 0.4°, so that the whole five-letter string consisting of the central target and the four flankers extended over 1.4° × 0.4°.

Procedure

Each session comprised two warming-up blocks and 40 experimental blocks. Blocks consisted of eight randomly ordered trials, whose type resulted from the possible combinations of two target letters (*S* or *H*), two critical flanker letters (*S* or *H*), and two critical flanker locations (left or right). In each trial, the sequence of events was as follows: After an intertrial interval of 2000 msec, the fixation point was presented for 100 msec, followed by a blank interval of 1000 msec. The row of five letters was then presented for 150 msec. The program waited until the response was given but no longer than 1000 msec. Responses with the wrong key were counted as errors, and responses with latencies above 1000 msec were considered missing. In both cases, audible error feedback was given, and the trial was recorded and repeated at some random position in the remainder of the block. The subjects were asked to respond only to the central target letter, as fast and as correctly as possible. It was emphasized that flanking letters were irrelevant and should be ignored.

Results

For each subject, mean reaction times (RTs) and proportions of errors (PEs) were computed as a function of side (left vs. right) and compatibility of critical flankers (compatible vs. incompatible).

A 2 × 2 factorial analysis of variance (ANOVA) of the RTs revealed three effects. The highly significant effect of compatibility, $F(1, 14) = 78.24$, $p < 0.001$, showed that responses were about 32 msec faster with compatible than with incompatible critical flankers (494 vs. 527 msec). A marginally significant effect of side, $F(1, 14) = 3.85$, $p < 0.07$, indicated faster responses when the critical flankers were on the right than on the left side. Finally, the highly significant interaction of compatibility and side, $F(1, 14) = 24.61$, $p < 0.001$, confirmed that the compatibility effect was twice as large when the critical flankers were on the left (492 vs. 535 msec) than when they were on the right side (497 vs. 519 msec). Planned comparisons, however, showed that even the right-side compatibility effect was clearly significant ($p < 0.001$; always one-tailed).

An analysis of the error data revealed a highly significant main effect of compatibility, $F(1, 14) = 13.70$, $p < 0.005$, produced by lower PEs with compatible as compared to incompatible critical flankers (3.0% vs 6.4%). The interaction of compatibility and side only reached the 10% level, but it also indicated a larger compatibility effect with critical flankers on the left (2.4% vs 7.1%) than on the right side (3.6% vs. 5.7%).

Discussion

The results are clear-cut in demonstrating a larger FCE when compatible and incompatible flankers appear on the left than on the right side of the target. This replicates the findings of Harms and Bundesen (1983) and corresponds to the several left-side advantages demonstrated by Hell (1987) and by Pashler (1984). The finding of a spatial asymmetry in the effectiveness of irrelevant stimulus information is not anticipated by spotlight approaches, as proposed by C. W. Eriksen and Yeh (1985), LaBerge (1983), or Posner (1980). Nevertheless, let us consider three possible arguments that may be put forward to account for the present data from a spotlight view:

1. As originally assumed by Harms and Bundesen (1983), the asymmetry may be due to processing differences between the two cortical hemispheres. The left-side superiority of the FCE may result from a stronger activation of the right as compared to the left hemisphere, this leading to a preference for information from the left hemifield. A hemispherical account may come in two versions. A material-independent version would predict a left-side superiority, no matter which stimulus material is used. As we will see further on that different stimuli bring about different FCE distributions, the material-independent version of the hemispherical explanation can be discounted. A material-dependent version proposes that different stimuli activate the hemispheres in different ways, so that stimulus-dependence as such cannot be used as a counter-argument. In fact, there is abundant evidence that, in right-handers, verbal stimuli are processed faster (or are more likely to be) in the left hemisphere, and pictorial stimuli produce symmetrical effects or a right-hemisphere advantage (e.g. Bryden, 1965; Heron, 1957; Moscovitch & Klein, 1980). However, as stimuli in the

visual hemifields are processed in the contralateral hemisphere, one would then expect stronger impact of right-side versus left-side letter flankers, which is, of course, contrary to the results of Experiment 1. So, an account of the present results in terms of differential hemispherical activation seems implausible.

2. The attentional focus, which spotlight approaches propose to be directed at the target location, may be asymmetrically extended to the left, so that left-side flankers would be more likely to fall within the attended area. A related version would be that the focus, irrespective of its form, is not neatly centred at the target position but shifted somewhat to the left side. Again, the predictions from these accounts vary, depending on whether material dependency or independency is assumed. A material-independent version can be discounted for the same reasons as a material-independent hemispherical account. A material-dependent version may refer to findings from reading and visual search studies that strongly suggest the existence of an asymmetrically extended attentional focus in the case of letter processing (McConkie & Rayner, 1976; Osaka & Oda, 1991; Prinz, 1983; Prinz & Kehrer, 1982; Rayner, Well, & Pollatsek, 1980). However, these studies demonstrate an attentional bias that is directed forwards (i.e. to the right and/or down, depending on reading direction) but not backwards (i.e. to the left or up), so that a right-side advantage would be expected in the present experiment. Thus, the available data do not support a spotlight asymmetry account of the left-side bias emerging from the present data.

3. One may consider a spotlight drift hypothesis: In a trial, the attentional spotlight may first be attracted by the upcoming fixation point, but then (after this has disappeared again) drift somewhat to the left before the actual stimulus is presented, thus enhancing the impact of left-side flankers. This hypothesis may account for the data from Experiment 1, but it is not overly plausible. On the one hand, the presence of spatial markers does not change the outcome very much: Here and in the following experiments, spatial information was not only provided by the transient fixation point but also by continuously visible markers to the left and right of the stimulus. In the original experiment of Harms and Bundesen (1983), there was even a constant fixation mark directly below the target position, and the result was the same. Moreover, an unpublished experiment showed that the left-side asymmetry is also obtained when the target position is marked by prepresenting a dot that is a part of either (forthcoming) stimulus alternative.[1] On the other hand, it is obvious that the drift hypothesis cannot handle the material-specific effects reported below better than the hemispherical or the spotlight asymmetry account.

In sum, then, spotlight approaches have no convincing explanation of the asymmetrically distributed FCE, and it is difficult to see how they might plausibly be extended to do so. In search for a theoretical alternative, it is interesting to note the striking resemblance between the present results and the common

[1]I am grateful to Jan Theeuwes for suggesting this experiment to me.

finding of left-side advantages in the processing of multi-letter strings in whole-report tasks. For example, Crosland (1931) found that when letter-strings exposed briefly have to be reported, accuracy decreases monotonously from the leftmost to the rightmost element. This left-side advantage does not simply result from rehearsal strategy or response order bias, as it also occurs when subjects report in a right-to-left order (Mewhort, 1974; Scheerer, 1972), or search through the string for a target letter (Krueger, 1976).[2] Even memory load does not play a major role, as the left-side advantage does not disappear with long exposure durations (Estes, Allmeyer, & Reder, 1976). To account for these findings, several variants of an attentional theory first proposed by Heron (1957) have been put forward. All have at their core the assumption of an attentional scanning mechanism operating on elements that are identified more (Mewhort & Campbell, 1981) or less (Bryden, 1967; Scheerer, 1972; Wolff & Mewhort, 1986; Yund, Efron, & Nichols, 1990).

Although these experiments demonstrate scanning-like effects in the processing of letter strings, the tasks employed required subjects to pay attention to all elements, whereas the present flanker task required them to ignore the flankers. So, even if scanning processes are involved in the sequential processing of rows of equally relevant elements, why should scanning occur in a task that merely requires the processing of a single element at a known location? I see at least two explanations: (a) Letters may automatically induce a reading-like habit, so that a letter string attracts attention to its leftmost element(s). This would interfere with attending to the target and permit a greater impact of the scanned element(s). (b) The presence of incompatible flankers may induce a response conflict that can only be solved by localizing the target - that is, by associating letter identities with positions. Possibly, in order to localize the target relative to another string element, the other element must be given some attention. If subjects used their reading skills for relative localization, they might start with the leftmost element and then work through the string until the target position is reached. With a constant number of flankers, it would be of no use to continue beyond the target position, so that right-side letters would not be involved. Both explanations are very similar in their reliance on reading-like habits, either as a cause of conflict or as a means to solve it, and, consequently, their predictions are often identical. As the results of the present study will not permit a distinction to be made between the two possibilities, I will subsume them under the term "scanning hypothesis". The most important prediction of this scanning hypothesis—namely that reading-like habits are more probably invoked or applied with word-like structures and with letter strings than with other material—is tested in Experiments 3–5.

[2]Evidence for the spatially or positionally ordered processing of letter material in a wider range of tasks has been reported by Harris, Shaw, and Altom (1985), Hockley (1984), Proctor and Healy (1987), and Townsend and Roos (1973), among others. Numerous demonstrations of scanning effects with non-alphanumerical material by Efron and colleagues have been summarized by Efron (1990).

EXPERIMENT 2

The second experiment was conducted both to replicate the results of Experiment 1 and to get a more differentiated picture of the spatial asymmetry. Specifically, it would be of interest to know whether flankers on the same side would yield comparable FCEs, or whether these are modulated by other variables, such as eccentricity. As already mentioned, there is a great deal of evidence that the FCE is reduced when the distance between target and incompatible flankers increases (e.g. B. A. Eriksen & C. W. Eriksen, 1974; C. W. Eriksen & Hoffman, 1973; Miller, 1991; St. James, 1990). As with horizontal letter strings, distance and retinal eccentricity are confounded, and this reduction may be due to attentional or peripheral factors. A common interpretation from a spotlight perspective is that the resolution of a hypothetical attentional spotlight may be too limited to exclude inner positions but sufficient to exclude outer positions (B. A. Eriksen & C. W. Eriksen, 1974). It may also be that retinal acuity modulates flanker processing, so that outer flankers are processed either more slowly or are less likely to be processed than others (Hagenaar & Van der Heijden, 1986). In any case, the available evidence suggests less influence of outer as compared to inner flankers.

The same logic was applied as in Experiment 1. However, there the two flankers on the same side were always identical, whereas here only one critical flanker appeared in each trial. That is, there was always a central target (Position 3, from left to right), one critical flanker in Position 1, 2, 4, or 5, and three neutral flankers in the remaining positions.

Method

Subjects

Five female and eleven male adults were paid to participate in single sessions. They reported having normal or corrected-to-normal vision and being right-handed, with one ambidextrous exception. Subjects were not familiar with the purpose of the experiment.

Apparatus and Stimuli

These were exactly as in Experiment 1, with only one exception. Here, each central target was accompanied by only one critical (i.e. compatible or incompatible) flanker, and the remaining three positions were filled with neutral *D*s.

Procedure

The only changes as to Experiment 1 were as follows. Each session comprised one warming-up block and 320 experimental blocks. Blocks consisted of 16 randomly ordered trials, whose type resulted from the possible

combinations of two target letters (*S* or *H*), two critical flanker letters (*S* or *H*), and four critical flanker locations (Positions 1, 2, 4, or 5 in the five-letter string, from left to right).

Results

For each subject, mean RTs and PEs were computed as a function of side, eccentricity, and compatibility of the critical flanker. Figure 1 shows the results.

An ANOVA of the RTs revealed five highly significant effects. A main effect of compatibility, $F(1, 15) = 97.41$, $p < 0.001$, showed that compatible flankers led to faster responses than did incompatible flankers. An effect of eccentricity, $F(1, 15) = 15.26$, $p < 0.001$, indicated that responses were faster with critical

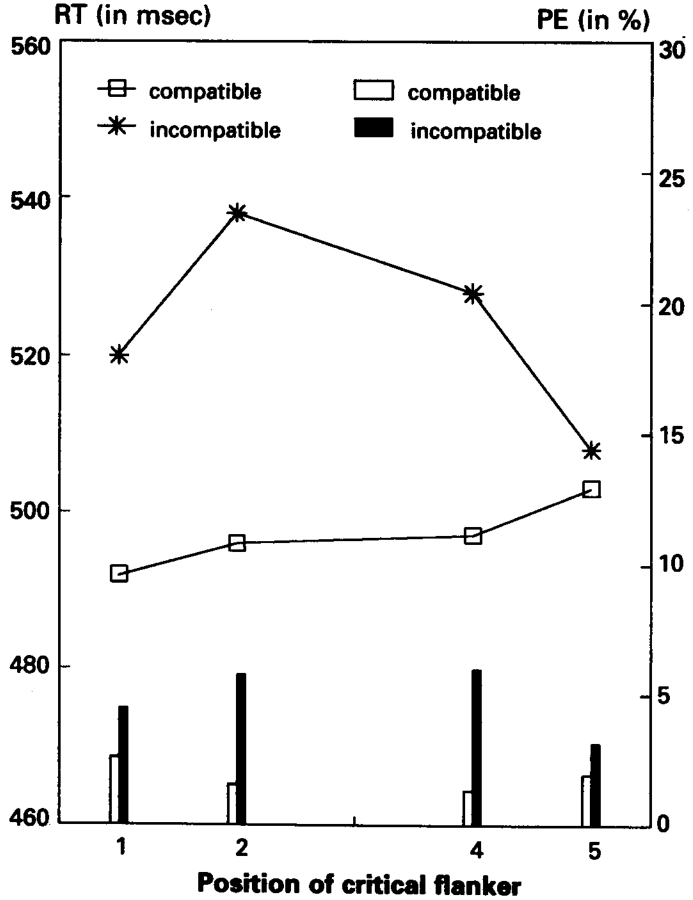

FIG. 1. Experiment 2: Reaction time (RT, lines) and proportion of errors (PE, bars) as a function of position of critical flanker and flanker compatibility.

flankers in outer than in inner positions. Furthermore, there was a Compatibility × Eccentricity interaction, $F(1, 15) = 16.93$, $p < 0.001$, produced by compatibility effects that were more than twice as large with inner than with outer critical flankers, as well as a Compatibility × Side interaction, $F(1, 15) = 21.15$, $p < 0.001$, that resulted from larger compatibility effects with left-side than with right-side flankers. Finally, a three-way interaction, $F(1, 15) = 14.02$, $p < 0.005$, indicated that, with critical flankers on the right side, the diminishing impact of eccentricity on the compatibility effect was much stronger than with left-side flankers. Planned comparisons showed that compatibility effects were highly significant ($p < 0.001$) for all but the rightmost position ($p > 0.11$).

An analysis of the PEs revealed only two effects—a highly significant compatibility effect, $F(1, 15) = 51.50$, $p < 0.001$, which was modified by a significant Compatibility × Eccentricity interaction, $F(1, 15) = 7.70$, $p < 0.05$. As in the RTs, compatibility effects were larger with critical flankers in inner than in outer positions. Although no other effect reached significance, the pattern of the error data strongly resembled the RT pattern.

Discussion

Experiment 2 yielded several noteworthy results.

1. The left-side superiority of the FCE as found in Experiment 1 is replicated. Obviously, the size of the FCE depends on the position of the critical flanker, and, in accordance with the scanning hypothesis outlined above, left-side flankers exert a greater impact on performance than do right-side flankers.
2. The distance effect demonstrated by B. A. Eriksen and C. W. Eriksen (1974) and others was replicated. That is, the FCE decreases with increasing distance between target and flanker or, as distance and eccentricity were confounded, with increasing flanker eccentricity. Whether this result is due to loss of retinal acuity towards the periphery or to attentional factors is discussed in Experiment 3.
3. The significant three-way interaction confirms that eccentricity does not affect left-side flankers in the same way as right-side flankers. As Figure 1 shows, eccentricity had a strong effect on the FCE for flankers on the right but not on the left side. On the right side, the FCE is almost completely eliminated at the rightmost position, and the eccentricity effect is only modest for left-side flankers. It seems that eccentricity can unfold its large impact on flanker selection only if it is not counteracted by a strong tendency to process outer flankers, such as a reading habit.

Although the overall results support the hypothesis of a scanning mechanism in general, a closer look at the individual spatial distributions of the FCE revealed that scanning did not uniformly proceed in a left-to-right manner. In fact, the largest FCE was associated for three, seven, and four subjects with Position 1, 2, and 4, respectively, and no subject had a large FCE at the rightmost position. Thus, letter strings do not invariably induce a certain habit or strategy; they only make its activation or employment more likely than that of others. This is further evidence against the views that the FCE asymmetry results from a hard-wired property of the information processing system or from an invariant left-side bias due to, for example, asymmetrical activation of cortical hemispheres. Obviously, the asymmetry is produced by some kind of tendency or strategy that may or may not be invoked or applied. If so, we should be able to modify the spatial distribution of the FCE by means of manipulating display features or the stimulus material. This was the logic behind the following experiments, in which spaced letters (Experiment 3), pictorial stimuli (Experiment 4), and mirror-letters (Experiment 5) were used.

EXPERIMENT 3

Experiments 1 and 2 employed word-like letter strings as stimulus material. Consequently, it was assumed that reading habits involving left-to-right scanning were induced, so that left-flankers were scanned more often than were right-side flankers. Visually, a word is characterized by a considerable proximity of its letters. If the left-side superiority of the FCE really arises from an induced reading habit, and if this habit is triggered by the word-likeness of the stimulus material, the left-side superiority of the FCE should depend on word-likeness. In Experiment 3 it was attempted to modify the spatial distribution of the FCE by using a wider letter-spacing of the stimuli. In all other respects, Experiment 3 replicated Experiment 2. It was assumed that the resulting letter strings would be less likely to be perceived as word-like entities, and would, therefore, be less likely to induce a reading habit. So, we expected the left-side superiority of the FCE to be reduced, if not eliminated.

Method

Subjects

Eleven female and six male adults were paid to participate in single sessions. They reported having normal or corrected-to-normal vision and being right-handed. Subjects were not familiar with the purpose of the experiment.

Apparatus, Stimuli, and Procedure

These were as in Experiment 2, with the following exceptions: The spacing between the letters making up the stimulus string was approximately 0.3°, so that the five-letter string extended over 2.6° in width. Consequently, the marker arrows were located 1.8° to the left and right of the centre.

Results

RTs and PEs were treated analogously to Experiment 2. The results are given in Figure 2.

The RT analysis only revealed a highly significant effect of compatibility, $F(1, 16) = 21.07, p < 0.001$. Planned comparisons confirmed that the compatibility effects were significant for all positions ($p < 0.05$). In a comparison of the corresponding conditions of Experiment 2 (Positions 1 and 5) and Experiment 3 (Positions 2 and 4), the experiment variable—apart from producing a significant main effect—entered into a highly significant three-way interaction with side and compatibility ($p < 0.005$), which further illustrates the absence of any asymmetrical FCE in Experiment 3.

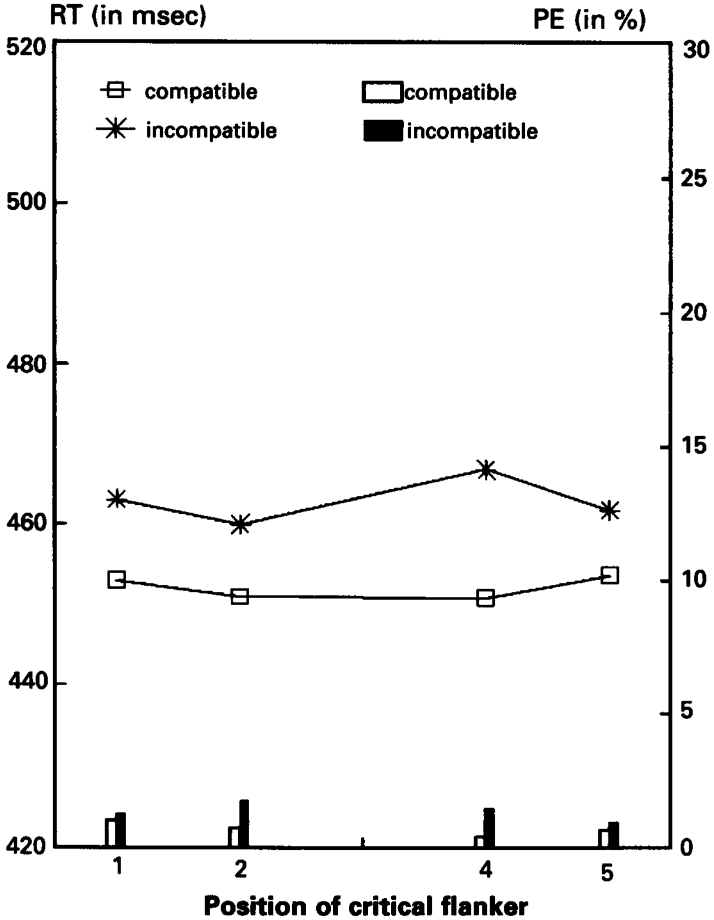

FIG. 2. Experiment 3: Reaction time (RT, lines) and proportion of errors (PE, bars) as a function of position of critical flanker and flanker compatibility.

In the PE analysis, a highly significant main effect of compatibility was obtained, $F(1, 16) = 13.37, p < 0.005$, which was modified by a highly significant Compatibility × Eccentricity interaction, $F(1, 16) = 12.67, p < 0.005$. The latter resulted from larger compatibility effects for inner than for outer positions of the critical flanker.

Discussion

It was expected that the spacing of string elements would reduce or eliminate the left-side FCE superiority found in Experiments 1 and 2. This is confirmed by the data of Experiment 3, as there is no indication for any left-right asymmetry in the effects of compatible or incompatible flankers. This is obvious after comparing Positions 1 and 5 of Experiment 2 with Positions 2 and 4 of Experiment 3. These positions are identical in terms of spatial location and flanker–target distance; they differ only in relative string position. So, from a spotlight view, one would expect similar compatibility effects from flankers appearing there. In striking contrast to this, however, the compatibility effects differ greatly: Whereas the left location produced an effect three times higher in Experiment 2 than in Experiment 3 (28 vs. 9 msec), the right location yielded exactly the opposite result (5 vs. 16 msec). Thus, compatibility effects depend strongly on relative position, suggesting that the wider spacing between the string elements modified the stimulus string such that it no longer triggered a particular habit or strategy more than others. This also corresponds to the fact that the position of the maximum FCE was rather variable over subjects: Position 1 yielded the largest FCE for four subjects, Position 2 for five, Position 4 for six, and two subjects had a maximal FCE at the rightmost position. On average, the individual FCE maxima amounted to 32 msec (ranging from 11 to 56 msec), so that the absence of a left-side superiority cannot simply be ascribed to the small size of the overall FCE. In other words, the rather small overall FCE does not indicate that scanning was absent, but only that, as a result of wider letter-spacing, the scanning behaviour was less uniform than in the preceding experiments. And this was what we had expected.

A further interesting result is the absence of eccentricity effects, at least in the RT data. At first sight, this seems to contradict the finding that the FCE decreases with target–flanker distance. However, Experiment 2 gave us some indications that scanning may compensate for distance/eccentricity effects. So, here, wider spacing may have induced a preference for outer flankers to a degree that just compensated for the eccentricity-related disadvantage. The result would be a uniform FCE distribution as obtained, only mimicking a null effect of eccentricity. In fact, the individual distributions showed that the overall RT pattern was composed of contributions from subjects showing considerable decreases in the FCE for the two outermost positions and from about one third of the subjects showing a preference for outer flankers–that is, the present results are not necessarily incompatible with the finding that the FCE depends on flanker distance.

Still, the fact that distance effects can be eliminated or compensated for poses further problems for spotlight or other resolution-related approaches to the FCE, at least if filtering operations are proposed to precede stimulus analysis. These approaches assume that a larger flanker–target distance increases the likelihood of the flanker to fall outside the proposed spotlight. As a consequence, outer flankers should produce a smaller FCE than inner flankers. It is difficult to see how such an explanation can account for the absence of an overall eccentricity effect. This absence would only be possible if the flanker–target distance is either so small that all flankers lie within the spotlight, or so large that all flankers fall outside it. The first possibility would be more likely in Experiment 2, where all flankers were within an area of 1.4°, compared with Experiment 3, where the area was about twice as large. The expectation would be that an effect of eccentricity would be more likely in Experiment 3 than in Experiment 2, which is, of course, the opposite of what we obtained. The second possibility—that all flankers fall outside the attentional spotlight—would suggest an absence of the FCE in Experiment 3. However, the results yield a small but clearly significant FCE, and the individual distributions argue even more against the prediction of a null effect.

EXPERIMENT 4

The prediction of a left-side FCE superiority in Experiments 1 and 2 was based on the idea of a reading habit that is triggered by word-like letter strings. If this view is correct, the hypothetical habit as expressed in the FCE asymmetry should depend on the stimulus material and, thus, disappear with stimulus elements other than letters or numbers. Consequently, in Experiment 4, the letters used in the preceding experiments were replaced by tiny pictures. In whole-report tasks, left-to-right scanning has been found to be less likely with geometric figures than with letters (Bryden, 1960). If similar scanning tendencies are involved in whole-report and flanker compatibility tasks, figure strings should be processed differently from letter strings—that is, a less reading-like scanning tendency should be induced in Experiment 4. If so, the clear left-side superiority of the FCE as found in Experiments 1 and 2 should decrease or even disappear.

Method

Subjects

Seven female and five male adults were paid to participate in single sessions. They reported having normal or corrected-to-normal vision and being right-

handed, with one ambidextrous exception. Subjects were not familiar with the purpose of the experiment.

Apparatus and Stimuli

Those were as in Experiment 2, with the following exceptions: Targets as well as flankers were not letters but tiny pictures of fruits, of the same size as an uppercase letter. Pixel maps are given in Figure 3. The apple and the carrot symbol assigned to the left and right response key, respectively, served as target stimuli; the banana picture was used as neutral flanker. As in Experiment 2, each central target was accompanied by only one critical (i.e. compatible or incompatible) flanker, and the remaining three positions were filled with neutral banana symbols.

Procedure

The only changes from Experiment 2 concerned the stimuli: The warming-up block and each of the 20 experimental blocks consisted of 16 randomly ordered trials, whose type resulted from the possible combinations of two target symbols (apple or carrot), two critical flanker symbols (apple or carrot), and four critical flanker locations (Positions 1, 2, 4, or 5 in the five-symbol row, from left to right).

Results

RTs and PEs were treated analogously to Experiment 2. The results are given in Figure 4.

The RT analysis revealed four significant effects. A highly significant compatibility effect, $F(1, 11) = 19.37$, $p < 0.001$, showed that compatible symbols led to faster responses than incompatible ones. A highly significant effect of eccentricity, $F(1, 11) = 24.90$, $p < 0.001$, indicated that responses were slowed down more by critical symbols at inner positions than by outer symbols.

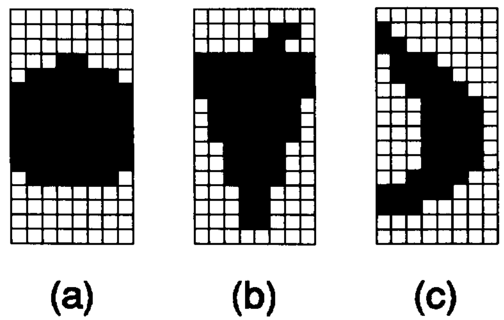

FIG. 3. Pixel maps of (a) an apple, (b) a carrot, and (c) a banana, used as stimuli in Experiment 4.

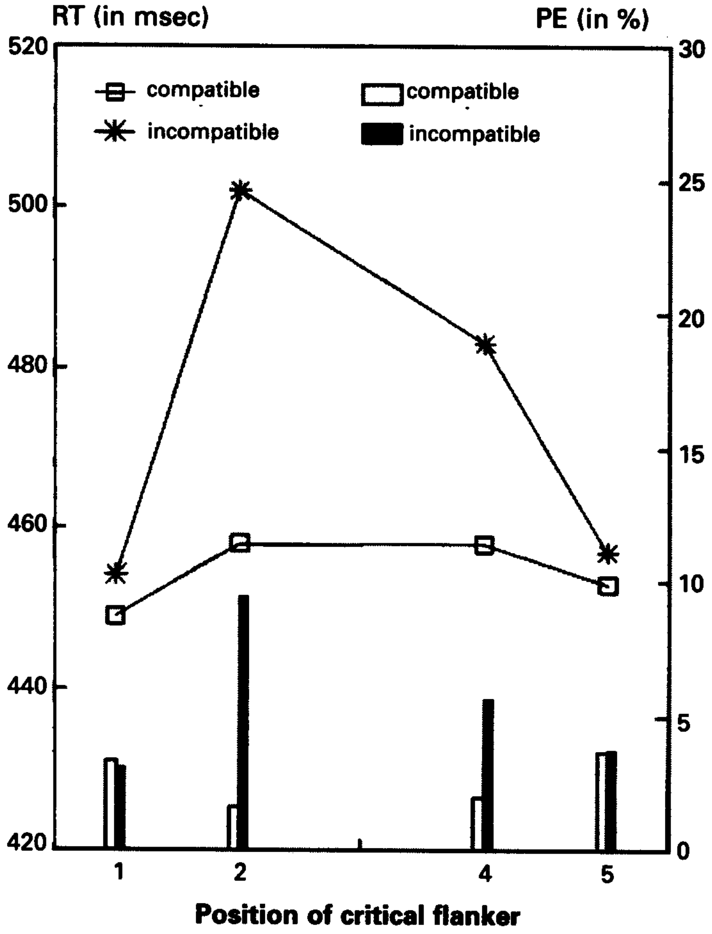

FIG. 4. Experiment 4: Reaction time (RT, lines) and proportion of errors (PE, bars) as a function of position of critical flanker and flanker compatibility.

The Side × Eccentricity interaction, $F(1, 11) = 6.93$, $p < 0.05$, resulted from a larger eccentricity effect with critical symbols on the left than on the right side. The Compatibility × Eccentricity interaction was highly significant, $F(1, 11) = 12.23$, $p < 0.005$, whereas the Compatibility × Side interaction missed the significance criterion ($p > 0.1$). Planned comparisons confirmed that compatibility effects were significant for Positions 1, 2, and 4 ($p < 0.05$, at least), but only marginally significant for the rightmost position ($p < 0.06$). In a comparison of Experiments 2 and 4, the experiment variable interacted with eccentricity ($p < 0.01$), and entered into a four-way interaction with side, eccentricity, and compatibility ($p < 0.05$).

The error analysis showed significant effects of compatibility, $F(1, 11) = 4.90$, $p < 0.05$, and of the Compatibility × Eccentricity interaction, $F(1, 11) = 5.00$, $p < 0.05$, that paralleled the RT effects, respectively. Importantly, the Compatibility × Side interaction clearly missed significance ($p > 0.4$). Again, the pattern of the error data mirrored the RT pattern.

Discussion

The main goal of Experiment 4 was to demonstrate a dependency of the spatial distribution of the FCE on stimulus material. In particular, it was expected that the left-side superiority of the FCE as found in Experiment 2 would decrease or disappear. The results provide somewhat mixed support for this expectation.

On the one hand, the left-side superiority did not simply disappear. Although the Side × Compatibility interaction was not reliable, the RTs as well as the PE data show that most of the subjects seem to have problems especially with incompatible flankers at Position 2. This is confirmed by the individual results: Seven of the twelve subjects had their largest FCE at Position 2, only three subjects at Position 4, and two at the leftmost position. Thus, some left-side bias was also present with non-alphanumeric stimuli.

On the other hand, the result pattern does not very much resemble the outcome of Experiment 2 either. (a) The FCEs for the two outer positions were virtually identical in both RT and PE data, whereas Experiment 2 yielded a clear left-side superiority even for outer flankers. (b) Eccentricity had a strong effect on outer flanker positions on both sides, whereas in Experiment 2 the eccentricity was much stronger on the right side. Both differences suggest that the leftmost position was more often attended or more likely to be attended with letter stimuli than with pictures. So, although the evidence is far from being impressive, the results lend some preliminary support for the assumption that the spatial distribution of the FCE is material-dependent.

EXPERIMENT 5

A further variable that may affect the spatial distribution of the FCE was suggested by results from studies on the processing of mirrored letters. For example, Krueger (1976) successfully attempted to reverse the left-to-right direction of scanning in a whole-report task by using stimulus letters that were mirrored on their vertical axis. However, not all studies found a perfect reversal, at least not in all subjects. Wolff and Mewhort (1986) showed that, when there is no restriction regarding report mode, subjects spontaneously reported normally oriented letters in a left-to-right order. Mirrored letters, on the other hand, were sometimes reported in the same order and sometimes in the reverse order. So, even though a mirroring manipulation cannot be expected to reverse the scanning direction completely, it should affect the likelihood of invoking or choosing a left-to-right scanning tendency or strategy. Accordingly, Experiment 5 employed mirrored stimulus letters. The expectation was that, in comparison to Experiment 2, the left-side superiority of the FCE should be drastically reduced if not reversed.

Method

Subjects

Eight female and seven male adults were paid to participate in single sessions. They reported having normal or corrected-to-normal vision and being right-handed. Subjects were not familiar with the purpose of the experiment.

Apparatus, Stimuli, and Procedure

These were identical to those in Experiment 2, with one exception: The asymmetric letters *S*, *K*, and *D*, mirrored at their vertical axis, were used as left-key, right-key, and neutral stimuli, respectively.

Results

RTs and PEs were treated analogously to Experiment 2. The results are given in Figure 5.

The RT analysis showed only a highly significant effect of compatibility, $F(1, 14) = 64.32$, $p < 0.001$, which was modified by a highly significant Compatibility × Eccentricity interaction, $F(1, 14) = 32.87$, $p < 0.001$, this resulting from larger compatibility effects with critical flankers in inner than in outer positions. However, planned comparisons revealed that compatibility effects were significant for all positions ($p < 0.01$) but the rightmost ($p > 0.39$). In comparing the data from Experiments 2 and 5, the only effect that significantly interacted with the experiment variable was a Compatibility × Side interaction ($p < 0.05$). That is, the left-side superiority of the FCE as found in Experiment 2 was clearly not present in Experiment 5.

An ANOVA of PEs produced significant main effects of compatibility, $F(1, 14) = 9.91$, $p < 0.01$, and side, $F(1, 14) = 4.79$, $p < 0.05$, as well as a marginal effect of eccentricity ($p < 0.1$). Furthermore, there were Compatibility × Side and Compatibility × Eccentricity interactions, as well as a three-way interaction, which, however, just approached significance ($p < 0.07$, $p < 0.18$, and $p < 0.12$, respectively). Again, the patterns of RTs and PEs were very similar.

Discussion

Experiment 5 demonstrates an additional effect of the stimulus material on the kind of scanning operation, as evidenced in the spatial distribution of the FCE. Although the statistics show that a reversal of scanning direction has certainly

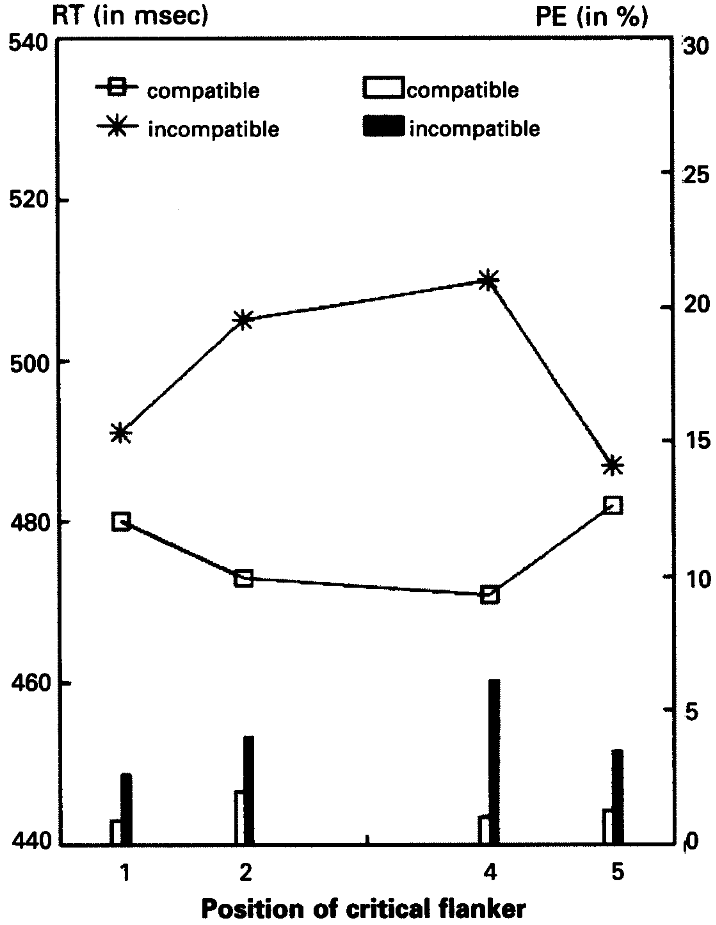

FIG. 5. Experiment 5: Reaction time (RT, lines) and proportion of errors (PE, bars) as a function of position of critical flanker and flanker compatibility.

not taken place in all subjects, a numerical right-side superiority of the FCE is apparent in both RT and PE data. In fact, nine of the fifteen subjects had a maximal FCE at Position 4, and one at Position 5, but only five at Position 2. The analysis over Experiments 2 and 5 provides further evidence that the mirror manipulation had a large impact on flanker processing. It is obvious that the pronounced left-side superiority of the FCE in Experiment 2 broke down with mirrored letters. Therefore, the spatial distribution of the FCE is clearly not invariant but depends on stimulus material. However, the stimulus material does not seem to determine the scanning direction (or the locations to be scanned) completely: Normally oriented letters produce a rather consistent performance over subjects (resulting in a pronounced overall left-side asymmetry), but mirrored letters do not. Interestingly, this parallels the already cited findings from whole-report tasks, where asymmetries are also much more consistent over subjects with normal than with mirrored letters (Wolff & Mewhort, 1986). So, Experiment 5 gives further evidence for the assumption that the same mechanism is involved in whole-report and flanker tasks.

GENERAL DISCUSSION

Five experiments were conducted to investigate the dependency of a flanker's influence on whether it appears on the left or right side of the target in the flanker-compatibility task. Experiment 1 demonstrated a left-side superiority of the FCE when compatible or incompatible letter flankers did not flank both sides of a central letter target but only one side, and the other was filled with neutral letters. That is, flanker compatibility had a greater impact on performance when the critical flankers were on the left side of the target. Experiment 2 replicated this result and demonstrated that flankers are most effective when they appear on the left side near the target. Outer flankers had a smaller impact, but this loss was more pronounced for right-hand flankers. Experiment 3 showed that the left-side superiority disappears with wider letter-spacing. Although there was evidence for position-specific FCEs even in this case, these revealed no systematicity over subjects. Experiment 4 demonstrated that when tiny pictures instead of letters are used, the left-side superiority of the FCE is no longer reliable. Furthermore, outer flankers had very little impact, no matter on which side they appeared. Experiment 5 employed mirrored letters as stimuli. The left-side superiority of the FCE vanished completely, and there was even some evidence for a reversal, hence a right-side superiority.

The findings that FCEs depend strongly on flanker location, even with constant flanker–target distance (or eccentricity), are difficult to explain from a precategorial spotlight or zoom-lens view of attention, unless we introduce arbitrary and empirically unwarranted assumptions about the form of the focus. Moreover, the common spotlight view encounters considerable problems with the observation that eccentricity effects can be compensated for by other factors. Especially the fact that an overall FCE was found in the presence of eccentricity effects with narrow stimuli (Experiment 2) as well as in the absence of such effects with spaced stimuli (Experiment 3) is rather damaging to the idea that only stimuli falling into a circumscribed area are selected for further processing.

This neither rules out the existence of precategorial selection mechanisms, nor does it mean that stimulus analysis is completed before postcategorial selection takes place (Pashler, 1984). That is, there may very well be filter mechanisms of the kind assumed by C. W. Eriksen and Yeh (1985), LaBerge (1983), and Posner (1980), and they may be responsible for the eccentricity effects obtained. However, the hypothetical lens or spotlight does not seem to exclude information from processing but may, rather, attenuate irrelevant stimuli (Treisman, 1964) or selectively enhance relevant stimulus information (Van der Heijden, 1992; see Schneider, 1993, for an overview). This is consistent with several demonstrations showing that the impact of flanking noise may be reduced but stays significant even with flanker–target distances of up to 5° (Driver & Baylis, 1991; Hagenaar & Van der Heijden, 1986; Miller, 1991; St. James, 1990). It also corresponds to the interaction of eccentricity and side in Experiment 2: Although it would be hard to understand how scanning can affect the impact of already excluded stimulus information, it seems plausible that scanning operations partly compensate the hypothetical attenuation or non-enhancement of noise stimuli.[3]

A further conclusion to be drawn from the present results is that the asymmetries observed are very probably produced by (automatically invoked or strategically applied) attentional operations rather than by structural factors. Obviously, the position-dependent influence of flankers varies with the stimulus material, the spacing and orientation of stimulus elements, as well as with subjects. This rules out explanations of FCE asymmetries in terms of neuroanatomical hardware, invariant population stereotype, or general bias of the information-processing system. In contrast, the individual FCE distributions exhibit a considerable variability of positional preferences, and the variability is stronger the less a certain (e.g. reading) tendency is suggested by the stimulus material. Although a slight overall left-hand bias was apparent in this study, the results rule out the possibility of an obligatory "reading-off" of any stimulus string from left to right. This is consistent with findings from whole-report studies, showing that normally oriented letters, mirrored letters, and symbols are not scanned in the same way (e.g. Bryden 1960; Krueger, 1976; Wolff & Mewhort, 1986). Thus, there is considerable evidence that FCE asymmetries can be traced back to individual tendencies or strategies in handling the selection problems posed by irrelevant flankers.

Moreover, the present data suggest that the proposed scanning operations are unlikely to precede the analysis of stimulus features. This is suggested by the observation that all experiments in this study yielded remarkably flat position curves for compatible conditions, so that the FCE × Position interactions resulted mainly from variations in incompatible conditions. If scanning preceded feature analysis, its course should not depend on flanker identity; hence compatible flankers would be scanned in the same way as incompatible ones. If so, one would expect mirror-symmetrical curves for compatible and incompatible conditions (i.e. comparable amounts of facilitation and interference), because scanned compatible flankers (or their features) should prime the correct response

[3]This is not to say that the present data necessarily require a spotlight concept. In contrast, as retinal eccentricity (i.e. retinal resolution) and flanker–target distance are completely confounded with symbol strings, eccentricity effects may be explained exclusively by peripheral factors (Hagenaar & Van der Heijden, 1986), without any recourse to attentional mechanisms. However, my argument is restricted to stating that *if* a spotlight concept is evoked, the spotlight is not likely to exclude information from processing completely.

in the same way as scanned incompatible flankers (or their features) prime the incorrect response. In contrast, our data suggest, rather, that scanning operations are performed only when stimuli (or features) are coded that call for opposite responses, thus posing a localization problem. That is, incompatible but not compatible flankers seem to be regularly scanned, so that scanning preferences for certain positions have consequences for incompatible but not for compatible conditions.

Obviously, there is no current theory of attention that would have clearly predicted the results of this study. In search for a post hoc account, the idea of a scanning mechanism may be combined with one of at least three different theoretical perspectives: First, following the feature integration theory proposed by Treisman and Gelade (1980), one may argue that features are coded in parallel—that is, from all positions of a symbol string (although information from some positions may be handicapped due to peripheral factors). If there is no feature coded that calls for a conflicting response, the correct response is selected and carried out. If not, as with incompatible flankers, features have to be localized by applying an attentional mechanism (cf. Gratton et al., 1988; Mozer, 1989) that produces identity codes and aligns them with location codes. As already sketched above, this operation may lead to a spatially asymmetric distribution of the FCE in one of two ways: (a) The direction of attention to the centre of the stimulus string (to integrate information from this location) may be counteracted by an automatic tendency to attend the left elements (as with word-like stimuli) or other preferred locations. (b) The central target may require to be located relative to other elements, so that some attention would be directed to the flankers used for relative localization. For example, attention may be necessary to integrate feature information sequentially into a stimulus-centred letter shape map (Caramazza & Hillis, 1990), and the derivation of relative letter position from this map may require the integration of one or more (reference) letters in addition to the target.

A second interpretation of the present results refers to postcategorial selection approaches, such as those proposed by Van der Heijden (1981, 1992) and Miller (1987), among others. The main difference from the feature integration account, in this context, would be that selection (including target localization) may be conceived to succeed not only feature analysis, but a more-or-less complete identification of all elements of the stimulus string. As in our experiments, the target alternatives could be discriminated on the basis of simple features alone; hypothetical response conflicts could be induced by flanker features as well as by flanker identities. So, the data of this study cannot serve to decide between feature integration and postcategorial selection approaches. However, it should not be too difficult to conceive experiments that provide more decisive evidence for this issue.

Third, one may consider attentional selection as a process of competition between candidate stimulus elements (i.e. letters) that have been assigned selection weights reflecting their similarity to an internal target description (Bundesen, 1990; Duncan & Humphreys, 1989). Assume that the strengths of these weights are not exclusively determined by the match between element and description but can also be modified by material- and subject-specific selection preferences or strategies. As normal letters are often processed and selected in a left-to-right order, the weights for the first (i.e. leftmost) letters of a word or letter string (or, more precisely, string positions) may be increased relative to the weights for the remaining string elements (or string positions). Consequently—other things being equal—leftmost flankers would compete more with target selection than would right-side flankers. Hence the term "scanning" and the corresponding hypothesis do not necessarily imply a serial, orderly, and search-like operation but may, rather, be understood as the temporarily superior impact of (the code of) the wrong stimulus element on action control. This temporary superiority may efficiently guide serial behaviour in reading and memory tasks, as already assumed by Lashley (1951) and Heron (1957), but it may also hamper flanker task performance in an asymmetric way.

In sum, then, we can conclude that our findings do not support attentional spotlight accounts of the FCE, insofar as they propose an all-or-none selection of information according to spatial criteria. Rather, flankers seem to be analysed at least up to a featural level (and perhaps further) before attentional selection sets in. This explains why the FCE may be reduced but does not disappear with increasing flanker–target distance. Target selection succeeds feature (and perhaps stimulus) analysis, and the selection process is influenced by the stimulus material as well as by individual spatial preferences. Whether these preferences are due to automatic tendencies or voluntary strategies and how they affect the selection process in detail remain to be determined.

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Aging and Mechanisms of Visual Selective Attention: Effects on Word Localization and Identification

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The present study investigated age differences in attentional allocation in a word localization and identification task. Response times for valid and invalid spatial cue conditions were compared for each of two age groups under two SOA conditions: 500 msec and 1000 msec. Very high benefits for valid cues in terms of response time were found for both groups. Results indicated that attention was more important for words when compared with similar earlier studies using a simple shape identification task. A sensitive model-fitting technique was used to compare the cost and benefit of selective attention to words; it revealed that attention can be concentrated away from the fovea to benefit in word identification in much the same way for both age groups. The model-fit analysis also revealed that attention for word identification, and perhaps any more complex visual stimuli, is more diffuse than for simple shape identification. In addition, older adults are more likely to avoid the foveal area in order to distribute attentional resources to the periphery and are able to increase these effects of selection at the longer SOA. This suggests that older adults are using attention to offset visual processing deficits for peripheral information such as letter information in the reading process. The results support a two-process view of attention where attention consists both of selection and inhibition and provide evidence to support a theory of reduced inhibitory processes as a cause for cognitive slowing associated with aging.

Recent age comparison studies by McCalley and Bouwhuis (1992, 1995) have indicated that, when acuity is controlled, a single resource-allocation model of attention can explain the behaviour of both old and young adults. Nevertheless, within the model, differences in strategies between the two groups can be identi-

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