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Parallel computation of vernier offsets, curvature, and chevrons in humans

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Abstract

A vernier offset is detected at once among straight lines, and reaction times are almost independent of the number of simultaneously presented stimuli (distractors), even if absolute orientation cues are masked by varied orientation of the verniers. This result implies that the human visual system processes vernier offsets in parallel. Reaction times for identifying one straight target among offset verniers, on the other hand, increase with the number of stimuli. The same is true for the identification of a vernier offset to one side among verniers offset to the opposite side, if absolute orientation cues are masked. These tasks require serial or semi-parallel processing. Chevrons and curved targets show the same pattern of results. Even deviations below a photoreceptor diameter can be detected at once. The visual system thus attains positional accuracy below the photoreceptor diameter simultaneously at different positions. I conclude that deviation from straightness, or change of orientation, is detected in parallel over the visual field. Discontinuities or gradients in orientation may represent an elementary feature of vision.

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Introduction

The visual system supplies and analyzes information about the visual world. To attain this goal, redundancies of the input must be eliminated while all relevant information should be preserved. It appears that specifically designed processors detect certain salient features of the stimuli, such as color and orientation of short line segments (Julesz, 1984; Treisman, & Gormican, 1988). These features convey more relevant information than homogeneous areas do, and few cortical cells respond to unstructured stimuli (Laim & Gilbert, 1989). The visual system identifies objects more swiftly than even the most advanced computers; possibly by using a large number of dedicated processors for salient features in parallel (one for each visual field position). It has been argued that features, called 'textons', which are detected in parallel represent the elementary features, or building blocks, of vision (Julesz, 1981; 1984). The identification of all of them would greatly contribute to our understanding of vision. So far, parallel processing was found for line segments (of a given color, luminance, orientation, length and width), their terminators, crossings, stereoscopic depth, and motion (Julesz, 1984; Treisman & Souther, 1985; Voorhees & Poggio, 1988; Treisman & Gormican, 1988). There seems to be a gradual transition rather than a sharp borderline between ´parallel` and ´serial` processing, with some tasks showing ´semi-parallel` behavior, especially near threshold (Olson & Attneave, 1970; Treisman & Gormican, 1988; Fahle, 1990). Nevertheless, some tasks are still solved fast and almost effortlessly, regardless of the number of distractors, while others need significantly more time for each additional item displayed. I will use the standard term ´parallel` for tasks that require less than 15 msec for each additional item, and ´serial` for tasks that require more than 30 msec searchtime per item.

Here I show that a vernier offset (or a chevron, or a bent, or slanted target; cf. Fig. 1c) can be detected in parallel. The underlying feature seems to be deviation from straightness, or change of orientation. Surprisingly, even displacements below one photoreceptor diameter are detected at once. This is to say that spatial accuracy below the size of the photoreceptors can be achieved simultaneously (within 150 msec) over the visual field.

Eight experiments were performed. In the first, *reaction times* for vernier targets were measured for vertical orientations of the stimuli, while stimulus orientation varied independently in the second experiment. The third experiment measured *thresholds* rather than reaction times for vernier targets. The following three experiments measured again reaction times, but for curved targets (exp. 4), chevrons (exp. 5), and for orientation discrimination (exp. 6). The sixth experiment determined thresholds for the curved, slanted, and bent targets, and the seventh experiment evaluated the effects of practice.

Most experiments were performed with two different line lengths. The rationale was that the visual system seems to use different mechanisms to detect and evaluate breaks in vernier stimuli (Andrews, Butcher & Buckley, 1973; Watt, Morgan & Ward, 1983; Watt & Campbell, 1985). Thresholds for short vernier targets increase strongly if stimulus orientation varies randomly, indicating the involvement of an orientation selective process for detection. Detection of longer verniers, on the other hand, deteriorates far less with variable orientation.

Material and Methods

A 32 bit microcomputer generated the stimuli and displayed them on the face of a Tektronix x/y monitor 608 with fast fading P31 phosphor via custom made fast 16 bit D/A-converters. Verniers, chevrons, and curved, or slanted lines served as stimuli (Fig. 1c). The precision of positioning on the screen was approximately 5 µm, corresponding to less than 1" (arcsec) at an observation distance of 2.5 m. The standard presentation consisted of between two and sixteen stimuli that were presented simultaneously at equal distances (eccentricities) around the fovea (cf. Fig. 1). A central cross served as a fixation aid. It had a line length of 40' for the stimuli at 4.5° eccentricity and a line length of 2' for the stimuli at 12' eccentricity. Eccentricities, i.e., distances between the stimuli and the fixation point, of 4.5°, 0.4° and 0.2° were used. Observation distance varied between 0.5 m (for an eccentricity of 4.5°) and 2.5 m (for eccentricities of 12' and 24'). The stimulus configuration was scaled, to a first approximation, according to the so-called cortical magnification factor (Daniel & Whitteridge, 1961; Rovamo & Virsu, 1979; Rovamo et al., 1982; Levi, Klein & Aitsebaomo, 1985), such that stimulus size was directly proportional to eccentricity. For the experiments at 4.5° eccentricity each of the stimuli was 2.5' wide and 21' (´short`) or 85' high (´long`), except for observer UK (41' high). The vertical gap size was 1' for the short and 5' for the long vernier stimuli. For the experiments at 24' and 12' eccentricity, the stimuli were 0.5' wide and 12' long with 1.5' vertical gapsize. In all reaction time (= response time) experiments, vernier offset (or chevron displacement, or bent, or slant) was 5' (cf. Fig. 1). This offset was slightly above two point resolution at 4.5° (Westheimer, 1982; Levi, Klein & Aitsebaomo, 1985).

In part of the experiments, eye position was monitored by means of a commercially available eye tracker (AMTech) to check whether the subjects fixated or scanned the stimuli sequentially. Stimulus luminance was 450 cd/m^2 as measured with a large test field with a point density corresponding to that of the vernier targets. This corresponded to a linear luminance of 0.15 cd/m (Westheimer, 1985). Background illumination of 20 cd/m^2 was supplied by overhead incandescent lighting. When thresholds were measured, presentation time was limited to 150 msec to prevent fixational eye movements (Westheimer, 1954; Burr, 1979). In the reaction time experiments, the stimulus was presented until the observer responded. Acoustical feedback was given after incorrect responses.

In the first two experiments, as well as in the fourth, fifth, and sixth, *reaction times* were measured, while *thresholds* were measured in the third (for verniers) and in the seventh experiment (for all other stimuli). The stimuli of the first three experiments were verniers, while targets curved to the left or right were used in the fourth experiment, chevrons in the fifth experiment, and slanted targets in the sixth experiment (an orientation discrimination task). The eighth experiment tested the effects of practice, mainly in vernier stimuli.

In a two alternative forced choice task, three basic conditions were tested for all types of stimuli: A) Identify the target that is offset (bent, curved, or slanted) among straight lines (Fig. 1a). B) Identify the straight target among distractors that are offset, bent, curved, or slanted. C) Identify the target that is offset (bent, curved, or slanted) to the direction opposite to that of the distractors (Fig.1b). In the last condition, the direction of the target's offset, bent, etc. could be fixed, e.g., to the left while all other stimuli were offset to the right, or could vary randomly — with a corresponding opposite variation of the distractors. Additional experiments with verniers and slanted stimuli (but not with the rest of the stimuli) measured the detection of a target with a double sized offset which was to the same direction as that of the distractors. As a control, (vernier) thresholds were also measured for a single target that appeared randomly at one out of a number of possible positions. In the part of the experiments that measured thresholds, a masking stimulus with a raster of long, straight lines intersecting at the positions previously covered by the offsets of the stimuli was presented after the stimulus for one second to eliminate any influence of possible after effects.

Only half of the presentations contained a target. The observers had to indicate whether or not a target was present in the display and to push the appropriate one of two push-buttons. Reaction times plotted throughout this paper refer to the average reaction time of both positive (target present) and negative (target absent) presentations, if not stated otherwise (Fig. 3 & Tab. 4). Different offsets were used and the percentage of correct responses recorded. Thresholds were calculated by fitting a psychometric function based on a Gaussian cumulative

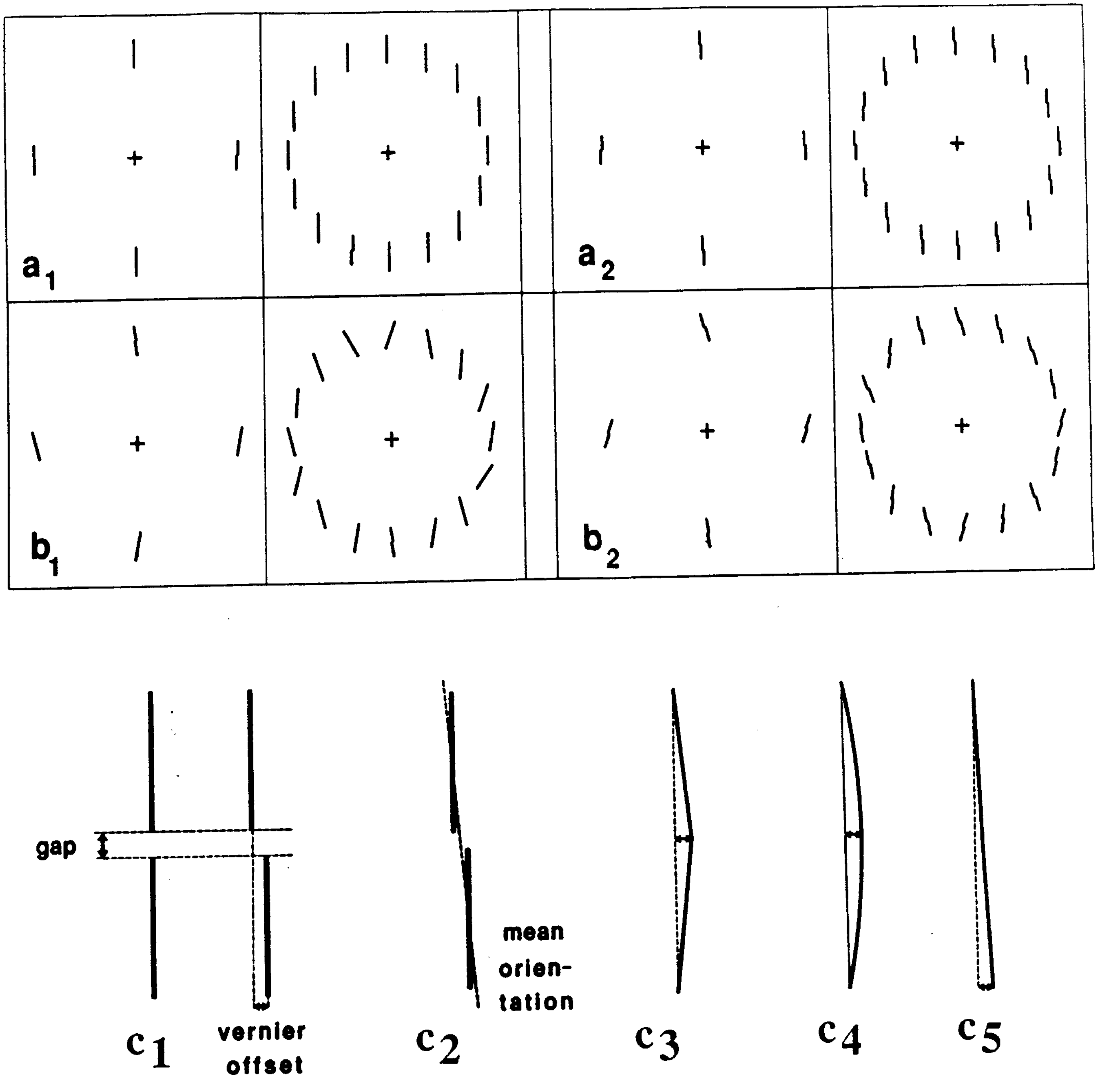


Fig. 1 Examples of the stimulus presentations used. Two to sixteen stimuli were shown simultaneously in every presentation. All stimuli were oriented vertically in (**a**). In (**a**$_1$), a vernier target (T) had to be detected among straight distractors (D), while in (**a**$_2$), a vernier target offset to the left had to be detected among distractors offset to the right. In (**b**), orientation of the stimuli varied by up to ±20°. Distractors were either straight (**b**$_1$), or offset to the opposite side (**b**$_2$). **c**) shows offsets (horizontal arrows) for vernier (**c**$_1$), chevron (**c**$_3$), curved (**c**$_4$), and slanted targets (**c**$_5$), as well as ´mean orientation` (**c**$_2$) for a vernier stimulus.

function (Finney, 1971) to the results and by determining the midpoint (75%) of this function, i.e. the mean between chance level and 100% correct. Means and standard errors were calculated for both reaction times and threshold experiments. In a series of controls, all presentations contained a target and observers had to indicate the direction of offset.

All reaction times and thresholds of the figures rely upon at least 120 responses per condition and observer. As outlined in the Introduction, I will denote ´parallel` all tasks that require less than 15 msec per additional item, and ´serial`, tasks that require more than 30 msec. Search times between 15 and 30 msec will be referred to as ´semi-parallel`. These search times refer to the average of positive and negative presentations, i.e., presentations with and without the target. (Since if processing is indeed parallel, this should be the case for both the presence and absence of the feature; see Discussion). *All* the results in the text, figures, and tables represent the average of positive and negative presentations, the only exceptions being Fig. 3 and Table 4. For the sake of shortness, the expression ´search time/item` will usually replace the more precise ´search time/additional item`.

Before the experiments proper, the four observers had undergone a standard ophthalmological examination as well as a training period with more than 1000 stimulus presentations. Three of the observers had previously participated in similar experiments where the position of a vernier target had to be indicated (Fahle, 1990). The observers all had normal or corrected-to-normal visual acuity, and, with the exception of the author, were unaware of the purpose of the experiment. Not all of them participated in all experiments.

First experiment: Reaction times for vernier targets.

In the first experiment, reaction times were measured for the detection of a) a single vernier target among variable numbers of straight distractors; b) a straight target among vernier distractors, and c) a vernier offset to the left among verniers offset to the right. (´Detection` of a feature is used throughout this paper for the discrimination between a presentation that contains the feature versus a presentation that does not.) An additional control used a vernier with a double sized offset among vernier distractors. All stimuli were oriented vertically.

Results

The reaction times required to find one offset vernier target amidst 2 to 16 stimuli were relatively constant, independent of the number of stimuli (Fig. 2a). This was true for both the short (left half of Fig. 2) and the long stimuli (right half of Fig. 2). Regression lines through the data yielded slopes of -0.98 to 12.4 (mean: 6.3 ±3.2; cf. Tab. 1) msec/item for the short stimuli, and between 6.0 and 13.0 (mean: 9.5 ±3.5) msec/item for the long stimuli, depending on observers. The mean additional reaction time per item was 7.9 msec for the combined data of both line lengths. Crowding, defined as a high stimulus density on the monitor decreases performance even for single verniers (cf. Westheimer & Hauske, 1975). Since crowding was especially pronounced with 16 stimuli displays (cf. also the discussion of the third experiment, and Beck & Ambler, 1973) regression lines were calculated not only for the whole range of distractors, but in addition for the range of 2 to 12 stimuli. There, reaction times increased between -6.3 and 10.9 (mean: 2.9 ±1.4) msec/item for the short stimuli and between 1.2 and 13.9 (mean: 9.2 ±1.7) msec/item for the long stimuli, with a mean of 5.6 ±2.8 for all stimuli and observers.

When the vertical gap sizes of all the verniers were varied independently from each other by up to ±4', preventing the identification of the offset target through its larger gap size, reaction times were not significantly affected (Fig. 2b). The slopes of the regression lines for short and long stimuli were similar, between 6.1 and 16.0 msec/item, with a mean of 10.0 ±1.8. For the range of 2 to 12 stimuli, slopes ranged between 1.3 and 11.5 msec/item, with a mean of 6.6. ±1.5.

It turned out to be significantly more difficult and time consuming to discriminate between a display with all stimuli offset versus a display with a single stimulus lacking offset (Fig. 2c). The increase in reaction times with the number of stimuli was steeper for long stimuli (right half of Fig. 2c; slopes: 44 to 86 msec/item; mean: 62 ±12.6) than for short ones (left half; slopes: 4.5 to 32 msec/item; mean: 15.4 ±5.9). The mean of all observers and stimulus lengths was 35 ±10.9 msec/item.

Fig. 2 Reaction times for identifying an odd-man-out among two to sixteen stimuli. Stimulus lengths were 21′ for the left column and 85′ for the right column. **a)** The searchtime for one offset vernier (T) among straight distractors (D) was almost independent of the number of stimuli, the graphs are very shallow. **b)** This was true even if vertical gap size varied at random. **c)** Response times increased markedly with the number of stimuli for detection of one straight target among vernier distractors. **d)** The identification of a vernier with an offset opposite to that of the distractors was almost parallel. Unexperienced observers, however, required serial search for the identification of a target with an opposite offset (Fahle, 1990). Data points represent means of at least 120 presentations. Standard deviations of the means correspond to approximately 15% to 40%.Results of four observers. Insets symbolize the types of stimuli used, with 'T' for target, and 'D' for distractors.

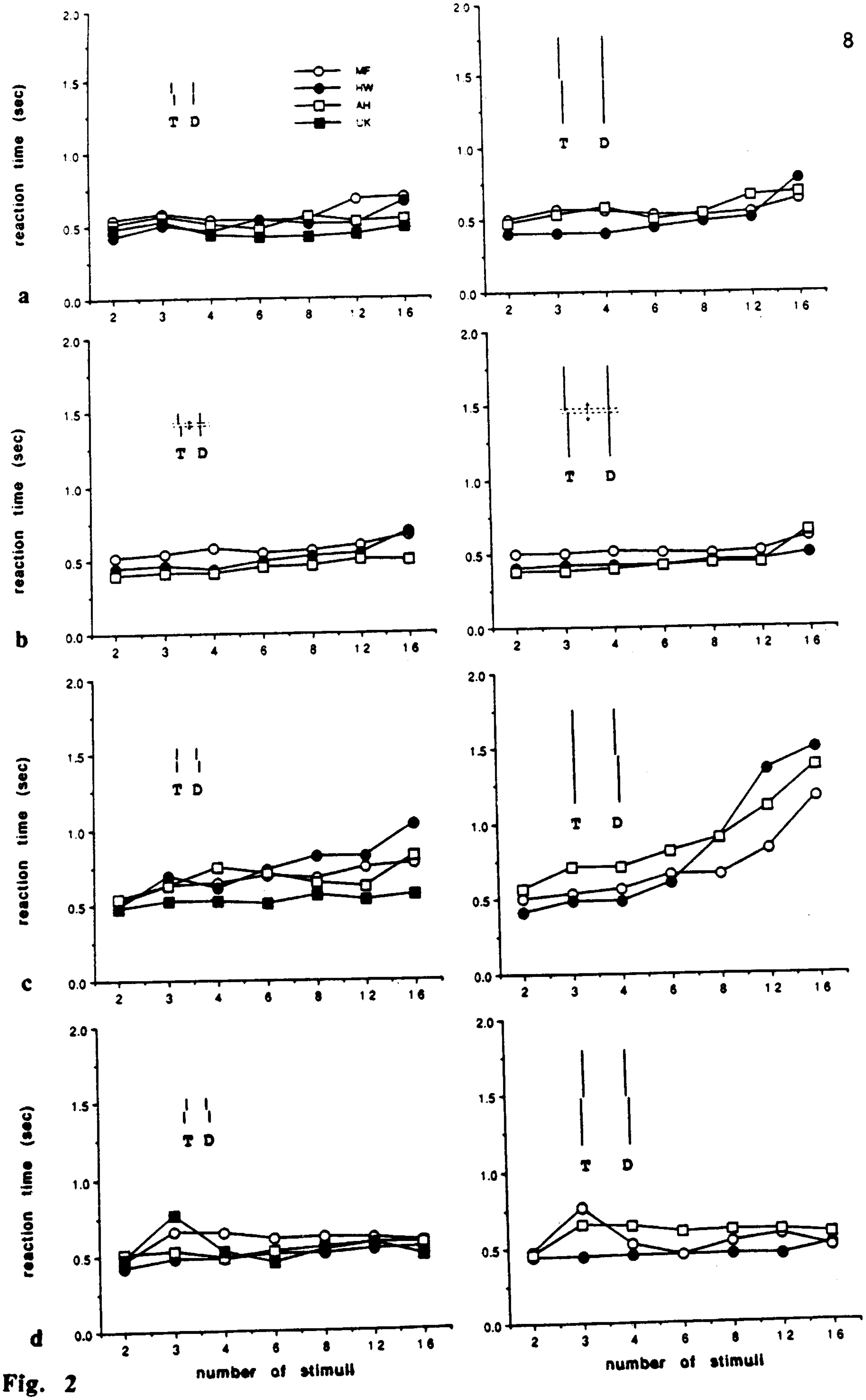

MF
HW
AH
UK
T
D
reaction time (sec)
0.0
0.5
1.0
1.5
2.0
2
3
4
6
8
12
16
a
b
c
d
number of stimuli

Fig. 2

Initially, observers had difficulties finding one vernier offset to the left among verniers offset to the right, and reaction times increased with the number of stimuli. After several hundred presentations, however, they were able to perform the task quickly with up to 16 stimuli (Fig. 2d). Even if the direction of offset of the vernier target varied between presentations (right or left, at random) and had to be inferred from the direction of offset prevailing in the individual display, reaction times increased only moderately with display size, both for short (Fig. 4a) and long stimuli (Fig. 4b). The slope of the regression lines through the data points in Fig. 2d varied between -4.4 and 7.2, with a mean for both stimulus lengths of 1.5 ±1.7 msec/item. Subjectively, the improvement in performance during training was associated with a switch in strategy: observers used an orientation cue, such as the tilt of an imaginary regression line through the whole stimulus (cf. Fig. $1c_2$) rather than the offset as the discriminating feature. Some observers learned the switch in strategy fast when the whole stimulus configuration was blurred, a measure which removed the high spatial frequencies of the stimulus. Generally, the orientation cue was much more obvious at small eccentricities (0.2°, 0.4°) than at larger ones (4.5°). There might be a relation to the finding by Sagi and Julesz (1987) that the detection of targets defined by deviant orientation is parallel only at a sufficient density of distractors.

For all conditions, the intercepts of the regression lines with the ordinate were generally between 400 and 550 msec (Tab. 2), and the percentage of correct responses decreased slightly with the number of distractors (Tab. 3). The standard errors of the individual data points were usually around 10% to 15% of the results (cf., however, the much larger errors of the slopes of the regression lines, Tab. 1). Reaction times were often higher for presentations without a target (negative) than for those with a target (positive).

Fig. 3 (Page 10) Reaction times plotted separately for target present (solid symbols) and no target present (line symbols), for the same four conditions as in Fig. 2, but only for long stimu-li. The left column gives the results for fixed orientation, with conditions identical as in the right column of Fig. 2, the right column gives results for varied orientation, with conditions as in the right column of Fig. 5. **a)** one vernier target among straight distrac-tors; **b)** as in a) , but vertical gap size of all stimuli varied independently; **c)** one straight target among vernier distractors; **d)** one vernier target offset to the right among distrac-tors offset to the left. Results of two observers. Note the different scales of the ordinates.

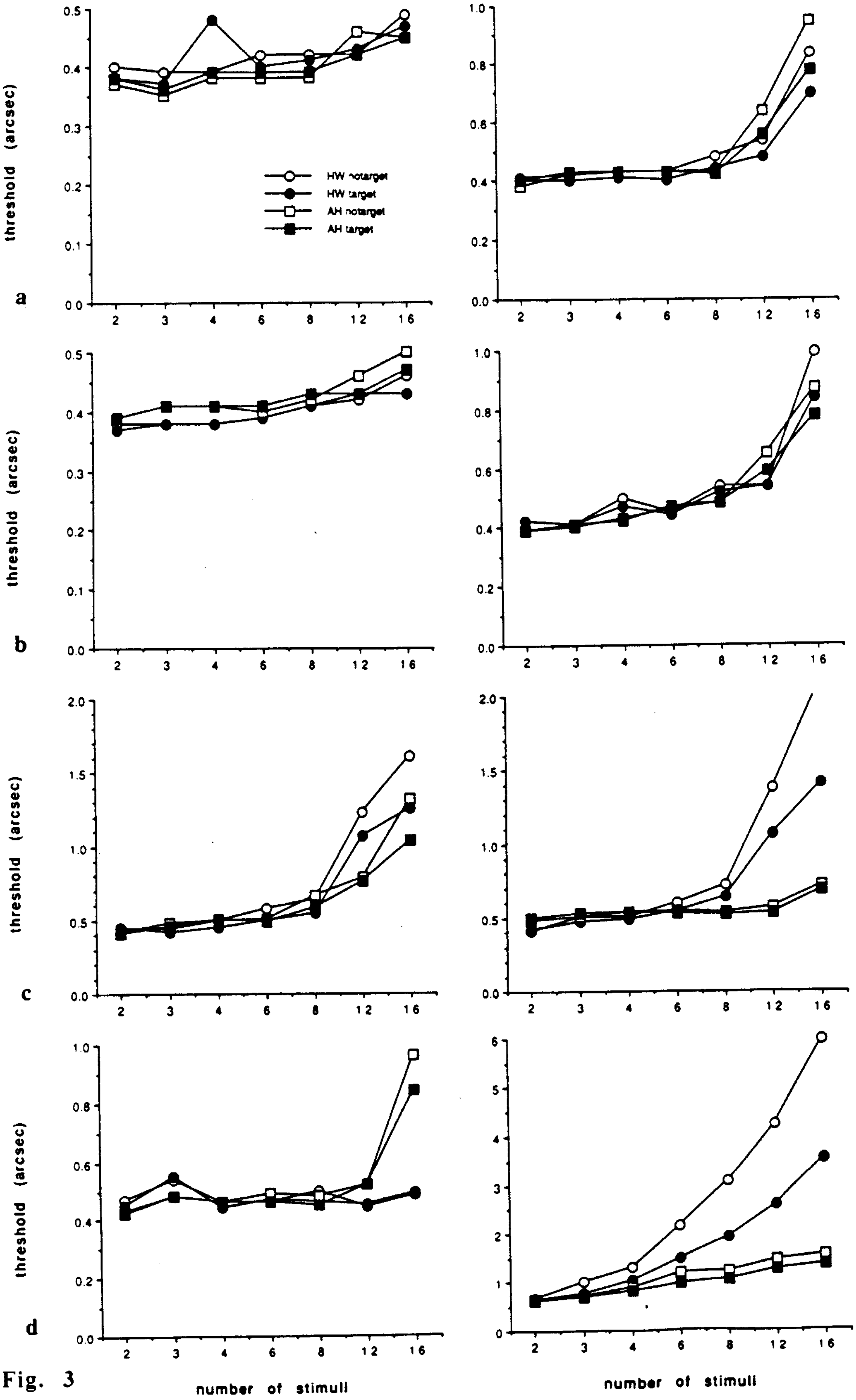

threshold (arcsec)
HW notarget
HW target
AH notarget
AH target
a
b
c
d
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.5
2.0
0
1
2
3
4
5
6
2
3
4
6
8
12
16
number of stimuli

Fig. 3

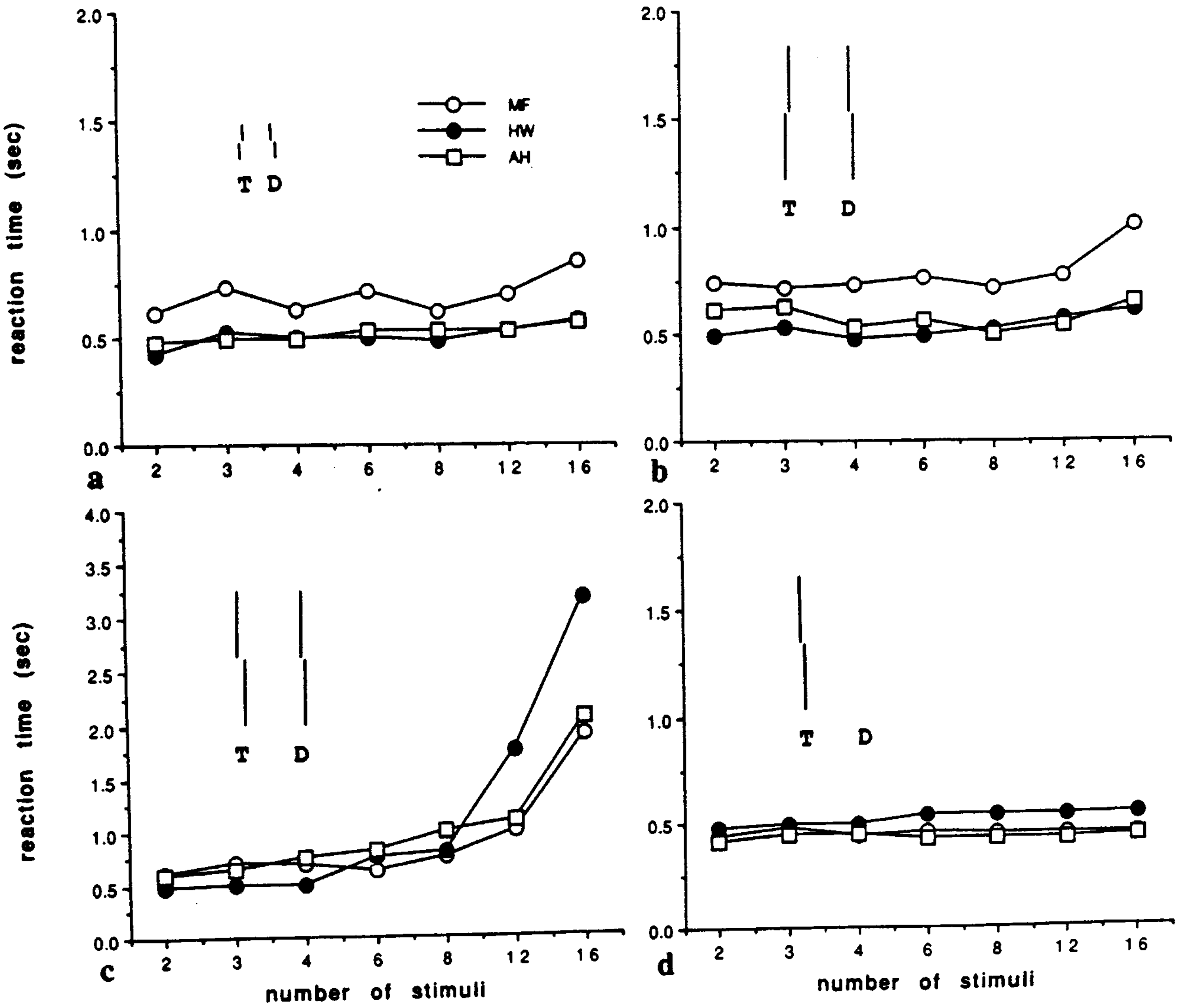


Fig. 4 Reaction times for the identification of **a**) a vernier, offset to the opposite side than the distractors, as a function of stimulus number. The direction of the distractors (and hence that of the target) varied at random between presentations. Stimulus length was 21´. **b**) As in a), but stimulus length was 85´. **c**) Reaction times for detection of a stimulus with an offset twice as large as that of the distractors. **d**) Reaction times for a single vertical vernier target that could be presented in one out of two to sixteen possible positions. Results of three observers.

Interestingly, the largest increase of response time with the number of displayed stimuli occurred for the task of identifying a vernier which was offset twice as much, in the horizontal direction, as its distractors (Fig. 4c). The slopes were 79, 91 and 185 for the three observers, with a mean of 118 ±34 msec/item.

As a control, reaction times for a single vernier stimulus were measured. The stimulus was presented randomly at one out of 2 to 16 positions around the fovea, without distractors, to measure the effect of (pure) spatial uncertainty on the reaction times (cf. Lasley & Cohn, 1981). There was barely any effect, with slopes between -0.4 and +1.75 and a mean of 0.44 ±0.66 msec/item (Fig. 4d).

Discussion

All observers detected a single vernier offset almost independently of the number of simultaneously displayed distractors (Fig. 2a).

The offset vernier was usually the only stimulus with a gap — a feature that might introduce into the stimulus two terminators, which are known to be detected in parallel (e.g. Julesz, 1984). However, when the gap sizes of all stimuli were varied at random (Fig. 2b), parallel detection of a single vernier was still possible at least with displays of up to six stimuli, though all stimuli had gaps in this experiment. (For larger horizontal offsets, the range of parallel detection was extended to displays with more stimuli; cf. Tab. 4: L.O.). Hence, the identification of the odd-man-out could not rely on the presence of the gap alone, but must have used another cue.

Initially, response times of all observers increased strongly with the number of simultaneously displayed distractors when a vernier had to be identified with an offset opposite to that of its partners, which indicated serial processing under this condition. However, as shown in Fig. 2d, observers learned after several hundred presentations to identify the target much faster, transforming the response pattern from serial to parallel (see above: 1.5 msec/item; cf. the eighth experiment). This was true even if the direction of offset was not known beforehand but had to be inferred from the offsets of the distractors. Uncertainty about the direction of offset led to a slight increase in average response times, as to be expected with an additional step in the detection process, but not to a stronger increase of reaction time per additional item (Fig. 4a,b). Observers reported that, after the learning period, they paid attention mostly to the mean orientation of the stimuli (such as an imaginary regression line through the stimuli as in Fig. 1c$_2$), rather than to the offsets. This leads to the interpretation that the improvement of performance in this case might be due to a switch of strategy (namely to attend to *orientation* as a cue which can be detected in parallel), rather than due to learning of a cue which could not be detected in parallel: the direction of offset. Indeed, subjects never achieved parallel performance for direction of offset if orientation cues were masked. (cf. Tab. 4).

Reaction times for more complex displays (eight and more stimuli) were much shorter when the task was to detect a target offset to the opposite side than for detecting a straight target — especially in longer stimuli (cf. Figs. 2d and 2c). This finding can easily be understood under the hypothesis that observers indeed used a cue based on absolute orientation under the conditions of Fig. 2c and d: The difference in orientation between target and distractors was twice as large in Fig. 2d than in 2c. Also, at the given horizontal offset of 5´, an imaginary regression line through the shorter verniers with small vertical gap size deviated almost four times more from the vertical than a line through the longer verniers with larger vertical gaps. Informal control experiments required the detection of a single straight line amidst verniers, offset twice as much as those used in the experiments shown in Fig. 2c. The results of these controls (not shown) suggest that the explanation based on the different degrees of orientation difference is not the whole truth: performance was still not completely parallel for the detection of a straight target in spite of an almost twofold increase in orientation difference. This finding is in line with results of Treisman and Gormican (1988) who found a special role for vertical and horizontal orientations, as well as an influence of the monitor`s frame.

Another result can be understood under the hypothesis that absolute orientation is used as the discriminating cue. Reaction times increased sharply with the number of stimuli if a vernier with an offset twice as wide as that of the distractors had to be detected (Fig. 4c). The difference in orientation between a target with a double sized offset among distractors with a simple offset was again roughly half as large as between a target offset to one direction and distractors offset to the opposite direction. Hence, the task was much more difficult in the first than in the second case. Reaction times were even longer than for the detection of a ´vertical` (i.e. straight) stimulus amidst tilted (i.e. offset) verniers (Fig. 2c). Here, a certain superiority of the vertical orientation in visual search experiments, as described by Treisman and Gormican (1988) and Wolfe (1989) might have played a role. Previously, Attneave and Olson (1967) and Olson and Attneave (1970) had found that orientation differences between elements in stimuli consisting of many lines produced excellent grouping. The grouping depended on the dominant orientation of the stimuli, with better grouping for horizontals and verticals than for diagonals. The differences in orientation used in these studies were, however, by far larger (clearly above the hyperacuity range) than the differences used in the present study. Orientation can be a potential cue in vernier detection; as shown both experimentally: Andrews, Butcher & Buckley, 1973; Watt, Morgan & Ward, 1983; Watt & Campbell, 1985, and theoretically: Klein & Levi, 1985; Carlson & Klopfenstein, 1985; Wilson, 1986. The role of orientation was therefore studied in more detail in the second experiment.

Reaction times were usually slightly longer for presentations without a target (negative) than for presentations with a target (positive). This difference was quite small, usually around 10%, in tasks yielding flat slopes (left sides of Fig. 3 a,b), but much more pronounced in tasks that required semi-parallel or serial processing (Fig. 3c; right side of Fig. 3d; Tab. 4). In serial search, it was faster to find the specified odd-man-out than to make sure it was NOT present. Since the differences in response times between ´target present` an ´target absent` presentations were small compared to the differences between parallel and serial tasks, all subsequent graphs will show the combined data of both ´target present` and ´target absent` presentations. It should be kept in mind that the subsequently presented search times would be even faster if only the ´target present`, or 'positive' data would have been used.

Fig. 4d shows that uncertainty about the exact position of the next target alone did not contribute essentially to the increase of reaction times with the number of distractors, hence with the number of possible positions. Uncertainty effects which, according to Signal Detection Theory, decrease the observer´s sensitivity to stimuli and increase the slope of the psychometric function, as discussed, e.g. by Lasley & Cohn (1981), will therefore not play an important role here.

In summary, the results of the first experiment show that vernier offsets can be detected in parallel over the visual field, i.e., with search times clearly below 15 msec per additional item, even if their offsets are close to two point resolution at the eccentricity tested. This is true for both the detection of a single vernier among straight distractors and for a vernier offset to one side among distractors offset to the opposite side, whereas search times for a straight target among vernier distractors are clearly longer.

Second experiment: Masking of the implicit orientation information.

The second experiment basically replicated the measurements taken in the first experiment, with the important difference that the orientations of all stimuli were varied independently and at random, in three steps by up to 20° clockwise or counterclockwise from the vertical (30° for subject AH). This is to say that in any presentation, the stimuli could have up to 7 different orientations (including the vertical), which differed by up to 40° from each other (60° for AH).

Results

Even if the orientations of all stimuli varied independently, a single offset vernier could be identified relatively quickly, among up to 16 stimuli (Fig. 5a). As to be expected with a more difficult task, slopes were steeper for variable than for fixed orientation: 15.8 to 25.7 (mean: 22.9 ±4.9) msec/item for long stimuli whose orientation varied by 20°, 35 msec/item for variation by 30° (AH), and 8.6 to 44 (mean: 24.5 ±7.0) msec/item for short stimuli. Mean increase in search time of all observers was 23.7 ±4.0 msec/item. If, in addition, vertical gap size was varied by up to 4', then processing by all observers became slower, especially for short stimuli (44, 44, and 55 msec/item; Fig. 5b), whereas it was still intermediate for longer stimulus lengths (9.6 to 38 msec/item, depending on observer, with a mean of 25.2 ±8.3). Since crowding can be expected to be more pronounced under the conditions of variable orientation, search times were calculated in addition for displays with 2-6 (and with 2-12) stimuli, in which the stimuli were clearly discriminable even at variable orientation and variable gap size. Slopes for the results obtained for the detection of one long vernier target were 1.4, 2.2, and 13.4 (mean: 5.7 ±3.9) msec for the three observers in Fig. 5b.

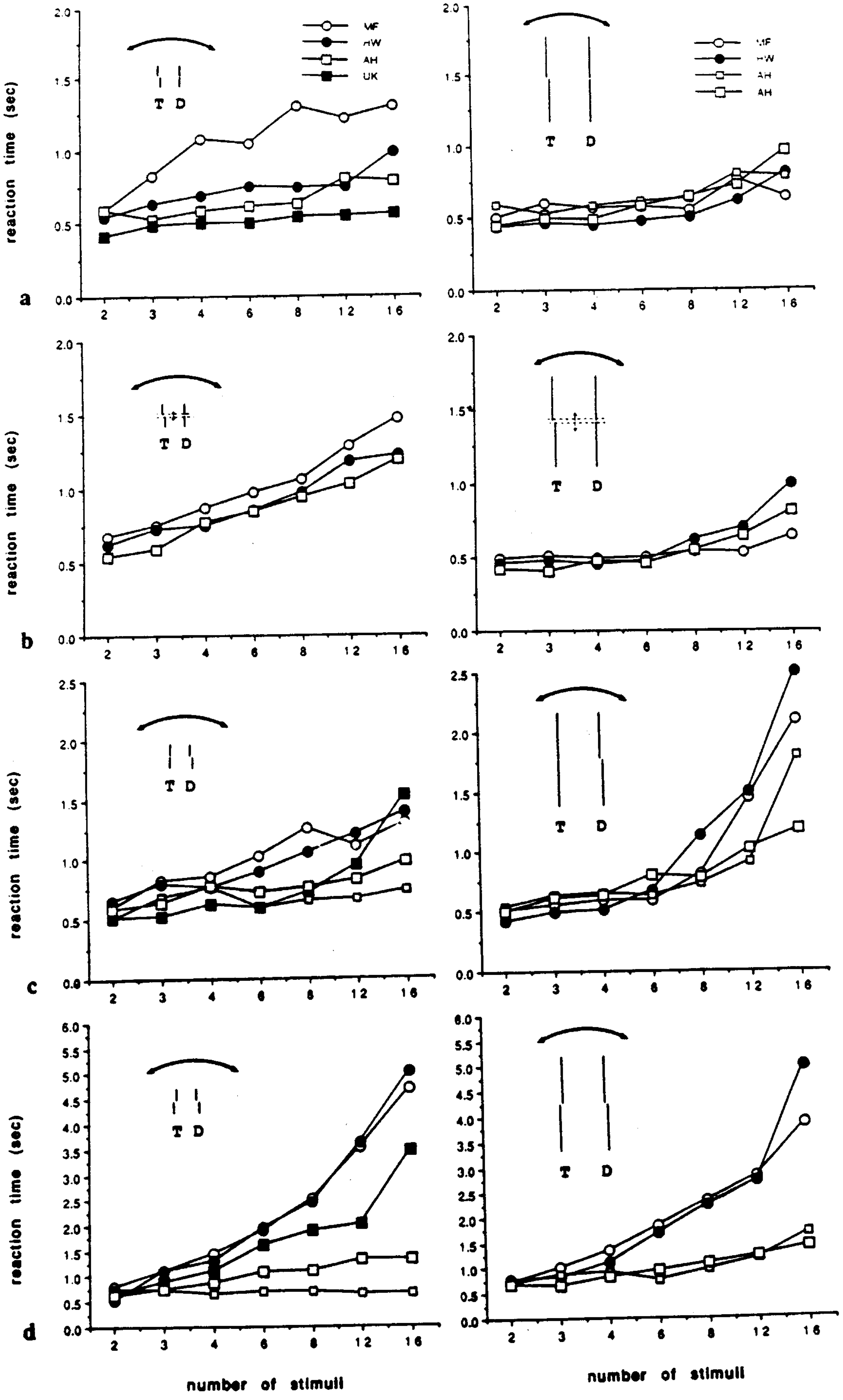
Detection of a single straight stimulus among vernier distractors was somewhat more difficult in complex displays if orientation varied than if orientation was fixed (cf. Figs. 2c and 5c). The increase in reaction times varied between 7.1 and 67 msec/item (mean: 38 ±10.5) for short stimuli and between 46 and 140 msec/item (mean: 93 ±20.4) for long ones. The difference between results with short versus long stimuli was significant on the 5% level ($t=-2.55$; $p=0.038$). The mean search time for all observers and stimulus lengths was 70 ±12.1 msec per additional item.

By far the most difficult task for the observers was to detect the presence or absence of a vernier with an offset to the left amidst distractors offset to the right, if no absolute orientation cue could be used (Fig. 5d, note the changed scale of the ordinate). Search times were between 56 and 308 msec/item, for both stimulus lengths (exception: AH at ±20° orientation variation of the stimuli needed only 4.3 msec/item with the short stimuli). The mean of all observers was 158 ±39. If the direction of offset was not known beforehand, reaction times again increased slightly, but the slope of the curves did not differ significantly (Fig. 6a,b).

Interestingly, the task of finding the vernier with the ´double sized` offset (Fig. 6c) required barely longer reaction times with variable orientation of the stimuli than with fixed orientation (cf. Figs. 4c and 6c), and the slopes ranged between 62 and 190 msec/item in Fig. 6c, with a mean of 120 ±28.6. Reaction times for displays with 16 stimuli were more than 1 sec shorter for the detection of a double sized offset than for the detection of a vernier offset to the opposite side at varied orientation — while the opposite had been true with vertical stimuli (cf. Figs. 4c and 2d versus 6c and 5d). This was mainly due to the strong increase in response times in Fig. 5d as compared to Fig. 2d.

Reaction times for a single vernier target were independent of the number of possible spatial positions, even for variable orientation (Fig. 6d), but longer — at least for one observer — than with fixed orientation. The slopes of regression lines for Fig. 6d varied between -1.6 and 2.2 msec/item, with a mean of 0.64 ±0.87. The standard errors of the data points were again around 15% of the results. The results of, for example, Figs. 2c & 3c,d made an exception insofar as the standard errors were 60% and above, both for the presentations with a target present (positive) and without a target (negative presentations).

As an additional control for the importance of vernier gaps in parallel detection, stimuli with identical gaps were presented at varied orientations (Fig. 7). These stimuli had identical gap size both in the direction of the stimulus (1') and perpendicular to it (5'), but differed in line length. Whereas the response times for the short stimuli increased considerably with display size (18 to 43 msec/item; mean: 27 ±5.5; Fig. 7a), response times for long stimuli were far less affected (5.9 to 16 msec/item; mean: 10.6 ±2.4; Fig. 7b). Search times for a larger offset of one of the short stimuli were also relatively fast (9 to 16 msec/item, mean: 11.6 ±1.8). This is to say that a small offset in a short vernier is detected serially. To speed up detection, either the offset has to be increased or the line length of the stimuli must be increased at identical gap size! This is telling in another respect, since it demonstrates that parallel tasks become ´serial` near threshold.


MF
HW
AH
UK
T D
reaction time (sec)
number of stimuli
2
3
4
6
8
12
16
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
a
b
c
d

Discussion

Reaction times tended to be slightly longer when the absolute orientation cue was masked than with vertically oriented stimuli (cf. Figs. 5 and 2). The uncertainty about the orientation of the target increased reaction times for even a single vernier (cf. Figs. 6d and 4d) and thus seems not to be a sufficient indicator of serial processing. The increase of response time per additional stimulus, however, indicated that search became more difficult for all tasks when orientation varied (Tab. 1). This was in line with results of Beck (1966, 1967) who found that the orientation of lines was an important cue in the grouping of complex figures.

The difference in response times between fixed versus variable orientation of the stimuli was relatively small for the detection of a single straight target amidst vernier distractors. Processing had already been semi-parallel or serial for this task when all orientations were vertical, and we had assumed above that (among other things) the orientation cue was too weak in this kind of stimuli to assure parallel processing. The increase in slopes was more prominent for the short (more than a factor of 2) than for the long stimuli (less than a factor of 1.5; Fig. 5c; Tab.1).

The results on the detection of a single vernier target among straight distractors were more difficult to interpret. Clearly, the search for a single vernier was no longer independent of the number of distractors, if both absolute orientation and gap information were masked — especially for the short stimuli (Fig. 5a,b). It appears that observer MF did not make use of a gap cue under the condition of masked orientation information, while the other observers did (Fig. 5a). All observers achieved relatively flat slopes for detection of a single vernier with the longer stimuli, whether the gap cue was masked or not. This is true in spite of masked orientation for display sizes up to 6 or 8 stimuli, and, with larger horizontal offsets, for display sizes up to 16 stimuli (Tab. 4, 'vernier L.O.'). The search times for the right part of

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Fig. 5 (Page 17) Response times for the same four conditions and two stimulus lengths as in Fig. 2, but here, the orientations of all stimuli in each presentation varied independently of each other by up to 20° (observer AH: 30°). Relative to the results of Fig. 2, all reaction times were slightly longer under these conditions, and increased with the number of stimuli especially when the task was to identify a short vernier among straight lines with variable vertical gaps (b), to detect a (long) straight target among vernier distractors (c), or to detect a vernier offset oppositely than the distractors (d). Results of four observers; AH was measured twice: with a variation of stimulus orientation of ±20° (small squares), and of ±30° (large squares).

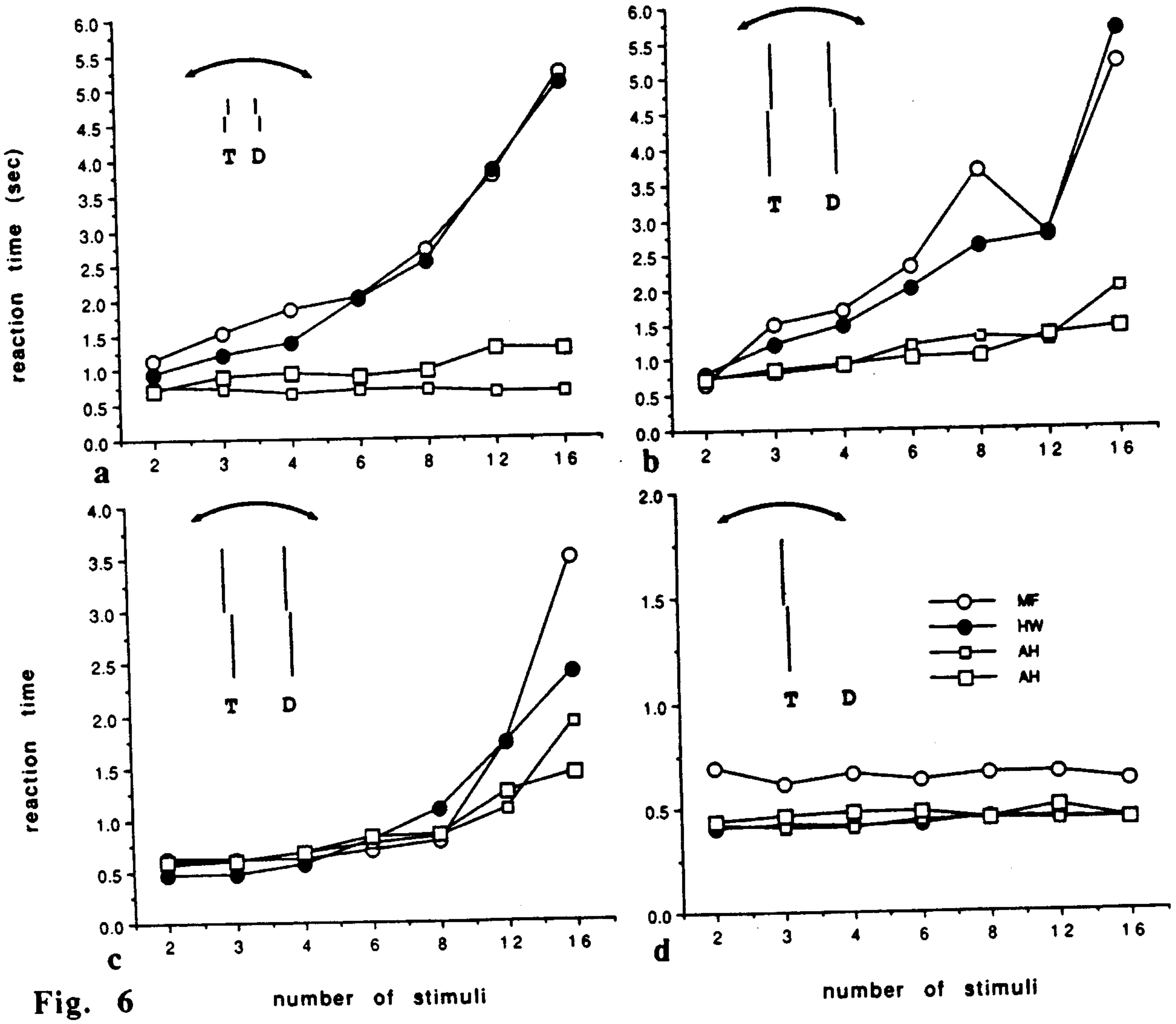

Fig. 6

Fig. 6 Reaction times for the same conditions as in Fig. 4, but for variable stimulus orientation. Response times increased with the number of stimuli for the detection of an oppositely offset vernier (a,b), and for the detection of a target with a double sized offset (c), but not of a single vernier target presented at one out of 2 to 16 possible positions. Results of three observers, AH was again measured twice: ±20° (small squares), ±30° (large squares).

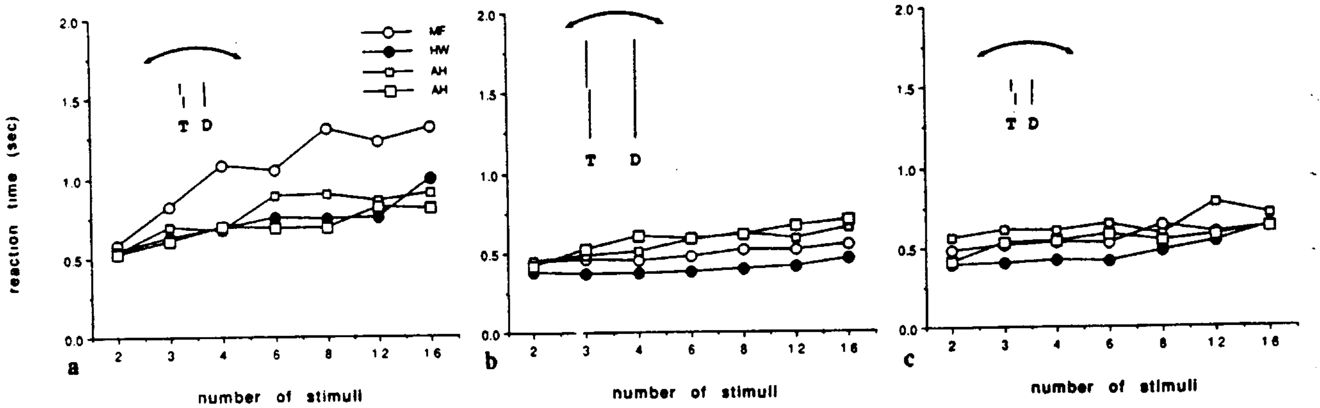

Fig. 7 Response times for the detection of a single vernier among 2 to 16 stimuli. **a)** short stimuli (21') with small vertical gap (1') and a small horizontal offset (5') **b)** long stimuli (81') with gap identical to (a) (1' vertical, 5' horizontal) **c)** Detection of a vernier as in (a) but with a larger horizontal offset (10'). Results of three observers, with AH measured twice.

Fig. 5b were 1.4, 2.2, and 13.4 msec/item for the first six stimuli, with a mean of 5.7 ±3.9. This was still in the range accepted for parallel processing. Short verniers could be processed in parallel as long as either an orientation cue was present (as in Fig. 2a,b) or a gap cue (as in Fig. 5a). But if neither cue was available, processing became serial, as in Fig. 5b. One observer, AH, was able to use the orientation cue with the varied stimulus orientation while the remaining observers could not. When the amplitude of variation increased to ±30°, however, AH was no longer able to use the implicit orientation cue. It is noteworthy in this context that the largest deviation in orientation from the vertical in the short stimuli, namely the imaginary line between the near ends of the two vernier segments at the gap, was almost 80° for the gap size used in these experiments (5' lateral offset, 1' vertical gap size), while a regression line through the stimulus deviated by only 25° from the vertical. The corresponding angles for the long stimuli (5' lateral offset, 5' vertical gap size) were 45° and 7°.

For larger and more complex displays, i.e., 12 stimuli and more, search times also increased for the task of searching a vernier target among (long) straight distractors (Figs. 5a & b). This transition might be caused by (inhibitory) lateral interactions between vernier stimuli, as described by Westheimer and Hauske (1975). The interactions have a width of around 30' at

4.5° eccentricity (Levi et al., 1985), and must be expected to be much more effective in the case of variable orientation than when all stimuli are oriented vertically, since the individual stimuli approach one another more closely when they are irregularly oriented (cf. Fig. 1).

Fig. 5d shows that observers were unable to detect the *direction* of offset in parallel, but required serial search. This in line with the results of Olson and Attneave (1970) who reported that differences in line orientation produced grouping (see above), but differences in the grouping of lines (i.e. right corners versus left corners) produced no clear grouping, leading to larger reaction times.

Search times of up to around 300 msec/item are relatively high, even for serial search. The main reason for the extremely slow search in 3 observers was the occurrence, at different degrees, of scanning eye movements under the conditions of Fig. 5d, as was revealed in control experiments that used an eye-tracker. One observer (AH) could still process short stimuli in parallel (4.3 msec/item) when stimulus orientation varied by up to 20°, but needed serial processing (50 msec/item) when orientation varied up to 30°, and with long stimuli (where orientation information is less explicit, see below). But even then, she made no or very few eye movements. Thus, the difference between her search time per item (50 msec) and the search time of the other observers (around 250 msec) amounts to approximately 200 msec. This value conforms to the range of times found to be required for planning and performing a saccadic eye movement (e.g. Carlow et al., 1975; Becker & Jürgens, 1979; Hallet & Adams, 1980).

The results of the second experiment show that reaction times were longer with variable stimulus orientation especially for displays with many stimuli, probably due partly to an increase of thresholds even for single verniers (especially for short stimuli), and partly to crowding and stronger inhibitory interactions between verniers (especially for longer stimuli). Variable gap size further increased search times as a function of stimulus number, but, at least for displays with up to six to eight stimuli and for larger horizontal offsets, the increase of search time for each additional item was well below 10 msec. Processing might therefore still be called parallel. Then, a vernier target with an offset close to two point resolution can be detected in parallel even if no absolute orientation cue is available to allow its discrimination from the distractors, and without the possibility of discrimination between target and distractors according to gap size.

Third experiment: Detection thresholds for vernier targets.

While *reaction time* was the dependent variable in the first two experiments, *thresholds* were measured in the third experiment. Observers had to decide whether or not a vernier target was present amidst straight distractors. Presentation time was usually limited to 150 msec to prevent scanning eye movements. A mask of straight vertical and horizontal lines (as described in the Methods section) immediately followed the stimulus presentation in part of the experiments. The results demonstrate the ability of the visual system to process hyperacuity information (Westheimer, 1976) even within this very short time.

Results

At 4.5° eccentricity, results differed somewhat between observers. While thresholds of two observers increased almost linearly with the number of stimuli, another observer (MF) showed barely any increase. This was true both for presentations with a subsequent mask (right side of Fig. 8c) and without (left side of Fig. 8c). It is not clear where to draw the limit of the hyperacuity range at this eccentricity, but it lies probably around 100" to 150", with best thresholds for single targets around 20" (Westheimer, 1982). Hence, some of the thresholds with up to 8 simultaneous stimuli are clearly in the hyperacuity range.

Thresholds below the photoreceptor diameter and below two point resolution were attained by all observers at 0.4° eccentricity for up to 6 or 8 simultaneously displayed stimuli (Fig. 8b), even with a subsequent mask. Hence, hyperacuity thresholds can be attained even with short parallel presentation of several stimuli. At 0.2° eccentricity, thresholds were even lower, down to 20" or below for up to 8 stimuli (Fig. 8a). It should be noted, however, that thresholds tended to increase with the number of stimuli, in a nonlinear way. Typically, thresholds increased more from 12 to 16 stimuli than from 4 to 8 stimuli, at least at the smaller eccentricities.

All stimuli were oriented vertically for the experiments of Fig. 8. Thresholds increased, as to be expected, when the orientations of the stimuli varied independently from each other for up to 20° (AH: 30°). The results at 0.4° and 4.5° (Fig. 9b,c) were clearly above the hyperacuity range, but two observers still attained thresholds of 30" and below at 0.2° eccentricity, even with a subsequent mask (Fig. 9a).

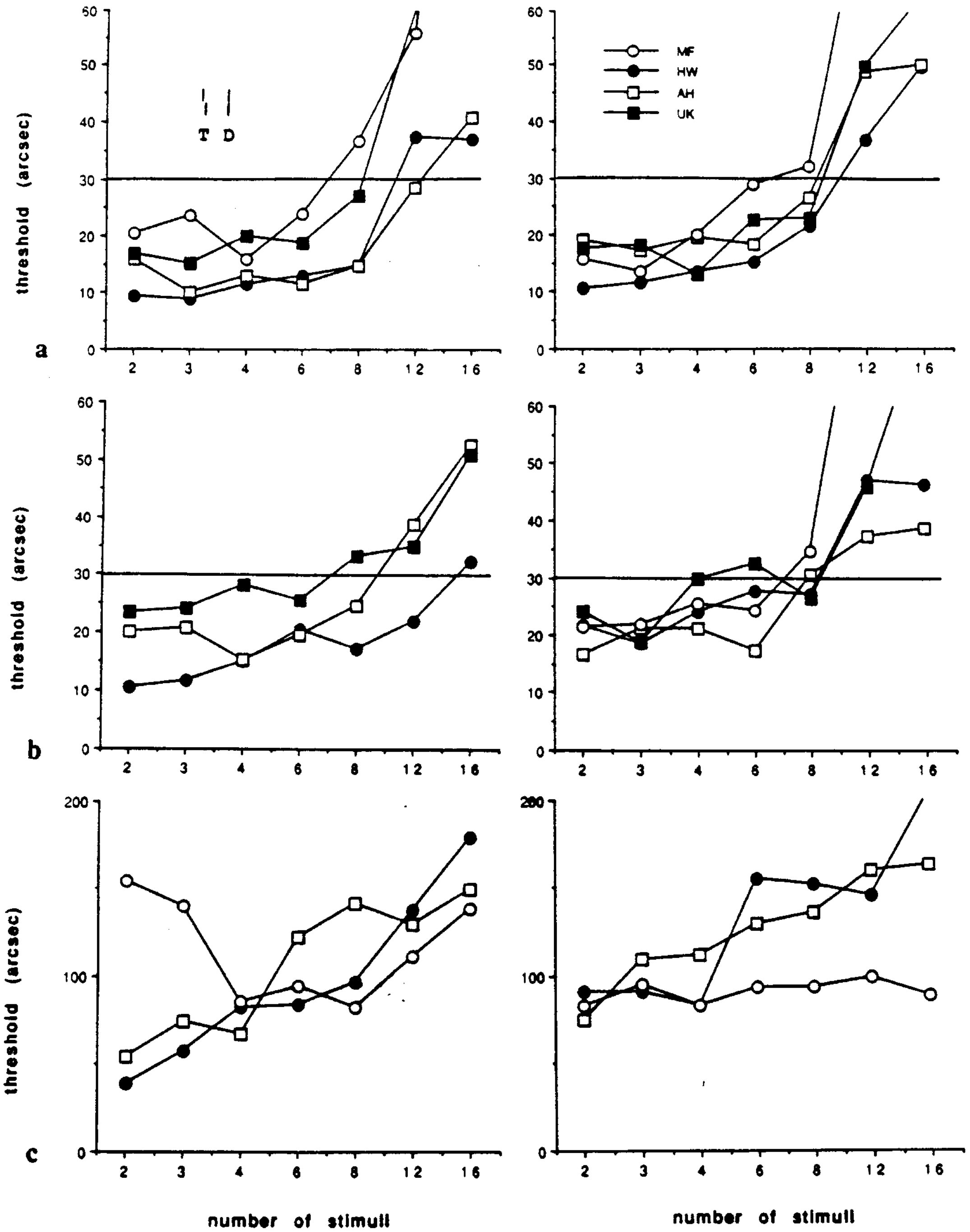

Fig. 8 *Thresholds* for the detection of a single vernier target among straight distractors at different positions of the visual field. **a)** at 0.2° eccentricity **b)** at 0.4° **c)** at 4.5°. The left column shows results without a mask, the right column graphs those with a subsequent mask. Horizontal lines indicate the approximate size of foveal photoreceptors. Some thresholds for display sizes of up to 12 stimuli were in the hyperacuity range.

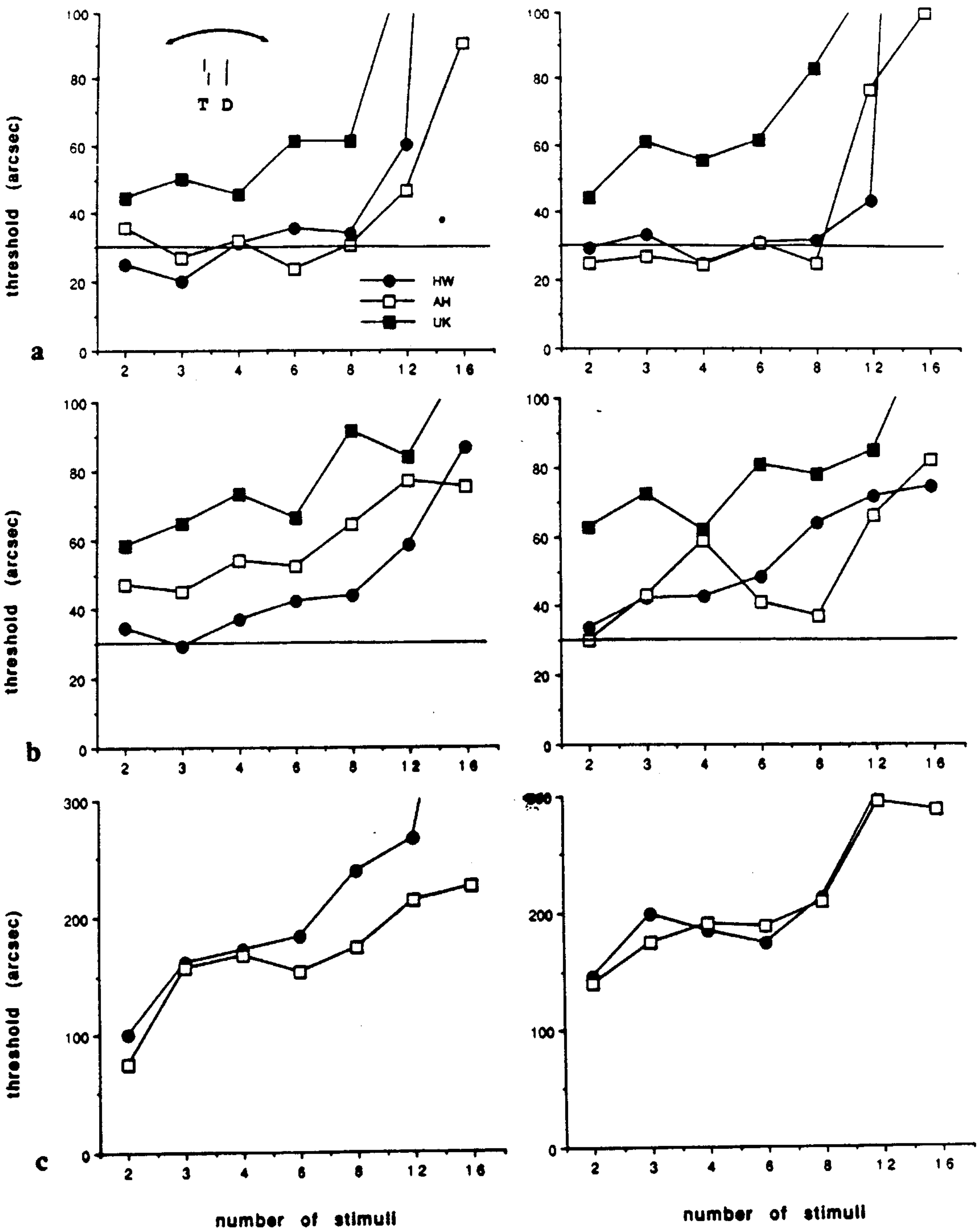

Fig. 9 *Thresholds* for a single vernier target, as in Fig. 8, but here, the orientation of all stimuli varied independently, at random, for up to 20° (AH: 30°) clockwise or anticlockwise relative to the vertical. **a)** 0.2° **b)** 0.4° **c)** 4.5°; left column: without mask, right column: with subsequent mask.

In these two observers, additional thresholds were measured at 0.4° and 0.2°, with a vertical gap between the two vernier segments varying between 1' and 9' (mean: 5'). Both observers reached thresholds that were clearly in the hyperacuity range for detection of a vernier target among straight distractors, even with a subsequent mask (Fig. 10a). If in addition orientation of the stimuli varied, thresholds rose above 30" at 0.4° eccentricity (Fig. 10b); but at 0.2°, one observer obtained hyperacuity thresholds with up to 12 displayed items at fixed orientation, and with up to 4 stimuli at varied orientation.

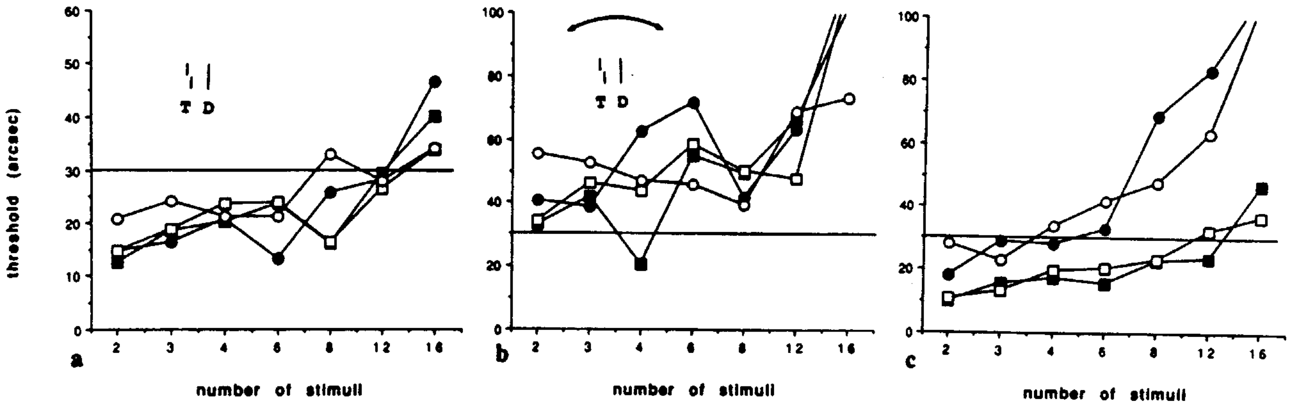

Fig. 10 *Thresholds* for detection of a single vernier target among distractors. The size of the vertical gap of the stimuli varied randomly. **a)** at 0.4°, with (line symbols) and without mask (solid symbols; results of the two best observers, where AH: squares, HW: circles); **b)** 0.4°, as in (a), but in addition, orientation of the stimuli varied independently; same observers as in (a); **c)** at 0.2° eccentricity, with (line symbols) or without mask (solid symbols), and at fixed (squares) or variable orientation (circles). Results of one observer (AH).

Discussion

The threshold experiments at 4.5° closed the gap between the reaction time experiments (which were performed at this intermediate eccentricity to minimize the inhibitory interactions between the individual stimuli, while still allowing a relatively high vernier acuity) and the remaining threshold experiments, aimed at detection of offsets below a photoreceptor diameter. The results show that the vernier displacement of 5' (used in the reaction time experiments) was close to thresholds at this eccentricity, at least for complex displays. It is not astonishing, then, that observers performed scanning eye movements with some of the stimuli. It has been reported that hyperacuity thresholds increase towards the periphery faster than thresholds for two point resolution do. At 4.5° eccentricity, two point resolution is around 100"-150", and the best thresholds for single verniers are around 25" to 40" (Westheimer, 1982; Levi et al., 1985). Thus, some of the thresholds of our observers are in the hyperacuity range if one adopts the definition that the hyperacuity range begins immediately below two point resolution at any given eccentricity. It is not clear why thresholds for two observers increased linearly with display size while they were basically unaffected in another observer (MF). The fact that observer MF yielded better results with a subsequent mask than without the mask is probably due to training effects (the experiments with the mask were performed after the ones without the mask).

At 0.4°, most thresholds were below the hyperacuity limit as defined above, up to a display size of around 8 stimuli. At 0.2°, thresholds for two observers were as low as 10-15" for up to 8 stimuli (Fig. 8a). These observers could detect a vernier offset far below a photoreceptor diameter within a presentation of 150 msec duration even if the vernier target was displayed among 7 straight distractors and even if a mask followed immediately upon the stimulus presentation. This performance is extremely precise, given the fact that inhibitory interactions between a vernier target and flanking lines have been described to extend over 3-6' in the fovea (Westheimer & Hauske, 1975; Levi et al., 1985). If 8 vernier stimuli were displayed at equal distances from each other and at an eccentricity of 0.4°, the average distance between their midpoints was less than 20'; and at 0.2°, this distance was less than 10'. Since the verniers were 7' long, their minimal distance was even smaller than the distance between the midpoints. The horizontal distance over which the 8 stimuli were distributed (twice the eccentricity), i.e. 48' for 0.4°, and 24' for 0.2°, divided by the number of horizontal intervals (= 4), gave an average horizontal distance of 12' at 0.4°, and of 6' at 0.2°. This was already within the range of inhibitory interactions. For 12 simultaneously displayed stimuli, the mean distance decreased to 8' and 4', respectively, for the two eccentricities tested. Finally, in a 16 stimulus display, mean horizontal distance was 6' and 3', respectively. The latter had been found to be the distance most detrimental for vernier thresholds, increasing thresholds by a factor of three even with unlimited viewing time. It is hardly astonishing that thresholds increased for these densely packed displays. The increase of thresholds at an eccentricity of 0.4° was approximately a factor of three, while the increase was more pronounced at the lower eccentricity of 0.2°, at least in two observers (UK, MF). The above calculations show that the increase in thresholds with display size can be attributed, at least to a large part, to inhibitory interactions between the vernier target and the distractors. This interpretation is supported by the results, in one observer (AH), with the same stimuli and unlimited presentation time. Thresholds were, in most instances, not much lower - and sometimes even higher - than with 150 msec presentations.

Naturally, the average distance between the stimuli further decreased when their orientation was varied independently and at random (cf. Fig. 1, right versus left sides). This was true for all eccentricities. In addition, thresholds even for a single vernier (cf. Watt, Morgan & Ward, 1983; Watt & Campbell, 1985; and in some observers also reaction times, cf. Figs. 4d & 6d) increased when the vernier was presented at varied orientations. The amount of increase in threshold depends on stimulus length, and is probably around a factor of three in the fovea for the stimulus length used here (12'; Watt & Campbell, 1985). And indeed, thresholds increased by around a factor of three between fixed orientation (Fig. 8) and variable orientation (Fig. 9). This increase can be understood on the basis of the two factors just outlined. It is reassuring that, even under these very difficult conditions, two observers attained several thresholds below 30" (Fig. 9a).

The thresholds obtained by the best observer, for vernier targets of variable gap size, variable orientation, and a subsequent mask are indeed remarkable. Even under these extremely difficult conditions, AH detected a target with an offset below a photoreceptor diameter within a 150 msec presentation among a few distractors. The results of Fig. 10 clearly demonstrate that hyperacuity performance can be achieved simultaneously even when no gap information and no information about the absolute orientation can be used (cf. also thresholds for chevrons and curved targets in the seventh experiment).

Fourth experiment: Reaction times for curved targets.

All the previous experiments measured reaction times or thresholds for stimuli consisting of verniers and straight lines. Curvature is another feature known to yield thresholds in the hyperacuity range (Andrews, Butcher & Buckley, 1973; Ogilvie & Daicar, 1967; Watt & Andrews, 1982; Wilson, 1985; cf. also Foster, 1983). For a number of reasons, curvature detection is an interesting ability of the visual system. It seems to be a more natural stimulus for the evolution, during phylogenesis, of hyperacuity: the visual world is not full of vernier stimuli, but of curved contours. In the fourth experiment, reaction times for curved targets were determined, basically in the same way as for vernier targets in the first and second experiments, i.e., for vertical and variable orientations of the individual stimuli, at 4.5° eccentricity. The curved stimuli deviated from a straight line by 5', (cf. horizontal arrow in Fig. 1c$_4$), corresponding to the vernier offset used in the first two experiments. The same three conditions as before were tested: detection of one curved target amidst straight lines, detection of one straight target among curved distractors, and detection of a line curved to the left among lines curved to the right. Observers did *not* perform, as had been the case for vernier targets, practice sessions before the experiments proper for this and the subsequent experiments.

Results

The pattern of results for curved stimuli resembled closely that for vernier stimuli. Detection of a single curved target was very fast, and response time increased hardly at all with display size, both for long and short stimuli (Fig. 11a). Search times were between 21 and 5.7 msec/item (mean: 3.6 ±0.8) for the short stimuli, and 1.0 to 1.7 (mean: 1.5 ±0.23) for the longer ones. The mean slope for all observers and both stimulus lengths was 2.7 ±0.6 msec/item. Response times for the detection of a line curved to one side among lines curved to the opposite side were somewhat less homogeneous than for the detection of a single curved line, but increased only moderately with the number of stimuli. Search times varied between 0.7 and 21.0 msec /item (mean: 10.1 ±4.2) for the short stimuli and between 1.4 and 15.0 (mean: 6.1 ±4.4) for the longer stimuli (Fig. 11c). The overall mean was 8.4 ±2.9. The most difficult task obviously was to find a straight line among curved distractors (Fig. 11b) — at least as long as all stimuli were oriented vertically. Regression lines through the data points in Fig. 11b had slopes between 8.5 and 23 msec/item (short stimuli; mean: 16.5 ±4.3), and between 17 to 48 msec/item (long stimuli; mean: 35 ±9.3). This is to say that the increase of search time with display size was somewhat, but not significantly ($p>0.1$), more pronounced for the long (!) stimuli. The overall mean for the search times in this condition was 25.8 ±6.2 msec/item.

As with the vernier stimuli, the reaction times were, on the average, slightly higher, if orientation of the stimuli was varied independently and at random by up to ±20° (AH: 30°) — even for simple displays that only encompassed a few stimuli. Reaction times for the detection of a single bent target among straight ones were moderately longer for complex displays than for simple ones, with search times of 6.1 to 15 msec (mean: 11.2 ±2.1) per additional item for short stimuli, and 6.3 to 8.3 (mean: 7.1 ±0.5) for longer stimuli (Fig. 12a). The mean of all observers was 9.1 ±1.25 msec/item. When the results for the (crowded) 16 stimuli displays were not taken into account, search times for the long stimuli ranged between 4.2 and 7.2 (mean: 5.7) msec/item.

While search times for a single straight target increased only moderately with the number of vertically oriented stimuli (Fig. 11b), the increase was far stronger when stimulus orientation varied (Fig. 12b). Search times for the latter condition increased by 26 to 93 (mean: 45 ±16) msec per additional short item, and by 55 to 110 (mean: 86 ±23) per long item, with an overall mean of 65.6 ±11.9 msec/item. A similar increase in response times was measured for the detection of a stimulus curved to the left among distractors curved to the right (Fig. 12c), with slopes around 19 (short), and 27 msec/item (long) for observer AH, and around 60 to 120 msec/item for the other observers. Means of all observers for short stimuli were 61 ±27, for long stimuli 52 ±16.8, and for both lengths 56.5 ±14.8. While results in the previous condition (find one straight target, Fig. 12b) had been better for shorter than for longer stimuli, this difference between the two line lengths was not found in the search for a stimulus bent to the opposite side (Fig. 12c).

Discussion

Processing of curvature was clearly parallel. Observers could detect a curved target among 15 straight distractors even faster (within 453 msec ±15 s.e.; Fig. 11a) than a vernier target between the same 15 distractors (638 msec ±38; Fig. 2a). Independent variation of the orientations of all stimuli had only a moderate effect upon mean response time (566 msec ±21 for 16 stimuli). The more complex presentations generally required slightly longer response times and yielded slightly more errors, as shown in Tables 1 & 3; there was no trade-off between speed of the reactions and the level of performance. The results indicate that the cue underlying curvature detection was not absolute orientation but a deviation from straightness, or a change in orientation. The parallel processing of bent stimuli lends further evidence to the conclusion drawn above that parallel detection of a vernier target is not mediated by its gap - since none of the stimuli used in the fourth experiment had a gap, but parallel processing was still possible.

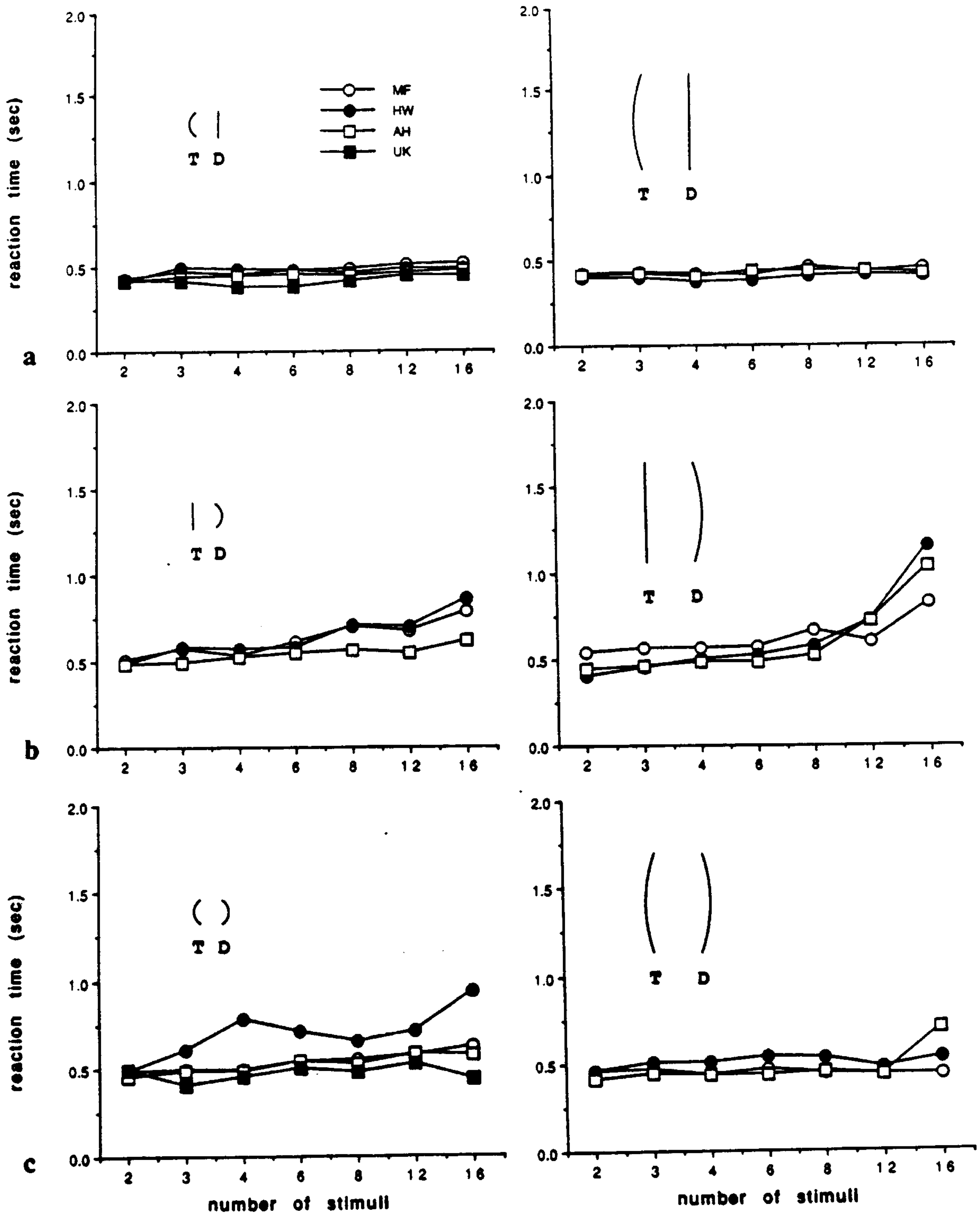

Fig.11 Reaction times for detecting an odd-man-out for **a)** a curved target amidst straight distractors, **b)** a straight target amidst curved distractors, and **c)** a target bent to the left amidst distractors bent to the right. Left column: short stimuli; right column: long stimuli.

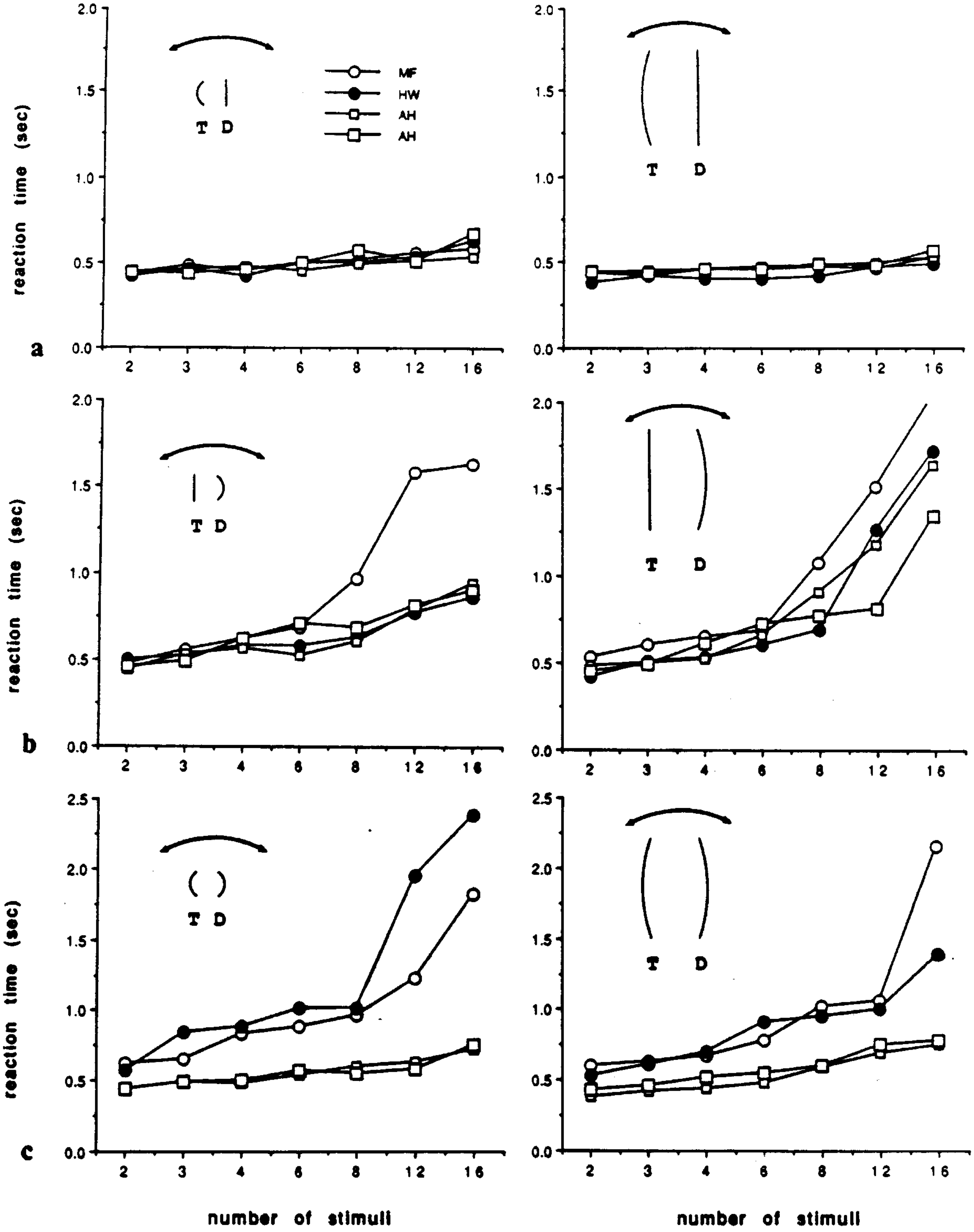

Fig.12 Reaction times for the detection of curved targets, respectively a straight target among curved distractors, as in Fig.11, but the orientations of all stimuli varied independently. Left column: short stimuli; right column: long stimuli.

With fixed orientation, the detection of an oppositely bent target was parallel (Fig. 11c). The loss of this ability with stimuli of varied orientation (Fig. 12c) indicates that some form of absolute orientation cue might have been used for the vertically oriented stimuli, though the case is more difficult here than with the vernier targets. The bent lines were mirror-symmetrical around their horizontal axis, and a regression line through a vertically oriented bent line does not deviate from the vertical orientation, whereas the regression line through a vertically oriented vernier deviates from the vertical. In addition, a line bent to the right contains the same orientations as a line bent to the left — just in opposite order when the line is scanned from above to below (or vice versa).

As with vernier stimuli, observers could detect whether or not a curved target was present, but were unable to identify its direction of bend if the absolute orientation cue was masked. Response times increased considerably, up to more than 100 msec/item for this condition — still less than in the corresponding vernier tasks (cf. Figs. 12c and 5d; note different ordinate scales). Possibly, this difference is due to the observers were more experienced when they underwent the fourth experiment than during the first two experiments. Alternatively, the difference might be partly due to the fact that curved stimuli contain less terminators than verniers (another feature processed in parallel and which might increase the noise in the system), or to another factor.

A plausible explanation for the difference between the results for fixed versus variable orientation might be that, in the former case, the deviant target was a mirror-symmetrical image of the distractors, while it was not when stimulus orientation varied. To rule out loss of symmetry relative to the vertical as the critical factor for the increase in thresholds, the experiment of Fig. 11c was repeated with the whole display rotated by 20°. Under these conditions, the (mirror) symmetry in relation to the vertical meridian was suspended. The results ruled out the hypothesis that (vertical) symmetry detection was actually involved in this task (not shown). Similar results were obtained for a corresponding display of *vernier* stimuli, rotated by 20° relative to the vertical. Alternative explanations might postulate that the visual system might use any given axis of mirror symmetry for the purpose of detecting a deviant curvature (or vernier offset), or that it can make use of the discrimination between the order of different but similar orientations (e.g. clockwise versus anticlockwise change), or the influence of a ´frame effect`.

As always, the most difficult task (at least for fixed orientations) was to find a straight target among bent distractors. This search asymmetry is quite common for features processed in parallel (Treisman & Souther, 1985). Treisman and Gormican (1988) discovered a similar asymmetry between detection of a single, slightly curved line among straight distractors (6.1 msec/item for positive, 12.9 msec/item for negative presentations) versus detection of a single line among curved distractors (29.0 msec/item for positive and 54.7 msec/item for negative presentations). However, if the curved line was strongly rather than slightly curved, no such search asymmetry was present, and slopes were far shallower. As can be seen in Tab. 1 and Tab. 4, the slopes described by Treisman and Gormican conform well with our results for variable orientation. The only discrepancy between our results and the results by Treisman and Gormican (loc. cit) is that they found a much larger difference between positive and negative presentations. This discrepancy might be due to the more extensive training of our subjects who had learned to decide extremely fast when there was no target.

Basically the same arguments as with vernier targets hold for curved stimuli. The difference between conditions (a) and (b) in Fig. 11 can be attributed to neuronal mechanisms ´looking at` the stage of the elementary feature detectors and discriminating much easier between ´no feature detector activated` versus ´one feature detector activated`, than between ´16 detectors activated` versus ´15 detectors activated`. A possible explanation for the difference between conditions (b) and (c), is the twofold greater difference in orientation between a target tilted to the right versus distractors tilted to the left as compared to the same target versus straight distractors.

With variable orientation of the bent stimuli, as with vernier stimuli, slopes for the increase of reaction times were slightly, but significantly higher than with fixed orientation (cf. Tab. 1: 1.5 ±0.23 msec/item versus 7.1 ±0.5 msec/item for one offset, long stimulus). Several possible explanations spring to mind, such as the impossibility of improving performance by attending to a specific orientation, or an inferiority of performance at oblique orientations (the oblique-effect, cf. Appelle, 1972; but control experiments ruled out this possible explanation, since reaction times were identical with the whole display rotated by 20° while orientation of the stimuli was fixed). Another explanation would be that observers were unable, at varied stimulus orientation, to compare directly the retinal image of a set of stimuli with the preceding set. (This strategy would require a parallel memory and a parallel comparison mechanism with hyperacuity resolution). In any case, the increased reaction times fit well with reports in the literature that thresholds for vernier offsets increase if the orientation even of a single (short) vernier presented to the fovea is varied between presentations (Watt et al., 1983; Watt & Campbell, 1985).

Curved stimuli show a similar pattern of results as verniers do. One difference is that curvature detection seems to be somewhat less susceptible to crowding than verniers are, and parallel processing is possible even with displays of 16 stimuli. The results with the curved targets further corroborate the notion that gap size is *not* the crucial factor in the detection of the odd-man-out in the parallel detection of hyperacuity targets such as verniers because the curved stimuli do not have gaps.

Fifth experiment: Reaction times for chevrons

Chevrons differ from curved stimuli in two important ways: First, they contain only two orientations (instead of a continuum), and second, they posses an angle, i.e., a discontinuity of orientation that is lacking in smoothly bent stimuli, such as the ones used in the fourth experiment (cf. Foster, 1980). Partly as a control over the results of the preceding experiment (since the stimuli in both experiments are still relatively similar), and partly to investigate whether the differences between the stimuli lead to different responses of the visual system, all conditions investigated in the fourth experiment were also measured with chevrons.

Results

Reaction times as a function of the number of stimuli produced very flat curves for the first condition: detection of a single chevron among straight distractors. Search times laid between 3.6 and 8.5 (mean: 5.6 ±1.5) msec/additional item for short stimuli, and between 1.2 and 3.5 (mean: 2.4 ±0.7) for longer stimuli (Fig. 13a). The overall mean of this condition was 4.0 ±1.0 msec/item. The reverse task of finding a straight target among chevrons was clearly more difficult, especially for longer stimuli. Search times varied between 17 and 48 (mean: 29 ±9.6) msec/item for short stimuli and between 41 and 79 (mean: 56 ±11.7) msec/item for long ones. The overall mean was 43 ±9 (Fig. 13 b). The difference between line length had the opposite sign for search of a chevron poin-ting to the left among chevrons pointing to the right. There, search times were between 24 and 30 (mean: 27 ±1.7) msec/item for the short chevrons and between 0.3 and 3.0 (mean: 1.3 ±0.9) for long ones, with a mean of 14 ±6 for all conditions (Fig. 13c).

Observers needed in general longer response times with variable orientation of the chevrons (Fig. 14) than with fixed vertical orientation (Fig. 13). Even the detection of a single chevron among straight distractors was no longer truly parallel but required search times between 12 and 21 (mean: 18.5 ±2.2) msec/item for short and 8.4 to 14.9 (mean: 10.8 ±1.4) for long stimuli, with an overall mean of 14.6 ±1.9 (Fig. 14a). Detecting a straight target among chevrons, on the other hand, was no more difficult with variable than with fixed orientation, and the mean search time of all observers increased by 38.0 ±12.7 msec/item (Fig. 14b).

Response times for the detection of a chevron pointing to the opposite side increased by 27 to 110 (mean: 71 ±23) msec/item for short stimuli, and by 14 to 90 (mean: 48 ±16.2) msec/item for long stimuli (Fig. 14c). The overall mean of this condition showed an increase of 59.1 (±13.7) msec per additional item.

Discussion

In general, results for simultaneously presented chevrons were very similar to those with bent stimuli, thus adding evidence to the results of the fourth experiment. A single chevron among up to 16 stimuli was detected in parallel at fixed vertical orientation. At variable stimulus orientation, parallel detection was only achieved with long stimuli. The detection of a single straight line among chevrons required ´semi-parallel` search at fixed orientation, and serial search at variable orientation. This pattern of results was similar as with curved or vernier targets. Again, a distinct search asymmetry prevailed in detecting the presence of a feature in a stimulus, versus detecting its absence. Detection of a chevron open to one side, among distractors open to the opposite side, required serial search if the absolute orientation of the stimuli varied but could be performed in parallel at a fixed vertical orientation of all stimuli.

The tendency for better results, i.e., shorter reaction times, with *short* rather than long stimuli in detecting a single straight target, found with curved and vernier stimuli, was also present with chevrons. Oppositely, detecting a curved target among straight distractors or detecting an oppositely curved target yielded slightly better results with *long* stimuli also in chevrons. The results with the chevrons are quite similar to those with curved stimuli, supporting the evidence gained from the results of the fourth experiment.

Sixth experiment: Reaction times for orientation discrimination.

The preceding experiments with vernier, curved, or chevron targets all yielded results, especially in the case of detecting an oppositely offset or bent target, that depended critically upon whether all stimuli shared a common orientation or were oriented randomly. This finding indicates that a cue was used that exploited absolute orientation. The possible use of absolute orientation under the conditions of simultaneous presentation of several or many stimuli, as used in the preceding experiments, was investigated in the sixth experiment. Reaction times were measured for the detection of a target under the same three conditions as with the vernier, curved, and chevron stimuli. Since absolute orientation was the discriminating feature here, the experiment was performed only for the ´fixed orientation` condition.

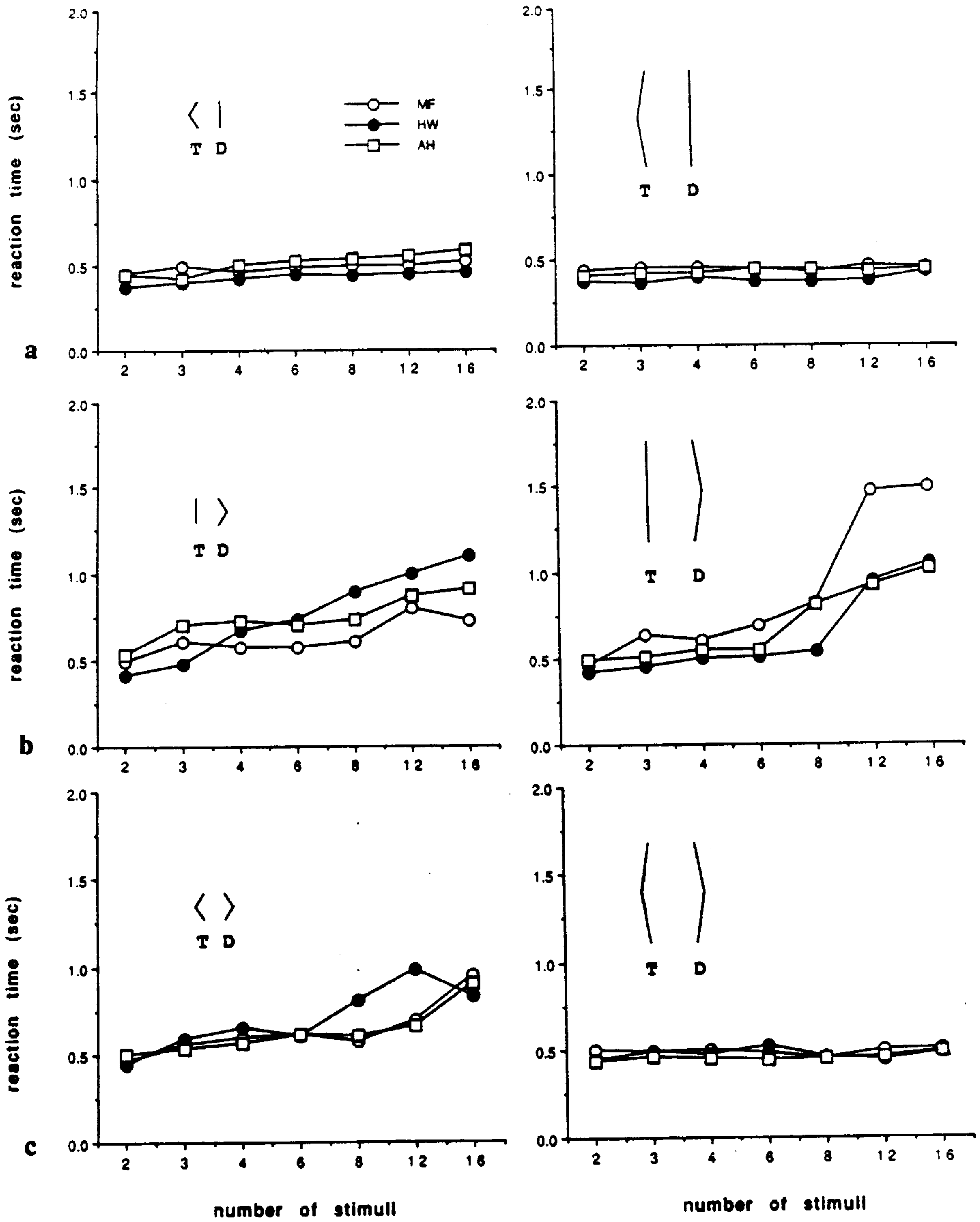

Fig.13 Response times for detecting an odd-man-out for **a**) a chevron target among straight lines, **b**) a straight target among chevron distractors, and **c**) a chevron pointing to the left among chevrons pointing to the right. Left column: short stimuli; right column: long stimuli.

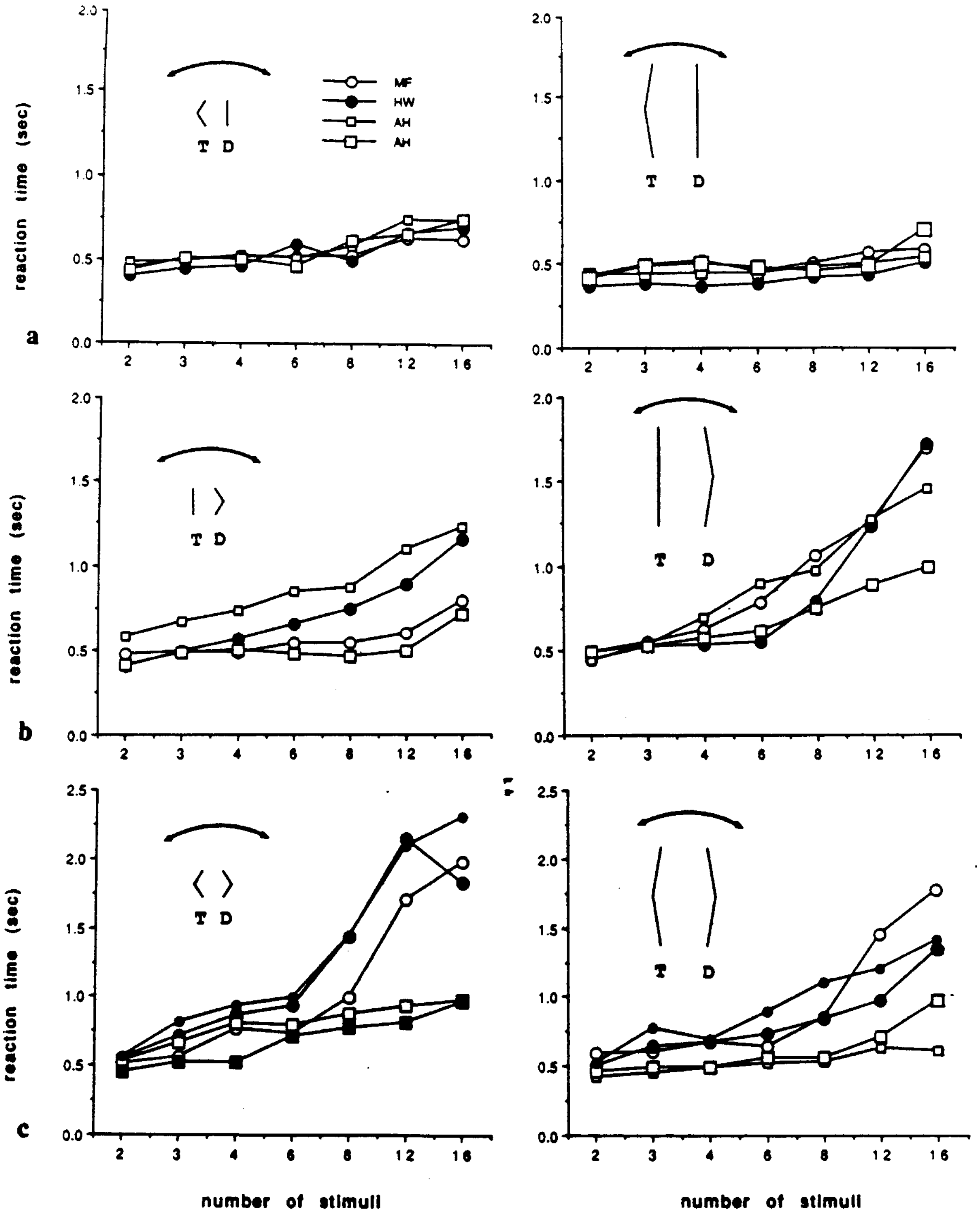

Fig.14 Response times for the detection of chevron targets, respectively a straight target among chevrons, as in Fig. 13, but stimulus orientations varied independently of each other. Left column: short stimuli; right column: long stimuli.

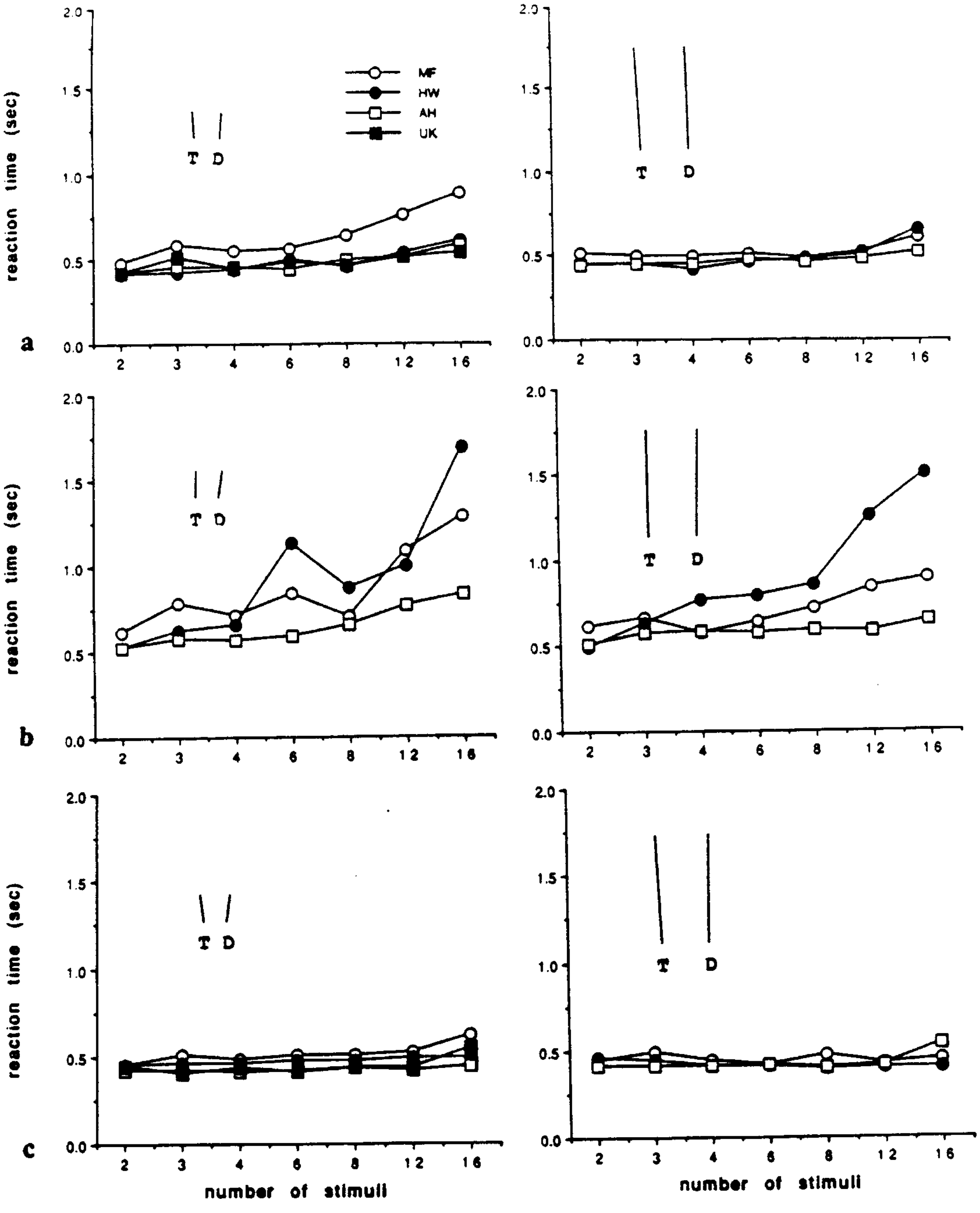

Fig.15 Reaction times for detecting a deviant orientation. Detection of **a)** a tilted line among vertical distractors, **b)** a vertical target among tilted distractors, and **c)** a line tilted to the left among lines tilted to the right. Left column: short stimuli; right column: long stimuli. Since the horizontal offset (cf. Fig. 1c) was identical for short and long stimuli, the angle between the target and the vertical was larger in short than in long stimuli.

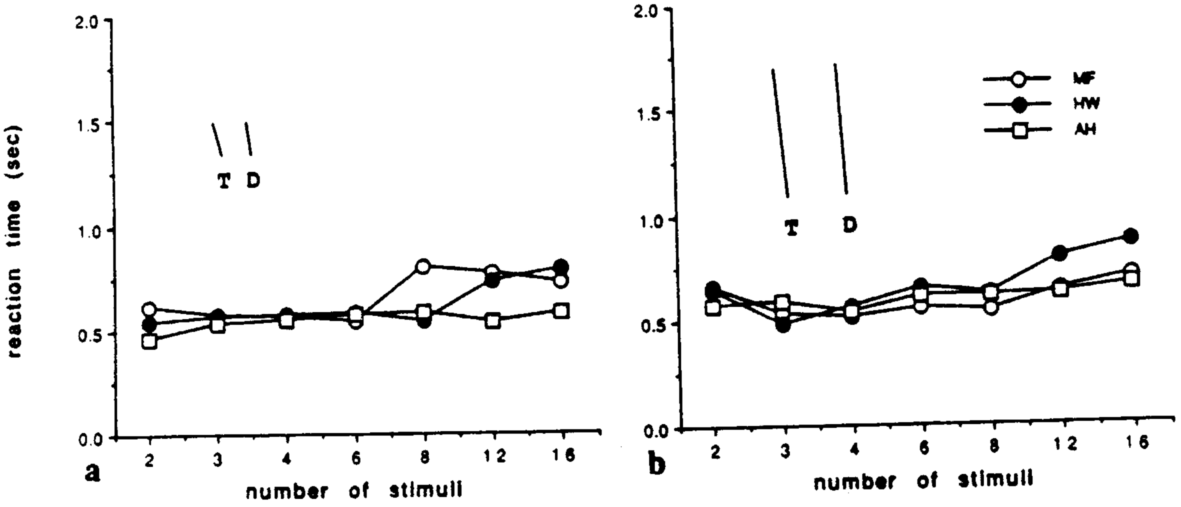

Fig.16 Response times for detection of a target tilted relative to the vertical by twice the offset (10´) by which the distractors were (5´). The corresponding angles for short stimuli (**a**) were 25° and 13°, resp. 7° and 3.5° for long stimuli (**b**).

Results

Most observers detected a stimulus of deviant orientation relatively quickly among vertical lines, i.e., processing was semi-parallel with search times between 11 and 27 (mean: 17 ±5.0) msec/item for short, and parallel with search times of 7 to 15 (mean: 9.3 ±2.9) msec/item for long stimuli, giving a mean of 13.1 ±3.1 for both conditions (Fig. 15a). One observer (MF) clearly needed longer response times for complex presentations of short stimuli, but not for long ones.

The detection of a single vertical target among slanted distractors proved to be significantly more time consuming in most observers. Response times increased by 22 to 70 (mean: 45 ±13.9) msec/item for short stimuli, and by 6.1 to 68 (mean: 32.0 ±18.6) msec for long ones (Fig. 15b). A target slanted to the left among distractors slanted to the right was detected almost as quickly among 15 distractors as with just one, with 1.4 to 9.2 (mean: 4.5 ±2.4) msec required for each additional short item displayed, while 1.0 to 3.4 (mean: 2.3 ±0.7) msec were needed for each additional long stimulus (Fig. 15c). The overall mean was 3.4 ±1.2 msec/item.

In the experiments for Fig. 16, the target deviated from the vertical by twice the amount (10') of the distractors (5'), corresponding to a slant of 7° for long stimuli and 25° for short ones. This is a condition similar to the detection of a vernier with twice the offset of its distractors. Reaction times were slower than for the detection of a single slanted target (cf. Figs. 16 and 15a), but were relatively independent of the display size. The increase of search time per additional item varied between 4 and 14 (mean: 11.7 ±3.9) msec per short stimulus and between 6.4 and 22.5 (mean: 12.4 ±5.1) msec per long stimulus.

Discussion

Complex presentations of short stimuli, but not of long ones, required longer response times for one observer (MF) than for the other observers. The same observer needed significantly longer response times to detect a single vernier among straight distractors, if the stimuli were short and especially at varied orientation (Figs. 2a, 5a, 7a). A possible explanation is that due to the stimulus being near absolute threshold for complex presentations, this observer's ability to discriminate between both absolute and relative orientations was below average for short stimuli, leading to a semi-parallel performance.

The response times for search of a vertical target among differently oriented distractors showed the same search asymmetry as in verniers, chevrons, and curved targets and hence were compatible with the notion that an orientation cue might be used in these tasks. The same was true for the results under the third condition: detection of an oppositely slanted target. Performance for this task was clearly parallel, even with orientation differences of 10', corresponding to an angle from the vertical of 13° for the short and of 3.5° for the long stimuli.

These results are in good agreement with earlier findings demonstrating that orientation can be detected in parallel (cf. Riggs, 1973; Sagi & Julesz, 1985; Sagi & Julesz, 1987; Treisman & Gormican, 1988). The present results corroborate these findings and extend them towards smaller orientation differences. The results in Fig. 16 add further evidence to the notion developed above that, although the vertical orientation is special in several respects (cf. oblique effect: Appelle, 1972), deviation from a non-vertical orientation can be detected in parallel, too (cf. Treisman & Gormican, 1988).

A target deviating by twice as much from the vertical as the distractors was quickly detected (Fig. 16). This result contrasts to what was found for vernier stimuli (Figs. 4c, 6c). The reason might be that a deviation from the prevailing orientation can be easily detected even if the prevailing orientation is not vertical, but that the detection of vernier offset, especially with long stimuli, does not rely on absolute orientation cues. Again, frame effects as found by Treisman and Gormican (1988) might influence the results.

Response times for the detection of a deviant orientation yielded results that were very similar to those obtained with vernier, curved, or chevron stimuli. Parallel processing with an increase of search times of less than 10 msec per additional item was attained. Interestingly, search times for orientation detection did increase somewhat stronger than in some of the preceding experiments, indicating that even orientation processing is not completely parallel near threshold. The threshold experiments of Nothdurft (1985) fit in well since he found that the perception of a texture border required a stronger orientation stimulus, i.e., a stimulus further above threshold than the discrimination between orientations did - parallel processing was obviously not achieved near threshold.

Seventh experiment: Hyperacuity thresholds for chevrons, curvature, and slant.

The results of the third experiment had demonstrated clearly that thresholds below a photoreceptor diameter, i.e., in the hyperacuity range can be attained even with an instantaneous presentation of a single vernier target hidden amidst up to 15 distractors. In the seventh experiment, *thresholds* were measured for chevrons, curved, and slanted stimuli under conditions identical to those of the third experiment. As in the third experiment, the task was to discriminate between presentations that displayed all identical stimuli and others that contained a single curved, slanted, or chevron-target. Only the two best of the previous observers took part in this experiment.

Results

Thresholds for the detection (respectively the detection of the absence) of a curved line amidst vertically oriented distractors were clearly below the photoreceptor diameter for display sizes up to 8 (observer HW) or even 16 items (observer AH) at both eccentricities: 0.2° (Fig. 17a,b) and 0.4° (Fig. 17c,d). A mask immediately following the presentation of the stimulus increased thresholds only moderately, or not at all. When the orientations of all stimuli varied at random up to ±20° (HW) or 30° (AH), thresholds increased (Fig. 17b,d). At 0.4°, only observer AH still achieved hyperacuity thresholds for up to 8 items per display, but at 0.2°, both observer's thresholds were below 30" for up to 8 items (Fig. 17b).

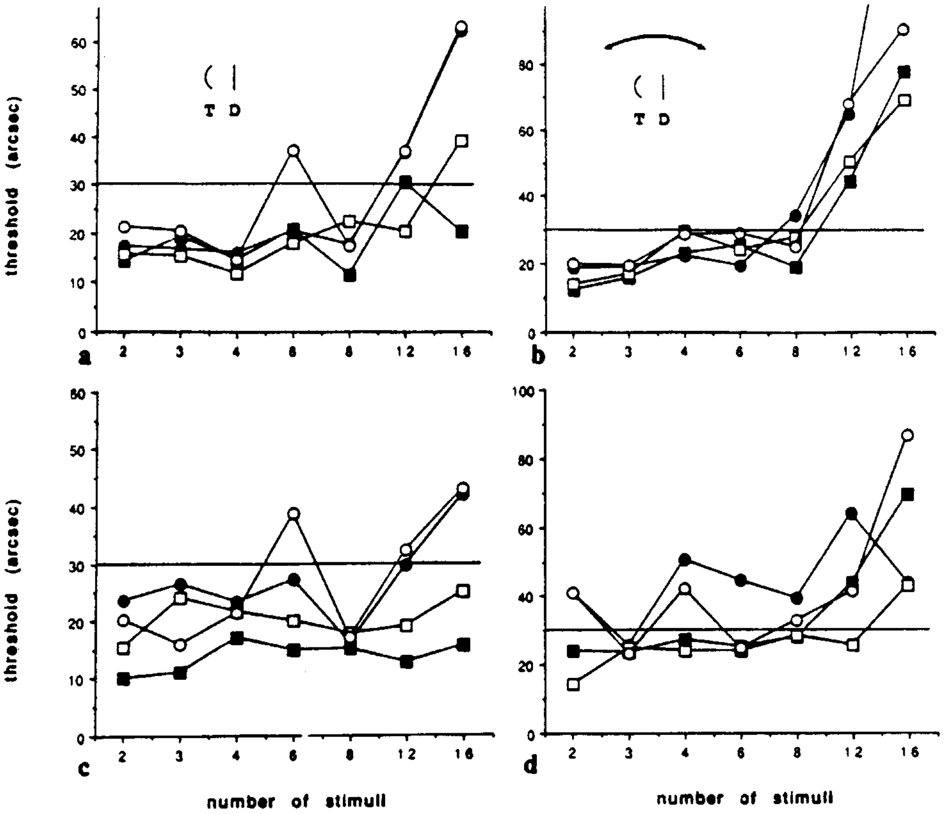

Fig.17 *Thresholds* for the detection of a single curved target among straight distractors at eccentricities of 0.2° **(a,b)** and 0.4° **(c,d)**. The stimuli were either oriented vertically (left column; a,c) or orientation varied by ±20° (HW; circles) or 30° (AH; squares) relative to the vertical (right column; b,d). For each condition, thresholds were measured both with (line symbols) and without subsequent mask (solid symbols). Results of two observers.

Results for chevrons were similar to the ones for curved targets (Fig. 18). Both observers achieved thresholds well below 30" for vertically oriented stimuli, both with and without a subsequent mask and at both eccentricities. Variation of stimulus orientation increased thresholds moderately, and many thresholds were clearly below 30" especially at the smaller eccentricity. Orientation thresholds were similarly low, with the best results around 15" at 0.2° without mask in a 8-item presentation, and around 20" with subsequent mask (Fig. 19).

Discussion

The results of this experiment demonstrated that hyperacuity thresholds were achieved not only in flash presentations of vernier stimuli, but in additional tasks such as curvature, chevron, or slant detection. This finding lends further evidence to the claim that the cue discriminating the vernier target from the straight distractors is *not* the gap of the vernier, but

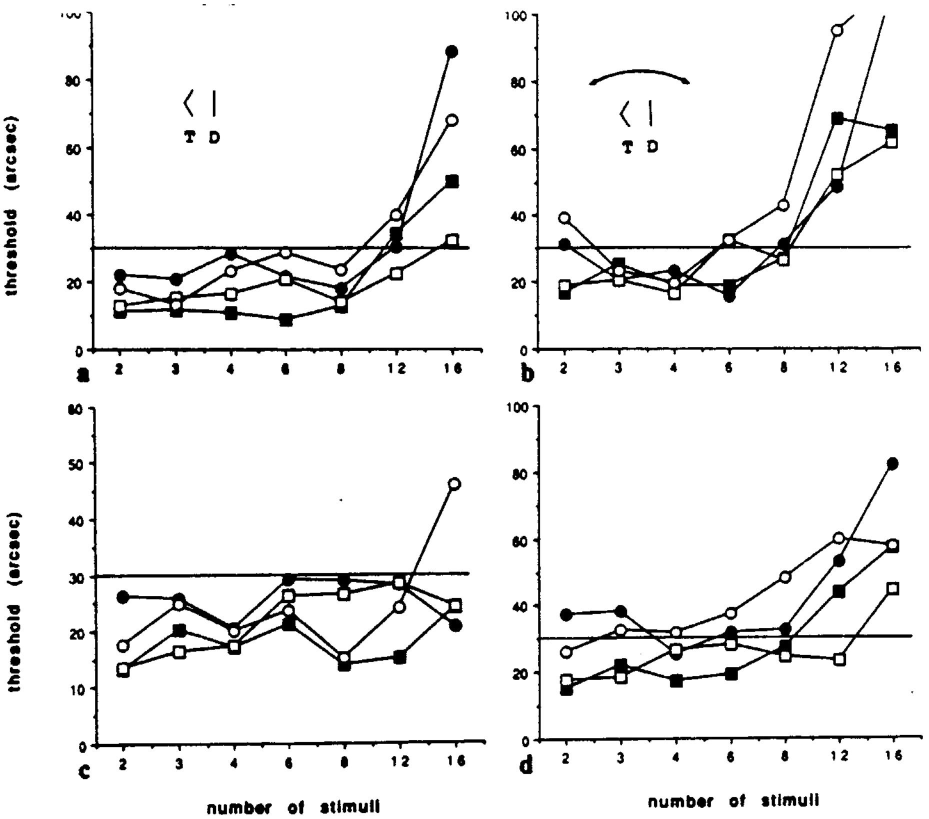

Fig.18 *Thresholds* for the detection of a single chevron among straight distractors under the same conditions as in Fig. 17. Eccentricities were 0.2° (**a,b**) and 0.4° (**c,d**); orientation was either vertical (left column) or varied (right column), and presentations were followed by a mask (line symbols) or not (solid symbols). Two observers (AH: squares; HW: circles).

the lateral offset — be it coded in one way or the other. Similarly, the finding that a chevron or a bent target can be detected in a 150 msec presentation with subsequent mask, even if the absolute orientation cues are masked by variable stimulus orientation, further supports the notion that the underlying cue is not absolute orientation, either. Hence, we must look for another feature able to discriminate between these targets and distractors. The graphs show generally only a moderate increase of thresholds for up to 6 or even 12 stimuli, and a steeper increase for presentations with more stimuli. This fact can be taken as another indicator for inhibitory interactions between the stimuli, possibly already on a relatively peripheral level in the visual system.

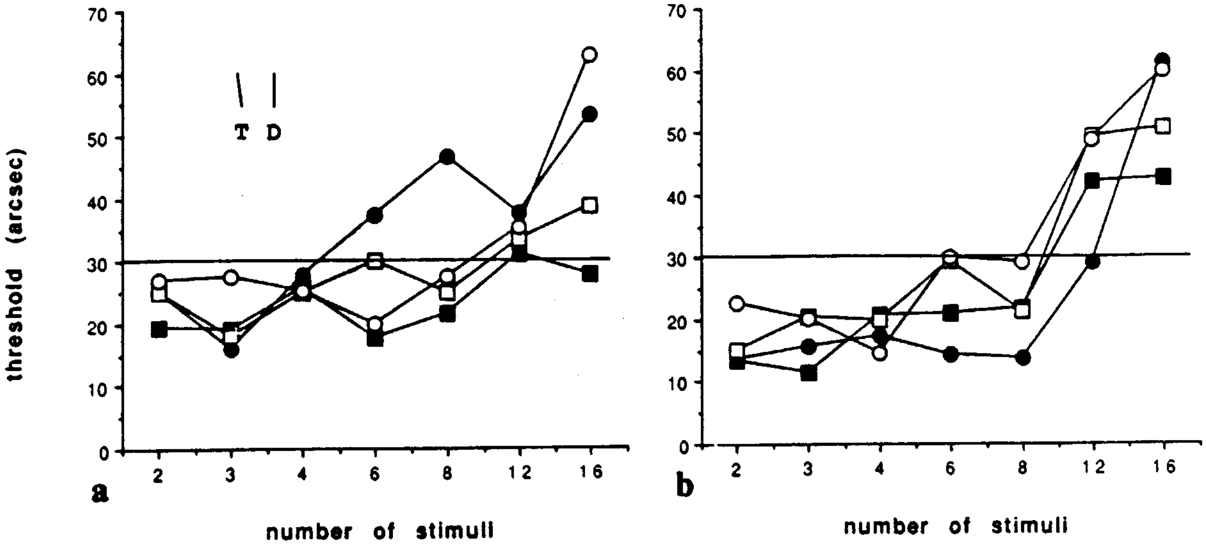

Fig.19 *Thresholds* for the detection of a straight, tilted target among straight, vertical distractors. Eccentricities were 0.4° (left; **a**) and 0.2° (right; **b**). Results of two observers with and without subsequent masking. Symbols as in Fig. 18.

Eighth experiment: The effect of practice

Already in the first experiment, we experienced the effect of practice: while detection of an opposite offset among a number of vernier distractors required serial search in unexperienced observers, reaction times increased only marginally with the number of distractors for the same task after some practice. Practice effects are not uncommon in hyperacuity tasks. Fendick and Westheimer (1983) investigated the development of stereoacuity thresholds as a function of practice. They found an improvement between approximately 25% and 75% over the course of several thousand presentations, and a relatively stable level thereafter. McKee and Westheimer (1978) found a mean improvement of performance in the detection of single vernier offsets by 40% over the first two to three thousand presentations in seven subjects and Poggio, Fahle & Edelman (1991) measured a continuous improvement in vernier acuity that was linear on a logarithmic scale up to 10.000 presentations. Conjunctions of features such as vernier offset and orientation can be learned within a couple of hundred presentations (Steinman, 1987), but in his study, vernier offsets were 8′, i.e., far above the hyperacuity range for foveal viewing.

To evaluate the effects of practice, two of the observers performed additional control experiments after the end of experiments 1 to 7.

Results

The two observers, H.W. and A.H. were very experienced observers already at the begin of this study. At the time of the control experiment, each of the two had undergone more than 100.000 presentation of parallel hyperacuity stimuli, presented over a period of more than a year. Therefore, further learning can be expected to influence thresholds only marginally. The controls encompassed vernier stimuli, curved stimuli, and chevrons. Only the slopes and standard errors of the slopes of regression lines are presented in Table 4, rather than the complete graphs. An important difference between Table 4 and the first three tables is that only long stimuli were used. The results for negative presentations (that lack a target) and positive presentations (with a target, i.e., an odd-man-out) are listed separately. The first two columns of Table 4 (vernier, S.O. = small offset) give the slopes and standard errors for the repetition of the first experiment. These results are also shown in Fig. 3. Comparison the results of this control (Tab. 4) with the original results (Tab. 1) shows very similar results, with overlapping standard errors for most conditions, indicating that no significant learning occured in-between. In several cases, the new slopes were even higher than the old ones. This is especially true for the task of finding one target with offset opposite to that of the distractors. Slopes for fixed orientation had been astonishingly low in Table 1 - while they were more conforming to expectations in Table 4. By far the steepest slopes, i.e., the strongest increase of reaction times with the number of additional distractors, was found for the detection of a target offset to the left among distractors offset to the right. Reaction times in Tab. 4 were no shorter than they had been 80.000 presentations ago (Tab. 1), and the slope for negative presentations was about twice as steep as for positive presentations.

The next two columns of Table 4 show the results for the same conditions, but here, the vernier offset was twice as large than before (vernier, L.O.= large offset). Reaction times tended to be somewhat lower with this larger offset, but the same pattern of results evolved. Most noteworthy, the long reaction times and the difference between negative and positive presentations for one opposite offset under variable orientation was preserved. The difference between positive and negative presentations of one offset vernier under straight distractors of variable orientation was not significant, due to the very large standard errors; this difference disappeared almost completely if the same stimuli were presented with variable vertical gapsize. Slopes for this task were clearly below 10 msec per stimulus. Slopes of regression lines for detection of a curved stimulus and a chevron with a double-sized offset were very low, with virtually no difference between positive and negative presentations.

Discussion

The control experiments showed that the results of the first seven experiments represent, to a large degree, a stable level of performance which can barely be improved by further practice. Reaction times for the detection of a single vernier or curved target or a chevron among straight lines increased in most instances by less than 10 msec per additional stimulus. This was clearly within the range accepted for parallel search. Moreover, results for positive and negative presentations were usually very similar. An exception were the slopes for vernier targets at variable orientation, which were around 30 msec/item for small offsets, too large for true parallel search. But the ratio between reaction times for negative versus positive presentations amounted to less than a factor of 1.5, and slopes decreased drastically for larger vernier offsets - hence the results were not typical for serial search, either. This might be another indication that transitions exist between pure parallel and truly serial search. The increase of reaction times for stimuli near threshold has been described before (Olson & Attneave, 1970; Treisman & Gormican, 1988; Fahle, 1990). For larger vernier offsets, reaction times for a single vernier target among straight distractors yielded slopes around 6 (positive) to 7 msec/stimulus (for negative presentations), even if orientation and vertical gapsize of the vernier were varied at random (fourth row, fourth column, of Tab. 4). For smaller offsets, the corresponding values were 26 (positive) and 34 (negative presentations). This is another example for the transition from parallel to semi-paralell search near threshold. At the same time, these experiments demonstrate that truly parallel detection of a vernier offset could be achieved even if orientation and vertical gapsize both varied at random.

The detection of *conjunctions* between features detected in parallel, such as orientation and vernier offset, required serial search in naive subjects but was detected in parallel after several hundred presentations (Steinman, 1987). One possible interpretation is that the visual system is able to learn to segregate the visual field instantaneously in terms of one of the relevant features. An alternative interpretation, in line with the above results on semi-parallel search near threshold, might stress that attending to two features simultaneously might increase detection thresholds for each of the features. This would shift the stimulus closer to threshold, leading to longer reaction times. It is in line with this interpretation that reaction times in Steinman´s experiments increased considerably in untrained observers even for conjunctions that he considered to be searched in parallel. Here, additional experiments with larger offsets would be required to discriminate between the possible interpretations.

Results for the detection of a single straight line among vernier distractors showed much steeper slopes. Negative presentations required clearly longer reaction times than positive presentations, usually by approximately a factor of 1.5. The steepest increase of reaction times with the number of distractors appeared for the task of detecting a vernier target offset opposite to the distractors, if stimulus orientation varied. Under these conditions, more than 100 msec were required per additional stimulus, and negative presentations yielded reaction times about twice as long as positive presentations (bold figures in Tab. 4) — indicating self terminating serial search. One of the observers (AH) yielded relatively flat slopes not only for vertical stimuli but also for variable stimulus orientation, if the variation of orientation was up to 20°. After extensive training, even the slopes for a 30° variation became flatter, but she never achieved parallel processing with a variation of orientation of 40°. For these stimuli, the slopes of the reaction times were 41 msec/item - close to the thresholds of this observer for 30° variation and less extensive training.

The results of the last experiment demonstrate that certain features cannot be processed in parallel even after fairly extensive training. The discrimination between tasks that can be solved effortlessly and, to a first approximation, independent of the number of distractors on one side, and others that require item-by-item search seems to hold even after extensive training, and in spite of the fact that transitions between the two modes of processing exist for certain stimuli.

General Discussion

In an extensive series of experiments, the ability of the human visual system to detect deviations from straightness was tested, using vernier, curved, slanted, or chevron targets. It should be stressed that all experiments described in this paper required the detection of a single feature, such as curvature or vernier offset, rather than detection of the conjunction of two different features, as do many other experiments on parallel detection (e.g. Treisman, 1977; Nakayama & Silverman, 1986; Steinman, 1987). Experiments using single features seem to be subject to learning, but less so than conjunctions of features are (McKee & Westheimer, 1978; Fendick & Westheimer, 1983; Steinman, 1987).

The effect of stimulus length

Longer stimuli tended to yield faster response times in one of the three principal conditions, namely detection of a vernier target among distractors offset, bent, or curved to the opposite side (Tab. 1; '1 opposite'). The same tendency was found with curved, tilted, and chevron targets. Slopes of regression lines through the data points sometimes differed by a factor of two or even more between the two stimulus lengths. On the other hand, reaction times were shorter for the shorter stimuli when one straight target had to be detected among vernier, curved or chevron distractors. This was true both with fixed and variable orientation.

The difference between the results for the long versus short stimuli can be understood as mirroring the different strategies used by the visual system to identify vernier breaks: while the detection seems to depend on orientation cues in short vernier stimuli, another cue that is less dependent on absolute orientation seems to be used in longer stimuli (cf. Andrews, Butcher & Buckley, 1973; Watt, Morgan & Ward, 1983; Watt & Campbell, 1985). The results on parallel detection are in full agreement with this dichotomy.

The 'long` and 'short` stimuli used in Fig. 5 differed not only in stimulus length, but also in vertical gap size. The experiments of Fig. 5a were repeated with stimuli of identical gap size that differed only in line length. Detection of a single vernier was parallel for long stimuli and serial for short stimuli (Fig. 7a,b). This result demonstrates again that a cue is available to the visual system which strongly relies neither on absolute orientation nor on gap size, at least for long vernier stimuli. Increasing the line length of the stimuli used in Fig. 7a by a factor of four (Fig. 7b) while keeping the gap identical had a similar effect on the results as doubling the offset of the vernier had (perpendicular to its long axis; Fig. 7b).

Reaction times in parallel tasks: positive versus negative presentations

Shifts of attention from one item to another usually require around 30-50 msec (Bergen & Julesz, 1983; Julesz, 1984; Kröse & Julesz, 1989; Ericksen & Schultz, 1977; Tsal, 1983; Jonides, 1983). Search times of less than 15 msec/item, consequently indicated the existence of underlying parallel detection mechanisms — at least several items must have been processed simultaneously in experiments such as the one represented in Fig. 2d, with a mean search time of 0.2 msec (±2.4) which does not differ significantly from zero. At present, the reason for the increase in response times (however short it may be) even for so-called parallel tasks, is not fully understood. It might be due, e.g., to lateral interactions between (not completely) independent detectors at a relatively peripheral level (such as the 'crowding` effect elicited by flanking lines (Westheimer & Hauske, 1975) that is to be expected especially in presentations with 12 or 16 nearby stimuli), or to serial processing (or just higher 'workload`, or increased noise levels) at higher levels of visual information processing. Even tasks usually processed in parallel might require at least semi-parallel processing near threshold (Treisman & Gormican, 1988; Fahle, 1990)! Spatial uncertainty about the presentation of a single vernier target, on the other hand, did not influence reaction times significantly.

Reaction times were shorter, even in so-called parallel tasks, for presentations that incorporated a target (positive), than in presentations that lacked a target (negative) (Fig. 3; Tab. 4). In the case of *serial* processing, the obvious interpretation for the shorter response in the positive trials is that the target was found, on average, after half of the simultaneously displayed stimuli had been scanned — while the negative presentations, where there was no target, required a scan of the whole display. This straightforward interpretation also explains why the standard errors were larger for the positive trials: the target might have been detected early or late during the serial search (e.g. Treisman & Gormican, 1988).

In the case of *parallel* processing, the slightly higher reaction times for negative presentations (no target present) as compared to positive presentations (target present) cannot be attributed to the factors outlined above for serial search, since no serial scan should take place by definition. The difference in reaction times between positive and negative presentations even in parallel search can be tentatively linked to the assumption that the feature triggers a strong response in positive presentations, whereas, after negative presentations, a certain time must elapse to ascertain the lack of a response. This difference, as to be expected, is far smaller than the difference between positive and negative presentations in *serial* search. A related finding is that a target defined by the presence of an elementary feature (e.g., a vernier offset) among distractors without the feature was detected faster than a target defined by the absence of that feature among distractors that all showed the feature (cf. Figs. 2a & c). This fact was termed ´search asymmetry` (Treisman & Souther, 1985; Treisman & Gormican, 1988). The difference between the reaction times in the detection of the presence of a feature (e.g. Fig. 2a) versus detection of the absence of a feature (e.g. Fig. 2c) might be explained along the same line of reasoning as above for the difference between positive and negative presentations: It is easier to discriminate between the presence versus absence of this feature (and the strong response it triggers) than to discriminate between fifteen versus sixteen signals.

The effect of orientation

All reaction times and slopes were longer when stimulus orientation varied, as compared to fixed stimulus orientation. The most pronounced difference occurred for the condition of detecting an opposite target, and here especially with the vernier stimuli. Vernier targets, because of the spatial discontinuity in the stimulus and the additional terminators produced by this discontinuity, might be especially susceptible to variation of one of their cues, namely absolute orientation.

If all the verniers were oriented vertically, observers were able to detect a vernier offset to the left amidst verniers offset to the right in parallel (Fig. 2d). From the results in Fig. 5d, however, it is obvious that observers used a cue based on absolute orientation under the conditions of Fig. 2d, since processing was no longer parallel if the absolute orientation cue was masked. This is to say that the parallel processing of a vernier, offset opposite to the distractors, clearly relied on a cue of absolute orientation rather than on the direction of the vernier offset. While the existence of a vernier offset is detected in parallel, its direction has to be evaluated serially!

If absolute orientation cues were masked by variable orientation of the stimuli, response times increased least with the number of stimuli for the detection of a single offset target among straight distractors, far more for the detection of a straight target among offset distractors, and even more for the detection of an opposite target.

		vernier		curved		chevron		orientation
		fixed	*variable*	*fixed*	*variable*	*fixed*	*variable*	*fixed*
1 offset	*short*	6.3 ± 3.2(1)	24.5 ± 7.0	3.6 ±0.8	11.2 ± 2.1	5.6 ± 1.5	18.5 ± 2.2	17.0 ± 5.0
	long	9.5 ± 3.5(2)	22.9 ± 4.9	1.5 ±0.23	7.1 ± 0.5	2.4 ± 0.7	10.8 ± 1.4	9.3 ± 2.9
1 straight	*short*	15.4 ± 5.9	38.0 ±10.5	16.5 ±4.3	45.0 ±16.0	29.0 ± 9.6	28.9 ±11.2	45.0 ±13.9
	long	62.0 ±12.6	93.0 ±20.4	35.0 ±9.3	86.0 ±23.0	56.0 ±11.7	47.0 ±24.0	32.0 ±18.6
1 opposite	*short*	2.5 ± 2.6	203.0 ±57.9	10.1 ±4.2	61.0 ±26.9	27.0 ± 1.7	71.0 ±23.0	4.5 ± 2.4
	long	0.2 ± 2.4	152.0 ±55.7	6.1 ±4.4	52.0 ±16.8	1.3 ± 0.9	48.0 ±16.2	2.3 ± 0.7
1 offset	*short*	10.6 ± 2.7	48.0 ± 3.7					
var. gap	*long*	9.5 ± 3.2	25.2 ± 8.3(3)					

(1) 2-12 stimuli 2.9 ±1.4
(2) 2-12 stimuli 9.2 ±1.7

(3) 2-12 stimuli 18.0 ±6.6
2- 6 stimuli 5.7 ±3.9

Table 1 Search times (± standard errors) per additional item for the main stimulus configurations and conditions.

		vernier		curved		chevron		orientation
		fixed	*variable*	*fixed*	*variable*	*fixed*	*variable*	*fixed*
1 offset	*short*	475 ±18.0	585 ±54.0	423 ±11.6	416 ± 8.4	432 ±18.6	417 ±11.7	412 ±12.0
	long	427 ±48.9	478 ±39.4	403 ±10.0	408 ±10.5	401 ±19.5	392 ±18.4	421 ±21.2
1 straight	*short*	540 ±21.1	549 ±60.8	480 ± 5.1	383 ±40.2	491 ±42.0	419 ±36.4	424 ±12.7
	long	351 ±70.7	219 ±82.0	354 ±58.1	230 ±35.1	336 ±30.0	311 ±48.1	432 ±13.6
1 opposite	*short*	521 ±29.3	414 ±110	479 ±17.6	396 ±23.2	452 ±13.0	407 ±53.0	477 ±30.0
	long	527 ±40.7	393 ±115	439 ±34.2	369 ±35.6	464 ±13.2	399 ±33.4	491 ±38.2
1 offset	*short*	430 ±32.4	591 ±35.2					
var. gap	*long*	395 ±35.5	370 ±35.4					

Table 2 Intersections with the ordinate (± standard errors) of the regression lines whose slopes are shown in Tab.1.

Response times for detecting a target with a double sized offset were almost identical for fixed or variable orientation (cf. Fig. 6c and 4c). This is another indication that absolute orientation cues do not play a major role in this detection task. Processing was always serial, indicating that the size of offset cannot be processed in parallel, similar to the case with the direction of offset.

Chevrons, Curvature and Orientation

Reaction times for the detection of a single non-straight target increased least for curved stimuli of fixed orientation, and somewhat more for the very similar chevrons (at least for fixed orientation). Processing was almost purely parallel in both cases. On the other hand, performance was equal or better for chevrons than for curved stimuli at varied orientation (Tab. 1). Verniers and slanted targets suffered notably stronger increases in search times under similar conditions. But these stimuli yielded the lowest increases in search times for the detection of a target of opposite direction at fixed orientation. It is important to note that search times even for a feature such as orientation, which is widely accepted as being a texton or elementary feature of vision, increased slightly with the number of stimuli if the orientation difference between target and distractors was very small (Fig. 15). In another series of experiments where the position of a vernier target had to be identified (rather than its presence of absence), clearly parallel processing was found for vernier offsets well above threshold, while performance became 'semi-parallel' close to threshold (Fahle, 1990; cf. also Nothdurft, 1985). The transition from truly parallel to 'semi-parallel' processing might be a general tendency for displays in which the difference between target and distractors approaches detection threshold.

		vernier		**curved**		**chevron**		**orientation**
		fixed	*variable*	*fixed*	*variable*	*fixed*	*variable*	*fixed*
1 offset	*short*	-0.43 ±0.16	-0.38 ±0.31	-0.37 ±0.15	-0.63 ±0.11	-0.21 ±0.07	-0.25 ±0.30	-0.60 ±0.15
	long	-0.05 ±0.39	0.50 ±0.38	-0.05 ±0.21	-0.64 ±0.20	0.17 ±0.08	-0.35 ±0.17	0.16 ±0.18
1 straight	*short*	-0.31 ±0.14	-0.62 ±0.13	-0.86 ±0.15	-0.43 ±0.07	-0.61 ±0.28	-0.52 ±0.15	-0.61 ±0.46
	long	-0.80 ±0.18	-1.09 ±0.22	-0.75 ±0.07	-0.87 ±0.21	-0.19 ±0.18	.65 ±0.10	-0.13 ±0.23
1 opposite	*short*	-0.26 ±0.05	-0.11 ±0.21	-0.38 ±0.19	-0.32 ±0.15	-0.40 ±0.40	-0.24 ±0.15	0.00 ±0.18
	long	-0.13 ±0.01	-0.54 ±0.32	0.10 ±0.09	-0.53 ±0.24	-0.12 ±0.12	-0.43 ±0.22	0.20 ±0.18
1 offset var. gap	*short*	-0.78 ±0.04	-0.36 ±0.17					
	long	-0.47 ±0.46	-0.69 ±0.12					

Table 3 Slopes (± standard errors) of regression lines through the percentages of correct responses as a function of the number of stimuli, in % per additional item. A

value of -1.0 corresponds to a decrease by 1% of the correct responses with each additional stimulus. Only four regression lines had positive slopes, indicating that, in general, performance decreased with the number of stimuli.

Error rates increased, in most cases, with the number of distractors (Tab. 3), indicating that there was no trade-off between speed and performance, but that performance generally decreased when longer reaction times were required

There remain some open questions: What is the cue that lets one discriminate the target bent to one side from distractors bent to the opposite side in parallel when all stimuli are oriented vertical, but not when their orientation varies? What happens at slopes of 20 or 30 msec/item, which could indicate ´semi-parallel` processing? Is there a gradual transition between parallel and serial processing, with the processing being semi-parallel, e.g., near the detection threshold of the stimuli? Applying the tools of, e.g., signal detection theory on the present data might help to answer these questions.

		vernier, S.O.		vernier, L.O.		curved, L.O.	chevron, L.O.
		fixed	*variable*	*fixed*	*variable*	*variable*	*variable*
1 offset	***negative***	6.7 ± 0.7	32.9 ± 4.1	6.7 ± 1.1	14.6 ±11.9	1.9 ± 0.9	2.3 ± 0.9
	positive	6.1 ± 0.7	22.5 ± 1.8	5.4 ± 0.2	9.2 ± 7.6	1.7 ± 0.4	2.6 ± 0.3
1 straight	***negative***	72.6 ±14.6	90.6 ±26.6	33.6 ±29.0	61.1 ± 1.0		
	positive	52.2 ±11.5	61.3 ±10.1	25.7 ± 4.1	38.7 ±10.5		
1 opposite	***negative***	14.0 ±15.8	**220 ±155**		**183 ±143**		
	positive	11.6 ±12.0	**128 ± 77**		**101 ± 65**		
1 offset var.gap	***negative***	6.5 ± 0.8	33.7 ± 0.7		7.1 ± 0.7		
	positive	4.7 ± 0.01	26.3 ± 0.03		5.5 ± 1.6		
1 opposite var. gap	***negative***				**201 ±46.0**		
	positive				**103 ±51.9**		

Table 4 Search times (± standard errors), per additional item for the main stimulus configurations and conditions, as in Tab. 1. Results of the final control experiment (eighth experiment). Here, results of negative and positive presentations are shown separately, all for the *long* stimuli. S.O = small offset; L.O.= large offset. Bold numbers indicate serial search.

Conclusions

The main finding of the present paper is that response times for the detection of a vernier offset, a chevron, a bent, or a slanted target among straight distractors are relatively independent of the number of simultaneously displayed distractors, with search times especially of the long stimuli often below 10 or even 5 msec per additional item. In keeping with the literature, the term ´parallel processing` is used to denote this pattern of results. The experimental results demonstrate parallel processing basically for all stimulus types used, even if the orientation of the stimuli varies independently. Parallel detection cannot rely on absolute orientation, because parallel processing is possible even if orientation of the stimuli varies. Since stimuli like chevrons or curved targets are processed in parallel, as well as verniers with variable gap size, parallel processing can rely neither on the vernier gap. It is therefore safe to hypothesize that another elementary feature must underlie parallel detection of these stimuli. This feature might be called ´deviation from straightness`, or ´orientation gradient`. The presence of this feature can be detected in parallel; its direction, or sign, however, cannot: discrimination between offset, etc., to the right versus offset to the left requires serial processing if absolute orientation cues are masked, with search times of around 50 to 200 msec per additional item.

The simple question whether the human visual system can detect in parallel features in the hyperacuity range, i.e., below a photoreceptor diameter, proved to be the most difficult of the questions addressed in the present study. Unfortunately, the standard methods to decide whether a feature is detected in parallel or not, fail partly in this case. It seems that processing for all kinds of stimuli is no longer parallel near threshold. Hyperacuity, on the other hand, requires extremely fine spatial resolution - near absolute threshold. To solve this contradiction, I have shown that reaction times for the detection of a single ´hyperacuity` target such as a vernier, a chevron, or a bent target rise with the number of distractors by no more (and sometimes less) than for a classical parallel feature, namely orientation. In complementary experiments, detection thresholds for ´flashed` hyperacuity stimuli were measured. As to be expected, these thresholds increased with the number and density of distractors, but even with flash presentation and a subsequent mask, many thresholds were clearly in the hyperacuity range.

From the results of the present study, we can conclude that vernier offsets, curvature, and chevrons can indeed be detected in parallel by the visual system, while the classification of the offset or bent as right or left requires serial search. We can also conclude that an offset in the hyperacuity range can be detected among distractors in a flash presentation - suggesting that (with the proper definition of ´parallel processing`) hyperacuity precision is achieved in parallel by the visual system. This interpretation supports the original claim by Julesz and Spivack (1967) of parallel processing in the hyperacuity range that later had been shown to rely on insufficient evidence (Nishihara & Poggio, 1982).

Obviously, the human visual system devotes a considerable amount of neurones and of computing power to the parallel extraction of a feature such as ´change of orientation` of a line element. This feature is detected with a precision clearly below the pixel size of the input device, here the eye. The fact that orientation gradients seem so important for the visual system might encourage speculations that changes in orientation play a crucial role during the early stages of visual pattern recognition in humans.

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A vernier offset is detected at once among straight lines, and reaction times are almost independent of the number of simultaneously presented stimuli (distractors), even if absolute orientation cues are masked by varied orientation of the verniers. This result implies that the human visual system processes vernier offsets in parallel. Reaction times for identifying one straight target among offset verniers, on the other hand, increase with the number of stimuli. The same is true for the identification of a vernier offset to one side among verniers offset to the opposite side, if absolute orientation cues are masked. These tasks require serial or semi-parallel processing. Chevrons and curved targets show the same pattern of results. Even deviations below a photoreceptor diameter can be detected at once. The visual system thus attains positional accuracy below the photoreceptor

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diameter simultaneously at different positions. I conclude that deviation from straightness, or change of orientation, is detected in parallel over the visual field. Discontinuities or gradients in orientation may represent an elementary feature of vision.

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