Humans can discriminate among elementary features such as orientation, color, and depth in parallel. The author showed that discontinuities in lines, such as a vernier offset, can be detected in a flash presentation with subsequent mask, and an offset, even below the diameter of foveal photoreceptors, is identified among distractors. This result suggests that the visual system simultaneously detects misalignments or gradients of orientation in the hyperacuity range at many positions in the visual field. The direction of the vernier offset, however, cannot be classified simultaneously in several stimuli, but requires serial search. Invest Ophthalmol Vis Sci 32:2151-2155, 1991

Differences in features, such as orientation or color, are easily distinguishable in a stimulus. These features, also called textons, are processed in parallel, ie, yield reaction times that are independent of the number of distractors. Other features that cannot be processed in parallel require serial, item-by-item search, the reaction times increase with the number of distractors presented simultaneously. Parallel processing was found for line segments (of a given color, orientation, length, and width), for their terminators, for stereoscopic depth, and for motion. The transition between parallel and serial processing is sometimes gradual, and processing of the parallel features can become serial near the detection threshold of the feature. Nevertheless, elementary features that are detected in parallel could represent the building blocks of visual perception. Cortical neurones that extract at least some of these building blocks are known.

Materials and Methods. Between 1 and 16 stimuli were arranged in a circle around the fixation point. Stimuli were presented on a computer-controlled Tektronix 608 monitor via fast, 16-bit D/A converters. The length of the verniers was either $85'$ with a $5'$ gap or $21'$ with a $1'$ gap. The results for both stimulus lengths were similar for all observers. Vernier offset was $5'$, eccentricity was $4.5^\circ$, and the observation distance was 0.5 m. In the first set of experiments, all stimuli were oriented vertically (upper inset, Fig. 1), whereas in the second set, a random slant of up to $20^\circ$ off the vertical orientation was seen (lower inset). In both experiments, two conditions were tested. In the first condition, a vernier with an offset (=target) was embedded in stimuli without offset (=distractors; left insets of Fig. 1, line symbols). In the second condition, all but one stimulus was offset to one side, whereas the target was offset to the opposite side (right insets, solid symbols).

Half of the randomly mixed trials contained a target (positive), whereas the second half did not (negative). In a two-alternative forced-choice task, four observers discriminated between the two types of trials, ie, they decided whether a trial contained a target (Figs. 1, 2). Presentation of the stimulus ended with the subject's response, and reaction times and percentages of correct responses were measured. Observers fixated a central cross as steadily as possible, and an eyetracker (AMTech, with a resolution below $1'$) monitored fixation in some of the experiments to check whether the stimuli were scanned sequentially.

In additional experiments, thresholds for a 150-msec presentation of the stimuli were measured with a method of constant stimuli (Fig. 3). All observers had normal visual acuity and, apart from the author, were unaware of the purpose of the experiments.

Results. In the first experiment, all stimuli were oriented vertically. Reaction times were relatively independent of the number of stimuli, with an average increase of 2-13.5 msec per stimulus for the identification of an offset vernier among straight distractors (means of positive and negative trials; Table 1). Means were within the acceptable range for parallel search. The percentage of correct responses decreased slightly with increasing reaction times. This finding was true for both conditions: identifying an offset stimulus among straight distractors (means of positive and negative trials; Table 1).
Fig. 1. The search for one offset vernier among straight distractors (upper left inset: line circles) and for one vernier offset opposite from the others was nearly parallel (upper right inset: solid circles). Unexperienced observers required serial search in the latter case. The same was true for identifying a vernier offset if orientation varied randomly (lower left insets, line squares). Reaction times for an opposite vernier offset increased steeply without (absolute) orientation cue (solid squares). Data points represent means of at least 120 presentations. Each observer contributed more than 40,000 responses on related tasks to eliminate the effect of practice. Standard deviations of the means correspond to approximately 15% of the thresholds for parallel search and up to 40% for serial search (solid squares). Results were obtained from four observers.
Fig. 2. Reaction times for the identification of a vernier offset increased with the number of simultaneously presented straight distractors especially for short verniers (10', circles; the stimuli as shown to the right of the left ordinate). Increasing the line length (40', line triangles) or doubling the offset (solid triangles) of the short vernier under otherwise identical conditions decreased reaction times for stimuli encompassing many verniers ($P < 0.01$; Wilcoxon signed ranks test). Two observers participated.

Averaged reaction times for the two subjects are shown in the figure. Reaction times for the second condition, one vernier with an opposite offset, increased (solid squares). In all but one observer (AH), scanning eye movements for sequential foveation of stimuli occurred in this condition. The ability to detect one straight target among offset stimuli rested between the two other conditions. Similar results were obtained with the use of chevrons instead of vernier stimuli.

As an additional control for the influence of presentation time, reaction times were measured for one offset target with vernier stimuli that differed in line length, but had identical offsets and gap sizes. Although reaction times for short verniers increased strongly with the number of verniers when the presentation time was masked, they were almost constant for the longer verniers and for larger offsets (Fig. 2).

Parallel tasks yield increasing reaction times if the feature to be detected is near the threshold. Therefore, to test the limits of simultaneous detection of a vernier offset, thresholds were measured with a flash presentation of the stimuli, rather than with the standard reaction-time experiment with longer presentation times. The standard reaction-time experiment would have allowed scanning of the stimuli. Thresholds for the detection of a vernier offset embedded in up to 11 distractors were less than 100" (arc sec) at 4.5° eccentricity, below two-point resolution at this eccentricity. The thresholds for one vernier among eight stimuli were mostly less than 30" (arc sec) at 0.4° eccentricity and less than 20" (arc sec) at 0.2°. Thus, they were below the photoreceptor diameter and two-point resolution, even when presentation time was restricted to 150 msec with a subsequent mask (Fig. 3a). Again, detection could not rely on the gap in the offset stimulus, because gap size was below two-point resolution. Reaction times with these near-threshold stimuli increased moderately with the number of distractors, slopes being between 9–34 msec/item for one observer, and between 7–26 msec/item for another (Fig. 3b).

**Discussion.** The results of the first experiment show that vernier displacements are detected within less than 15 msec per additional item, ie, in the range defined as parallel search, in agreement with earlier findings. If the simplest features detected in parallel are the elementary features of vision, verniers still might not qualify, because discrimination could rely on an orientation cue (eg, the mean orientation of the offset vernier, Fig. 2). The second experiment indicates that rapid detection of a vernier displacement persists even without absolute orientation cues and without the gap cue, but classification of the offset as rightward or leftward does not. Detection could not be based on the difference in interval size (right inset, Fig. 2) between the targets with and without a gap, because gap size was varied randomly in the second experiment, and the difference in gap size between target and distractors was identical for the short and the long verniers of Figure 2. Detection of offset was...
Fig. 3. Thresholds (a), and reaction times (b) for verniers presented simultaneously around the fovea at 0.4° (triangles) or 0.2° eccentricity, with fixed (squares) or variable orientation (circles). Presentation time was 150 msec to prevent scanning eye movements, and a mask followed the stimulus in part of the experiments (line symbols). The dotted line (a) represents the limit of the hyperacuity range. Even verniers with variable orientation and subsequent mask yielded thresholds in the hyperacuity range for these observers. Due to crowding, maximal stimulus number was limited to 16. At 0.2° and 0.4° eccentricities, crowding was present with eight or fewer verniers. Standard deviations were typically less than 15% of the thresholds. Two observers participated (out of four).

quick even when orientation and gap size varied at random, and in chevrons without a gap instead of vernier targets. Hence, the underlying mechanism detects misalignment or deviation from straightness, not just vernier breaks or gaps and is not based on absolute orientation (cf. Fig. 2).

Table 1. Slopes (msec/item) of linear regression lines through the data of Figure 1, and their correlation–coefficients (R)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Subjects</th>
<th>MF</th>
<th>HW</th>
<th>UK</th>
<th>AH</th>
</tr>
</thead>
<tbody>
<tr>
<td>opposite offset</td>
<td>Slope</td>
<td>R</td>
<td>Slope</td>
<td>R</td>
<td>Slope</td>
</tr>
<tr>
<td>offset</td>
<td>6.1</td>
<td>0.71</td>
<td>12.4</td>
<td>0.84</td>
<td>-1.0</td>
</tr>
<tr>
<td>opposite offset</td>
<td>18.5</td>
<td>0.86</td>
<td>7.2</td>
<td>0.88</td>
<td>4.4</td>
</tr>
<tr>
<td>offset, variabl. orient.</td>
<td>11.7</td>
<td>0.70</td>
<td>25.0</td>
<td>0.92</td>
<td>8.4</td>
</tr>
<tr>
<td>opposite offset, variabl. orient.</td>
<td>296.0</td>
<td>0.99</td>
<td>316.0</td>
<td>0.99</td>
<td>179.0</td>
</tr>
</tbody>
</table>

Slopes for the detection of one vernier among straight distractors vary between -1.0 and 13.5 msec/item for fixed orientation, and between 8.4 and 25.0 msec/item for variable orientation. Slopes for the detection of a target offset to the opposite direction are similar, but increase dramatically if orientation varies.
Vernier acuity below the diameter of photoreceptors can be achieved within a 150-msec presentation time, with reaction times increasing moderately with the number of distractors. Thus, a nonstraight feature in the hyperacuity range can be detected simultaneously (within a 150-msec presentation time) among straight distractors and seems to represent an elementary feature of visual perception. The actual cue used by the underlying neuronal mechanism is not necessarily lateral offset, but could be, eg, the orientation gradient that exists explicitly in a bent or implicitly in an offset target. Absolute orientation is an important parameter in vernier detection; the new results show that relative orientation or orientation gradient is equally important.

Neurones similar to the ones that are believed to code orientation should exist for detection of miniature lateral displacements, or orientation gradients. It seems promising to search for such neurones in the visual cortex.

Key words: hyperacuity, visual psychophysics, early visual processing, parallel processing, serial processing

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References