Temporal characteristics of line orientation identification

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The hypothesis that identification of line orientation is based on different mechanisms—a detector mechanism at large orientation differences and a computational one at small orientation differences—was tested in three experiments. The first two experiments compared reaction time and time of complete temporal summation (t_c) in two tasks, line detection and line orientation identification. Identification at orientation differences 15° or more was similar to detection in several respects, suggesting that it was accomplished according to the principle of “labeled lines.” In agreement with the initial hypothesis, identification at differences smaller than 15° had a slower time course and could not be explained by the “labeled lines” principle. Experiment 3 explored the orientation acuity as a function of exposure duration and stimulus energy. Energy could not completely substitute for time in providing high orientation acuity, a result suggesting the involvement of neurophysiological mechanisms of large time constants.

Studies on human perception, machine vision, and animal experiments provide converging evidence that the encoding of contour orientation is a crucial step in the process of object recognition. Marr (1982), in his theory of visual information processing, considered the contour orientation as a basic feature in early representation of objects. Barlow (1986) emphasized the importance of orientation as a “linking feature” in the process of organization of contours into distinct objects. Koenderink (1986) suggested that the orientation of local image details in the optic flow could be a rich source of information about the three-dimensional shape of objects. The possible role of contour orientation in a great diversity of visual analyses is a tempting explanation of the orientation tuning of most cortical neurons (Hubel & Wiesel, 1959, 1962, 1968; for review, see Henry, Michalski, Wimbome, & McCart, 1994) in almost all visual areas of the primate cortex (Van Essen, 1985).

This paper is concerned with the mechanisms of encoding the orientation of short lines as a stage in contour orientation perception. There is now sufficient evidence that at a relatively early stage there exist orientation selective channels that operate in parallel, automatic fashion (Glezer, 1995; Glezer & Nevskaya, 1964) at a preattentive level (Beck, 1966; Treisman, 1985). In general, the problem of how identification is accomplished by selective channels has been elaborated in detector models (Watson & Robson, 1981), which assume that the activation of a single channel is sufficient for the identification of the

stimulus due to the specificity (“label”) of the activated channel; that is, the channels act as “labeled lines.” In the case of orientation perception, this assumption is supported by experiments showing that the contrast thresholds of detection and identification coincide if the stimuli differ in orientation by more than 15° (Thomas & Gille, 1979; Vassilev, Simeonova, & Zlatkova, 1981). This orientation difference was assumed to be an estimate of the distance between the independent labeled channels (Thomas, Gille, & Barker, 1982; Vassilev, Simeonova, & Zlatkova, 1982). Thus, a system of finite number of such channels, not more than 12, would span the whole orientation range. Scobey (1982) made the same inference on the basis of information theory.

It is obvious that a description based on a low number of channels is not a precise one. However, the orientation acuity of human observers (Andrews, 1967; Dick & Hochstein, 1989; Orban, Vandenbussche, & Vogels, 1984; Westheimer, Shimamura, & McKee, 1976) and of animals performing discrimination tasks (Vogels & Orban, 1991) is extremely high relative to the tuning width of channels estimated psychophysically (for review, see Braddick, Campbell, & Atkinson, 1978) or the tuning width of orientation selective neurons (Schiller, Finlay, & Volman, 1976). The striking lack of correspondence has led to the concept that high orientation acuity is based on more complex processes resulting from some kind of interactions among activated channels, for example, in the form of opponency (Regan, 1989; Regan & Beverley, 1985) or of weighted sum of signals (Gilbert & Wiesel, 1990; Vogels, 1990). However, this hypothesis has not been sufficiently verified in experiments. Although the mechanism based on relative activities could explain the high orientation acuity, it is not clear whether it is the only mechanism responsible for the encoding of contour orientation. Stimulus orientation is identified with a low

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precision (15° – 20°) at the detection threshold, where only the most sensitive channels are presumably activated. The high orientation acuity requires suprathreshold stimulation where many channels with different optimal orientations would be activated and their levels of activities could be compared (Vassilev et al., 1982). Thus, we proposed the existence of two types of orientation identification: coarse identification of detector type (with precision of 15° – 20°) and fine identification (orientation differences smaller than 15°) based on comparisons of signals between all activated channels (Vassilev et al., 1982).

According to the detector models, detection and identification are equivalent processes, but their equivalence has been studied mainly with regard to contrast thresholds. Investigations to compare the dynamics of detection and identification processes have yet to be made.

EXPERIMENT I

Reaction Time in Detection and in Orientation Identification Tasks

In this experiment, reaction time (RT) was measured in two different tasks: detection of a line stimulus and identification of its orientation. The effects of the following variables on RT were studied: stimulus intensity, orientation difference, and number of possible orientations. Stimulus intensity is assumed to influence the earliest stage related to stimulus encoding (Mansfield, 1973; Nissen, 1977; Pins & Bonnet, 1996; Sternberg, 1969). RT variations caused by stimulus intensity should be the same in detection and identification tasks, provided orientation is identified by a detector mechanism. Therefore, the effect of the degree of difference between neighboring orientations on RT in an identification task was studied in order to distinguish between the mechanisms of coarse and fine orientation identification. To validate our hypothesis in a more complex situation when the decision processes are altered, we examined the effect of one more variable, the number of alternatives, a factor known to affect the decision processes (Posner, 1978; Schweickert, Dahn, & McGuigan, 1988; Sternberg, 1969).

Method

Subjects. The subjects passed a test that measured their visual acuity in different meridians. They had to resolve bars of square-wave standard gratings in four orientations—vertical, horizontal, and two obliques at viewing distances of 5 and 0.35 m. The subjects selected for participation in all experiments had visual acuity of each eye 1.0 or higher (both 5/5 and 0.35/0.35 or higher) in all principal meridians tested. Four emmetropic subjects took part in Experiment I. They had experience in psychophysical experiments but none was trained in RT tasks.

Stimuli and Apparatus. The test stimulus in this experiment was a light bar, 5 min of arc wide and 60 min of arc long. It was superimposed on a large screen, 90 deg of arc in diameter. The screen contained a concentric thin black circle, 5 deg of arc in diameter, to facilitate fixation and accommodation. The test stimulus was flashed at the center of this circle. The stimulus and the background were provided by a two-channel optical system. The light source in the test channel was an electronically driven glow modulator tube, Sylvania R 1131C. The screen was uniformly illuminated and had a lu-

minance of 16 cd/m². Stimulus orientation could be changed in steps of 1° . Viewing was binocular and with natural pupils. The subjects sat in a darkened room 50 cm from the screen with their head stabilized by a forehead and chinrest. They were told to look at the center of the fixation circle and to initiate the trials by pressing a button as soon as they were able to fixate steadily.

Procedure and Design. In the first task (detection), the stimulus was a vertical line. A warning tone appeared on each trial. The stimulus was presented for 0.05 sec in 50% of the trials 1 sec after the warning signal. In the rest of the trials, the warning signal was not followed by a stimulus (blanks). The test and blank trials were randomly intermixed.

In the second task (orientation identification), the stimulus line was always presented 1 sec after the warning signal. Its orientation was selected at random from a set of possible orientations (two or eight). Each orientation occurred equally often. The subject's task was to respond to the onset of a line in vertical orientation and to ignore lines in other orientations. Stimulus duration was the same as in the detection task.

The same type of reaction, the so-called selective response or c-reaction (Welford, 1980), when two or more signals are presented (or a signal and a blank) and the observer has to react to only one of them (the relevant signal), was used in both tasks. The subject had to respond by pressing a key with the right hand as soon as he/she saw the stimulus and with minimum errors. False reactions were less than 2%.

The set of possible orientations consisted of either two, vertical and oblique, or eight, vertical and arranged on either side of the vertical, orientations (Figure 1). The angle between neighboring orientations was 10° , 15° , or 22° ; 1 subject was also tested at the angle of 45° in a two-orientations experiment.

Practice sessions preceded the main experiment. Each session comprised 230 trials. Five practice sessions for each condition were sufficient to obtain stable RT values.

Because the RT measurements for two and eight orientations were found to interfere, they were performed in separate daily sessions grouped in two blocks. The order of block presentations was counterbalanced across subjects. At the beginning of each session, the threshold intensity for detection of the vertical line was measured by the staircase method. The values of stimulus intensity were selected to be 0.2, 0.5, or 2 log units above this threshold. The lowest intensity did not increase the proportion of false responses. Seven blocks of trials at a constant level of intensity within each block

Figure 1. The set of stimulus orientations used in Experiment 1. (A) The set of two orientations. (B) The set of eight orientations. The difference between neighboring orientations is shown on the left. See text for further details.

were presented during a daily session: RT for detection was measured at one of the three stimulus intensities in a block of 36 trials; RT for identification was measured in six blocks for the three values of intensity combined with two orientation differences. Each block comprised 36 trials in the session with two alternatives and 48 trials in the session with eight alternatives. The order of block presentations was counterbalanced. Each daily session lasted for about 50 min.

Two subjects were tested with all combinations of factors and the other two were tested with the set of two orientations only.

Results and Discussion

Figure 2 illustrates the main findings in this experiment. The results are for the 2 subjects tested with all combinations of the factors. The values of intensity were chosen in such a way as to cover the range where the greatest changes of RT have been observed (Roufs, 1974). On the basis of a large body of experimental evidence (e.g., Mansfield, 1973; Roufs, 1974), we accepted that at the highest level used in the present study—that is, 100 times above the detection threshold—should be high enough to obtain RT close to the asymptotic value.

As shown in Figure 2, RT shortened as stimulus intensity increased under all experimental conditions. The relationship between RT and stimulus intensity in the detection task and RT in the identification task depended on the orientation difference to be resolved.

1. At large orientation differences (15°, 22°, or more), the identification curves were simply displaced vertically with respect to the detection curve; that is, RT for identification remained longer at all intensity levels but the task did not change the effect of intensity on RT. In order to evaluate the statistical significance of the inter-

action between intensity and task, an analysis of variance (ANOVA) was performed with subjects as a random factor separately for each orientation difference. Only the experiments with two alternatives were included since the number of alternatives was equal for both detection and identification. At 22°, significant effects of intensity [$F(2,840) = 142.5, p < .001$] and task [$F(1,840) = 528.8, p < .001$] were found, but the interaction between them was not significant [$F(2,840) = 1.33$]. The effect of subjects and the interaction between subjects and task were significant [$F(3,840) = 104.14, p < .001$ and $F(3,840) = 6.58, p < .001$, respectively]. The other effects were not significant. The difference between RTs at the extreme values of intensity was 45 msec in the detection task averaged across subjects and 49 msec in the identification task at 22°, respectively. The effects of intensity and task were also found to be additive at the orientation difference of 15°. One of the subjects, P.G., was also tested at the orientation difference of 45°, and the same additive effects were found. Recently, Pins and Bonnet (1996) obtained similar results for orientation discrimination of stimuli differing by 90°: The curve RT versus stimulus intensity in choice RT task for orientation discrimination is parallel to the curve in simple RT task.

2. RT at the smallest orientation difference, 10°, increased as the intensity decreased to a larger extent than RT for detection and coarse identification. A between-subjects ANOVA for two alternatives showed significant effects of intensity [$F(2,840) = 180, p < .001$] and task [$F(1,840) = 927.6, p < .001$], as well as a significant interaction between intensity and task [$F(2,840) = 17.08, p < .001$]. A significant effect of subjects [$F(3,840) =$

Figure 2. Mean reaction time as a function of stimulus intensity for line detection and line orientation identification for Subjects P.G. and M.M. Lower panels: detection task (open circles) and identification task with two alternatives (filled symbols). Upper panels: identification task with eight alternatives (filled symbols). Parameters of the curves are orientation difference (see inset) and number of alternatives (n).

88.5, $p < .001$], as well as significant subject $\times$ intensity [$F(6,840) = 2.89$, $p < .01$] and subjects $\times$ task $\times$ intensity interactions [$F(6,840) = 2.12$, $p < .05$], was also found. In this case, the mean difference between RTs at the extreme values of intensity was 103 msec in the identification task and 45 msec in the detection task.

Most models explain the magnitude of the effect of stimulus intensity on RT by its influence on the rate of accumulation of sensory information and by the response criterion adopted by the subjects (for a review, see Nissen, 1977). The equal effects of stimulus intensity on RT in the detection task and in the identification task, given that the orientation difference was greater than 15° , indicate that the relative rate of accumulation and the time of reaching the criterion level was the same for detection and coarse identification; that is, both processes had an identical time course at least during the intensity-dependent phase of signal processing. However, the information currently available is not sufficient for identifying fine differences in orientation because it follows from the significantly greater effect of intensity on RT for identification at the orientation difference of 10° .

To evaluate the effect of the number of orientations on the observed relationships of RT and intensity in the identification task, we performed an ANOVA with the factors of intensity, orientation difference, and number of orientations separately for each of the 2 subjects who took part in sessions testing all combinations of these factors. Table 1 summarizes the results of the ANOVA.

F ratios for the main effects showed that all three factors had significant effects on RT in the orientation identification task. There was no significant interaction between intensity and number of alternatives for both subjects; that is, the effects of these factors on RT were additive. Table 1 and Figure 2 show that an increase in number of alternatives from two to eight did not affect the change of RT caused by the intensity in any condition.

The additivity between the effects of intensity and number of alternatives has been documented in several studies (Nissen, 1977; Posner, 1978; Schweickert et al., 1988) and has usually been interpreted as supporting the additive model of RT (Sternberg, 1969). According to

this model, intensity and number of alternatives affect different stages arranged in series. Alternative models (see, e.g., Ericksen & Schultz, 1979; Vickers, Burt, Smith, & Brown, 1985) assume that the evidence for each alternative accumulates gradually until the criterion is reached. According to these models, there are no discrete stages between input and response, and the process of decision develops in the course of accumulation. Schweickert et al. (1988) pointed out that these models predict an overadditive interaction between intensity and number of alternatives; that is, the combination of lower intensity and higher number of alternatives would produce a larger difference in RT than in the case of additivity. Most authors agree that it is difficult to predict the wide range of additive effects on the basis of nondiscrete models, and thus they consider the discrete stage model as more plausible in the case of additivity (Miller, 1993; Nissen, 1977; Schweickert et al., 1988). We accept that intensity and number of possible orientations influence separate, non-overlapping stages—an early intensity-dependent stage, and a later intensity-independent stage, respectively. It follows that the intensity-dependent changes of RT in the detection and identification tasks reflect early stages of these processes.

The observed similarity in the time course of detection and identification is valid only if an early level of processing is considered. RT was always longer in the identification task than in the detection task even if the stimuli were so different that they were never confused. Furthermore, the RT difference increased with increased number of orientations or decreased angle between neighboring orientations. These two factors interacted, and the interaction was underadditive (Table 1, Figure 3). At the smallest orientation difference, 10° , which produced the longest RT, the number of orientations had a smaller effect than the predicted one from perfect additivity. We expected an interaction in the opposite direction. Increasing the number of alternatives in the case of greater similarity between stimuli made the task more difficult and hence more time-consuming. However, a greater effect of the number of orientations (40–50 msec) was observed in the case of the easier task when the orientations differed by 22° than in the case of the more difficult task when the orientations differed by 10° .

In the set of two stimuli, the oblique (irrelevant) orientation was always at one side of the vertical while in the set of eight orientations, irrelevant orientations were present on both sides of the vertical (target) orientation (Figure 1). Assuming an effect of the distribution of orientations around the target one, we performed an experiment with sets of three (vertical and two oblique, symmetrical about the vertical) and eight orientations. The graphs on the right side of Figure 3 show the results. The pattern of interaction between orientation difference and number of orientations was the same as with two orientations: The number of orientations had a smaller effect than expected on the basis of additivity.

Table 1
***F* Ratios From ANOVA With Factor Intensity (I), Orientation Difference (D), and Number of Possible Orientations (N)**

	Subjects	
	P.G.	M.M.
Main effects		
I	134.8**	86.00**
D	31.2**	26.00**
N	123.9**	185.00**
Interactions		
I $\times$ D	3.4*	3.72*
I $\times$ N	0.09	0.93
D $\times$ N	3.3*	4.5*
I $\times$ D $\times$ N	0.68	1.83

* $p < .05$; ** $p < .01$.

Figure 3. The interaction between number of alternatives and orientation difference (see inset) for Subjects P.G. and M.M.; the lines should be parallel in case of perfect additivity.

Several authors have provided theoretical and empirical evidence that interactions of the underadditive type are better explained by nondiscrete models—for example, the cascade model, developed by McClelland (1979), or the queue-series model, proposed by Miller (1993), assuming that the response preparation starts early in the process of stimulus processing (for a review, see Miller, 1988). In the case of increased difficulty of the task, the process of response organization might start before the stimulus identification has completely finished. The possibility of a temporal overlap between response stage and perceptual stages has been discussed in detail by Stanovich and Pachella (1977). They consider it as the most likely explanation of the underadditive interactions they found. The same explanation might be valid for our results.

EXPERIMENT 2

Temporal Summation in Detection and in Orientation Identification Tasks

The findings of Experiment 1 supported the hypothesis tested in the present study: Stimulus intensity changed identification RT by the same amount as detection RT if orientation identification was a coarse one and to a larger extent for fine orientation identification. However, identification RT was longer than detection RT even for the larger orientation difference, a result suggesting that the time courses of detection and coarse identification are not completely identical. In order to be able to analyze the results, we studied the effects of the task (detection or iden-

tification) and the orientation difference on another temporal characteristic of perception, the critical duration of complete summation, t_c .

Method

Subjects. Three emmetropic subjects took part in this experiment. Two of them had already participated in Experiment 1. The test stimuli and apparatus were the same as in Experiment 1.

Procedure and Design. The psychophysical method was the method of constant stimuli combined with the 2×2 forced-choice procedure. The stimulus was presented with equal probability in one of two subsequent observation intervals and in one of two possible orientations—vertical or oblique. The difference between orientations (D) was 5° , 10° , or 22° . The intervals containing the test line as well as line orientation were randomly and independently varied. The observation intervals were marked by tones. Stimulus duration varied within the range of 0.01–1.2 sec. The subject's task was to report both the interval containing the stimulus (detection) and the stimulus orientation (identification). The percentage of correct responses was recorded separately for each task as a function of stimulus intensity at each duration. Thus the psychometric functions for detection and identification were obtained simultaneously. A correction for guessing was made according to Blackwell's (1953) rule. The proportion of corrected responses, P'_c , was calculated as follows:

$$P'_c = (P_c - 1/m) / (1 - 1/m),$$

where P_c is the proportion of correct responses obtained in the experiment and m is the number of possible responses (two in this case).

Each daily session contained blocks of 30 trials at a constant intensity for combinations of two stimulus durations and five or more intensity values. The order of block presentations was counterbalanced. The orientation difference was kept constant throughout the daily session. Two of the subjects were tested under all experimental conditions, and the 3rd subject was presented with the orientation difference of 5° only.

Results and Discussion

Figure 4 illustrates the typical relationship between the psychometric functions for detection and identification at the orientation differences of 22° and 5° .

Figure 4. An illustration of psychometric functions obtained for Subject N.N. in the detection task and in the identification task with different precision, 22° and 5° . Stimulus duration = 0.1 sec.

The data in the detection task did not depend on the orientation difference and were averaged over both orientation differences. The resulting detection curve coincided with the identification curve at $D = 22^\circ$. However, the identification curve at 5° differed significantly from both curves in two respects: First, its slope was shallower, and second, it flattened off without reaching 100% of correct responses even at high stimulus luminance. This relationship between the psychometric functions makes the comparison of separate points, conventionally accepted as thresholds (e.g., 50% or 75%), unrepresentative. Therefore, we compared the psychometric functions instead of single points.

Figure 5 shows the psychometric functions obtained in the detection and identification tasks at each duration for the 2 subjects tested under the full set of experimental conditions. The abscissa is in energy units, $L \times T$, where L is stimulus luminance and T is its duration. The ordinate is the proportion of positive responses corrected for accidental guesses and expressed in probits (i.e., in standard deviation units). Each experimental point is based on 64 trials. The regression lines at each duration were

calculated by the methods of probit analysis and the principle of maximum likelihood (Finney, 1971).

The left panel of Figure 5 compares detection and identification at $D = 22^\circ$. The data obtained at each stimulus duration are denoted by different symbols. The pairs of psychometric functions for both tasks overlap. The comparison of regression lines (Brownlee, 1977) for detection and identification at each stimulus duration showed that they did not differ significantly ($p > .05$) within the whole range of stimulus duration. Furthermore, there was no difference between the psychometric functions for 0.01 and 0.02 sec for either subject ($p > .05$). They are presented with a common regression line in Figure 5. As far as the abscissa is in energy units, this overlap means that both durations were in the range of complete temporal summation. A failure of the time-intensity reciprocity would result in displacement of the psychometric functions. A displacement to the right was observed at durations longer than 0.02 sec. Both detection and identification functions were displaced to the right by the same amount for both tasks. Thus, the detection and identification psychometric functions were identical in the whole range of

Figure 5. Psychometric functions in the detection task (solid lines and open symbols) and in the orientation identification task (dashed lines and filled symbols) at different stimulus durations (T) for Subjects N.N. and V.B. Stimulus duration: 0.01 sec (circles), 0.02 sec (triangles), 0.05 sec (squares), 0.1 sec (diamonds), 0.3 sec (crosses), 0.8 sec (inverted triangles). Abscissa, stimulus energy in cd/m^2 ; ordinate, the proportion of correct responses in probits. Left panels, orientation difference 22° . Right panels, orientation difference 5° . Dotted lines are drawn by eye across the points obtained at stimulus durations of 0.1 sec or shorter at high stimulus intensities. All other lines are calculated by probit analysis.

stimulus duration tested. This means that detection and coarse identification had identical temporal integrative properties and that the complete temporal summation was finished within 0.02–0.05 sec for both tasks.

The right panel of Figure 5 compares detection and identification at $D = 5^\circ$. In this case, the identification psychometric functions were quite different from the detection ones. They were displaced to higher energy levels, their slopes were shallower, and the percentage of correct reports leveled off without reaching 100% at durations shorter than 0.3 sec. These flat portions of the psychometric functions were excluded from further analysis. The separation of the functions into two parts was located at a point of intersection between two regression lines fitted to the data points by means of the iterative procedure proposed by Bogartz (1968). The statistical test of coincidence of several regression lines, based on analysis of variance (Brownlee, 1977), showed that the psychometric functions did not differ significantly up to $T = 0.1$ sec for either subject [N.N., $F(12,15) = 1.12$, $p > .53$; V.B., $F(12,15) = 1.07$, $p > .55$], and they are presented by a common line with a mean slope. When data for stimulus duration $T = .15$ sec were added, the hypothesis of coincidence of lines was rejected [N.N., $F(15,19) = 4.25$, $p < .005$; V.B., $F(15,19) = 3.37$, $p < .01$]. This result means that the reciprocity relation held at least to 0.1 sec in the case of fine orientation identification, a time interval two to five times longer than in the case of detection and coarse identification.

Because the slope of the psychometric functions was constant within the range of complete summation, we could also estimate the critical duration. In Figure 6, stimulus threshold energy ($L_0 \times T$) is presented as a func-

tion of stimulus duration (T) for the detection task and for the identification task at all orientation differences studied. L_0 is the 50% threshold, determined from the probit regression lines. The experimental data were approximated by two lines—a line with a zero slope, forced through the initial points, which represented a constancy of stimulus energy (complete summation), and a line with a slope of 0.6–0.7 fitted by the least squares method to the remaining points, which were found to significantly deviate from the zero slope. The critical duration t_c was determined as the time interval at the point of intersection between the two lines (Bogartz, 1968). Its values are shown in Table 2.

It is apparent from Figure 6 and Table 2 that detection and identification had identical temporal summation curves and critical duration, respectively, when the orientations differed by 22° . A possible interpretation of these results is that the neural event limiting the time of energy integration occurs at the same moment in both detection and coarse identification. This is consistent with the hypothesis that the processes of detection and coarse identification follow the same time course at an initial intensity-dependent stage of signal processing.

The reduction of the orientation difference to 10° and especially to 5° produced a marked increase of t_c , which reached 100 msec. The long-lasting temporal summation could not be explained solely by the labeled lines concept. Evidently, fine identification involves more complex processing.

Typical of identification at the orientation difference of 5° was also the finding that the short duration could not be fully compensated for by any increase in stimulus intensity. At neither intensity was the level of 70%–80% of correct identification reached at durations shorter than 0.3 sec (Figure 5). This result suggests that stimulus duration is much more important than stimulus intensity for accurate performance.

EXPERIMENT 3

The Effect of Stimulus Duration on the Orientation Acuity for Stimuli of Equal Energy

The data of the previous experiment suggest that the involvement of some time-dependent process in addition to the energy summation must be assumed in order to explain the better performance for long-lasting stimuli. This assumption was tested in the present experiment. The orientation acuity was measured for stimuli of different duration but of equal energy in order to compensate for the energy summation. Two suprathreshold energy levels differing by a factor of 40 were used. This choice was based on the assumption that an energy-dependent inertial process would be speeded up by very intensive stimulation, and thus the performance for brief stimuli would be improved.

Method

Subjects. Three emmetropic subjects took part in the experiment. Subject N.N. also participated in the two previous experiments.

Figure 6. Stimulus threshold energy ($L_0 \times T$) as a function of stimulus duration (T) in the detection task (solid curve and open symbols) and in the orientation identification task (dotted lines and filled symbols) at different angles between neighboring orientations for Subject N.N.

Table 2
Critical Duration t_c (in Milliseconds) for the Tasks of
Detection and Orientation Identification With Varied Precision

Subject	Detection	Identification		
		$D = 22^\circ$	$D = 10^\circ$	$D = 5^\circ$
N.N.	32	30	49	100
V.B.	31	34	45	83

D , angular difference between neighboring orientations.

Stimuli and Apparatus. The test stimulus was a light bar, 3 min of arc wide and 10 min of arc long, presented in the center of a screen 10 deg of arc in diameter. Background luminance was 50 cd/m². Stimulus duration was 0.01, 0.05, or 0.5 sec. To equalize the stimuli with respect to their energy, the product $L \times T$ was kept constant, where L is stimulus luminance in cd/m² and T is stimulus duration in seconds. Two levels of energy were used, 10 cd/m² sec and 31 cd/m² sec. Viewing was monocular, through an artificial pupil 2 mm in diameter. The viewing distance was 50 cm. The subjects were instructed to fixate the center of the screen.

Procedure and Design. Orientation acuity was measured by the method of constant stimuli combined with the forced-choice procedure. The test line was presented in a single observation interval marked by a tone in one of two possible orientations. One of the orientations was tilted 45° clockwise to the vertical (labeled A) and the other orientation was variable (labeled B). Each of the two oriented lines appeared equally often and the order of presentation was randomly varied. The subjects had to identify the orientation as A or B. The percentage of correct reports was recorded as a function of the orientation difference, which varied in steps of 2°. A correction for accidental guesses was made as described in Experiment 2. This function was measured for each of the three durations and at the two energy levels. The orientation difference was kept constant within blocks of 30 trials. Each daily session consisted of 12 blocks for combinations of two stimulus durations and six orientation differences. The order of block presentations was counterbalanced. The energy value was kept constant throughout the daily session. The percentage of correct reports was calculated on the basis of 60 trials.

Results and Discussion

The data of the 3 subjects did not differ considerably and were averaged across subjects. Figure 7 shows the psychometric functions for the two energy levels. The psycho-

metric functions for 0.01 and 0.05 sec coincided up to the orientation difference of 6°; that is, complete summation was observed in this temporal range. This result is similar to the data obtained in Experiment 2.

Increasing the exposure duration up to 0.5 sec resulted in improved performance, despite the use of stimuli of the same energy; that is, this result could not be assigned to temporal energy summation. Stimulus luminance exceeded the detection threshold more at the duration of 0.01 sec than at the duration of 0.5 sec. Nevertheless, the psychometric curve at the short duration, $T = 0.01$ sec, was displaced toward larger orientation differences; that is, the orientation acuity was lower and the percent correct responses was less than 100% even at the largest orientation difference used. The course of the curves was not changed at the higher energy level, as indicated by comparison of the left and right graphs, where the energy levels differed by a factor of 40; that is, stimulus duration rather than stimulus intensity was the critical factor.

To test the significance of the effects observed, the proportion of correct responses was transformed in probits and probit regression lines were calculated for each condition using the method of probit analysis. Regression lines at the two energy levels were compared separately for each duration, as described in Experiment 2. The pairs of curves did not differ significantly [0.01 sec, $t(9) = 1.01$, $p > .34$; 0.05 sec, $t(9) = 0.78$, $p > .45$; 0.5 sec, $t(9) = 0.85$, $p > .85$]. In contrast to the lack of an effect of energy, stimulus duration effects were found: The regression lines at 0.01 and 0.5 sec differed significantly at both energy levels [$t(9) = 3.15$, $p < .01$; $t(9) = 3.4$, $p < .01$].

The results in Figure 7 show no saturation of the duration effect, suggesting that a further increase in exposure duration would improve the orientation sensitivity even more. Therefore, we performed an additional experiment with 2 subjects, N.N. and M.M., including a stimulus duration of 1.2 sec. The orientation difference was varied in steps of 1°. The psychometric functions at the stimulus duration of 0.5 and 1.2 sec are presented for both sub-

Figure 7. Percent correct identification as a function of the orientation difference at two energy levels, E_1 and E_2 . Parameter is stimulus duration. Vertical bars represent ± 1 SE.

Figure 8. The effect of long stimulus duration (0.5 or 1.2 sec) on the percent correct identifications for Subjects M.M. and N.N.. Vertical bars represent ± 1 SE.

jects in Figure 8. The curves coincided in most parts, but the percent correct reports in identifying the orientation difference of 1° was significantly higher when the stimulus duration was 1.2 sec for each subject ($p < .001$). Watt (1987) also found an improvement in orientation acuity over at least 1 sec (the longest exposure time tested in his experiment).

GENERAL DISCUSSION One Mechanism or Two?

The hypothesis experimentally studied in the present paper is that two types of mechanisms of orientation identification take place: a mechanism of coarse identification and a mechanism of fine identification. The results supported the hypothesis. In addition to the previously observed identical intensity thresholds (Thomas & Gille, 1979; Vassilev et al., 1982), the intensity-dependent changes of RT for detection and coarse identification (orientation difference of 15° or more) were the same, as shown in Experiment 1. These results suggest that both detection and coarse identification are equivalent at an early energy-dependent stage, presumably the stage of encoding. This conclusion was further supported by the results of Experiment 2, showing that both processes have identical time-integrative properties. The existence of a common encoding stage is in line with the hypothesis of "labeled lines." Our results support, therefore, the conclusion that coarse identification is based on signals from separate orientation channels, which ensure both stimulus detection and its identification.

Fine identification (orientation differences smaller than 15°) differs from both detection and coarse identification. The present study showed that the magnitude of the intensity effect on RT for fine identification increased considerably. The time of complete summation also increased in comparison with detection and coarse identification. These differences in temporal characteristics indicate differences in processing. It seems that fine iden-

tification is based on a more complex mechanism than the detector-type principle of "labeled lines."

It could be argued whether a sharp transition exists between coarse and fine identification—that is, whether there are two separate types of mechanisms of line orientation identification. The present results support this possibility: The effect of intensity on RT and t_c did not change monotonously as a function of orientation difference. These characteristics were constant within the whole range from 45° to 15° but sharply changed for differences smaller than 15° .

Critical Duration and Critical Features

The greater effect of stimulus intensity on RT for fine orientation identification than for coarse identification might be due to development of some features in the internal representation of the stimulus that are needed at higher levels of processing and that are not available. A similar interpretation could be made with respect to the time interval of complete summation, t_c . Several studies have shown that t_c varies within a wide range with the observer's task (Alport, 1970; Kahneman & Norman, 1964; Kahneman, Norman, & Kubovy, 1967; Ueno, 1977). The fact that the critical duration in the visual system is not constant, but rather variable, with variations of the task and stimulus, is in line with the concept of Hartline (1934), who posited the critical stimulus duration as the maximal latency of some response characteristics, which might be considered an event in the neural response. If stimulus duration is shorter than the latency of this hypothetical event, the whole stimulus energy could be used (complete summation). When stimulus duration exceeds this latency, the stimulus energy is no longer effective since the critical event cannot be influenced by changes in energy taking place after its occurrence. In the present experiments, the critical duration was the same for detection and identification tasks if the orientation difference was 22° , but increased for identification of smaller orientation differences; that is, the hypothesized event, critical

for the performance, occurs later in this case than in the case of detection or coarse identification. Similar to the RT data, these results suggest that the mechanism of fine identification requires some critical properties of the neural response that are not available immediately after stimulus presentation.

Possible Neurophysiological Mechanisms of Orientation Acuity Dynamics

The present data, as well as those of Andrews (1967); Bouma and Andriessen (1968); Yakimoff, Mitrani, and Mateeff (1977); Watt (1987); and Dick and Hochstein (1989), have shown that orientation acuity strongly depends on stimulus exposure time. Line stimuli, the exposure duration of which is shorter than 0.05 sec, might appear in orientations far away from the actual orientation (Andrews, 1967; our observations). Orientation perception improves with stimulus duration and, as shown in Experiment 3, duration cannot be completely substituted for by energy. Orientation perception is, therefore, a genuine dynamic process. Neurophysiological studies have shown that inhibition within the retina has a longer time constant than excitation (Enroth-Cugell, Robson, Schweitzer-Tong, & Watson, 1983; Glezer & Bertulis, 1967). Therefore, the mosaic of the initial output of the retina should be blurred and far from similar to the optical image. Time of the order of 0.05 sec would restrict excitation and shape the mosaic of signals closely to the optical image. The result would be a restriction of the set of excited cortical neurons to those with an orientation preference similar to stimulus orientation. As can be seen from Figure 7, orientation acuity increased significantly within the 0.01–0.05 sec range. Longer durations (1–2 sec) result in still a higher orientation acuity (Andrews, 1967; Watt, 1987; present data). The neurophysiological mechanism of such an acuity increase is not clear, but it should include sets of neurons rather than single neurons. The best a neuron can do is to respond according to a tuning curve of $\pm 15^\circ$ or so without discerning between orientation and intensity of the stimulus. We could only speculate about how an ensemble of neurons might signal line orientation with higher accuracy or what a type of neural mechanism would interpret the signals of different strength produced by a large set of neurons, each neuron responding according to its tuning curve. Opponency is a likely candidate (Regan & Beverley, 1985), and its presence has been suggested by neurophysiological data on cross-orientation inhibition (Morrone, Burr, & Maffei, 1982; Shelepin, 1982).

The continuous improvement in performance up to 1.2 sec could involve eye movements that are known to exist during attempted fixation (Riggs, Armington, & Ratliff, 1954). Furthermore, a stimulus duration of 0.5–1.2 sec would allow for the execution of several voluntary saccades. A possible hypothesis about the role of eye movements in the improved performance at long exposures is that during prolonged inspection, the observer could take

multiple samples from the stimulus. (It should also be taken into account that orientation perception is a complex process based on retinal as well as other signals, e.g., eye position and vestibular signals. Multiple sampling and comparison of all these signals would allow for an increased accuracy of perception.) Unfortunately, we cannot verify this assumption.

The inference from the present investigation is that the mechanism of coarse identification is a simple activation of individual orientation selective channels, which has the advantage of a fast initial analysis and provides a basis for further and more precise image analysis. Fine orientation identification appears to be a result of multiple mechanisms that have longer time constants.

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