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Visual orientation estimation

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A systematic error is reported in orientation estimation, in that on average, estimates are closer to the vertical axis than are the stimuli by up to 6°. This systematic error results from a specific mechanism that may be related to depth perception, and that is avoided in certain circumstances or when other mechanisms take over. For example, the estimates of one observer who was a well-trained professional draughtsman did not show this systematic error. Furthermore, for all observers tested, estimation of clock time is not subject to the regular orientation estimation error. Rather, observers tend to estimate times as slightly further from the quarter hour than they really are. Orientation judgment channel capacity was also studied under various conditions. The number of discriminable orientations is far above the magic number "7" limit, reaching over 20 in optimal circumstances. The distribution of discriminable orientations is nonlinear, in that these are more closely packed about the horizontal and vertical axis than at the oblique.

When performing a series of absolute judgment tasks, observers may be subject to two types of errors: systematic and random. Systematic errors have a fixed direction and magnitude for a particular task, while random errors are responsible for response frequencies that are distributed symmetrically about the expected "correct" response. Random errors may be due to the limited precision of the sensory system, related to a channel capacity and to noisy signal transmission. Systematic errors, which are due to a biased sensory system, derive from an inherent inhomogeneity. The average response over a large number of trials will be independent of random errors. On the other hand, we cannot average away a systematic error. Here averaging only allows us to better estimate its (mean) magnitude.

When observers are asked to estimate the orientation of a long light bar stimulus, their responses are subject to these two types of error. We report here that there is a systematic deviation of observers' responses in performing the task of absolute orientation estimation. Our second purpose in this study, following from this finding, is to measure the magnitude of this systematic error, as well as to measure the random errors in this absolute judgment task, and to find the experimental conditions that influence them. We describe below the results for five related experiments. In each case, observers were asked to estimate the orientation of a light bar stimulus from a restricted set.

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For these experiments, we chose various subsets of the 180° of possible bar orientations, and varied also the presentation time and the method of labeling for the observer's estimation. We changed the labels of the estimates in order to test whether the case of familiar categories would reduce estimation errors. Evidence from one and two-dimensional sinusoidal grating experiments indicates that observers cannot discriminate orientations closer than ±5° (Caelli, 1982). In Experiment 1, we therefore used a set of 19 orientations equally spaced (every 5°) between the vertical and horizontal orientations. We also tested the effect of very brief stimulus presentation durations for the same experimental set.

In Experiment 2, we tested the use of a less restricted set of light bar stimuli, using orientations spaced 1° apart. We used four partial subsets of the range of orientations: ±10° (21 stimuli) around vertical, horizontal, and oblique (45°), and 0°-90° (91 stimuli).

In Experiment 3, we changed the estimate label by asking the observers to answer the question, "What is the time past the hour?" (as on an analog clock). Here the subset was the 16 "minutes" from 0 to 15 (each 6° of orientation).

In Experiment 4, we used an unequal spacing of orientations (more closely spaced near vertical and horizontal) and gave them ordered labels. In this way, we hoped to overcome the unequal discrimination of oblique lines (shown in Experiment 2), and to introduce an unfamiliar label (for comparison with Experiment 3).

The last experiment, Experiment 5, was designed to examine a hundred-year-old hypothesis (Helmholtz, 1865/1962), concerning the possible origins of the deviation.

Information transmitted by the visual system has been measured for many modalities (see Garner, 1974). Here we report measurements of information transmitted in the absolute judgment of orientation of the visual stimulus.

We refer to the limitations on this estimate as a channel capacity, using the nomenclature of information theory.

A large body of physiological evidence is available concerning orientation detection. Most cells in primary visual cortex (area 17 in cats or the interblob region of V1 in the monkey) are orientation selective. It has been suggested that there is an overrepresentation of cells in V1 that are tuned to horizontal or to vertical orientations (Pettigrew, Nikara, & Bishop, 1968). Orban, Vandenbussche, and Vogels (1984a,1984b) suggested a link between the oblique effect in line orientation discrimination and the orientation anisotropy of S-cells (Orban & Kennedy, 1981) in area 17 of the cat and V1 of the monkey. Nevertheless, they suggested a different mechanism for orientation discrimination.

Orientation perception has also been studied psychophysically. Blakemore and Campbell (1969) found that adaptation by spatial frequency grating was also orientation selective. Campbell and Kulikowski (1966) found that masking effects between spatial frequency gratings were orientation dependent. Movshon and Blakemore (1973) studied the spatial limits of orientation specificity.

Though the number of cells available for orientation tuning may be responsible for the anisotropic precision of orientation estimation—the oblique effect—it should *not* result in an average deviation from correct estimation. Furthermore, any systematic errors introduced in a system should be corrected for by the system. In the discussion section, we analyze possible sources of this systematic error.

It is currently popular to talk of a number of cortical streams, each of which analyzes a different aspect of visual perception (DeYoe & Van Essen, 1988; Hubel & Livingstone, 1987; Livingstone & Hubel, 1987; Ungerleider & Mishkin, 1982; Van Essen & Maunsell, 1983). The sensory feature of 2-D retinal orientation and its interpretation into the inferred attribute of 3-D orientation in space play an important role in these models. In the present study, we consider specific aspects of this orientation processing by using psychophysical methods.

GENERAL METHOD

We will first describe the general features of the experimental method that are common to all the experiments. Specific details of method will be added for each experiment subsequently.

Psychophysical Procedure

Observers were presented with a light bar stimulus. They were asked to estimate the orientation of the stimulus bar relative to the vertical (or horizontal) imaginary axis, for each trial, and to type the result on the computer keyboard. The set of stimuli was limited in various ways, and the observers were asked to restrict their estimation to the chosen set. Each observer typed a final carriage return to initiate each following trial. Examples of a few stimuli are given in Figure 1, row a.

Each stimulus was randomly presented 5 or 10 times during an experiment, and experiments were repeated at least 3 times by each observer.

Stimulus

The stimulus, a single light bar of 12 × 1 mm, was presented on an oscilloscope screen. A computer-driven visual stimulator was used to provide the inputs to a CRT screen, on which a bar was seen. The oscilloscope had a P31 phosphor, and the stimulus brightness was well above threshold (5 cd/m^2). The observer saw the stimulus through a 1-m-long viewing cone (whose diameter was 100 mm close to the oscilloscope, and 200 mm close to the observer).

The outer field of vision was covered with a black curtain. Thus, there was no external visual clue with respect to which the observers could make relative orientation judgments.

We chose the bar's length according to both physiology and psychophysics. Scobey (1982) had shown that for line lengths that exceed 10′ of arc the accuracy for orientation estimation is fixed and independent of the eccentricity. Since electrophysiological studies of cats (Kato, Bishop, & Orban, 1976) and monkeys (Schiller, Finlay, & Volman, 1976) had shown that the optimal bar length is 1.4° for end-stopped visual cortical cells and 6.5° for end-free cells, the stimulus we used throughout these experiments thus subtended 1.7°. The center of the bar was always at the same location, at the center of the screen.

Observers

Twelve observers participated in this task: one of the authors and 11 paid or volunteer students, who were experimentally naive. All had normal or corrected-to-normal visual acuity.

Analysis

Two measures were used to describe the psychophysical results. We computed the average deviation of the responses from the stimulus in the following way: Let y_{ij} be the response of trial j with stimulus x_i. The average systematic deviation for N such trials is given by the equation

$$d_i = -x_i + \frac{\sum_{j=1}^{N} y_{ij}}{N}.$$

For M observers, the average deviation is therefore

$$D = \frac{\sum_{k=1}^{M} d_{ik}}{M},$$

where the summing variable k refers to the different observers. Note that the deviation is expected to vary as a function of the stimulus variable x_i.

The second measure we computed from the same data was the amount of information transmitted (IT—see Dick & Hochstein, 1988), which in absolute judgment tasks measures the degree of correlation between the stimulus set x and the response set y. The IT measure for a noisy channel was computed, under certain restrictions, by Shannon and Weaver (1949):

$$\mathrm{IT} = H(y) - H(y|x) = \sum_{i,j} P(y_i,x_j)\mathrm{lg}_2 \frac{P(y_i,x_j)}{P(y_i)P(x_j)},$$

where $H(y)$ and $H(y|x)$ are the entropies (uncertainties) of the output set and the output set conditional upon the input set, respectively, and $P(x_j)$, $P(y_i)$, and $P(y_i,x_j)$ are the probabilities of a stimulus x_j, a response y_i, and a response y_i, given a stimulus x_j, respectively; IT is measured in bits of information per stimulus. The capacity of the channel is defined to be the maximal amount of information transmitted over all input probabilities. $P(x_j)$ is determined by the experimental stimulus set, and $P(y_i)$ and $P(y_i,x_j)$ are calculated from the experimental responses in each experiment.

Miller (1956) found that for absolute judgment tasks done by the nervous system there is a limit to the amount of information transmitted, which is dependent upon the dimensionality of the stimulus set. In a single dimension (as in orientation detection) the observers may perform better (increase IT) as a function of their degree of experience until the channel capacity is reached. This channel capacity has been characterized, by Fulgosi and Bartolović (1971), by the observation that if the experiment is repeated, or is performed upon various partial ranges of the experimental set, the IT will not exceed this channel capacity.

We also measured the response time of the observers. We added to the computer program a clock that measured the time elapsed from the onset of the stimulus until the observer, by means of a keystroke, signaled that he or she knew the answer (and only then typed the answer). All stimuli were presented until the keystroke occurred.

EXPERIMENT 1

We started by examining the simplest estimation of orientation of a tilted bar. It was not clear a priori whether estimation depends on the reference axis, or whether the whole 360° range is divided in another way. We therefore divided the range into quarters—horizontal to vertical or vertical to horizontal, clockwise (CW) and counterclockwise (CCW). The question put to the observers was, "What is the orientation of the tilted light bar stimulus in units of 5°, calculated from one of the axes to the other?" An example of a few study stimuli is given in Figure 1, row a, where the reference axis was an imaginary vertical line and orientation was measured CCW from this axis. The experimental procedure started with an unlimited study period, in which the observer could become acquainted with the set of stimuli by asking for any tilt of the bar, simply by typing the angle on the computer's keyboard. The set for training contained only CCW stimuli. In the experiment that started immediately after the training period, bars were presented with either a CCW or a CW tilt. In this way, all possible rotations were studied. The observer was asked to respond to the CW stimuli with the same response as to their CCW mirror image (see example in Figure 1, row b). The CW and CCW results were analyzed by the computer program separately. It is worth noting that others (Fiorentini & Berardi, 1980) have shown that learning of accuracy is not transferred from horizontal to vertical, but that for orientations surrounding those of the learned stimuli accuracy is increased as well.

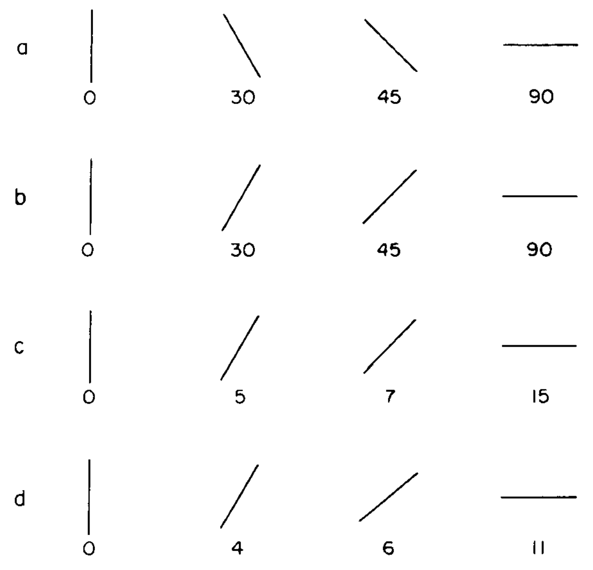

Figure 1. Examples of the experimental stimulus sets that were used in these experiments. a: Orientation absolute judgment. Examples out of the 19 possible CCW stimuli. The required, computer-typed response was as indicated below each stimulus. b: Examples of CW stimuli that were presented in the experiments for which the observers were not trained. Mirror images upon which the observers were self-trained are in 1a. The required responses were the same as for their mirror images. c: Minutes in the clock estimation. Examples out of 16 possible CW stimuli and the required response in minutes. d: Examples of the artificial experimental set and their numerical names.

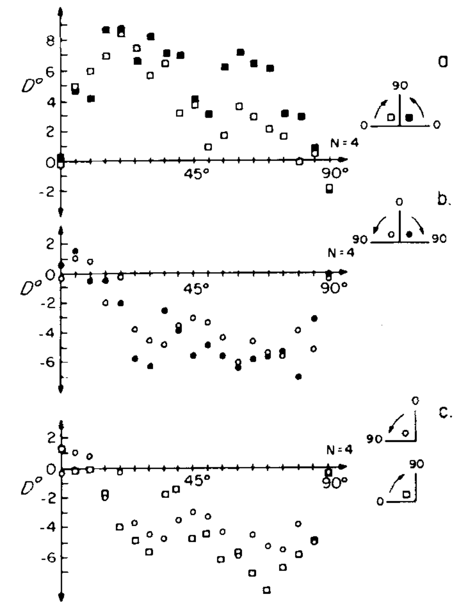

Figure 2. The average results of 4 observers on orientation absolute judgment. a: Estimation of orientation using an imaginary horizontal line as reference. b: Estimation from an imaginary vertical line reference axis. Results are separately plotted for the practiced (CCW open dots) and the nonpracticed (CW filled dots) areas. c: A comparison between the above results for the practiced regions: the squares are inverted data from 2a.

The average deviations (*D*) for 4 observers are plotted in Figure 2 for four experimental conditions: two experiments in which the reference axis was an imaginary horizontal axis, and two others in which the reference axis was vertical. CW and CCW data are plotted. The standard deviations of the results were 1°–2° in every case, and were a bit longer for oblique lines than near the primary axes.

In Figure 2, panel c, the practiced region's data of these two experiments is replotted for convenience. A few conclusions may be inferred from the graphs in Figure 2:

1. There seems to be no large systematic difference between the CCW orientation for which the observers were trained and the CW mirror image stimulus bars.

2. The absolute judgment results are similar for the two reference axes (horizontal and vertical).

3. There is an obvious systematic error, in that estimates are closer to the vertical axis than were the stimuli (e.g., observers tended to estimate a bar that was 30° from the vertical as being 24° from the vertical). Note that, close to the edges of the ranges of stimuli (0° and 90°), the only possible direction of deviation is within the examined range. This may account for the apparent reversal of direction of the deviation near one of the axes. Since the results are very similar for the case of a horizontal or a vertical reference axis, from now on we shall refer to all data as if the vertical axis is the reference axis.

4. We excluded from the data the results for one observer who is an experienced draughtsman. This result did not show any significant deviation, presumably due to his training.

We also calculated IT for each set of stimuli as a general perceptual measurement. We wished to find out whether variations in the stimulus set may influence the information transmitted in the orientation channel. In this absolute judgment experiment, we provided the equivalent of 19 (i.e., $2^{4.25}$) independent stimulus groups, so that $I = 4.25$ bits. Estimation of IT derived from the observers' performance is only 3.09-3.27 bits, which can be regarded as the observers' ability to divide the stimulus space into 8-10 independent groups (see Table 1). This poor performance may be due to the choice of the set of stimuli, which divided the 90° range by a fixed step of 5°. We examined the deviation and this hypothesis by performing further experiments in which the stimulus range was divided in other ways (see Experiment 4).

Others (Garner, 1974; Lockhead, 1966) have shown that energy limits such as exposure time, contrast, or salience against the background can decrease the amount of IT of a channel. One of these limits, the exposure time, was examined. In order to estimate the influence of the prolonged presentation time of the stimuli in Experiment 1, we tested the same set of stimuli described in Figure 1, but with an exposure time that was shorter than 25 msec. The results for 7 observers are given in Figure 3. This figure shows that for short exposure times, the deviation of a tilted bar is somewhat different, especially for orientations between vertical and 45°. For orientations close to the vertical, the deviation is in the direction opposite to that found with long exposure periods.

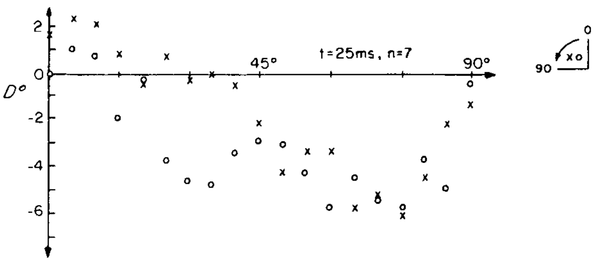

Figure 3. The average results of 7 observers on orientation estimation from an imaginary vertical axis, when exposure times were shorter than 25 msec (denoted by ×s), compared with results of the same observers for long exposure times (denoted by open circles).

Table 1
Information Transmitted (in Bits) and Number of Groups in the Orientation Estimation Task with 19 Different Stimuli Between Horizontal and Vertical (5° Separation)

	Observer					
	Y.E.	N.	M.D.	A.	E.	Avg.
	Long Exposure					
IT	3.21	3.27	3.22	3.15	3.09	3.19
Number of Groups	9.25	9.64	9.32	8.87	8.50	9.11
	Short Exposure					
IT	2.99	2.98	2.76	2.87	2.88	2.89
Number of Groups	7.94	7.89	6.77	7.31	7.36	7.45

Another noticeable difference between prolonged and short presentation times is in the amount of IT, as was expected. Table 1 compares the results for the two exposure times as seen for 5 observers. On the average, about 0.3 bits are lost with short exposure times (more than one orientation group is lost). The loss of IT in this experiment was expected, but the change in the deviation is not simply explained. We therefore had first to try to measure the channel capacity, and then to find out more about the source of this deviation.

EXPERIMENT 2

It is to be expected that our sensitivity for the orientation space will be unequally distributed, since our accuracy was shown to be better around the main axes. Performance on a variety of perceptual tasks (e.g., acuity, contrast sensitivity, discrimination, memory, etc.) is superior for stimuli arranged in the horizontal and vertical orientations as compared with the oblique orientations. For example, Onley and Wolkmann (1958) found that observers were most accurate at adjusting a perpendicular line to a fixed reference line when that reference line corresponded to the objective primary axes. Claims have been made about the origin of this "oblique effect" (Appele, 1972); it has been attributed to innate characteristics of the visual system (Essock & Siqueland, 1981; Orban & Kennedy, 1981), modification of the neurological basis through experience with predominantly vertical and horizontal carpentered environments (Anstis & Frost, 1973; Gregory, 1963), and genetic factors (Ross & Woodhouse, 1979). On the other hand, it has also been claimed that line orientation discrimination improves with selective practice (Vogels & Orban, 1985) for oblique orientations and not for the principal orientations.

Guided by these facts, we wanted to know if our capacity to transmit information is different in various parts of the orientation space. We looked at partial ranges of this orientation space while using separations of a single degree. We looked at the sensitivity near the vertical and

Table 2
Information Transmitted (in Bits) and Number of Groups in the Orientation Estimation Task with 21 Different Stimuli in Three Ranges (1° of Separation)

	Range					
	0° ± 10°		45° ± 10°		90° ± 10°	
Observer	IT	2^{IT}	IT	2^{IT}	IT	2^{IT}
M.D.	2.40	5.29	2.29	4.89	2.32	5.01
S.	2.54	5.83	2.30	4.94	2.67	6.36
Y.C.	2.82	7.07	2.42	5.35	2.86	6.28
Avg.	2.58	6.06	2.34	5.05	2.61	5.88

horizontal axes and the diagonal. Three separate experiments were carried out with stimuli that varied ±10° around the vertical (0°) and horizontal (90°) axes and around the diagonal (45°) line. Table 2 shows the results of 3 observers for the different experiments. From the information available in each set of 21 stimuli (≡ 4.39 bits), more was transmitted around the main horizontal and vertical axes. We found that on the average, in the same range of ±10°, there is one more independent channel around each of the main axes than there is around the diagonal. It is very clear that our ability to perceive differences in tilt is not equally spaced. For this reason, the amount of IT found above does not reflect the full channel capacity. In order to find the real channel capacity, 2 very well trained observers were given a set of 91 stimuli (tilted bars separated from each other by 1°), which is the equivalent of 6.5 bits of information. The observers were instructed to respond in single degrees as well. The amount of IT in this experiment (which lasted about 2 h; there were five repetitions of each one of the stimuli) was 4.65 bits.

We therefore concluded that the effective number of unequally spaced groups is 25. It is worth noting that Caelli (1982) claimed that no more than 18 classes of orientations were detected while using stochastic textures with low-frequency components. The longer and sharper (the higher the frequency of) the stimulus, the more the orientation classes that are detected. Furthermore, Scobey (1982) showed that for a stimulus that is 10′ of arc long, the orientation discrimination can resolve half hours on the clock (for a range of 180°—12 orientation groups). He also showed that observers can perform better when the duration of the stimulus is longer (to 100 or 200 msec), and the size of the bar is greater (72′ of arc). Under these conditions, 16–20 categories of orientations were obtained.

One can think about the information processed in this orientation channel as follows: Most of its accuracy is around the main axes (2.6 bits). A smaller amount is spread between 35° and 55°, and at least two groups are responsible for the gaps in the orientation range. One can conclude that for orientation estimation our accuracy is better than the magic number 7 (Miller, 1956). The non-magic number is approximately 20 groups. This may be due to the division of the range into three groups: around the vertical, horizontal, and oblique, respectively. So that the processing may be done on more than one channel.

Looking at the deviation in these experiments, we found that besides border effects (one could estimate 35° from the vertical only as 40°, since 30° was not in the stimulus set), the deviation near the principal orientation is smaller (about 2°–3°), but its direction is similar to the one found in Experiment 1.

EXPERIMENT 3

In order to learn more about the deviation in the estimation from the vertical, we searched for another task that might reveal another deviation.

People are very used to estimating the time on ordinary clocks by measuring the tilt of the clock hands from the vertical and translating it into minutes or hours. We therefore used an experimental set appropriate to the minute hand of a clock (the passing of 1 minute is equal to the separation of 6°) and asked the same observers to estimate the time (see examples in Figure 1, row c). The responses in this case were therefore given in minutes (0 to 15).

The average deviation of 7 observers for estimation in terms of minutes is given in Figure 4 (bottom panel). It seems that the deviation from the vertical in our "clock estimating system" is quite different near the vertical axis: the estimation was 14° when the stimulus was 10° (rather than 5° as obtained in Experiment 1); data of Experiment 1 is replotted in Figure 4 (top panel). Observers tend to exaggerate the differences between the correct time and either the vertical or the horizontal: Times between 1 and 6 min before or after the hour are seen as farther from the hour, and times between 8 and 14 min before or after the hour are seen as closer to the hour or farther from the quarter hour. The possible usefulness of such an error may be that we become sure that it is past the hour (or not yet the hour) or past (or not yet) the quarter hour. Still, on the average, we are not more than 1 min "wrong."

The amount of IT in this case was similar to that obtained in angular tilt estimation, even though less information is conveyed in the stimulus set (16 possibili-

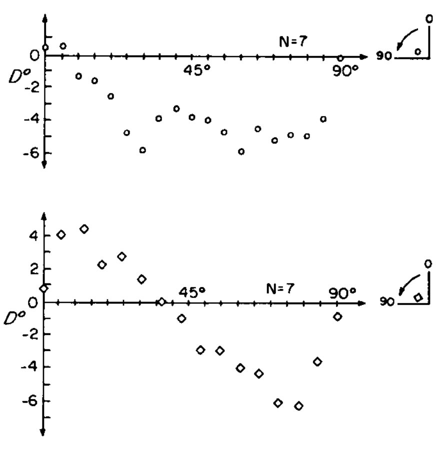

Figure 4. A comparison between the results of an experiment in which 7 observers were asked to estimate minutes (diamonds) and another experiment in which they estimated the tilt (circles).

Table 3
Stimulus Set for Experiment 4

Stimulus	0	1	2	3	4	5	6	7	8	9	10	11
Corresponding tilt from imaginary vertical	0°	4°	12°	20°	30°	40°	50°	60°	70°	78°	86°	90°

Note—Range, given from horizontal to vertical, was unequally divided.

ties ≡ 4 bits, while 19 possibilities ≡ 4.25 bits). This is not surprising, since, as shown above, we were not at the channel capacity.

It is not clear whether minutes estimation is a unique process using fast processing channels, or whether it uses a better correction procedure in the processing path, or, finally, whether it is a more trained mechanism and is therefore processed by some special path.

EXPERIMENT 4

In order to check the importance of the numerical response (reporting minutes of time instead of the trigonometric angle), we invented a new set of stimuli and trained the observers to identify them by numbers. The stimulus set is presented in Table 3, and examples are given in Figure 1, row d.

We used short exposure times (t = 25 msec), and observers were required to type the name of the appearing stimulus on the computer's keyboard. The average response deviation for 5 observers is plotted in Figure 5, where it can be seen that the obtained deviation is similar to that obtained in tilt estimation (see Figure 2, panel b, and Figure 3). The IT in this experiment was also similar, 2.9 bits, out of a set of 12 stimuli ≡ 3.58 bits.

EXPERIMENT 5

Helmholtz (1865/1962) describes a vertical-horizontal illusion, whereby observers underestimated the length of a vertical bar compared to a horizontal one:

> The comparison of vertical and horizontal linear dimensions with each other is much more difficult. In this case we find a constant error owing to the fact that we are disposed to regard vertical lines as being longer than horizontal lines of the same length. The best way to see it is to hold a piece of paper perpendicular to the line of vision and try to draw a square on it by eye. The height of the square is invariably made too low. (Vol. 3, p. 170)

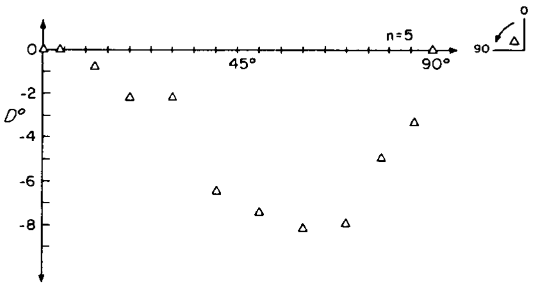

Figure 5. The average results obtained by 5 observers when estimating a learned set of stimuli that were unequally separated in space.

Could this illusion be the basis of the deviation in estimation of tilt from the real orientation? If instead of having the ability to judge directly the orientation of the tilted bar we had to measure the horizontal and the vertical projections, and derive the orientation from their ratio, a deviation would indeed arise from a wrong estimation of the projections of the stimulus bar. In order to examine this notion we performed a "similarity" experiment.

During Experiment 5, one out of three pairs of lines appeared on the screen (randomly chosen by the computer program). Each pair had two perpendicular lines (shown in Table 4) tilted 0° and 90°, −45° and 45°, or −30° and 60°. One of the lines remained fixed in length at 30 mm, while the length of the other was varied in the range of 27–33 mm (±10% of the fixed line's length). Exposure time was limited to 30 msec, to prevent measurement by eye movements. No training period was provided. We called the horizontal bar or the bar tilted (45° or 60°) CW from the vertical an "*X*-bar". Similarly, "*Y*-bar" was the name we used for the vertical bar or the bar tilted (45° or 30°) CCW from the vertical. The observer was asked to respond by pressing the *X*-, *0*-, or *Y*-key on the computer's keyboard, if the *X*-bar seemed longer, the bars appeared equal, or the *Y*-bar seemed longer, respectively.

Table 4 shows the results from 4 observers, in terms of the percent difference in length at which each observer estimated on the average that the bars were equal. We can see that the average error is 7.5% in estimation that the vertical axis is longer than it really is, as Helmholtz claimed. Note that, since the judgment was biased, most of the responses were of the *X* type. This might be the source of the preference of one of the diagonal lines by 2 of the observers.

According to this theory of Helmholtz, the deviation seen in our results might result from incorrect estimation of the projections of the tilted bar, from which the orientation estimation may derive. We show here an example (see Figure 6) of results from one observer (YC), in which we calculated the expected deviation that derives from a 6.5% difference in estimation of the axes (as obtained in the experiment that this observer performed—filled circles), and compare it with the orientation estimation performance (open circles).

The magnitude of the vertical–horizontal illusion is only 7.5% (see Table 4), so that the maximal expected orientation judgment deviation is about 2° and should appear

Table 4
Median Percent Difference in Length of Bars for which Observers Reported Equal Length for Various Bar-Pair Tilts

	Observer			
	P.H.	Y.C.	R.P.	R.
Horizontal-vertical	6	6.5	8	8.5
Diagonals	0	0	1	3
−30° and 60°	4	4.5	5	6

near the 45° tilt. We can see that the expected direction of this deviation is indeed in the direction of the deviation we found, but it cannot account quantitatively for the 6°-7° deviation found here and in most of the experiments, for orientations smaller and greater than 45°.

DISCUSSION

When estimating the orientation of a light bar stimulus, observers are subject to both systematic and random errors. The systematic errors are responsible for the deviation of the estimates of the orientations of the bars in degrees from the true (stimulus) values, in that obliques are seen as closer to the vertical than they really are. The average deviation can be as large as 5°. It is still unclear what may be the advantage, if any, of such a systematic error in tilt estimation.

A number of observations restrict the possible mechanism that may be responsible for this deviation. There are no deviations at vertical and horizontal orientations. The same deviation is found for bars that are tilted CW or CCW from the vertical.

The deviation in orientation estimation may be related to depth perception, since tilt is a known cue for depth. For example, the two-dimensional perspective representation of railroad tracks consists of two lines that are tilted towards each other. The perception of these lines as increasing in depth rather than leaning towards each other requires that we "correct" for the tilt. In general, contours have components of both depth and tilt. We must correct for the increased tilt seen due to the depth component, by perceiving tilted bars as closer to the vertical than their two-dimensional retinal projection.

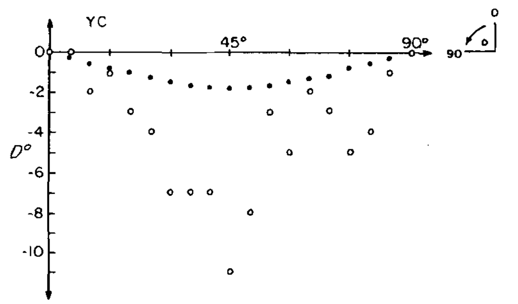

Figure 6. Results of Subject Y.C. to the orientation estimation, and the expected results if the only important parameter was the perceptual difference between the horizontal and the vertical axis. The standard error was between zero (near the main axis) and 2° (elsewhere).

Finally, we noted that two testing procedure parameters affect the tilt deviation. Short presentation exposure durations reduce the deviation for the range between vertical and 45°.

In addition, when using familiar labels—estimating the minutes on a clock—observers have an entirely different estimation deviation: Instead of estimates that are closer to the vertical, estimates are farther from both the vertical and the horizontal. It is as if in order to label time, one must know how different the time is from the cardinal points each quarter hour. Perhaps when depth is ruled out, as in estimating the time on a clock face that is presumed perpendicular to the line of sight, the tilt seen is not "corrected" as in the natural depth cue case. Short presentations may also reduce the deviation, since an elementary mode is assumed, limiting the higher order processes.

As mentioned in the Method section, we measured reaction times from stimulus presentation to first response keystroke. The reaction times for the estimation of tilt in degrees was longer in all experiments by 200-300 msec than in the experiment in which the response was in terms of minutes of time. This may also support the suggestion that time estimation is a more trained, automatic function, which is therefore performed faster.

Another interesting aspect is related to a learning process. Surprisingly, when a trained engineer was presented with the orientation estimation test (Experiment 1), his errors were only of the random type (no deviation was detected). Thus the visual system is able to correct for systematic errors with proper training. Orban et al. (1984b) claim that the improvement of orientation discrimination with line length over 1° is limited to the principal orientations, and that only S cells in V1 show meridian deviations in orientation performance (Orban & Kennedy, 1981). It is hard to compare between the training of observers performing psychophysical experiments and the practical training that engineering school requires, yet nevertheless we think that the deviation that we describe here is different from the one causing the oblique effect.

It is important to note that repetition of the experiment up to 10 times with naive observers did not produce a correction of the deviation. However, familiarity with the fact that estimates were "wrong" (as occurred when one author served as an observer) did result in correction and cancellation of the deviation. Again, these instances of learning may be related to changing the assumption to that of a vertical plane on which the bars are shown.

Since we did not keep the number of stimulus orientations constant in the experiments reported here, we cannot make quantitative conclusions regarding the information transmitted by the orientation detection system. However, a number of general conclusions may be made:

1. The channel capacity for orientation estimation is far above the magic number 7±2 of Miller (1956). It reaches 25 groups in optimal situations.

2. The division of orientation into discernible groups is nonlinear, in that their number around the main axes is greater than for those near the oblique.

3. Better trained observers are able to discriminate more orientation groups than are naive observers.

4. A limited processing time caused by a brief exposure resulted in a poorer discrimination.

REFERENCES

Anstis, R. C., & Frost, B. (1973). Human visual ecology and orientation anisotropies in acuity. *Science*, **182**, 729-731.

Appele, S. (1972). Perception and discrimination as a function of stimulus orientation: the "oblique effect" in man and in animals. *Psychological Bulletin*, **78**, 266-278.

Blakemore, C., & Campbell, F. W. (1969). On the existence of neurons in the human visual system selectively sensitive to the orientation and size of retinal images. *Journal of Physiology*, **203**, 237-260.

Caelli, T. (1982). On discriminating visual textures and images. *Perception & Psychophysics*, **31**, 149-159.

Campbell, F. W., & Kulikowski, J. J. (1966). Orientation selectivity of the human visual system. *Journal of Physiology*, **187**, 437-445.

DeYoe, E. A., & Van Essen, D. C. (1988). Concurrent processing streams in monkey visual cortex. *Trends in Neuroscience*, **11**, 219-226.

Dick, M., & Hochstein, S. (1988). Interactions in the discrimination and absolute judgment of orientation and length. *Perception*, **17**, 177-189.

Essock, E. A., & Siqueland, R. R. (1981). Discrimination of orientation by human infants. *Perception*, **10**, 245-253.

Fiorentini, A., & Berardi, N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature*, **287**, 43-44.

Fulgosi, A., & Bartolović, B. B. (1971). Practice and some methodological problems in unidimensional information transmission. *Perception & Psychophysics*, **10**, 283-285.

Garner, W. R. (1974). *The processing of information and structure*. Potomac, MD: Erlbaum.

Gregory, R. L. (1963). Distortion of visual space as inappropriate constancy scaling. *Nature*, **199**, 678-680.

Helmholtz, H. von (1962). *Treatise on physiological optics* (J. P. C. Southall, Trans.). New York: Dover. (Original work published 1865)

Hubel, D. H., & Livingstone, M. S. (1987). Segregation of form, color, and stereopsis in primate area 18. *Journal of Neuroscience*, **7**, 3378-3415.

Kato, H., Bishop, P. O., & Orban, G. A. (1978). Hyper-complex and simple complex cell classifications in cat striate cortex. *Journal of Neurophysiology*, **41**, 1071-1095.

Livingstone, M. S., & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement and depth. *Journal of Neuroscience*, **7**, 3416-3468.

Lockhead, G. R. (1966). Effects of dimensional redundancy on visual discrimination. *Journal of Experimental Psychology*. **72**, 95-104.

Miller, G. A. (1956). The magic number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, **63**, 82-96.

Movshon, J. A., & Blakemore, C. B. (1973). Orientation specificity and spatial selectivity in human vision. *Perception*, **2**, 53-60.

Onley, J. W., & Wolkmann, J. (1958). The visual perception of perpendicularity. *American Journal of Psychology*, **71**, 504-516.

Orban, G. A., & Kennedy, H. (1981). The influence of the receptive types and orientation selectivity in areas 17 and 18 of the cat. *Brain Research*, **208**, 203-208.

Orban, G. A., Vandenbussche, E., & Vogels, R. (1984a). Human orientation discrimination tested with long stimuli. *Vision Research*, **24**, 121-128.

Orban, G. A., Vandenbussche, E., & Vogels, R. (1984b). Meridional variations and other properties suggesting that acuity and orientation discrimination rely on different neuronal mechanisms. *Ophthalmology & Physiological Optics*, **4**, 89-93.

Pettigrew, J. D., Nikara, T., & Bishop, P. O. (1968). Responses to moving slits by single units in cat striate cortex. *Experimental Brain Research*, **6**, 373-390.

Ross, H. E., & Woodhouse, J. M. (1979). Genetic and environmental factors in orientation anisotropy: A field study of the British Isles. *Perception*, **8**, 507-521.

Schiller, P. H., Finlay, B. L., & Volman, S. F. (1976). Quantitative studies of single-cell properties in monkey striate cortex: I. Spatio temporal organization of receptive fields. *Journal of Neurophysiology*, **39**, 1288-1319.

Scobey, R. P. (1982). Human visual orientation discrimination. *Journal of Neurophysiology*, **48**, 18-26.

Shannon, G. E., & Weaver, W. (1949). *The mathematical theory of communication*. Champaign: University of Illinois Press.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press.

Van Essen, D. C., & Maunsell, J. H. R. (1983). Hierarchical organization and functional streams in the visual cortex. *Trends in Neuroscience*, **6**, 370-375.

Vogels, R., & Orban, G. A. (1985). The effect of practice on the oblique effect in line orientation judgment. *Vision Research*, **25**, 1679-1687.

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