The perception of 2D orientation is categorically biased

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Three experimental paradigms were used to investigate the perception of orientation relative to internal categorical standards of vertical and horizontal. In Experiment 1, magnitude estimation of orientation (in degrees) relative to vertical and horizontal replicated a previously reported spatial orientation bias also measured using verbal report: Orientations appear farther from horizontal than they are, whether numeric judgments are made relative to vertical or to horizontal. Analyses of verbal response patterns, however, suggested that verbal reports underestimate the true spatial bias. A non-verbal orientation bisection task (Experiment 2) confirmed that spatial errors are not due to numeric coding and are larger than the 6° error replicated using verbal methods. A spatial error of 8.6° was found in the bisection task, such that an orientation of about 36.4° from horizontal appears equidistant from vertical and horizontal. Finally, using a categorization (“ABX”) paradigm in Experiment 3, it was found that there is less memory confusability for orientations near horizontal than for orientations near vertical. Thus, three different types of measures, two of them non-verbal, provide converging evidence that the coding of orientation relative to the internal standards of horizontal and vertical is asymmetrically biased and that horizontal appears to be the privileged axis.

Keywords: space and scene perception, spatial vision, spatial cognition


Introduction

From the time of Jastrow (1892) and Wundt (1862), it has been argued that the perception of 2D angles is distorted. Fisher (1968) showed that acute angles presented about a horizontal axis were overestimated, while acute angles presented about a vertical axis were underestimated. Such a pattern suggests that lines tend to appear steeper than they are. Although Fisher argued that the numeric errors did not fully support this simple interpretation, his findings strongly suggested that oblique orientations appeared steeper than they were in both cases.

Several authors have argued on theoretical and empirical grounds that the perception of 2D orientation is indeed biased. For example, Dick and Hochstein (1989) asked people to categorize oriented lines into bins separated by 5° and found that orientations near horizontal were seen as farther from horizontal than they were, with a maximum error of about 6° for lines 30° from horizontal. Howe and Purves (2005) argued that the misperception of angles was due to the statistical predominance of shallow angles in natural scenes. However, because their argument was expressed in terms of angles rather than orientations, it does not directly predict the asymmetry observed by Fisher (1968) for angles about horizontal vs. vertical axes, even though it is consistent with such an asymmetry. With the exception of the work of Dick and Hochstein, the data supporting the idea that 2D orientation is distorted have come predominantly from judgments of angles rather than of orientation.

Although verbal estimates are often regarded as unreliable psychophysical measures of perceptual experience, verbal estimates of surface orientation have been shown to be surprisingly consistent with a variety of non-verbal methods (Durgin, Li, & Hajnal, 2010; Li & Durgin, 2009, 2010). In the present paper, we will employ verbal methods, as well as two different non-verbal methods to extend the findings of Dick and Hochstein (1989) in three ways. The results of all three methods support the same conclusions.

First, in Experiment 1, we show that even when participants are not constrained to coarse categorical judgments but are asked to make verbal estimates in degrees, a bias quite similar to that shown by Dick and Hochstein (1989) is present. This bias is argued not to be a numeric bias because it is spatially the same whether verbal estimates are made relative to horizontal or to vertical. This experiment provides an important replication of the patterns of bias reported by Dick and Hochstein. In a second experiment, we rule out verbal/numeric bias altogether by conducting an orientation bisection task to discover what 2D orientation appears to be equidistant from horizontal and vertical. These data show that, if anything, numeric reports have underestimated the vertical bias in 2D orientation perception. Moreover, the effect cannot be
attributed to the vertical–horizontal illusion. Finally, we use an “ABX” categorization task to demonstrate that the perceptual categories of vertical and horizontal are not symmetrically represented. The novel application of this task contrasts with prior tasks that have found little evidence of difference in information transmission between vertical and horizontal for simple oriented stimuli (i.e., Dick & Hochstein).

**Experiment 1: Magnitude estimation of 2D orientation**

Dick and Hochstein (1989) reported that when asked to categorize 2D oriented lines into verbal categories representing 5° increments, participants showed systematic perceptual biases that were independent of whether horizontal or vertical was defined as being 0°. Specifically, they reported a maximum signed error of about 6° that occurred for angles about 30° from horizontal. Such angles appeared steeper than they were. Dick and Hochstein pointed out that such an error could not be explained in terms of a horizontal–vertical illusion because such an illusion should predict a much smaller maximum error and should also predict that the maximum error would be near 45°.

Here, we replicate the main finding of Dick and Hochstein, while removing the requirement that participants use 5° categories. Instead, we had participants provide orientation estimates to the nearest degree. Unlike most magnitude estimation scales, angular units are conceptually predefined within the range of 0° and 90°, and thus, the scaling of angular estimates is unlike the scaling of most linear variables that do not have natural limits at perceptually given categorical boundaries.

**Methods**

**Participants**

Twenty-seven students (16 females) participated for a small payment.

**Stimuli and procedure**

On each trial, a single oriented line (10 arc deg × 10 arcmin) was presented at an orientation of 0°–90° (16 orientations separated by 6° intervals). The gray-on-black anti-aliased lines were viewed binocularly through a reduction tube containing a series of circular black baffles to reduce reflected light and eliminate external reference frames for orientation. Each line remained visible until an oral estimate was provided by the participant and entered by the experimenter.

**Design**

Each participant saw each of the 16 orientations in random order in each of two consecutive blocks of trials. Approximately half the participants of each gender made numeric angle judgments in degrees relative to vertical and half made judgments relative to horizontal. Within each condition, about half the participants saw left diagonal lines and half saw right diagonal lines. The experimenter who entered the responses could not see the stimuli.

**Results and discussion**

The data for each participant were graphically inspected prior to analysis. In two cases, participants consistently made judgments that were based on the wrong reference. These data were treated as belonging to the opposite conditions. There were 11 data points from among all 864 trials (1.2%) that were excluded because they were evident outliers.

Average verbal numeric estimates are plotted in Figure 1A separately for each reference condition. Estimates of the cardinal axes were essentially unbiased, but intermediate orientations showed a spatial bias to appear more vertical than they were. That is, estimates made relative to the vertical axis tended to underestimate the nominal orientation, whereas estimates made relative to horizontal tended to overestimate the nominal orientation. Figure 1B shows the signed error for the two conditions separately, and Figure 1C shows the combined error function when all estimates are recomputed in spatial terms relative to horizontal (i.e., verbal estimates in the from-vertical condition are subtracted from 90). This pattern of overestimation by about 6°, peaking at about 30°, replicates the observations of Dick and Hochstein (1989) when they limited responses to categories of 5° intervals.

If verbal overestimation were due to bias in numeric coding, such as might be introduced by logarithmic numeric representations, we would expect numeric responses to demonstrate the same biases relative to horizontal and vertical. Figure 2A shows a histogram of verbal numeric responses by condition. Responses are only shown for stimuli that were neither vertical nor horizontal and are binned to the nearest 5° verbal category. It can be seen that there is a disproportionate likelihood of estimates from 5° to 15° in the from-vertical condition and a disproportionate likelihood of estimates from 75° to 85° in the from-horizontal condition. These biases both represent an overrepresentation of responses of “nearly vertical.” To make these effects more visually obvious, Figure 2B represents the same response data, recoded into spatial bins (deg from horizontal) with the bin categories spanning 10-degree regions. This shows more clearly that responses belonging to the spatial category “nearly
“vertical” are overrepresented. Inspection of Figure 2A shows that this is a spatial bias rather than a verbal one, as the numeric biases are symmetrical in the two conditions, reflecting an asymmetrical spatial bias. In both conditions, however, it can be seen that estimates near “45°” are overrepresented as well.

These histograms show that although there may be residual verbal biases (such as toward the category of

Figure 1. Verbal numeric estimates (in degrees) of 2D orientated lines in Experiment 1. (A) Average estimates by presented angle, separated by whether estimates were made relative to horizontal or to vertical. (B) The same data plotted as absolute error deviations based on verbal coding. (C) The average signed error data recoded relative to the spatial horizontal (all data combined). Error bars represent standard errors of the means.

Figure 2. Histograms of responses from Experiment 1. (A) Frequency of responses for each condition binned to the nearest 5° category. (B) Plots of response frequencies in spatially defined categories (all coded relative to horizontal) for each 10° bin (labeled by its center value).
“45°” and, perhaps, toward multiples of 10), there are also clear spatial biases that lead to a disproportionate representation of “nearly vertical” responses compared to “nearly horizontal” responses. The overuse of “45°” suggests that the signed error function may actually be slightly distorted by the verbal response. According to the signed error function, the average response for an orientation of 42° from horizontal is 47° from horizontal. However, if angles perceptually near 45° are frequently rounded to 45°, then the signed error for a physical orientation of 42°, for example, would be underestimated by verbal methods. It now seems possible that the numeric discrepancies reported by Fisher (1968) between vertical acute angles and horizontal acute angles may have been partly due to verbal biases (e.g., toward “45°”) that are overlain on the underlying spatial orientation biases and that the magnitude of orientation biases may have been underestimated by verbal studies such as that of Dick and Hochstein (1989).

Finally, we note that the magnitude of the horizontal–vertical illusion necessary to explain a 6° signed error is 25% overestimation of vertical relative to horizontal, but even then the maximum signed error would be expected to be found at 42°, contrary to our observations. Typically, the horizontal–vertical illusion has a magnitude of less than 5% overestimation of the vertical relative to the horizontal (e.g., Prinzmetal & Gettleman, 1993).

**Experiment 2: Equidistance from horizontal and vertical**

The data from Experiment 1 replicate and extend similar findings by Dick and Hochstein (1989) and clearly suggest that most diagonal lines tend to appear steeper than they are, but the magnitude of the error may be slightly higher than our data suggest for two reasons. First, as we have mentioned above, the overuse of the responses near “45°” might tend to distort the signed error for angles perceptually near 45°. Second, the stimulus range used, which represented a uniform sampling of physical angles, may have caused participants to try to balance estimates about 45°. Thus, if 36°, for example, were normally perceived as 45°, then there would have been only 6 stimulus orientations that appeared less than 45° but 9 that appeared greater. Participants may have adjusted their estimates to compensate for this discrepancy. To remove these forms of verbal bias altogether, we next conducted an experiment in which we measured the point of subjective angular equidistance between horizontal and vertical. This allowed us to estimate the true point of perceived angular equidistance (perceived 45°) while minimizing both numeric response bias and range effects.

**Methods**

**Participants**

The participants were 32 students (17 females) fulfilling a course requirement.

**Design and procedures**

The apparatus and stimuli were like those in Experiment 1. In this experiment, however, the participant used a keyboard to indicate whether the presented line on each trial was nearer vertical or nearer horizontal. These responses controlled six interleaved series of trials (staircases). Two of the staircases (one for left diagonals and one for right) started with high orientations (69° from horizontal) and two (also left and right diagonals) started from low orientations (21° from horizontal). The step size for each staircase was 9°. A final pair of staircases, introduced after the first four staircases had progressed for four trials each, started at 45° (one left, one right). As a group, the six staircases were initially unbiased. These six staircases, by each moving 9° per step, could sample all orientations at intervals of 3°. When a participant indicated that an orientation was nearer vertical, the next orientation presented in that series was reduced by 9°. When judged nearer horizontal, it was raised by 9°. A total of 52 trials were collected. A psychometric function was computed by fitting logistic functions separately to left and right diagonal trials (in case of small errors in perceived vertical; Gibson & Radner, 1937). We computed both an angular point of subjective equidistance (PSE) and an angular just noticeable difference (JND, using a 75% threshold) and used the average PSE for each participant as an estimate of their perceived 45° point.

A JND computed from 26 trials is not a precise measure of sensitivity, but a high JND can indicate inattention to the task. We used a criterion of high variability to exclude the data of 2 participants whose average JNDs across left and right diagonals (viz., 9.7° and 20.2°) were more than 4 times the median of the JNDs averaged by participant (2.0°).

**Results**

The mean PSE for the 30 analyzed participants was 36.4° from horizontal (SE = 1.1°). Assuming that the PSE represents the perceptual “45°” point, this represents a signed error of 8.6°, which is reliably greater than the 6° error estimated by Dick and Hochstein (1989) using categorical report that was replicated in our Experiment 1 using numerical estimation, t(29) = 2.41, p = 0.0227. Note that this difference is consistent with our concern that a cognitive (verbal) bias to overuse the category “45°” in Experiment 1 would have led to an underestimation of the true spatial bias. Figure 3 shows a line...
that is 37° from horizontal. On average, our participants judged such a line to be about equidistant between the two main categories of vertical and horizontal.

**Experiment 3: Asymmetries between horizontal and vertical categories**

The bias for oriented lines to appear to deviate farther from horizontal than they do and also to appear more vertical than they are suggests that the categories of horizontal and vertical are not symmetrical. Dick and Hochstein (1989) measured information transmission around vertical and horizontal and found no differences. In Experiment 3, we tested for an asymmetry using an “ABX” categorization task (Gerrits & Schouten, 2004; Liberman, Harris, Hoffman, & Griffith, 1957). In such a task, three stimuli are presented in succession and the observer must indicate whether the third stimulus (“X”) is identical to the first (“A”) or the second (“B”). The task, which entails maintaining distinct representations of A and B in memory, is thought to be easier when A and B differ categorically in memory. It is not a measure of perceptual discrimination but of categorical discrimination (Gerrits & Schouten, 2004).

**Methods**

**Participants**

The participants were 10 students (gender not recorded) who were paid to participate.

**Apparatus and stimuli**

The stimuli were circular gratings of medium contrast briefly presented within a black circular aperture that covered the frame of a flat-screen cathode ray tube monitor. Gratings were used rather than lines to avoid the use of positional cues. The orientation stimuli were preceded and followed by a blank interval and a masking stimulus of high-contrast visual noise (i.e., non-oriented

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Table 1. Sequence (ms) of visual events for a single ABX trial.
random black and white noise patterns). The entire sequence of visual events for a single trial and their timings in milliseconds (total of 5500 ms) is depicted in Table 1. The gratings had a spatial frequency of 1.6 cpd and subtended approximately 10° of viewing angle at the viewing distance of 57 cm. The orientation stimuli included all orientations in increments of 10°. A and B were always 10° apart.

**Design**

Each participant completed 2 blocks of 72 trials of the ABX task following an initial practice block of 20 randomly selected trials. The full 72 trials represented the combination of 18 different orientations (0°–170° by 10° increments; N.B. visually, 30° is equivalent to 210°, for example, so the range of orientations included all 360°), paired with each of the two adjacent orientations and with the final stimulus being equally likely to be the first or second of the pair (18 × 2 × 2 = 72). Each block of 72 trials was fully randomized. Feedback (a beep if correct; silence if incorrect) accompanied all trials. This was done to motivate participants to perform at their best. The data were collapsed across left and right diagonals, so that performance of each participant on a total 16 trials per interval was averaged for each of the nine 10° intervals from horizontal to vertical.

**Results and discussion**

The mean proportion correct for each pair of orientations are plotted in Figure 4. The paired orientations are represented by their mean orientation, so that “5” refers to any ABX trial in which one of the initial orientations was horizontal and the other 10° from horizontal. Similarly, “85” refers to an ABX trial where one of the initial orientations was vertical and the other 10° from vertical. If the categories of vertical and horizontal were equivalent, then ABX performance for “5” and “85” should be equivalent. Based on the exaggeration of deviations from horizontal however, we should expect that ABX performance would be better for “5” than for “85.” Consistent with this expectation, mean performance for pairs that included a horizontal orientation (87.3%) was reliably better than that for pairs including vertical (79.9%), t(9) = 3.33, p = 0.0087.

The oblique effect (Appelle, 1972; Essock, 1980) is generally described as the precedence of cardinal orientations over oblique orientations. Essock distinguished between class 1 (roughly “sensory”) and class 2 (roughly “encoding”) oblique effects, but both are characterized as better representing cardinal than oblique orientations. This pattern is well known, and it is present in our ABX data as well. More importantly, however, our data indicate that there is an asymmetry between the categories of vertical and horizontal both in explicit measures of perceived orientation (Experiments 1 and 2) and in categorical discrimination (Experiment 3). This categorical difference between the two cardinal axes may help account for the asymmetrical distortions found by Dick and Hochstein and replicated and extended in Experiments 1 and 2. That is, all three experiments can be understood as reflecting greater categorical sensitivity to deviations from horizontal.

This difference between vertical and horizontal contrasts with the traditional class 1 and class 2 oblique effects (Essock, 1980). Essock, Krebs, and Prather (1997) have described the results of Dick and Hochstein (1989) as typical of class 2 oblique effects, but we emphasize that Dick and Hochstein found no difference between horizontal and vertical orientations in information transmission (though greater transmission for both cardinal orientations than for oblique lines). Similarly, some studies of environmental image statistics intended to explain oblique effects have emphasized the relative paucity of oblique lines, without reporting differences between vertical and horizontal (e.g., Coppola, Purves, McCoy, & Purves, 1998; but see Hansen & Essock, 2004). Essock et al. specifically identify “memory confusability” (p. 524) as indicative of a class 2 effect. However, the current ABX task, which measures confusability in memory, demonstrates a striking anisotropy between vertical and horizontal, which is consistent with the non-verbal spatial biases we measured in Experiment 2. Thus, this experiment provides additional support, in a non-verbal task, for the conclusion that the visual coding of vertical and horizontal orientations is not symmetrical.

**General discussion**

In Experiment 1, we replicated a pattern of spatial bias in 2D orientation perception first observed by Fisher.
Perceived slant also appears to be midway between vertical and horizontal (a discrepancy of 8.6°). Thus, if people match a 36.4° oriented line appears about midway between horizontal and vertical. A 36.4° line may appear as if it is equidistant between vertical and horizontal, even while oblique orientations are substantially less than 45°. This means that the spatial bias in the perceived slant of 2D lines and 3D surfaces (within reach) is fairly similar for orientations of about 35°. This could lead to the mistaken inference that the perceived orientation of a 34° 3D slant was quite accurate if the response were made by adjusting a (similarly misperceived) 2D line. The predicted match, according to our results, would be to a 36.4° 2D line. A researcher using such a measure might conclude that there was only a 2.4° error in 3D orientation perception, when the perceptual error was actually 11°. Related problems may arise for other non-verbal measures (Durgin, Hajnal, Li, Tonge, & Stigliani, 2010a, 2010b; Durgin, Li et al., 2010; Li & Durgin, 2011). Whereas verbal methods are often regarded as being unreliable measures of perception because they are subject to judgmental bias (e.g., Durgin et al., 2009), the present investigations support the conclusion that the careful use of verbal methods in studies of perceived orientation may provide a fairly stable and accurate picture of perceptual biases that might be masked by other methods.

There are important differences between the current 2D bias function (e.g., Figure 1C) and the recently observed bias function for 3D slant (Durgin, Li et al., 2010). The 3D bias function is of similar magnitude to the 2D bias function for angles near horizontal but shows even greater bias toward vertical for steeper surfaces, with a maximum signed error (15°) at about 60° from horizontal. Moreover, whereas the present data show a very marked bias to report 2D oriented lines as being “45°” (even if those orientations are substantially less than 45° from horizontal), the data from studies of perceived bias in 3D surface orientation do not show a marked bias toward 45° (Durgin, Li et al., 2010). This suggests that “diagonal” or “45°” may be a more salient category anchor for verbal estimation in the 2D case than in the 3D case, even while oblique orientations are misperceived in both cases. Note that the absence of evidence for a central (45°) category in Experiment 3 may simply signal that the category of “diagonal” is less precisely defined than the categories of vertical and horizontal.

Engebretson and Huttenlocher (1996) have proposed that the central category (e.g., diagonal) produces a categorical bias in memory for orientation, whereas Simmering, Spencer, and Schöner (2006) have suggested a model based on attraction and repulsion with respect to cardinal orientations to account for similar data. Durgin, Li et al. (2010) have suggested that perceptual matching tasks can show repulsion effects as a consequence of...
cognitive response biases present in analog measures when participants intend to signal that the target stimulus is near, but not at, a category. McIntyre and Lipshits (2008) found evidence of repulsion between 22.5° and 45° in a perceptual matching study, which may reflect response bias away from the subjective 45° point we measured here (i.e., 36.4° from horizontal). Visual search tasks have suggested that the categories of “steep” and “shallow” are perceptually distinct (Wolfe, Friedman-Hill, Stewart, & O’Connell, 1992), and this also suggests that subjective 45° forms a rough category boundary.

Findings of an asymmetry between horizontal and vertical have not typically been reported in studies measuring simple visual orientation discrimination, but complex images have been reported to show an asymmetry dubbed the horizontal effect in which the horizontal is actually disadvantaged (Essock, DeFord, Hansen, & Sinai, 2003; Hansen & Essock, 2004). Essock et al. suggest that the visual system “whitens” orientation information by suppressing the overrepresented horizontal. Evidence from natural scene statistics suggest that there may be a preponderance of vertical lines in carpentered environments (e.g., Switkes, Mayer, & Sloan, 1978) but a preponderance of horizontal in non-carpentered scenes and overall (e.g., Girschick, Landy, & Simoncelli, in press; see also Baddeley & Hancock, 1991; Hansen & Essock, 2004; Keil & Cristóbal, 2000; van der Schaaf & van Hateren, 1996).

Girschick et al. (in press) studied discrimination of mean orientation between patterns composed of oriented Gabors and concluded that the human prior for orientation is stronger for horizontal than vertical, consistent with the anisotropy in our data for Experiment 3. They propose that the origin of this anisotropy is in the adaptation of the cortical coding of orientation to natural scene statistics (see also Essock et al., 2003). While a cortical coding hypothesis is compatible with our results, it is worth noting that psychophysical studies showing anisotropies between horizontal and vertical have employed complex noise stimuli (Essock et al., 2003) or multielement patterns that seem to require integrative processing (Girschick et al., in press). In contrast, Dick and Hochstein (1989) found no evidence of such a horizontal–vertical anisotropy when analyzing channel capacity for simple oriented lines. This may mean that a component of the horizontal–vertical anisotropy is due to higher level integrative coding. On the other hand, greater cortical sensitivity near horizontal might be able to account for coding biases found in Experiments 1 and 2 on the assumption that the biases observed there can be described as perceptual repulsion from horizontal (Essock et al.) or as perceptual scale expansion about horizontal (Durgin & Li, 2011).

The categories of “vertical” and “horizontal” are clearly special in 2D orientation perception, as they are in 3D orientation perception (Durgin, Li et al., 2010). However, these two categories are not found to be visually symmetrical in either case. In the 2D case, as in the 3D case, there is a bias to see orientations as farther from horizontal (and thus closer to vertical) than they are. In the 2D case studied here, this effect is most pronounced in the shallower part of the range. Our findings are consistent with the idea that statistical regularities in images favor shallow slants (Girschick et al., in press; Hansen & Essock, 2004; Howe & Purves, 2005) and also with the idea that distorted perceptual scaling may be functional for the control of action with respect to the ground plane (Durgin, Hajnal et al., 2010a; Durgin & Li, 2011).

Differences in the coding of these cardinal orientations may also reflect the geometrical asymmetry, however, that in the 3D environment, “vertical” is a vector orientation (all vertical vectors are parallel, while vertical planes need not be parallel), whereas “horizontal” refers to a planar orientation (all horizontal planes are parallel, but horizontal lines need not be). That is, the spatial concepts of vertical and horizontal are complementarily defined but are not symmetric in 3D space. Of course, in the 2D case, vertical and horizontal are, in principle, symmetric categories divided by the 45° diagonals. It is therefore noteworthy that the verbal bias toward “45°” is more pronounced in the 2D case than in the 3D case (Durgin, Li et al., 2010). In both the 2D and 3D cases, however, deviations from horizontal, near horizontal, appear to be perceptually exaggerated in similar ways.

Acknowledgments

This research was supported by Award Number R15EY021026-01 from the National Eye Institute. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Eye Institute or the National Institutes of Health. This work was also supported by the Hans Wallach Fellowship Funds and by a Swarthmore College Faculty Research Grant. Anthony Stigliani and Natasha Tonge helped conduct Experiment 1. Caroline Pietsch conducted Experiment 3. We thank Daniel Grodner for suggestions regarding Experiment 3.

Commercial relationships: none.
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