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Reference frame for rapid visual processing of line orientation

LAURA M. DOHERTY [1,*] and DAVID H. FOSTER [2]

[1] *Colour and Imaging Institute, University of Derby, Kingsway House East, Kingsway, Derby DE22 3HL, UK*
[2] *Visual and Computational Neuroscience Group, Department of Optometry and Neuroscience, University of Manchester Institute of Science and Technology, Manchester M60 1QD, UK*

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Abstract—Detection of a uniquely oriented line element in a background field of uniformly oriented line elements depends on the orientation of the background field. Is the orientational reference frame for this anisotropy entirely dependent on the orientations of structures outside the line-element display, the spatial regularity of the stimulus elements, and the direction of gravity? The effects of these potential cues were investigated in target-detection experiments with brief displays. The anisotropy was found whether or not gravitational or visual cues defined an orientational reference frame. Stimulus orientation may be coded with respect to the retina or body axis in rapid visual processing.

Keywords: Orientation and texture vision; visual search; vestibular; visual context.

1. INTRODUCTION

Observers can detect a uniquely oriented line element (‘target') among uniformly oriented line elements (‘non-targets') even when viewing duration is very brief. For a given angle between target and non-targets, detection performance depends on the orientation of the non-targets (Treisman and Gormican, 1988; Foster and Ward, 1991; Marendaz *et al.*, 1991; Foster and Westland, 1995); that is, it is *anisotropic* with respect to orientation.[1] This anisotropy may be affected by the orientations of structures around the line-element display (Treisman and Gormican, 1988), by spatial regularities in the arrangement of the elements (Meigen *et al.*, 1994), and by nonvisual cues associated with the direction of gravity (Marendaz *et al.*, 1993). Is this anisotropy entirely dependent on these external factors, or do observers have an

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*E-mail: lmd@lmdoherty.org

internal orientation-coding system that is sufficient to define the reference frame for the anisotropy?

The effect of the orientations of structures visible around the stimulus display (the *visual context)* has been described by Treisman and Gormican (1988). They found that introducing a tilted frame (rather than a vertical or horizontal one) around the display modified the anisotropy. The anisotropy may also be affected by spatial regularities in the display such as those introduced by placing the line elements at the vertices of an imaginary square matrix rather than at random positions (Meigen *et al.*, 1994). When vertical or horizontal elements are placed at adjacent vertices in a square matrix, they provide a stronger collinearity cue than oblique elements (at 45° to the vertical), as the spacing of adjacent collinear elements that are horizontal or vertical is smaller (by a factor of $\sqrt{2}$) than the spacing of adjacent collinear elements that are oblique. Placing elements at matrix vertices could therefore influence target-detection performance, which is known generally to be better with collinear non-targets than with non-collinear non-targets (Meigen *et al.*, 1994).

Non-visual cues associated with the direction of gravity have also been found to affect detection performance (Marendaz *et al.*, 1993). Alternatively, the orientational reference frame might be determined by *egocentric* cues, such as the orientation of the retina or body axis.

The first experiment in the present study concerned the effect of context and spatial regularity on the anisotropy, and the second and third experiments concerned the effect of gravitational cues. The anisotropy was found even when there were no cues from spatial regularity or gravity defining the vertical and horizontal and no explicit visual cues from visible vertical or horizontal edges. Although, in some circumstances, these cues may modulate the anisotropy, in their absence it seems that coding of orientation with respect to the retina or body axis is sufficient to define a reference frame for an anisotropy.

2. EXPERIMENT 1: VISUAL CONTEXT AND SPATIAL REGULARITY

2.1. Purpose

In a previous target-detection experiment in which the anisotropy was found (Foster and Ward, 1991), a horizontal rectangular aperture limited the observers' view of the background field, and line-element positions, although chosen randomly, were constrained to fall near the vertices of an imaginary square matrix. As indicated earlier, because visual context (Treisman and Gormican, 1988) and array regularity (Meigen *et al.*, 1994) may have influenced detection performance, it was important to verify that the anisotropy was not produced solely by these factors.

2.2. Methods

2.2.1. Apparatus. Stimuli were presented on a cathode-ray tube (Hewlett–Packard, Type 1321A with white P4 sulfide phosphor with decay time less than

1 ms) controlled by a true-line vector-graphics generator (Sigma Electronic Systems, QVEC 2150) and additional digital-to-analogue converters, in turn controlled by a laboratory computer. The display was refreshed at intervals of 20 ms. (This temporal structure was not visually detectable.) This system produced very-high-resolution line-element displays: orientation accuracy was differentially better than 0.2° and absolutely better than 0.5°. The intensity of the elements did not vary with their orientation.

Observers sat on an adjustable chair and viewed the screen through a view-tunnel with a semi-reflecting plate and light box that provided a background luminance of about 35 $\mathrm{cd\,m^{-2}}$. Head position was stabilized with a chinrest and headrest. At the beginning of each experimental session, stimulus luminance was set to about 1 log unit above the observer's luminance-contrast detection threshold.

2.2.2. Stimuli. Stimulus displays comprised 20 line elements of length 1° visual angle and width 0.1° visual angle. Element centres could be no closer than 2° visual angle, so that the elements could not intersect.

There were two types of stimulus display, which defined two experimental conditions. In the MATRIX-RECTANGULAR condition, elements were placed exactly at randomly selected vertices of an imaginary square matrix with vertical and horizontal edges. The length of each side of the matrix was 20°, and vertices were spaced 1° apart, horizontally and vertically. Thus there were 20 vertices on each edge of the matrix and there were 400 vertices in total (see Fig. 1a). Displays were viewed through a horizontal rectangular aperture that subtended about 94° horizontally and about 41° vertically. In this condition, cues defining the horizontal and vertical could in principle have been provided by both context and regularity. In the RANDOM-CIRCULAR condition, elements were placed at random positions in a circular field of diameter 20° (see Fig. 1b) and were viewed through two circular apertures subtending 33° each, one for each eye (viewing through these apertures, observers saw the line-element displays within a circle that had blurred edges). In this last condition, vertical and horizontal orientations were defined neither by the placement of the elements nor by any contextual cues that accompanied the stimulus display on each trial.

In all conditions, a masking display was generated by placing a cluster of four randomly oriented elements at the location of each element in the stimulus display.

2.2.3. Procedure. At the beginning of each trial, a small fixation cross (comprising line elements at 45° to the vertical) appeared at the centre of the CRT screen. To initiate stimulus presentation, the observer pressed a button on a pushbutton switch-box held in the non-dominant hand. After a 40-ms interval, the stimulus display appeared for 40 ms. There followed a 60-ms inter-stimulus interval (ISI) during which the screen was blank. The masking display then appeared for 500 ms. The observer indicated whether a target was present in the stimulus display by pressing one of two buttons on a pushbutton switch-box held in the dominant hand.

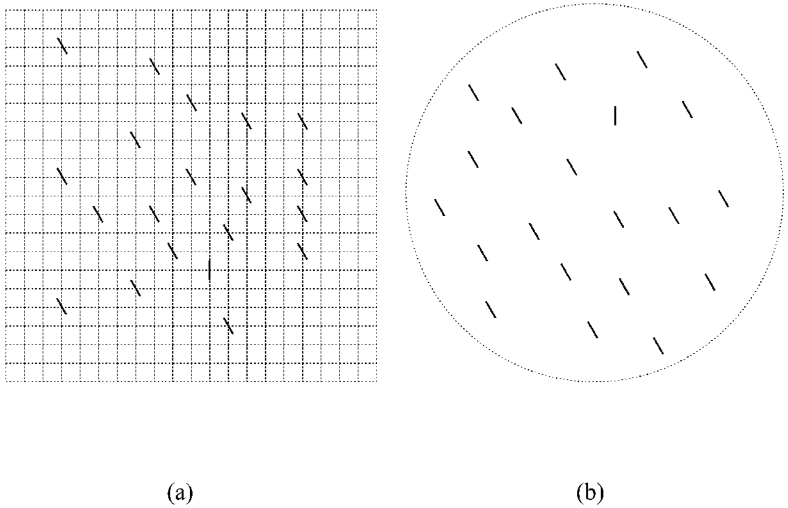

Figure 1. Stimulus displays for (a) the MATRIX-RECTANGULAR condition and (b) the RANDOM-CIRCULAR condition. In (a) the solid lines show, in reverse contrast, the line elements, which had length 1° visual angle. Each element was centred on a randomly chosen vertex of a square matrix, subject to the constraint that the minimum distance between element centres was 2°. The matrix, shown here by dotted lines, was not visible to the observer. Its sides were of length 20° and its vertices were spaced 1° apart horizontally and vertically. In (b) the solid lines show the line elements, which had length 1°. Line elements were placed randomly within a circle of diameter 20°, subject to the constraint that the minimum distance between their centres was 2°. The circle, shown here by a dotted line, was not visible to the observer.

2.2.4. Design. In each trial, the non-target orientation was randomly selected from the range 0°, 5°, ..., 175° to the vertical; the difference between non-target and target orientations was randomly selected from the range 10°, 20°, 30°, 40°. The probability of a target being present was 0.5. When there was no target, an extra non-target element was included in the display.

Each experimental session involved only one condition defined by spatial regularity and visual context (MATRIX-RECTANGULAR or RANDOM-CIRCULAR). The order of these conditions was randomized. Each observer completed 20 sessions of about 600 trials each, 10 for each condition.

2.2.5. Observers. Two observers participated in this experiment. They had corrected-to-normal visual acuity (Snellen acuity 6/6 or better) and astigmatism of not more than 0.25 D. One observer (the first author) had participated in similar experiments. The other, who had not and was unaware of the purpose of the experiment, completed several practice sessions on the task before beginning the experiment proper.

2.2.6. Analysis. For a given non-target orientation, the discrimination index d' from signal-detection theory (Green and Swets, 1966) was calculated for each increment between target and non-target orientations, and the resulting graph of *d′ versus* orientation increment was fitted with a linear function. (This function was constrained so that values of *d′* greater than zero could occur only with orientation increments greater than zero.) The threshold was taken to be the orientation increment for which the fitted function gave a value of 0.5 for *d′*. The standard deviation of this threshold was estimated with a bootstrap procedure (Foster and Bischof, 1997). In this way, orientation increment threshold and its standard deviation were obtained as a function of non-target orientation.

To test for periodicities in this orientation increment-threshold function, a statistical filtering procedure was applied. This procedure was based on repeated loess (Cleveland, 1993, Section 3.11; Foster and Westland, 1998, Appendix A). Repeated loess is a non-parametric method of decomposing a dataset into several components by progressive smoothing and differencing. For the present purposes, only the coarsest (most slowly varying) component was extracted.

2.3. Results

The variation of orientation increment threshold with non-target orientation is shown in Fig. 2 (open circles), with the coarsest component from the repeated-loess decomposition superimposed (solid line). A marked anisotropy is evident in both conditions, and is as strong in the RANDOM-CIRCULAR condition as in the MATRIX-RECTANGULAR condition.[2]

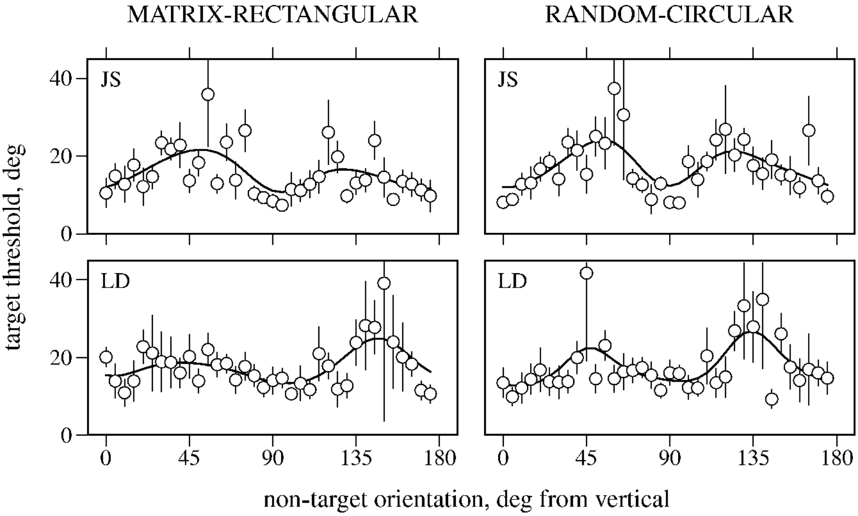

Figure 2. Variation of orientation increment threshold with non-target orientation for two experimental conditions: MATRIX-RECTANGULAR and RANDOM-CIRCULAR. Thresholds are shown by open circles and the coarsest component found by repeated loess is shown by the solid line. Vertical bars show ±1 SD. Data for two observers, JS and LD.

2.4. Comment

An anisotropy in line-target detection was found even when the aperture edges and element positions provided no explicit visual reference for the horizontal and the vertical (*cf.* Treisman and Gormican, 1988; Meigen *et al.*, 1994). Therefore, it seems likely that the anisotropy reflects a fundamental characteristic of early orientation processing rather than a bias introduced by visual cues. It remains unclear, however, whether the anisotropy in the RANDOM-CIRCULAR condition was defined by egocentric or gravitational cues. The following experiment was undertaken to determine how detection performance depends on gravitational information.

3. EXPERIMENT 2: EFFECT OF OBSERVER POSTURE: TARGET DETECTION WITH BRIEF DISPLAYS

3.1. Purpose

The anisotropy in visual search performance has been reported by Marendaz *et al.* (1993) as depending on gravitational cues. In that study, observers performed a search task while standing or supine (lying horizontally, looking upwards at the display), the number of elements in the search display (the *set size*) was varied, and response times were recorded. If response time was unaffected by changes in set size, it was inferred that the search process was spatially parallel. If response time increased with set size, it was inferred that the search process was spatially serial, indicating that the task could not be performed using parallel processes alone. (These inferences were based on hypotheses presented by Treisman and Gelade, 1980.)

With observers standing, the expected anisotropy was found (Marendaz *et al.*, 1993): search seemed parallel with tilted targets (at 18° to the vertical or horizontal) among vertical or horizontal non-targets, and serial with vertical or horizontal targets among tilted non-targets; with observers supine, no anisotropy was found: all searches seemed parallel. Thus it seemed that the characteristics of orientation-processing mechanisms underlying search asymmetry were determined dynamically according to the observer's perception of gravity (see reviews by Marendaz, 1998, and Leone, 1998).

As the range of target and non-target orientations in the aforementioned experiments was limited, the present experiment was undertaken to determine in detail the effect of observer posture on detection of oriented line targets.

3.2. Methods

3.2.1. Stimuli. Stimulus displays were the same as in the RANDOM-CIRCULAR condition of the previous experiment.

3.2.2. Apparatus. The apparatus was as in the previous experiment, except that a different CRT was used (Type 1317A with green P31 phosphor and decay time less than 1 ms; the choice of phosphor colour, green or white, had previously been found not to affect detection performance; Westland and Foster, unpublished data). For sessions in which the observers were supine (lying horizontally and looking upwards), a mirror was placed in front of the CRT at 45° to the vertical.

3.2.3. Procedure. The procedure was as in the previous experiment except that, for each observer, the ISI was set at 60, 120, or 180 ms, whichever gave a mean value of d' of about 0.5.

3.2.4. Design. The non-target orientation for each trial was randomly selected from the range 0°, 5°, . . . , 175° to the vertical. The probability of the target being present was 0.5. When there was no target, an extra non-target element was included in the display. The orientation increment between target and non-target orientations was varied between 2.5° and 40° according to the adaptive procedure PEST (Taylor and Creelman, 1967). (A separate PEST procedure was used for each non-target orientation.) The PEST procedure was generally set to converge to 66% correct: for an unbiased observer, this percentage is equivalent to a value of 0.5 for the discrimination index d'. Occasionally, the convergence value was adjusted by a few percent for a small number of sessions: this adjustment increased the range of performance levels and allowed better fitting of the psychometric function.

Each observer took part in 12 sessions seated and 12 sessions supine, where each session comprised about 600 trials.

3.2.5. Observers. There were five observers. They had corrected-to-normal visual acuity (Snellen acuity 6/6 or better) and astigmatism of not more than 0.25 D. Only one observer, the first author, had participated in similar experiments; the other four had not and were unaware of the purpose of the experiment. These four observers completed four practice sessions on the task (sitting upright) before beginning the experiment proper.

3.2.6. Analysis. The analysis was based on repeated loess as in the previous experiment.

3.3. Results

For all observers, orientation increment threshold averaged over all non-target orientations was affected little or not at all by posture. The variation of orientation increment threshold with non-target orientation is shown in Fig. 3 (open circles) with the coarsest component from the repeated-loess decomposition superimposed (solid line). This variation was also affected little by posture. The persistence of an anisotropy in the absence of gravitational cues is evident.

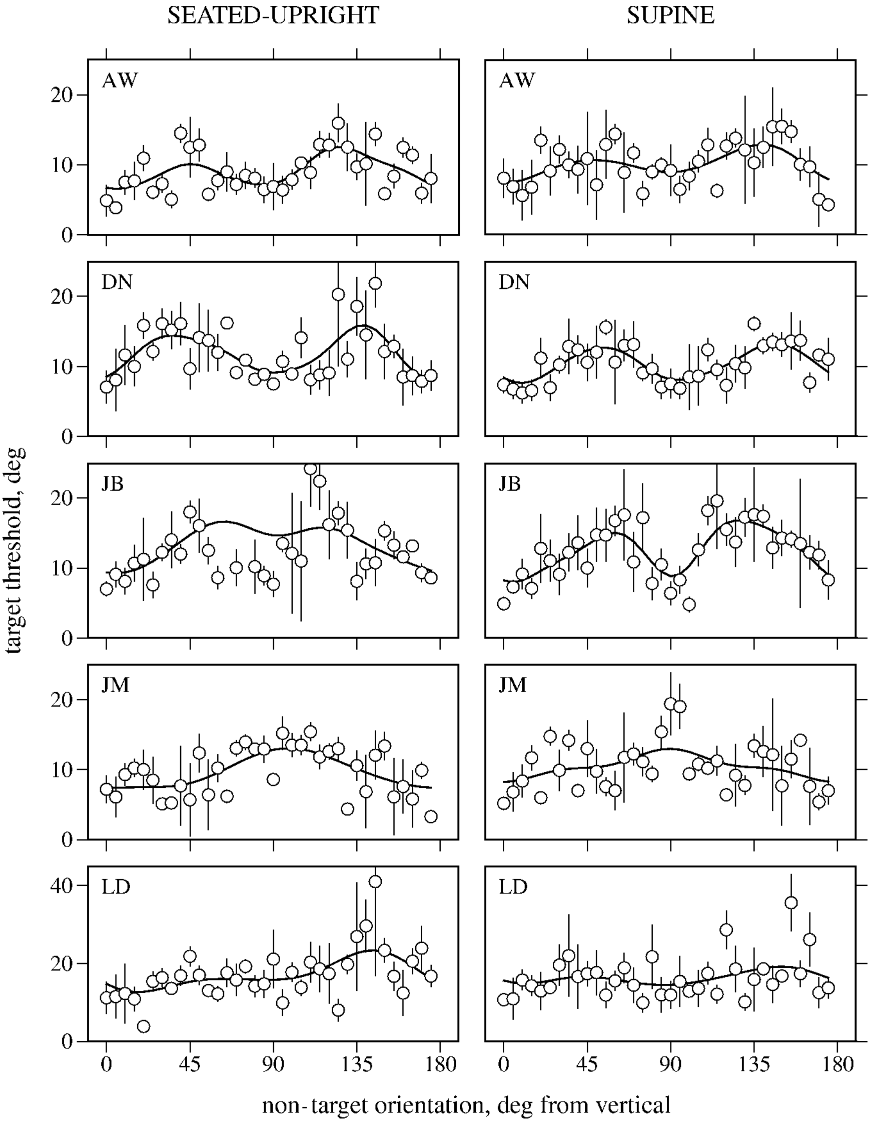

Figure 3. Variation of orientation increment threshold with non-target orientation for two experimental conditions: SEATED-UPRIGHT and SUPINE. Thresholds are shown by open circles and the coarsest component found by repeated loess is shown by the solid line. Vertical bars show ±1 SD. Data for 5 observers, AW, DN, JB, JM, and LD (notice the different ordinate for LD).

For three observers (AW, DN, and LD), evidence of a periodicity with period about 90° was provided by the coarsest component in the decomposition, and this periodicity seemed equally strong in both postural conditions. For observer JB, the evidence for a 90° periodicity provided by the coarsest component was greater in the supine than in the seated-upright condition. For observer JM, there was little evidence of a 90° periodicity in either condition.

These observations based on the repeated-loess decomposition were supported by consideration of the Fourier amplitude spectrum of the variation in orientation increment threshold with non-target orientation. For the datasets for which the repeated-loess analysis showed a 90° periodicity, there was a peak in the Fourier amplitude spectrum corresponding to that periodicity. (The significance of these peaks, determined by a comparison of the 90° and 60° Fourier component amplitudes in conjunction with their bootstrap standard deviations, was slightly greater for datasets with observers supine than for datasets with observers seated.)

3.4. Comment

An anisotropy was found both with observers supine and seated upright. The data seem inconsistent with the earlier finding by Marendaz *et al.* (1993) that anisotropy is absent when observers are supine. The next experiment was undertaken to examine two possible explanations of this inconsistency.

4. EXPERIMENT 3: EFFECT OF OBSERVER POSTURE: RESPONSE TIMES

4.1. Purpose

The difference between the results of Experiment 2 and the work of Marendaz *et al.* (1993) might be explained if, between trials, observers in the present study extracted a cue defining the vertical or the horizontal from some part of the apparatus (such as the horizontally aligned circular apertures for the two eyes or the inter-trial fixation cross, which contained lines at 45° to the vertical). Alternatively, the difference in findings might have arisen because, in the visual search task of Marendaz *et al.* (1993), response time was the performance measure and displays were shown until the observer responded, whereas in the present study orientation-increment threshold was the performance measure and displays were presented for a fixed, brief interval. Studies of postural effects on ‘attentive' orientation processing have similarly yielded conflicting results, which have sometimes been attributed to small changes in paradigm (e.g. Chen and Levi, 1996).

The hypothesis that response times might show some effect of gravitational cues, along with the notion that observers might extract orientation cues between trials, was tested in the present experiment.

4.2. Methods

4.2.1. Apparatus. The apparatus was the same as in Experiment 2, except that, in a new SUPINE-IN-DARKNESS condition, the mirror that reflected images from the CRT was viewed through a single black cylinder so that there were no visual cues, explicit or implicit, that could define an orientational reference frame during or between trials. (In the other conditions, the view-tunnel provided a light background field as in the two previous experiments.)

4.2.2. Stimuli. The dimensions of the stimuli were as in Experiment 2. The fixation cross was replaced by a fixation spot of diameter approximately 0.1°.

4.2.3. Procedure. The procedure was as in Experiments 1 and 2, except that there was no mask, and, as their response times were to be measured, observers were required to respond as quickly as was consistent with accuracy.

4.2.4. Design. There were three viewing conditions. The SEATED-UPRIGHT and SUPINE conditions were the same as in Experiment 2, and, as indicated earlier, the SUPINE-IN-DARKNESS condition was added as a further control. The displays used were the same in all these posture conditions, but the range of orientations tested was smaller than in the previous experiments, and the target and non-target orientations were randomly selected from the range 0°, 45°, 90°, 135° to the vertical. (These orientations were chosen as they had previously been found to give rise to anisotropy in the present paradigm, although see Sagi and Julesz, 1987.) The probability of a target being present was 0.5. When there was no target, an extra non-target element was included in the display.

Each observer took part in four sessions for each viewing condition; each session comprised 600 trials.

4.2.5. Observers. There were three observers. They had corrected-to-normal visual acuity (Snellen acuity 6/6 or better) and astigmatism of not more than 0.25 D. One observer was the first author. The others had previously participated in experiments on line-target detection with brief displays but were unaware of the purpose of the experiment.

4.2.6. Analysis. The mean time required for a correct response was calculated for each observer for each posture condition and orientation configuration. Response times differing from the mean by more than three standard deviations were excluded from the analysis (the proportion of response times excluded was less than 6%, 12%, and 9%, for observers RW, MB, and LD, respectively). The significance of the variation in response time with orientation configuration was assessed with a planned comparison. (One-tailed tests were used, as the asymmetry, if it occurred, had an expected direction.) There was no evidence of a speed–accuracy trade-off: in all conditions, the proportion of correct responses was 97% or greater for observer RW, 93% or greater for observer MB, and 90% or greater for observer LD; and the conditions in which percentage scores were lowest were also those in which responses were slowest.

4.3. Results

A systematic anisotropy was evident in the response-time data. For all observers in all posture conditions, the average response time with horizontal non-targets and an

Table 1.
Response times in ms (mean ± 1 SEM) for observers seated upright, supine, and supine in darkness. The p-values show the significance of orientation configuration in a (one-tailed) test by planned comparison

	Vertical non-targets, oblique target	Oblique non-targets, vertical target	Horizontal non-targets, oblique target	Oblique non-targets, horizontal target
Observer RW				
SEATED UPRIGHT ($p < 0.001$)	438.0 ± 1.9	452.7 ± 2.2	447.8 ± 2.1	451.9 ± 2.1
SUPINE ($p < 0.001$)	419.9 ± 1.5	437.4 ± 2.3	424.0 ± 1.8	435.9 ± 2.0
SUPINE IN DARKNESS ($p < 0.001$)	485.8 ± 2.0	506.3 ± 2.8	490.5 ± 2.2	505.4 ± 2.3
Observer MB				
SEATED UPRIGHT ($p < 0.05$)	545.4 ± 4.8	543.6 ± 4.6	533.1 ± 4.4	555.6 ± 5.3
SUPINE ($p < 0.005$)	605.2 ± 5.5	624.9 ± 6.1	607.8 ± 5.4	620.6 ± 6.2
SUPINE IN DARKNESS ($p < 0.001$)	638.1 ± 6.1	652.6 ± 6.6	632.5 ± 6.4	661.2 ± 7.4
Observer LD				
SEATED UPRIGHT ($p < 0.05$)	402.1 ± 2.2	404.7 ± 2.2	397.6 ± 2.0	402.5 ± 2.1
SUPINE ($p < 0.05$)	393.1 ± 2.1	397.1 ± 2.3	395.0 ± 2.2	400.5 ± 2.2
SUPINE IN DARKNESS ($p < 0.01$)	428.8 ± 2.5	435.5 ± 2.6	427.0 ± 2.5	432.9 ± 2.6

oblique target was lower than that with oblique non-targets and a horizontal target (see Table 1). For all observers in all posture conditions, except MB in the SEATED-UPRIGHT condition, the average response time with vertical non-targets and an oblique target was lower than that with oblique non-targets and a vertical target. There was no evidence of a decrease in anisotropy when observers were supine, even when they were in darkness. In all posture conditions, there was a significant effect of orientation configuration for all observers ($p < 0.001$ for RW; $p < 0.05$ for MB and LD). On average, response times were greater when observers were supine than when they were seated, and greater when observers were in darkness than when the view-tunnel provided a light background field.

4.4. Comment

With unmasked displays and with response time as the performance measure, the anisotropy was as great when observers were supine as when they were seated upright. It seems that the persistence of an anisotropy when observers are supine is not attributable to the limited viewing time used in Experiment 2 or to observers' use of implicit visual cues for orientation. There are, however, several other possible explanations of the different results from this and the study by Marendaz *et al.* (1993). First, individual differences in response times might have biased some previous results: in the study by Marendaz *et al.* (1993), different observers were assigned to upright and supine conditions, and response times were averaged across observers and within each condition. Second, the present study was based on many more trials than in the study by Marendaz *et al.* (1993) and it may therefore have been more sensitive to small, systematic variations in detection performance. It might be contended that using a large number of trials produced an anisotropy in the SUPINE and SUPINE-IN-DARKNESS conditions because of a progressive change in attentive processing. But no evidence of such a phenomenon was found: when data from the first half of the experiment and the second half of the experiment were analysed separately, the anisotropy in the SUPINE and SUPINE-IN-DARKNESS conditions (assessed by planned comparison) was generally slightly greater for the first half than for the second half of the experiment. Third, the measure of anisotropy in the study by Marendaz *et al.* (1993) was not reaction time itself (as in the present study) but the variation in response time with set size. It is possible that these two measures are affected differently by the removal of non-visual cues defining a reference frame for orientation. Finally, it is possible that the weakening of the visual reference frame for orientation becomes evident only when a reaction-time paradigm is combined with a more difficult orientation judgement than that used in the present study: in the study by Marendaz *et al.* (1993), the increment between non-target and target orientations was 18°, whereas in the present study it was 45°. This last explanation is considered in more detail in the following section.

4.5. Effect of increased task difficulty

A supplementary experiment was carried out in order to determine whether the persistence of the anisotropy in the absence of gravitational cues was specific to the stimuli used in the response-time experiment. The experimental methods were the same as those described in Section 4.2, except that the SUPINE condition was omitted, the increment between non-target and target orientations was always 18°, the elements had length 0.5°, and there were 10 elements in the display. Because of the reduction in orientation increment and element length, this task was more difficult than that used in the original response-time experiment (Section 4.2).

The proportions of correct responses were often less than 90%, so both these proportions and the reaction times were tested for anisotropies. Table 2 shows the percent-correct scores and reaction times. (For the percent-correct scores,

Table 2.
Percentage of correct responses, and response times in ms (mean ± 1 SEM) for observers seated upright and supine in darkness. The increment between non-target and target orientations was 18°, there were 10 elements in the display, and the element length was 0.5° visual angle. The p-values for percent-correct scores are for a chi-squared test with one degree of freedom: the first of these values is for vertical non-targets *versus* oblique non-targets (at 18° to the vertical) and the second is for horizontal non-targets *versus* oblique non-targets (at 108° to the vertical). The p-values for response times show the significance of orientation configuration in a (one-tailed) test by planned comparison, as in Table 1

		Vertical non-targets, 18° tilted target	18° tilted non-targets, vertical target	Horizontal non-targets, 108° tilted target	108° tilted non-targets, horizontal target
Observer RW					
SEATED UPRIGHT	Percent correct ($p < 0.01$; $p < 0.05$)	93.1	86.4	94.0	90.2
	Response time in ms ($p < 0.01$)	514.2 ± 2.3	526.2 ± 2.6	519.7 ± 2.4	521.5 ± 2.7
SUPINE IN DARKNESS	Percent correct ($p = 0.05$, $p = 0.4$)	91.4	88.1	88.8	87.4
	Response time in ms ($p < 0.05$)	484.9 ± 2.7	489.4 ± 2.9	491.0 ± 2.6	495.9 ± 3.1
Observer MB					
SEATED UPRIGHT	Percent correct ($p < 0.05$; $p < 0.001$)	76.8	71.1	73.6	60.7
	Response time in ms ($p = 0.5$)	687.2 ± 8.9	685.8 ± 10.5	683.7 ± 10.5	686.4 ± 10.5
SUPINE IN DARKNESS	Percent correct ($p < 0.01$; $p < 0.001$)	68.6	60.8	71.9	60.8
	Response time in ms ($p < 0.001$)	544.0 ± 8.3	509.5 ± 7.4	547.3 ± 7.6	515.8 ± 7.5

Table 2.
(Continued)

		Vertical non-targets, 18° tilted target	18° tilted non-targets, vertical target	Horizontal non-targets, 108° tilted target	108° tilted non-targets, horizontal target
Observer LD					
SEATED UPRIGHT	Percent correct ($p < 0.001$; $p < 0.01$)	88.9	78.0	84.5	77.0
	Response time in ms ($p < 0.001$)	442.0 ± 2.5	453.0 ± 3.0	444.7 ± 2.4	452.5 ± 3.0
SUPINE IN DARKNESS	Percent correct ($p < 0.01$; $p < 0.001$)	87.5	80.6	90.3	77.4
	Response time in ms ($p < 0.001$)	459.7 ± 2.5	465.4 ± 2.6	457.3 ± 2.4	468.9 ± 3.0

p-values are given both for vertical non-targets *versus* oblique non-targets and for horizontal non-targets *versus* oblique non-targets. For the reaction times, the p-values are based on the same planned comparison as in the previous experiment (Section 4.2.6.).) For observers RW and LD in both the SEATED-UPRIGHT and SUPINE-IN-DARKNESS conditions, both percent-correct scores and reaction times provided evidence of the anisotropy (although for observer RW, the anisotropy in percent-correct scores did not reach statistical significance in the SUPINE-IN-DARKNESS condition). For observer MB in both the SEATED-UPRIGHT and SUPINE-IN-DARKNESS conditions, the percent-correct scores varied significantly with non-target orientation and indicated the expected anisotropy. For observer MB in the SEATED-UPRIGHT condition, the reaction times did not vary significantly with orientation, and for observer MB in SUPINE-IN-DARKNESS condition, the reaction times were greater when non-targets were vertical or horizontal than when they were oblique, indicating a speed–accuracy trade-off. (For observer MB, the SUPINE-IN-DARKNESS condition is perhaps best considered as a brief-display experiment, as the percent-correct scores range from 60% to 72% and are thus much lower than those generally reported in response-time paradigms.)

Thus the effectiveness of detection processes was, overall, greater with vertical or horizontal than with oblique non-targets, even in the absence of gravitational cues. The anisotropy was present despite the reduction of the orientation increment from 45° to 18°.

The reduction or absence of anisotropy when observers are supine, as reported by Marendaz *et al.* (1993), seems to require a specific set of experimental conditions and performance measures. The effect of non-visual cues on the anisotropy is therefore less robust than the anisotropy itself, which is evident both in visual search experiments with response-time measurements (Treisman and Gormican, 1988; Marendaz *et al.*, 1991) and in brief-display experiments with threshold measurements (Foster and Ward, 1991).

5. GENERAL DISCUSSION

An anisotropy in line-target detection performance was found in all the experimental conditions examined in the present study. The removal of visual and gravitational cues defining orientation had very little effect on this anisotropy, whether the performance measure was orientation increment threshold or response time. It seems that external cues are not required to define a reference frame for orientation in rapid visual processing; rather, this reference frame may be defined by the orientation of the retina or body axis.

These findings do not rule out the possibility that in some circumstances the visual system uses other reference frames. For instance, contextual cues have been found to influence the observer's perception of the vertical in some alignment tasks (e.g. Spinelli *et al.*, 1995) and gravitational cues may have an effect on orientation acuity (Buchanan-Smith and Heeley, 1993). Comparison of the present work with previous work on anisotropy in visual search indicates that the effect of gravitational cues in such tasks depends strongly on the experimental paradigm. Specifically, an effect of the removal of gravitational cues was found when observers had access to the display until they chose to respond (in the experiments by Marendaz *et al.*, 1993), but not when displays were presented briefly — even if there was no post-display mask. Differences in the visual and attentional mechanisms of observers taking part in the different studies might have been a contributory factor, in which case such differences are to be expected within the population in general and the effect of gravitational cues should not be considered to be a reliable, general phenomenon. Another possible explanation is that the paradigm of Marendaz *et al.* (1993) allowed the operation of mechanisms that were not effective in the present experiments. Determining a reference frame for orientation in vision may be a process involving many factors, whose individual contributions are task dependent (Heeley *et al.*, 1997). The present experiments allowed only the most rapid orientation-processing mechanisms to affect performance: it may be that slower-acting low-level mechanisms (e.g. global integration mechanisms such as those described by Wenderoth and Vanderzwan, 1989), or higher-level attentional mechanisms, are affected by gravitational cues whereas the most rapid mechanisms are not. Although some visual search phenomena can be studied effectively in either a response-time or a brief-display paradigm, these paradigms should not be assumed to be equivalent. The present work indicates that egocentric cues are sufficient to define the reference frame for the anisotropy in very rapid visual processing — but evidence from other studies suggests that other cues may have an important effect when slower processes determine performance.

NOTES

1. An anisotropy is also found with tasks requiring focal attention such as vernier judgements (e.g. Leibowitz, 1955) and detection of stimuli at the luminance contrast threshold (e.g. Ogilvie and Taylor, 1959). In these contexts it is summarized by the oblique effect (Appelle, 1972).

2. An intermediate condition, in which elements were randomly placed but viewed through a rectangular aperture, was originally included in the experiment. This condition is not discussed further as the results were not essential to the test of the hypothesis on visual context and spatial regularity.

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