Multiple levels of orientation anisotropy in crowding with Gabor flankers

Tomer Livne

Dov Sagi

Using oriented Gabor patches, we found that for nearly cardinal target orientations, oblique flankers’ orientations induced more interference than did cardinal flankers’ orientations. This pattern was observed both at the local and global levels of flankers’ orientation. With respect to the global orientation (flankers’ global arrangement around the target), there was no difference between the effects of the two cardinal orientations, and both induced the same amount of interference. With respect to the local orientation (Gabors’ orientation), in accordance with previous reports, a difference was found between the effects of the two cardinal orientations—a considerable amount of interference with flankers equal in orientation to the target (although less than with the oblique flankers) and almost no interference from flankers orthogonal to the target. Crowding was also affected by an anisotropy based on the target–fixation axis (radial, tangential, and diagonal) and by the flankers’ relations. The magnitude of these latter factors was small relative to that of the former ones. The multiple factors that affected crowding, as well as the similarities and the differences between the effects at the two orientation levels, suggest that crowding is determined by multiple sources of interference operating at several levels of representation.

Keywords: crowding, orientation relations, Gabor patches, anisotropy


Introduction

In visual crowding, flankers interfere with the identification of a nearby target. Accumulating evidence suggests that flankers’ orientation may modulate the magnitude of interference. However, the exact nature of this modulation is unclear. It has been suggested that these effects relate to both first- and second-order orientations. Regarding the local (first-order) orientation level, it has been suggested that there is less crowding from flankers orthogonally oriented to the target compared with flankers iso-oriented to the target orientation (Andriessen & Bouma, 1976; Levi, Hariharan, & Klein, 2002). Regarding the global (second-order) orientation, horizontal arrangements of flankers were found to increase interference relative to the interference produced using vertical arrangements (Feng, Jiang, & He, 2007). In addition, increased crowding with radial arrangements of flankers (flankers located on the target–fixation axis) compared with tangential arrangements (flankers located perpendicular to the target–fixation axis) has been demonstrated (Bex, Dakin, & Simmers, 2003; Toet & Levi, 1992). The spatial relation between flankers was found to affect crowding. Aligned flankers surrounding the target (co-circular) have been found to produce little or no crowding (Livne & Sagi, 2007). The magnitude of crowding was well predicted by a computational model implementing grouping between stimulus parts (Livne & Sagi, 2010). More recently, Chakravarthi and Pelli (2011), following May and Hess (2007), suggested that target–flankers’ alignment, that is, the spatial relations between the target’s orientation, the flankers’ orientation, and their spatial layout, determines crowding.

In the present study, we were interested in determining the relation between the target’s orientation and the orientation of the flankers at different levels, local (Gabors’ orientation) and global (the orientation defined by the axis connecting the center of the two flankers), and evaluating the contribution of these relations in determining the magnitude of the interference. Testing crowding with oriented Gabor patches and using an orientation discrimination task is somewhat different than most crowding setups in one respect. In this specific stimulus–task combination, the target–flanker similarity dimension and the parameter used to probe performance are identical (both relate to the orientation of the Gabor patches), whereas in most experiments, the target–flanker similarity is varied along a dimension different from the one used to estimate performance and crowding (e.g., similarity is...
defined by contrast polarity while testing the orientation of a “T” target; Kooi, Toet, Tripathy, & Levi, 1994). Target–flanker similarity usually affects crowding in a monotonic fashion (the more similar the target and the flankers are, the stronger is the interference—e.g., Kooi et al., 1994; Nazir, 1992). With Gabor patches, however, the target–flanker similarity effect seems to be non-monotonic, with oblique flankers’ orientations possibly producing more interference than cardinal orientations (Livne & Sagi, 2010—Figure 1; Solomon, Felisberti, & Morgan, 2004). In this study, we tested the effects of two levels of flankers’ orientation (local and global, as defined above), in order to gain some insight regarding the nature and source of this non-monotonic effect. To this end, we tested four parameters: the flankers’ first-order orientation signal (local orientation), the flankers’ arrangement relative to the target (global orientation), the target orientation, and the location in the visual field. Two additional parameters can be evaluated by combining two of the above parameters: the flankers’ arrangement relative to the target–fixation axis (the interaction between the location in the visual field and the flankers’ arrangement) and the orientation relationships between the flankers (interactions between local and global orientations). In line with previous reports, the results indicated a non-monotonic relationship between crowding and target–flankers’ local orientation similarity. There was limited crowding from orientations orthogonal to the target’s orientation and more crowding with oblique flankers relative to iso-oriented flankers. Surprisingly, this increased crowding with oblique flankers was also found in relation to the global orientation level of flankers. However, at this latter orientation level (global), there was no difference between the effects of the two cardinal orientations. Orientation relations between flankers were also found to affect crowding. Finally, as both the local orientation of flankers and their arrangement around the target were manipulated, the present results can be used to argue against Chakravarthi and Pelli’s (2011) single-parameter alignment explanation to crowding with Gabor patches.

**Methods**

**Apparatus**

The experiments were constructed using the Psycho-physical toolbox extension to Matlab (Brainard, 1997; Pelli, 1997). They were run on a PC with gamma-corrected display luminance, linearized using the graphic card’s built-in option (and verified using a MINOLTA LS-110 luminance meter). The screen resolution was 1280 × 1024, with a single pixel being equivalent to 0.014° visual angle. The refresh rate was set to 85 Hz, and the mean screen luminance was 15 cd/m². The viewing distance was 100 cm.

**Procedure**

In a 2AFC orientation discrimination task, subjects reported the tilt of an oriented Gabor target as being either clockwise or counterclockwise relative to a reference orientation (vertical or horizontal, not visually presented, each measured in a separate experiment). We measured subjects’ thresholds for discriminating between the two opposing tilts, that is, the tilt yielding ~80% correct responses. The average orientation of the target across trials was kept constant in each experiment, being equal to the reference, either 0° (horizontal) or 90° (vertical). To measure the discrimination threshold, we employed an adaptive 3-down 1-up staircase method (Levitt, 1971) in which the orientation deviation from the mean (horizontal or vertical, depending on the experiment) was increased by 20% after a wrong response and was decreased by 20% after three consecutive correct responses. The procedure was terminated after 8 reversals (an increase following a decrease or a decrease following an increase), but only the tilt values during the last six reversals were averaged to yield the discrimination threshold. A 45° orientation deviation from the cardinal orientation was set as an upper bound for the adaptive procedure, resulting in termination if it was reached 3 times. The data were also fitted with a psychometric function to verify the threshold estimates and to check for possible effects owing to response bias (see Results section).

Experiments were blocked by the average orientation of the target. Each experimental session consisted of four separate blocks. In each block, the flankers’ orientation and global arrangement were kept constant, and two interleaved staircases were used to measure the threshold at two different locations in the visual field: either left/right, up/down, upper right/left, or lower right/left, relative to fixation (one staircase per location). After subjects had completed the task in all combinations of location, flankers’ orientation, and global arrangement, they were tested again. Block order was randomized between subjects and between repetitions.

Results are averaged across repetitions (two measurements per condition). They are log transformed and are presented as threshold elevation, calculated by subtracting the threshold of a target-only condition (treated as the baseline threshold—these thresholds are described in Appendix A) from each condition separately. Error bars in all figures represent the standard error (SE) of the mean log data.

Trials were self-initiated by pressing a mouse button. A fixation cross was presented on the screen throughout the experiment.

**Stimuli**

The stimuli consisted of 3 high-contrast (90%) Gabor patches, defined by wavelength λ, and an SD of the Gaussian envelope σ (Polat & Sagi, 1993), in this case...
\( \lambda = \sigma = 0.16^\circ \), presented for 100 ms. The central Gabor (the target) was located at one of 8 locations in the visual field, 2.5\(^\circ\) (visual angle) from fixation (Figure 1a). The other two Gabor (flankers) were arranged on opposite sides of the target in one of four arrangements (see Figure 1b). Different combinations of flankers' positions relative to the target and locations within the visual field also allowed us to test the effect of the flankers' position relative to the target–fixation axis (radial, tangential, and diagonal—\( \pm 45^\circ \)). The target–flanker center-to-center distance was 0.76\(^\circ\) (visual angle). In each trial, both flankers had the same first-order orientation signal (horizontal, vertical, and \( \pm 45^\circ \)—Figure 1c—referred throughout the paper as local orientation), and different orientations were tested in different blocks. Examples of the actual stimuli used in the experiment are shown in Figure 1d.

**Subjects**

Three naive subjects with normal or corrected-to-normal vision participated in the experiments (all three performed the horizontal target conditions; two of them also completed the vertical target conditions).

**Results**

A detailed description of the results of each subject in each condition are provided in Figures 2 and 3 (horizontal and vertical target conditions, respectively). Different rows represent different global arrangements, and different columns represent different local orientations. While there is a certain amount of individual differences in these detailed results, it is apparent that, overall, the orthogonal flankers (rightmost column in Figure 2 and second to the left column in Figure 3) produced less amount of interference than the other local orientations in the respective target condition. Averaged results, representing performance levels corresponding to the main experimental manipulated variables, are presented in Figures 4, 5, and 6 (all observers and their mean). The two main experimental manipulations were found to strongly affect the subjects' performance. Regarding the level of the flankers' local orientation (see Figures 2, 3, and 4), the results indicated that there were large threshold elevations (~0.4 log units) with three of the four flanker orientations used (iso-oriented and the two diagonals) but small effects (~0.1 log units) with the flankers that were oriented orthogonally relative to the target (90\(^\circ\) flankers under the horizontal target condition, Figure 2, and 0\(^\circ\) flankers under the vertical target condition, Figure 3). Regarding the level of the flankers' global arrangement relative to the target (see Figure 5), there was stronger interference from the diagonal arrangements (\( \pm 45^\circ \)) than with the horizontal and vertical arrangements. The main difference between the two target orientation conditions was the dependence of the local orientation effect on the target–flanker orientation similarity. Under the horizontal target condition, the iso-oriented flankers producing strong interference were the 0\(^\circ\) flankers, and the low-interfering orthogonal flankers

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**Figure 1.** (a) The Gabor target was presented in one of eight locations in the visual field, at an eccentricity of 2.5\(^\circ\). (b) Four different flankers ("F") global arrangements around the target ("T"). From left to right: horizontal, vertical, and two diagonal arrangements. The target–flanker separation was 0.76\(^\circ\), measured center to center between the Gabor elements. (c) Gabor stimuli. From left to right: horizontal, vertical, 45\(^\circ\), −45\(^\circ\). (d) Three examples of the actual stimuli used in the experiment. The different flankers' positions relative to the target–fixation axis can be appreciated by fixating to the left of the leftmost stimulus in (d) for a radial arrangement. Fixating below the same stimulus would illustrate a tangential arrangement.
were the 90° flankers, whereas under the vertical target condition the 90° flankers were the iso-oriented, and the 0° flankers were the orthogonal. Since the average overall threshold elevations under these two target orientation conditions were similar (their averages differed by 0.04 log units), and since the pattern with respect to the other factors was similar as well (see the results presented in Figures 4 and 5), we did not analyze this factor further, and in the analysis below, we used relative flankers' orientations (iso-orientation, orthogonal, and diagonal—±45°) instead of absolute orientations (0°, 90°, and ±45°) for the local orientation factor. It is worth noting that while the results in Figures 2 and 3 indicate a certain amount of individual differences in the performance levels at some of the conditions, a result that is in line with recent reports of asymmetries and idiosyncrasies in crowding zones of subjects (e.g., Petrov & Meleshkevich, 2011), the averaged results (Figures 4, 5, and 6) are quite similar across subjects.

To study the results in detail, we ran an ANOVA test with three fixed factors (the flankers' relative local orientation, the arrangement relative to the target, and location in the visual field), with the subject as an additional random factor and the threshold elevation as the dependent variable. The test indicated that the local orientation and global orientation produced significant effects. The results of the ANOVA indicated that different flanker orientations produced different degrees of interference ($F(3,12) = 78.34$, $p < 0.0001$). A post-hoc test indicated that the ±45° flankers produced the strongest interference (an average threshold elevation of 0.47 and 0.44 log units for the −45° and the 45° flankers, respectively), more than the iso-oriented flankers (0.32 log units) and more than the orthogonal flankers (0.1 log units; both...
The difference between the iso-oriented and the orthogonal flankers was significant as well ($p < 0.0001$). The results therefore indicate a non-monotonic relation between the target–flankers’ orientation similarity and crowding.

The effect of the flankers’ arrangement relative to the target was also significant ($F(3,12) = 71.32, p < 0.0001$); the results are displayed in Figure 5. A post-hoc test indicated that the diagonal arrangements produced the strongest effect (average threshold elevations of 0.45 and 0.44 log units for the $-45^\circ$ and $45^\circ$ arrangements, respectively), significantly more than both the horizontal (0.21 log units) and vertical arrangements (0.23 log units; all $p < 0.0001$). There was no significant difference between the two diagonal arrangements or between the horizontal and vertical arrangements (both $p > 0.1$). Our results with Gabor stimuli show no significant difference between the horizontal and vertical arrangements; however, the results with Landolt C and line stimuli (Feng et al., 2007) show that some differences exist between the horizontal and vertical arrangements.

Figure 6 presents the effects of the local and global orientation levels independently for each of the other levels’ tested values. This figure shows that, generally, the pattern of the results is similar across the different values tested for the other orientation levels. One exception is the horizontal global orientation ($0^\circ$) in which the oblique orientated flankers did not produce more interference than the iso-orientated flankers.

The location in the visual field did not result in a significant effect ($F(7,28) = 1.75, p > 0.1$). The average results are shown in Figure 7. Our results at $2.5^\circ$ eccentricity did not reflect an upper–lower anisotropy, which was reported for higher eccentricities with rotated
“T” stimuli, an effect attributed to attentional factors (He, Cavanagh, & Intriligator, 1996, 1997). Interestingly, the threshold elevation was somewhat smaller in the lower left and lower right locations in comparison with the other locations, which could be attributed to higher baseline thresholds at these locations (an average of 1.66 in the lower quadrants compared with an average of 1.21 at all other locations, which is a difference of 0.14 log units).

As indicated above, a combination of two factors (location in the visual field and the flankers’ arrangement) produced a secondary factor: the flankers’ arrangement relative to the target–fixation axis. Since the interaction effect of these two factors was significant ($F(21,84) = 4.05, p < 0.0001$), we ran a second ANOVA test with the meridian arrangement as the independent factor. Results are presented in Figure 8. We found a significant effect ($F(3,12) = 13.52, p < 0.0001$), with the radial arrangements producing the strongest effect (an average threshold elevation of 0.39 log units), followed by the diagonal arrangements (0.33 and 0.34 log units). The tangential arrangements produced the smallest effect (0.27 log units).

The difference between the radial and tangential arrangements was significant ($p < 0.0001$). Although the differences are quite small, this result is in line with several previous reports suggesting reduced crowding with tangential arrangements relative to radial arrangements (Fang & He, 2008; Toet & Levi, 1992).

Finally, because the interaction between global and local orientations was significant ($F(9,36) = 5.19, p < 0.0001$), the effect of the flankers’ relations was evaluated. We were interested in determining whether the relations between flankers affect crowding even with simple two-flanker displays. There are three orientation relations between the flankers in the present experiment with respect to the axis connecting their centers. They were either (1) collinear with respect to each other and the axis (Figure 9a); (2) parallel to each other and orthogonal to that axis (Figure 9b); or (3) parallel to each other and obliquely oriented relative to the axis (Figure 9c). When the data from the orthogonal flankers were excluded (to examine only cases in which crowding was significant), we found that the strongest interference was measured with the parallel–orthogonal pairs (0.55 log units), significantly more than the parallel–oblique pairs (0.33 log units; $t(4) = 4.74, p = 0.004$) and...
significantly more than the collinear pairs’ interference (0.42 log units; $t(4) = 2.95, p = 0.021$). The difference between the collinear and parallel–oblique pair was also significant ($t(4) = 2.22, p = 0.045$). All $t$-tests are paired-sample tests.

The results therefore suggest that even with these two-flanker displays, where each flanker is closer to the target than to the other flanker, the flankers’ relations affect crowding. This is also in line with the prediction of a model we suggested previously to account for the configural crowding effect (Livne & Sagi, 2010). The model predicts that such parallel–orthogonal relations between a pair of connected flankers would produce more interference than would other relations between connected flankers.

**Sensitivity and bias in crowding with two flankers**

The 2AFC method we employed, in which accurate response feedback is given in each trial, is expected to produce a bias-free estimation of subjects’ thresholds. Nevertheless, in view of previous results showing bias without feedback in crowding experiments (Solomon et al., 2004), we tested for its presence by fitting psychometric functions to the data. To construct the fits, we considered the actual orientation of the target in each trial and calculated the percentage of correct responses for each of these orientations. The data were fit using a weighted logistic model (using the built-in “glmfit” function in MATLAB) to account for the different number of measurements in the different orientations. There was considerable within- and between-subjects variability in the observed
bias. Local orientation had a significant effect in relation to the observed bias ($F(3,12) = 20.22$, $p < 0.0001$). The pattern was in agreement with that reported by Solomon et al. (2004), with a significant repulsion from the oblique ($T_{45}$) flankers ($45^\circ$: mean bias of $1.19^\circ$, $t(4) = 10.17$, $p < 0.0001$; $-45^\circ$: mean bias of $1^\circ$, $t(4) = -3.26$, $p = 0.03$) and no bias from the cardinally oriented flankers (horizontal: $-0.08^\circ$ and vertical: $0.13^\circ$, both $p > 0.5$). Interestingly, the biases from oblique flankers were, however, considerably smaller than those previously reported. We therefore reanalyzed our data to verify that the results reported above (with threshold estimated from the staircase reversals) correspond to a bias-free orientation sensitivity measure. To this end, we computed a sensitivity measure from the psychometric curves. We defined this sensitivity as the difference (in log units) between the point of subjective equality (the point on the curve that is equal to 50% discrimination—this is in fact the bias) and the point corresponding to an 80% performance level (the performance level used in the staircase computation). This estimate of sensitivity is, in essence, free of bias. The agreement between this estimate and the threshold derived from the staircase estimation was very high, with $r^2 = 0.81$ (based on Pearson correlation). An analysis of the results described above, using the threshold estimated from the psychometric fits, confirmed the effects described in the previous sections: local orientation ($F(3,12) = 88.59$, $p < 0.0001$), with threshold elevations of 0.41, 0.29, and 0.07 log units for the $\pm 45^\circ$, iso-oriented, and orthogonal flankers, respectively (post-hoc significance pattern unchanged); global orientation ($F(3,12) = 62.08$, $p < 0.0001$), with threshold elevations of 0.42, 0.39, 0.17, and 0.2 log units for $-45^\circ$, $45^\circ$, horizontal, and vertical arrangements, respectively (post-hoc significance pattern unchanged); visual field ($F(7,28) = 0.98$, $p > 0.1$); the interaction between visual field and global arrangement ($F(21,84) = 4.13$), with threshold elevations of 0.37, 0.29, 0.3, and 0.22 log units for radial, $-45^\circ$, $45^\circ$, and tangential arrangements, respectively (post-hoc significance pattern unchanged).

**Discussion**

We systematically varied the orientation and arrangement of two Gabor flankers to test their effect on orientation discrimination thresholds of a surrounded Gabor target. Our results show that for nearly cardinal target orientations (horizontal or vertical) diagonal flankers’ orientations (local orientation and global arrangement) produced more crowding than did horizontal and vertical orientations. These orientation effects were modulated by additional factors: (1) flankers’ arrangements relative to the target–fixation axis, (2) flankers’ orientations relative to their global arrangement, and (3) target–flankers’ orientation similarity. As long as these parameters were held constant, our results indicated no systematic differences between crowding of Gabor patches at different locations in the visual fields.

In previous reports investigating the effect of iso- and orthogonal target–flankers’ orientation relations (e.g., Andriessen & Bouma, 1976; Levi et al., 2002), the target orientation was held constant ($135^\circ$ in Andriessen and Bouma’s study and $0^\circ$ in Levi et al.’s study). As a consequence, the orthogonally oriented flankers (relative to the target) were never also tested as iso-oriented flankers and vice versa. The present study, testing both flankers’ cardinal orientations as iso- and orthogonal-oriented relative to the target, provided a needed confirmation for the generality of this effect.
Although the effects of the local and global orientations were similar in that the oblique orientations produced more interference than did the cardinal ones (with our vertical and horizontal targets), there was also a difference between the two levels. The cardinal orientations produced the same amount of interference at the global level, but at the local level, the iso-oriented flankers produced more interference than did the orthogonal-oriented flankers. It has been suggested that crowding results from the same mechanism that produces the tilt effect (Solomon et al., 2004). Based on the fact that we found both local and global orientation effects, and based on the similarity and the difference between them, we suggest that crowding with Gabor flankers results from several processes operating together, with the tilt effect being only one of them. The pattern observed with the global orientations represents a loss of sensitivity consistent with a tilt effect (possibly due to incorrect coding of the target’s orientation). This would explain the small effect with non-tilted elements and the large effect with tilted ones. The difference between the iso-oriented and orthogonal-oriented flankers at the local level is consistent with monotonic similarity–interference relations usually reported in crowding (e.g., Kooi et al., 1994; Nazir, 1992; see also Levi, 2008, for a recent review of similarity effects). We suggest that the local orientation effect we observed results from a combination of these two sources of interference: (1) sensitivity loss owing to general target–flanker similarity and (2) sensitivity loss resulting from a tilt effect. It has been previously shown that with respect to other properties, crowding with Gabor flankers exhibits effects consistent with those obtained with other kinds of stimuli (e.g., eccentricity–separation scaling, no effect on contrast detection, and the target–flanker contrast relations effect, see Livne & Sagi, 2007). The present explanation conserves this consistency by attributing the measured non-monotonic pattern of the similarity–interference effect to additional stimulus and task-specific processes (unlike other crowding experiments, in the present case, the similarity dimension is also the tested property). Finally, the results reported by Andriessen and Bouma (1976) indicate that for oblique targets, cardinal flankers’ orientations (that is, flankers that are tilted relative to the target) would produce more interference than cardinaly oriented flankers. Therefore, apparently the relative tilt of the flankers compared to the orientation of the target rather than the flankers’ absolute orientation (i.e., whether or not it has a cardinal or oblique orientation) determines the effect. This is consistent with the fact that for cardinal target and flankers’ orientations the effect also depends on relative orientation relations (iso- or orthogonal orientations).

In a recent paper, Chakravarthi and Pelli (2011) suggested that crowding with Gabor elements is determined by target–flankers’ binding. According to their claim, when flankers are aligned with the target (i.e., collinear), crowding should be maximal, and when they are misaligned, the interference is reduced. They suggest that the configuration effect reported in Livne and Sagi (2007) is merely due to this target–flankers’ binding factor. The present results in which misaligned target and flankers (oblique flankers conditions) did not produce less interference than aligned ones, and in most cases generated more interference, argue against their model. The same goes for the finding that iso-oriented flankers induced crowding even when they were misaligned with the target (and with each other—parallel). Therefore, it seems that the simple target–flankers’ alignment explanation of Chakravarthi and Pelli cannot account for the richness of the crowding phenomenon.

Our explanation of the non-monotonic target–flanker similarity effect with tilted Gabor elements suggests that different sources interact in crowding. It also suggests that different stimuli and tasks would be affected differently by similar manipulations. Although crowding seems to represent a general limitation in peripheral visual processing, its operation is not independent of other stimulus-specific processing. Further studies are therefore required to identify the specific mechanism that produces and integrates the effects of these different sources and to determine whether they behave differently in crowded and uncrowded situations.

### Appendix A

#### Table A1

<table>
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<tr>
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<th>AB vertical</th>
<th>NL horizontal</th>
<th>NL vertical</th>
<th>RZ horizontal</th>
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<td>1.32 (0.1)</td>
<td>1.16 (0.03)</td>
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<td>1.38 (0.16)</td>
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<td>0.92 (0.1)</td>
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<td>0.99 (0.01)</td>
<td>1.32 (0.09)</td>
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<td>1.19 (0.12)</td>
<td>1.29 (0.19)</td>
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<td>1.15 (0.25)</td>
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<td>1.4 (0.22)</td>
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</table>

Table A1. Baseline thresholds (and $SE$—in parenthesis) of the subjects at the eight different locations in the visual field (in degrees).
Acknowledgments

This work was supported by the Basic Research Foundation administered by the Israel Academy of Sciences and Humanities.

Commercial relationships: none.
Corresponding author: Dov Sagi.
Email: dov.sagi@weizmann.ac.il.
Address: Department of Neurobiology, Brain Research, The Weizmann Institute of Science, Rehovot 76100, Israel.

References


