Filling-in of Retinal Scotomas

Dror Zur[1] and Shimon Ullman[2]

[1]Dror Zur, Department of Computer Science and Applied Mathematics, The Weizmann Institute of Science, Rehovot, 76100, Israel

[2]Shimon Ullman, Department of Computer Science and Applied Mathematics, Weizmann Institute of Science, Rehovot, 76100, Israel

All correspondence: Dror Zur, The Neurobiology Laboratory, RU box 108, The Rockefeller University, 1230 York Avenue, New York, NY 10021, USA.
Phone: +1-212-327-7674, Fax: +1-212-327-8240, Email: zurd@mail.rockefeller.edu.

Key words: Filling-in, Retinal Scotoma, Density, Regularity, Cortical Mechanism

Abstract

In this study we examined the perception of one- and two-dimensional patterns across central retinal scotomas, caused by Age-related Macular Degeneration (AMD). In contrast with previous studies of disrupted visual input that used the blind spot and artificial scotomas, the current study used large central scotomas caused by physical retinal damage. Such damage is associated with atrophy and long-term cortical reorganization, and it was therefore unclear whether perceptual completion in the damaged system will be similar to that reported for artificial scotomas and the blind spot. In addition, the scotomas under study were much larger and more central than artificial scotomas for which perceptual completion has been reported. For 1-D line and grating patterns, we found perceptual completion across large central scotomas (up to radius of 7º), which is significantly beyond the range of perceptual completion in artificial scotomas. Gratings completion was better than that of a single line, and increased with bars density. The use of central scotomas allowed us to test the completion of 2-D patterns that are difficult to study in peripheral vision. We found completion of two-dimensional dot arrays over large regions that improved with pattern density and regularity. The results show that in the physically damaged system the range of perceptual completion is increased compared with artificial scotomas, they strongly support the view of an active filling-in process rather than simply ignoring the damaged location, and they show that perceptual completion of physical scotomas is likely to involve cortical processing at multiple levels. We finally discuss implications of the results to the possible use of image enhancement techniques to facilitate the perception of low-vision individuals.

1. Goals of the Study

The goal of this study was to test perceptual completion of different types of patterns across large and central retinal scotomas, caused by retinal damage in Age-related Macular Degeneration (AMD) patients. (We will use here "scotomas" rather than scotomata.) Informal observations suggest that patients with large retinal scotomas continue to perceive the visual world as uninterrupted, suggesting the possible completion of the damaged regions by perceptual filling-in processes. However, there are two main problems with this interpretation. First, under unrestricted viewing, the perception of uninterrupted input could rely on scanning eye movements. Second, it is not clear that the missing input is in fact filled-in. An alternative hypothesis relies on the notion of 'ignoring' rather than active filling-in. According to this view, the regions of missing input are ignored and remain unnoticed. A better understanding of the perceptual processes associated with regions of damaged retina will have three benefits. First, it can lead to a better understanding of general mechanisms in the visual system, in particular, related to lateral interactions and context effects. Second, it is known that retinal damage induces long-term cortical changes. The study of perceptual effects associated with retinal damage is important for understanding the mechanisms and function of this reorganization, and can have general implications to the study of plasticity and learning in the visual system. Third, if active filling-in mechanisms are implicated, the possibility arises of devising visual enhancement techniques that will improve the visibility of input patterns for visually impaired individuals by making the patterns easier to fill-in effectively.

Previous studies have examined perceptual filling-in across disrupted visual input. However, in contrast with the present study that used large central scotomas caused by physical retinal damage, past studies focused on the blind spot, and the use of artificial scotomas that were relatively small and placed outside the foveal region (see review below). There are several reasons why these studies are insufficient for drawing conclusions regarding perceptual completion in the physically damaged retina. The use of the blind spot to study filling-in across retinal region has two main limitations. First, since the blind spot is an anatomical feature of the normal visual system, the system may incorporate specific mechanisms that do not operate at other locations. It is known, for example, that the blind spot region has a special anatomical arrangement in the LGN of monkeys and other mammalian species (Kaas *et al*. 1972; Lee & Malpeli 1994). Second, compared with the scotomas in the present study, the blind spot is relatively small (about 2.5° of visual angle), and located peripherally (about 15° in the nasal direction), where vision is more limited compared with foveal vision. The use of artificial scotomas also has limited applicability to the study of the physically damaged retina. Retinal damage is associated with atrophy and long-term cortical reorganization (Gilbert & Wiesel 1992), and it is therefore unclear whether perceptual completion reported for artificial scotomas will also be effective in the damaged system. In addition, artificial scotomas cannot be filled-in at the center of the visual field, and therefore the artificial scotomas in past studies excluded the foveal region, and were significantly smaller than the physical scotomas used in the present study (see review below). This limitation has two main implications in relation to the present study. First, it leaves open the question of filling-in processes in the foveal and near-foveal regions. Second, the use of central scotomas allowed us to test the completion of relatively complex 2-D patterns (such as dot arrays) that are difficult to study in peripheral vision. Finally, to explore the possibility of visual enhancement techniques for the visually impaired, it is clearly advantageous to study directly perceptual effects associated with the physically damaged retina. For this purpose, we used in the current study patients with AMD, which is the most prevalent low-vision disease inducing central retinal scotomas. An example of AMD retinal scotoma is shown in Fig. 1.

FIGURE 1

2. Review of Related Studies

Past related studies can be classified according to the type of the input disruption (the blind spot, artificial scotomas, retinal disruption) and the type of the visual stimuli employed. In terms of visual stimuli, the main distinction is between simple stimuli, such as [* uniform *]regions, edges, and single bars - also called “brightness stimuli” (Paradiso & Nakayama 1991), and more complex patterns and shapes such as gratings, array of dots, and two-dimensional textures (Motoyoshi 1994, 1999; Caputo 1998). A classification of the studies according to the type of input disruption and the type of visual stimuli is shown in Table 1.

TABLE 1

The intensive investigation of the blind spot included studies of static, dynamic and interocular effects. Ramachadran (1992) demonstrated examples of the filling-in of background color, bars, and geometric patterns at the blind spot, and Brown and Thurmound (1993) found that the filling-in process preserves the edge separating regions of opponent colors. Other studies have shown that the filling-in of the blind spot in one eye can influence the perception related to the other eye (Tripathy & Levi 1994; Murakami 1995), that this filling-in takes place early in perceptional processing (Durgin *et al.* 1995), and that the filling-in at the blind spot induces little or no distortion of the surrounding region (Tripathy *et al.* 1996).

A small number of studies examined the perception of more complex shapes and textured regions by stimuli extending across the blind spot. Studies by Kawabata

(1982, 1984) showed that gratings, concentric circles and dotted lines can be filled-in across the blind spot. Brown and Thurmond (1993) studied the filling-in of texture using dot patterns with average density of 0.4 dots/deg, low degree of irregularity and uniform color. They found evidence for complete filling-in of dot patterns of different colors. However, no study has tested systematically the dependence of the filling-in effects on the density, regularity, and other parameters of complex patterns such as grating and two-dimensional dot patterns.

Other studies of perceptual filling-in have used artificial scotoma rather than the blind spot. Ramachadran and Gregory (1991) have shown that an artificial scotoma subtending 1.5°·1.5° at 6° eccentricity in a background of flickering noise or flickering gratings is gradually filled-in after about 10 seconds. Brightness stimuli were shown to be filled-in faster than texture stimuli, and flickering noise was filled-in faster than static noise or uniform brightness (Spillmann & Kurtenbach 1992). To study spatial distortions around artificial scotomas, Kapadia *et al.* (1994) used a three-line bisection task and found that the apparent position of a short line segment was biased toward the interior of the artificial scotomas. De Weerd *et al*. (1998) found that the time it takes to fill-in artificial scotoma depends on the scotoma size, and that there is an upper limit to the size for which artificial scotoma can be filled-in at each eccentricity. Aftereffect studies demonstrated that filled-in patterns in artificial scotoma can induce aftereffects (Tyler & Hardage 1998; Reich *et al.* 2000). As in the blind spot studies, no study has tested systematically the dependence of the filling-in of artificial scotoma on the parameters of complex patterns such as grating and two-dimensional dot patterns.

A previous study that used a physically damaged retina, which is the subject of the current study, was performed by Craik (1966), who used a self-induced retinal lesion created purposefully by a prolonged staring at the sun. However, his study was based on informal self-reports and sensations. Gerrits and Timmerman (1969) tested the filling-in of homogeneous color, color edge, and a narrow slit in five patients with central retinal scotomas. They reported filling-in of color and color edges that occurred "instantaneously" with no aftereffect, in contrast with artificial scotomas. Schuchard (1993, 1995) reported some cases of perceptual completion of lines in patients with central scotomas. He found that reports on the missing segments and distortions in the perception of a gird made of vertical and horizontal lines were insufficient to detect the macular scotomas (Schuchard 1993). He also found that the completion of line drawings of letters partially covered with central scotomas was dependent on whether the patients knew that the line drawings represented letters (Schuchard 1995).

Physiological data relevant to the processing of retinal disrupted input come mostly from cortical single cell recordings in adult monkeys and cats. Eysel *et al.* (1981) found that following a retinal lesion in the cat, excitation at the LGN level spread from surroundings cells to cells with receptive fields inside the lesion region. Fiorani *et al.* (1992) found that cells in V1 with a receptive field inside the blind spot of the contralateral eye respond to bars longer than the blind spot diameter, when the ipsilateral eye is closed and the bars are swept across the blind spot. Gilbert and Wiesel (1992) found that after inducing a retinal lesion, cells in monkey V1, with receptive field inside and outside the lesion near its border, expanded their receptive field within minutes. Following several months, cells with receptive fields inside the lesion expanded and shifted their receptive field out of the lesion region. Gilbert (1993) suggested that the circuitry responsible for this cortical plasticity may include the modulation of horizontal connections in V1. Using artificial rather than real scotoma, Pettet and Gilbert (1992) found that cat V1 cells with a receptive field inside the scotoma underwent a 5-fold expansion within ten minutes. However, the cortical reorganization they found in response to the exposure to artificial scotomas was much less massive than the reorganization found by Gilbert and Wiesel (1992) following retinal damage, and it vanished quickly after the artificial scotoma disappeared. De Weerd *et al.* (1995) found that monkey V3 cells with receptive fields inside an artificial scotoma surrounded by a texture stimulus, retrieved their firing rate following a brief silence, to the original level. [* These findings show that the compensation for the disrupted input can be traced at levels higher than V1, and, given the sizes and stimuli involved, they raise *] the possibility that the cortical processes involved may implicate multiple levels.

2.1 The size and complexity of filled-in patterns

Two general issues examined in past studies that are particularly pertinent to the current study are (1) the maximum size for which scotomas at different eccentricities can be filled-in, and (2) the complexity of the patterns that are being filled-in. Regarding size, the blind spot has a radius of 2.5° at about 15° eccentricity and can be filled-in effectively. Artificial scotomas have an upper limit on the size that can be filled-in at each eccentricity. The upper limit decreases with decreasing eccentricity (De Weerd *et al*. 1998), and even small artificial scotomas cannot be filled-in at the center of the visual field (see also control test in Exp. 1 below).

Regarding the complexity of filled-in patterns, studies using the blind spot usually employed only simple stimuli, partly because it proved difficult to test complex patterns at this relatively large eccentricity. All the blind spot studies mentioned above, with the exception of Kawabata (1982, 1984) and Brown and Thurmound (1993), dealt only with the filling-in of brightness and simple patterns. Studies of complex patterns in the blind spot did not vary the patterns and did not provide systematic comparisons between the filling-in of complex and simpler patterns.

Regarding artificial scotomas, the study of complex patterns was also limited since many studies used scotomas at relatively large eccentricities, where complex patterns are difficult to evaluate. Although more studies investigated the filling-in of complex patterns in artificial scotomas compared with the blind spot (see Table 1), as in the blind spot, previous studies did not provide a systematic analysis of the filling-in of complex patterns. In the current study we examined issues related to scotoma size and pattern complexity in real scotomas. We found significant differences in size limitations between real and artificial scotomas, and obtained systematic evidences regarding the filling-in of complex patterns. The implications of these differences and new findings are examined in the final discussion.

3. General Methods

3.1 Subjects

The characteristics of the four patients, three men and one woman, who participated in the experiments, appear in Table 2.

TABLE 2

We employed AMD patients who had central "macular scar", which is a final steady-state stage of the disease. The retinal fixation loci and scotomas were mapped in advance. We used static screening (flashes of small dots at different location with consistent size and intensity) and kinetic screening (continuous line movements of small dot with consistent size and intensity) to map the scotoma regions, and we found that the patients had scotomas with radii in the range of 5º-7º with no detectable residual vision inside the scotoma region. For control purpose, all the stimuli were presented to three students ("control subjects") with intact vision in the same way they were presented to the AMD patients. [* Control **]subjects were [***

males, age 26-34, *], and with 20/20 Snellen visual acuity in each eye separately, and in both eyes together.

3.2 Stimuli and Experimental Design

The stimuli were monocular and of short duration to exclude the possibility of using undamaged retinal regions. They were presented in a dark room by a high intensity projector to obtain high contrast images. The projector was a NEC MT810G with a 600 ANSI lumens maximum light intensity, 200:1 contrast ratio, $800 \cdot 600$ dot resolution, and using back-projection. In all the experiments we used black and white images (maximum contrast) and the maximum contrast of the projector. The projector was located 83 cm horizontally from the screen, producing image size of 40 cm diagonally. With this arrangement, the luminance of the entire image remained uniform, with measured luminance (white) of 400 cd/m^2 from the viewing side of the screen. The subjects were seated close to the screen, viewing it from a distance of 50 cm. They used one eye, their near-sight eyeglasses, and their head was stabilized by a chin rest in order to eliminate involuntary head movements. The subjects were instructed to avoid eye movements and fixate on a fixation target before each tested image was flashed. The fixation target was framed by a peripheral circle helping the subjects with severe central loss to fixate at the center of the circle.

3.3 Procedure

Prior to the experiments, we mapped the scotoma region of each subject by screening the central field with static and kinetic micro-perimeters with a resolution of under 1°. The lack of residual vision was tested in two ways. First by high-resolution ($\leq 1^\circ$) perimetry, second, none of the subjects detected any pattern, such as the disk presentation described in Exp. 1, when they were presented entirely inside the scotoma region. Each subject was asked to fixate on a slit lamp’s narrow beam, enabling a pre-measurement of his/her retinal fixation locus. A computer controlled the test procedure. Using the known scotoma region and the fixation locus, the test patterns were presented at controlled locations relative to the scotoma in the visual field. The subjects reported their perception by responding to specific questions, and sometimes by also drawing the perceived patterns using computer-graphics software with high magnification.

The images were flashed during presentation for 400 ms to achieve effective perception. This is somewhat longer than the minimum presentation time used to preclude eye movements, but it was preferred because presentation time of substantially less than 400 ms for the presented patterns was sometimes ineffective [*for*] the subjects with relatively large central scotoma and required a large number [*] of repeated flashes. Previous studies have shown that the likelihood of more than a single effective fixation occurring in AMD patients within this time period is small: Dagnelie and Schuchard (1992) showed, using patients tested by Scanning Laser Ophthalmoscope (SLO), that the probability of fixation staying within 0.25° or less during 400 msecs is at least 75%. To confirm directly that the subjects did not make significant eye movements during the 400 msec flashes they were exposed to, we repeated Exp. 2 below while having an observer monitoring and reporting any observed eye movement during each trial. We first verified that the observer could detect with high probability eye movements of 0.76° or less in our setup, and then tested all four subjects that participated in the study. No observed eye movements were reported in any of the trials, showing that effective eye movements are highly unlikely under the experimental conditions. As an additional test, we replicated a part of Exp. 2 below, but with a shorter flash duration of 200 msecs. This additional test showed that under the experimental conditions the results of the 400 msec flashes were highly similar to those of the 200 msecs flashes. Taken together, the results show that 400 msecs flashes can be used without significant effects of eye movements.

In all the experiments below, each stimulus was presented four times for each subject, and the reported results were averaged and analyzed for each subject separately. All the stimuli were presented for 400 msec to the three control subjects, and they reported normal perception, describing the stimuli accurately without effects such as blur, missing patterns, or discontinuity.

4. Experiment 1: Perceptual Completion of Lines and Gratings

In the first experiment we tested the perception of one-dimensional stimuli, single straight line, and square-wave gratings, across central retinal scotomas. In particular, we examined the perceived continuity and contrast of the stimuli, along their extent. For the gratings, we tested the effect of bar density on the perceived patterns.

4. 1 Method

4.1.1 *Subjects*

All four subjects (see general methods) participated in the experiment.

4.1.2 *Stimuli*

Stimulation patterns were a 45º diagonal line, and six 45º diagonal square-wave gratings tilted to the right. The line was white on a dark background, 0.73º width and 24° length, crossing the scotoma center of each subject. The gratings consisted of white and dark lines, covering the entire display (44° of diagonal visual angle). The gratings had bars density (the density of two adjacent white/dark bars) ranging from 0.26 to 3.93 bars/deg in six step intervals. All subjects could resolve the grating with the highest bars density in the regions surrounding their scotoma, except for SF who had difficulties with the high[* est*] density gratings. For this reason her results were [* excluded from the analysis of the results *]

4.1.3 *Procedure*

Subjects were asked to rate the uniformity of the perceived stimuli in numbers between zero and five. Five represented perfect continuity, for which no difference was perceived between the scotoma and the surroundings, and zero corresponded to perceived gaps. When a stimulus was reported as non-uniform, the subject was asked whether the non-uniformity was in straightness, contrast or blur (one or more of the three specified attributes could be selected). Finally, we presented to each subject a gray background with a disk, consisting of the 1.97 bars/deg grating. It was presented outside the scotoma region to verify its detection, and inside the scotoma region to test for residual vision inside. The eccentricity outside the scotoma was always larger than the eccentricity inside the scotoma.

4.2 Results

The results of the three subjects that remained after [* exclusing *] SF's results are summarized in Fig. 2.

FIGURE 2

All subjects detected the small disk when presented outside the scotoma region, but not inside it (left column, Fig. 2A-C). Two subjects (GN and ZL, Fig. 2B,C) reported a small gap (a segment as dark as the background) along the line. They therefore rated the line uniformity in the range 0-1. The third subject (YP, Fig. 2A) reported no gap but a dark gray segment along the line, and his average rated uniformity was 2. In terms of attributes of the line's non-uniformity, the only reported attribute was contrast [* variation *], otherwise the line was rated as straight and uniform.

On the whole, gratings appeared as more uniform and complete compared with single lines. There was a clear density effect: as the bars density increased, the uniformity rating increased monotonically. The monotonic increase of the uniformity rating with the bars density was significant ($p \leq 0.001$, Spearman correlation test) for YP and GN, and was not significant ($p \leq 0.1$) for ZL. In terms of attributes, all subjects described that the perceived non-uniformity of the gratings was in contrast and blur. None of them perceived a gap in the gratings. The subject whose results were eliminated, SF, had the largest scotoma with a radius of [* over *] 7º. For the three highest densities she was unable to resolve the gratings inside the scotoma region and reported a filling-in of uniform gray region.

To obtain a direct comparison of the filling-in of large and central scotomas that we found in this experiment and artificial scotomas used in past studies, we tested, as a control, the limits on the size of artificial scotomas for which perceptual filling-in is obtained. The background was the same grating pattern used in the main experiment with density of 1.97 bars/deg, and the artificial scotoma was defined by a uniform gray square with luminance identical to the mean luminance of the grating. [* A test] scotoma subtending 1.4°·1.4° at eccentricity of 9.5°, was perfectly filled-in for the three control subjects (see general methods). We next tested the scotoma, keeping its size, at the center of the visual field. The control subjects had to fixate at the center of the scotoma using unlimited viewing time. It was not filled-in for any of the control subjects. We finally enlarged the artificial scotoma at an eccentricity of 9.5° to subtend 7°·7° (such a square is delimited by a circle with radius of 4.95°), and for all control subjects it failed to be filled-in.

4.3 Discussion

The disk presentation together with the visual field mapping verified that the subjects had no detectable residual vision within the scotoma. The results show that even large central AMD scotomas (up to a radius of 7º) are perceptually filled-in in a manner that depends on the surrounding pattern. As indicated by previous studies and shown in the control test, such large filling-in in central vision cannot be achieved for artificial scotomas. The non-uniformity effects, reduced contrast and increased blur appearing in the scotoma region, indicate that the scotoma region is not simply ignored, but filled-in in a manner that allows the subjects to make perceptual judgments about properties of the perceived patterns in the scotoma. The continuity of the gratings across the scotoma suggests that the perceptual completion retains the orientation of the surrounding patterns. The monotonic increase of the uniformity rating with bars density shows a clear density effect of the completion process.

The high uniformity rating at the high densities cannot be predicted by the Contrast Sensitivity Function (CSF) of normal or AMD observers. The CSF shows a significant decrease at the high frequency range, from about 3 cycles/deg for a normal observer, and from a lower frequency for AMD observers with damaged central vision (Faye 1996). The grating with the highest density of 3.93 bars/deg and main harmonic of 3.93 cycles/deg was rated by all subjects with the highest uniformity. The density effect therefore appears to reflect specific properties of the filling-in process mechanism, which becomes more effective under the high-density conditions. The difference between the density effect and the CSF pattern also provides additional evidence that residual vision was not involved in the scotoma completion.

In terms of line vs. gratings completion, for all subjects (YP, ZN, GL), the rating of the line was below or equal to the lowest rating of the gratings. Moreover, its rating was always below that of gratings with similar line width.

5. Experiment 2: Perceptual completion of regular patterns

Since Exp. 1 demonstrated a dependency of perceptual filling-in on pattern density, we aimed in the second experiment at finding whether the dependency is also observed for two-dimensional pattern density. We therefore tested the perceptual filling-in of two-dimensional regular arrays of dots, and its dependency on array density.

5.1 Method

5.1.1 *Subjects*

The same four subjects (see general methods) participated in the experiment.

5.1.2 *Stimuli*

Eight dot arrays were presented to each of the four subjects. The dots radius was kept at 0.3°, and the density varied between 0.13 and 1.16 dots/deg in seven step intervals. [* Dror: because this is 2-D pattern, is this 0.13 dots/deg along one dimension, or a dot per 0.13 deg^2 ? *] Regular arrays of circular dots were employed because we wanted to extend the study in Exp. 1 to non-oriented stimuli, and because it proved easy for the subject to report missing dots, blur, and pattern distortion. The dot arrays covered the entire display (44° of diagonal visual angle).

5.1.3 *Procedure*

Subjects were first asked to report the number of missing dots (if any) in the regular arrays. They were then asked (i) if any of the dots appeared more blurred or with less contrast than the others (yes/no), and (ii) whether the array appeared entirely regular or distorted (yes/no and which part). To verify that the subjects' count of missing dots is [* reliable,] we performed a control test with the control subjects (see general methods). [* The test included several regular dot arrays, with the different densities used in the main experiment, and with a a region of missing dots. All the subjects with normal vision estimated the number of missing dots in a short flash of 200 msec with high accuracy for all the densities.

5.2 Results

Fig. 3a shows the number of perceptually missing dots, as a function of array density, for each of the four subjects.

FIGURE 3

Two subjects (YP, GN) reported no missing dots at high densities, SF reported a monotonic increase in the number of missing dots as the density increases, and ZL also reported a monotonic increase except for the highest density. To test the fraction of missing dots as a function of density, we normalized the number of missing dots by dividing them by the total number of dots estimated to fall within the scotoma region. Fig. 3b shows the percentage of missing dots in the scotoma as a function of array density for each of the four subjects. In all four cases, there was a significant monotonic decrease in the percentage of missing dots [($p \leq 0.001$, Spearman correlation test) *].

In terms of the three tested attributes (regularity, contrast, blur), the dot arrays appeared as geometrically regular, with reduced contrast and some blur in the scotoma region. For some low density patterns there were occasional reports of individual dots that appeared incomplete. The quantitative results regarding the missing dots were also supported by pictorial renditions made by YP and ZL. They drew the perception of repeating flashes of the stimulus, observing their drawing with two eyes and magnifying glass. The produced drawings appeared to them similar to the their perception of the patterns briefly presented during the experiment. Fig. 4 shows two dot arrays (upper row) and their perceived appearance (lower row) drawn by subject ZL after the four flashes that were required for the rendition task.

FIGURE 4

In summary, at low densities (0.13 dots/deg, Fig. 4a), dots within the scotoma were perceptually missing. At high densities (0.58 dots/deg, Fig. 4b) most of the dots within the scotoma were perceived, some with blur.

5.3 Discussion

The significant monotonic decrease of the percentage of missing dots with array density, and the lack of missing dots at high densities, suggest the involvement of a textural filling-in process that is density dependent. The efficiency of this process increases with density within the range tested. The high correlation between different reports supports the generality of the phenomenon. Since in the dot arrays, as in the gratings case, high densities involve high spatial frequencies, the results of Exp.1 and Exp.2 together suggest that the filling-in process is more effective at the high spatial frequencies.

6. Experiment 3: Perceptual completion of irregular dot patterns

Exp. 2 demonstrated density-dependent perceptual completion of a regular dot pattern. It is natural to also examine the effect of the patterns regularity on their perceptual completion. Regular dot patterns provide strong evidence regarding the expected location of unregistered dots, and they may therefore provide a stronger basis for perceptual completion compared with irregular patterns.

6.1 Method

6.1.1 *Subjects*

The same four subjects (see general methods) participated in the experiment.

6.1.2 *Stimuli*

Two types of dot arrays were used, differing in their degree of irregularity. The irregularity was controlled by parameter d defined below. The arrays were generated by starting from a regular grid, then shifting each dot randomly in the x and y direction, by a value drawn from a uniform distribution between $-d$ to d, where $0 \leq d \leq 100$ is measured in percentage of inter-dot distance. The dots radius was kept at 0.3º, and the density of the regular array was 0.87 dots/deg (with such array, Exp. 2 showed a high degree of perceptual completion). Two levels of irregularity were used, d=26.5% and d=79.5%. For the larger d the dot-order was infrequently changed by random displacement, but average density was maintained at 0.87 dots/deg in each dimension. The two irregular arrays, which were presented to all subjects covering the entire display (44° of diagonal visual angle), are shown in Fig. 5a.

FIGURE 5

6.1.3 *Procedure*

Unlike Exp. 2, for irregular patterns it is difficult to estimate the number of missing dots in the perceived patterns. Subjects were therefore asked to rate the completion of the patterns on a scale of 0 to 5, where 0 corresponded to the perception of a gap, and 5 to a continuous pattern, with no region where the pattern differed perceptually from the surroundings. In addition to the completion rating, subjects were asked to report which of three attributes (contrast, blur, and density) best characterized the non-uniformity in the perceived pattern (one or more of the three specified attributes could be selected).

6.2 Results

As shown in Fig. 5b, completion ratings for the more regular arrays (d=26.5%) were consistently higher than for the less regular (d=79.5%). The difference was significant according to the non-parametric Wilcoxon test ($p \leq 0.05$). The subjects gave different reports of the dimension along which the patterns varied; for YP, the main difference was an apparent blur of some of the points, for GN a density difference, for SF a difference in apparent contrast, and for ZL uncertainty in the location of some of the points.

6.3 Discussion

The degree of pattern irregularity had a significant effect on the perceived uniformity of the test patterns: the more regular patterns were consistently ranked as more uniform in all attributes. For patterns perceived non-uniformly, the dots within the scotoma differed from the surrounding regions along several dimensions including contrast, blur, and density.

7. General Discussion

Our study tested perceptual completion across physical scotoma in the center of the visual field using one- and two-dimensional patterns. It differs from, and extends, previous studies in several directions: it is the first systematic study of perceptual completion that used retinal lesions, the scotomas were much larger and more central than in previous studies, and the set of stimuli included different types of two-dimensional texture patterns. We will discuss below the results obtained in our study and their implications to the perceptual mechanisms involved, in light of these differences.

The first difference between the current and previous studies is in the source of visual disruption: our study used retinal lesions caused by retinal degeneration, compared with previous studies that relied on the blind spot or used artificial scotomas. It is not a priori clear whether these different types of disruption would show similar or different perceptual effects. The blind spot is a special anatomical feature of the intact visual system that may be treated in a special way by subsequent processing. Compared with artificial scotomas that are brief and transient in nature, long-lasting retinal lesion may lead to atrophy in the system, that may prevent effective subsequent filling-in processing. The results provide a clear answer to this question by showing that perceptual filling-in is highly effective across permanent and extensive retinal lesions. In contrast with artificial scotomas (Ramachadran & Gregory 1991; Spillmann & Kurtenbach 1992; De Weerd *et al.*, 1998), the completion of the scotoma regions was instantaneous, and the patients did not report any dynamic effects.

The second difference between the current and previous studies was in the size and location of the scotoma. The lesions we studied were much larger, and more central in the visual field compared with artificial scotomas used in previous studies. In studies using artificial scotomas, filling-in was not obtained for central scotomas or sufficiently large more peripheral scotomas. De Weerd *et al.* (1998) showed that a square subtending 1°·1° could not be perfectly filled-in at eccentricity of 2° or less, and that a square subtending 5.6°·5.6° (such a square is delimited by a circle with radius of 3.9°) approaches the upper size limit for filling-in at eccentricity of 8°. In the control test carried out in Exp. 1 we found that a square subtending 1.4°·1.4° cannot be filled-in at the center of the visual field, and that a square subtending 7°·7° (delimited by a circle with radius of 4.95°) cannot be filled-in at eccentricity of 9.5°. Based on this and previous data, one would expect the lesions used in this study to be far too large to allow effective filling-in processes. On the other hand, physiological studies in the monkey demonstrated massive long-term reorganization of V1 cortex following retinal lesion (Gilbert & Wiesel 1992). The anatomical results raise the possibility that the cortical rearrangement may allow the system to perform effective filling-in over larger regions. The results of our study strongly support this possibility, since we found filling-in of one- and two-dimensional patterns over central scotoma with radius as large as 7° of visual angle.

In terms of the brain mechanisms involved, filling-in over such a range is unlikely to be limited to the V1 receptive field expansion reported in primates, since the size of the scotoma in central vision requires, using magnification factors for humans (Sereno *et al.*1995; Engel *et al.* 1997; Tootell & Hadjikhani 2001), interconnections spanning about 35-40 mm in V1, from the scotoma border to its center. The long-range connections, probably mediating the receptive field expansion (Gilbert & Wiesel 1992), span in monkey V1 8 mm or less, whereas human V1 columns are only about twice the size of the macaque's V1 columns (Cheng *et al.* 2001). One possibility is that the filling-in process is mediated by a cascade of long-range interactions, proposed by Polat and Sagi (1994). This cascade of long-range interactions might be accompanied by feedback from higher cortical areas (Crist *et al.* 2001; Das & Gilbert 1999). It is interesting to observe in this regard that De Weerd *et al.* (1998) related the limitation on the size at which an artificial scotoma can be filled-in to the limited span of the lateral connections. This limitation appears to apply to artificial, but not to physical scotomas.

The third difference between the current and previous studies was in the use of different linear and two-dimensional patterns, and the systematic testing of different pattern densities. This difference in testing is linked to our use of central rather than peripheral scotomas: in peripheral scotomas perception is much more limited and it is difficult for subjects to carry out tasks such as counting and reporting missing dots, or judging the degree of pattern uniformity. The main result from using these patterns was that filling-in improves substantially with the density (within a wide range) and regularity of the presented patterns. For linear patterns, the perceptual uniformity in the scotoma region increased with density. For two-dimensional dot patterns, perceived uniformity increased with the density and regularity of the patterns. These results have several theoretical and possible practical implications. A natural question in the study of filling-in phenomena is whether the perceived patterns are indeed filled-in by the visual system, or perhaps the missing input is somehow ignored by the system, without involving active completion. The results using our range of stimuli provide new support for the active completion view. First, the uniformity of the perceived patterns, including their continuity, contrast, and blur, is dependent upon pattern properties such as density and regularity. This result is more compatible with the active filling-in view compared with simply ignoring the missing pattern, since the ignoring view precludes perceptual judgments in the missing region. Second, under some conditions, such as isolated lines, sparse or irregular patterns, perceptual discontinuity in the scotoma region is reported. This is again more compatible with the filling-in view that may fail under some conditions to be complete, leaving perceivable gaps.

The results with the different two-dimensional stimuli also place constraints on the mechanisms involved in the filling-in process, and suggest that they involve mechanisms beyond simple and complex V1 units. Units in primary visual cortex respond primarily to simple oriented stimuli such as bars and edges. A network of such units could account for the perceptual completion of lines, edges, and gratings. However, we also found effective filling-in for two-dimensional texture patterns, including, for example, sparse and regular dot patterns that are ineffective stimuli for V1 units. The filling-in of these two-dimensional patterns appears to be higher-order, and to depend on the degree to which the pattern is perceived as a uniform textured surface, as opposed to a collection of unrelated micro-patterns.

Finally, the results also raise the possibility of using special image enhancement methods for the benefit of low-vision patients. For example, the density, regularity, and uniformity of visual features could be manipulated to promote efficient filling-in across the central scotoma. This can be implemented in an apparatus that will help low-vision patients to watch TV, look around and read. We carried out initial observation with 70 AMD patients using images manipulated in this manner. Initial results indicated that the modified images are better perceived and preferred by AMD patients, raising the possibility of systematic image manipulation that could improve pattern visibility for AMD patients.

Acknowledgment

This research was supported by the MINERVA Foundation, Germany, and by the Moross laboratory at the Weizmann Institute of Science. We thank C. Gilbert, U. Polat, A. Das, and Z. Luz for their comments, A. Loewenstein for her comments and medical support, and the subjects for their patience and comments.

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