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Macular hole: Perceptual filling-in across central scotomas $\stackrel{\leftrightarrow}{\sim}$

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Abstract

The present study examined perceptual distortions of a vertical line before and after macular hole (MH) surgery in 25 eyes of 24 patients. Participants' perceptual reports of distortions were classified as solid, bent right/left, thinned at the center, or broken. The majority of patients (72%) reported symmetrical distortions of the line pre-operatively. After surgery, participants with larger MHs were more likely to retain residual distortions. Of particular interest is the group reporting thinning of the line preoperatively, as the center should be perceptually missing. Examination of MH diameters in relation to the line perceptions indicated that the shape of the perceived line can be explained at the retinal level, while its continuity must be perceptually created at the cortical level. © 2006 Elsevier Ltd. All rights reserved.

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1. Introduction

Macular hole (MH) is an age-related visual pathology that creates a circular defect in the central area of the retina (macula). In addition to acuity decline, this condition generates distortions (metamorphopsia) or blind spots (scotomas) in the central visual field that are often filled in perceptually. MH patients, therefore, experience deformations in their visual world; telephone poles seem bent and letters disappear while reading words. The detection and quantification of this type of metamorphopsia remains challenging. Clinical tests designed to measure distortions lack the proper parameters for optimal sensitivity (Schu-

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chard, 1993). Furthermore, patients may be able to perceptually fill in the missing information and, with time, become unaware of their deficit (Safran, 1997; Safran & Landis, 1999).

Very little work has focused on perceptual filling-in at the fovea. One case description is available where the researcher stared at the sun in order to study the effect (Craik, 1966). However, given the impossibility of experimentally investigating this phenomenon by creating central lesions in humans, the investigation of perceptual filling-in in the central visual field has turned to ocular pathology, accessing patients with naturally occurring lesions (Cohen et al., 2003; Gerrits & Timmerman, 1969; Valmaggia & Gottlob, 2002; Zur & Ullman, 2003). These studies have exclusively involved participants diagnosed with age-related macular degeneration, a slow degeneration of photoreceptors, or with retinal scars secondary to toxoplasmosis, an intraocular infection that destroys patches of retinal tissue. Therefore, any defects caused by these conditions were inherently heterogeneous in nature because scars and degenerated areas form without any particular pattern.

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The present study took advantage of the homogeneity of MHs, which create a consistently localized and circular defect in the retina and leave peripheral areas intact.

Thus far, only one case study has been published on a detailed psychophysical evaluation of an untreated MH. The study was undertaken by a physiologist who himself was affected by the condition (Burke, 1999). He decided to investigate perceptual changes to his visual abilities, driven by his understanding of psychophysics and the unique opportunity to experience first-hand the effects of a MH. Even though he did not report his level of visual acuity, he did undergo a detailed examination of his abilities to perceptually fill in several stimuli, such as lines, dots and annuli. His description of line stimuli is of particular importance for the present study. Burke's MH had an approximate diameter of 1.5° of visual arc (dva), which was evaluated by the size of his absolute scotoma when fixating at the center of circular targets. He then repeatedly viewed lines of varying diameters at different eccentricities. The thickness of a line determined his ability to perceive its completion across the scotoma, while the positioning of the line determined its amount of bending toward the center of the scotoma.

Since this case description, the development of Optical Coherence Tomography has greatly contributed to the anatomical evaluation of MHs. This technology is able to provide high-resolution cross-sectional images of the retina and can give detailed measurements on MH parameters, such as its diameter, in vivo (Jaffe & Caprioli, 2004). Unfortunately, a detailed assessment of Burke's MH with the use of OCT is not available. Furthermore, due to the low success rate in MH surgery at the time of his diagnosis, Burke chose not to undergo treatment of his condition and follow-up data on any perceptual improvements in his case are not available. Burke's case study is written in the tradition of basic psychophysics whereby the same observer is presented with a stimulus that undergoes an array of changing parameters. The present study added to the assessment of perceptual changes in patients with MH by reversing this approach. In the tradition of applied psychophysics, the same line-stimulus was presented to an array of patients with varying levels of MH diameter.

In order to evaluate perceptual distortions of a line stimulus before and after MH surgery, the following hypotheses were addressed: it was expected that MH diameter would determine the perceptual shape of a line stimulus before as well as after MH surgery. It was predicted that participants who have a larger MH would perceive a broken line before surgery while participants with smaller holes would perceive some type of distortion or a thinned line. In addition, after anatomically successful surgery, individuals who had smaller MH diameters before surgery would perceive a solid undistorted line stimulus and would, thereby, have more successfully restored visual perception. Finally, it was hypothesized that individuals who recovered from perceptual distortions and perceived a solid line at the final follow-up would have significantly better visual acuity than those who reported residual metamorphopsia after successful MH surgery.

2. Method

The protocol was approved by the Institutional Ethics Review Board at the Sir Mortimer B. Davis Jewish General Hospital, Montreal, Quebec, in accordance with the Canadian Tri-Council Policy Statement of ethical conduct for research involving humans and adhered to the tenets of the Declaration of Helsinki.

2.1. Participants

Between June 2004 and August 2005, 24 patients were recruited into the study. The sample consisted of 17 women and 7 men, ranging in age from 29 to 82 years. All patients were free of concomitant retinal disease, and were being treated by one retinal surgeon. They were scheduled to undergo 25-gauge transconjunctival sutureless vitrectomy surgery with gas tamponade (macular hole surgery). All participants spoke English or French and were able to give written informed consent.

2.2. Apparatus

The Line-Resolution Test (Wittich, Overbury, Kapusta, & Faubert, 2005) was displayed on a Toshiba 2060CDS portable computer (Toshiba, Markham, Ontario, Canada) with liquid crystal display (LCD). The display of this line on a LCD screen was not cause for concern as the stimulus only contained first-order information (luminance) and was presented at above-threshold levels with regard to brightness and display time. The stimulus was a vertical line pattern and has previously been described (Wittich et al., 2005). Its luminance distribution was the fourth derivative of the Gaussian function. The width of the line was measured in standard deviations (SD) of this function, whereby the width was set at ± 4 SD from the center of the line. Peak luminance at the center was 130 cd/m² and the line display had the same mean luminance (33 cd/m^2) as its grey background. It was expected that participants would be unable to fixate on a central target, because their foveas did not function properly. Therefore, an incomplete fixation cross indicated the area in which the line was to be displayed. This approach has been applied in previous work with MH patients (Bellmann, Feely, Crossland, Kabanarou, & Rubin, 2004; Davey, Ng, & Burke, 2004).

Standard retro-illuminated ETDRS and Landolt-C charts (Lighthouse International, New York, NY) were presented by the researcher at a distance of 1 or 2 m to accommodate the acuity range of the patients. The Landolt-C chart contained rings with gaps in 1 of 4 orientations (right, left, up, down). Black optotypes were displayed at full contrast on a white background (luminance 185 cd/m²). The luminance parameters fell within an acceptable range of previously established optimal values for eye-chart illumination (Sheedy, Bailey, & Raasch, 1984).

The structural measure of MH parameters was obtained using the Optical Coherence Tomograph (OCT 3; Carl Zeiss Meditec Inc., Dublin, CA, USA). Participants fixated on the center of a line pattern in the scanner display. An optical signal was reflected off the retinal tissue. Differences in the reflectance pattern were translated into a cross-sectional image of the macular area. The specifications of this technique have previously been described in detail (Jaffe & Caprioli, 2004). Six scans at different orientations to the horizontal (30°, 60°, 90°, 120°, 150° and 180°) were taken per eye and the clearest image was analyzed independently by the investigator and a research assistant. The Stratus OCT program determined the diameter of the macular hole, based on manually placed markers, and its software expressed the diameter in microns.

2.3. Procedure

Participants were recruited by the researcher or a research assistant in the Ophthalmology Department on the day of their diagnosis. The purpose and procedure of the study were explained and those expressing interest were invited to arrive at the Ophthalmology Department 30 min before their next scheduled appointment. Written informed consent was obtained and participants were refracted with trial lenses, using the NIDEK Autorefractor ARK-760A (VisionMedical, Montreal, Que., Canada), before vision testing began. They underwent a series of three psychophysical tests (line test, ETDRS and Landolt-C acuity) as well as an OCT scan. All testing was done with the eye that was scheduled to undergo surgery while the other eye remained patched. For acuity testing, participants were encouraged to identify optotypes consecutively in each line. Testing stopped whenever a participant was unable to correctly identify five consecutive optotypes in a line. The same procedure was repeated during each follow-up test session after MH surgery. For statistical analysis, acuities were expressed in logMAR units.

Before the line test began, a display that contained six possible categories of the line test (solid, bent right, bent left, small central hole, thinner center, broken) was shown to the participants (Wittich et al., 2005). They were able to view this display with their healthy eye and were instructed that they would be choosing from these categories during the testing procedure. Participants placed their heads in a chin rest and the screen display was positioned at a 90° angle to the participants' viewing direction. They were instructed to focus on the location where the two diagonal lines of the incomplete fixation cross would intersect. The test stimulus was then presented five times, for 500 ms at each trial. After each presentation, the participants chose among the six possible categories and were asked which one most closely represented what they saw. The most consistent reply (minimally 3 out of the five responses) was chosen as the final response. If the available choices were insufficient, participants were encouraged to draw what they saw.

The OCT scan required the participants to have their pupils dilated with 2.5% phenylephrine hydrochloride (Mydfrin, Alcon, Canada) and 1% tropicamide (Mydriacil, Alcon, Canada). The scan was performed on the day of diagnosis, as well as on each follow-up testing day. The identical testing procedure was repeated on two occasions post-operatively at approximately 3 and again after at least 5 months, when the patient returned to the eye clinic for a follow-up exam with the ophthalmologist. Total duration of each session, including pre-experimental preparation

Table 1

Macular hole diameter and line perceptions for all participants across three time categories

time, did not exceed 30 min. After the scan, participants were seen by the retinal surgeon, as part of their regular treatment.

3. Results

3.1. General descriptors

One patient developed a MH in the second eye during the study period; therefore, the analysis included 25 eyes of 24 patients. The sample consisted of 7 men and 17 women with a mean age of 71.0 years (SD = 7.7) at the time of recruitment. Follow-up time ranged from 5 months to 1.5 years. MH diameter ranged from 199.0 to 905.0 μ at the time of diagnosis, with a mean of 419.0 μ (SD = 174.5). Using average anatomical parameters of axial length (Cornsweet, 1970), MH diameter could be converted into dva, with a mean diameter of 1.54 dva (SD = .63), and ranging from .70 to 3.3 dva.

3.2. Line perception

Patients' perceptions of the line stimulus at each testing session were notably consistent across trials. Generally, they would have the same reply after the first or second presentation. Therefore, the final reported response reflected minimally three consecutive identical choices on trials 3, 4, and 5. However, most patients responded consistently from trial 1 or 2 onwards. Table 1 displays the individual line perception categories for each patient at each testing session.

Patient ID	Pre-Op MH diameter	Line perception Pre-Op	Post-Op MH diameter	Line perception at 3 months	Line perception at 5 months +
16	199.0	Thin	0	Solid	N/A
30	230.5	Thin	0	Solid	Solid
14	255.5	Broken	0	Solid	Thin
3	280.5	Thin	0	Thin	Left
21	280.5	Broken	0	Solid	N/A
17	317.5	Broken	0	Solid	Right
22	324.0	Thin	0	Solid	Solid
28	324.0	Right	0	Right	N/A
26	337.0	Broken	0	Thin	N/A
19	349.0	Right	0	Solid	Solid
18	355.0	Thin	0	Solid	Solid
29	355.0	Broken	0	Solid	Solid
13	374.0	Broken	0	Left	Right
5	386.5	Thin	0	Solid	Solid
1	392.5	Broken	0	Right	Right
11*	425.0	Solid	361.0	Left	Right
12	436.0	Broken	0	Solid	Solid
20	442.5	Thin	0	Solid	Right
15	455.0	Right	0	Left	Right
23	474.0	Right	0	Solid	Right
31	499.5	Broken	0	Thin	Thin
27*	560.5	Left	336.0	Right	Broken
6	573.5	Left	0	Small hole	Left
2*	879.0	Broken	149.0	Thin	Right
25	905.0	Broken	0	Right	Left

Note. Patients are sorted by increasing macular hole diameter, which is expressed in microns, as measured by Optical Coherence Tomography. The * indicates patients with failed surgery where the hole remained open.

Pre-operatively, participants' line perceptions did not depend on MH diameter (n = 25). Due to the distribution of eyes among perceptual categories, only descriptive statistics were possible. When grouping these participants' perceptual distortions of the line into symmetrical (thinned, small hole, broken) versus asymmetrical (bent right or left) categories, 18 (72%) eyes reported symmetrical distortion of the line.

When classifying the perceptual reports post-operatively, at 1–3 months for patients with successful MH surgery, into non-distorted (solid, n=13) versus distorted (all other, n=9) perception of the line, a statistically significant difference in pre-operative MH diameter became apparent, t(20)=2.04, p=.05, $\eta^2=.17$, observed power=.50. Eyes with larger MHs were more likely to retain residual metamorphopsia after successful closure of the defect. After minimally 5 months of follow-up, no statistically significant differences were found in pre-operative MH diameter, t(16)=1.47, p=ns, when classifying the perceptual reports into non-distorted vs. distorted line perception.

3.3. Metamorphopsia and visual acuity

The final component examined visual acuities on the ETDRS as well as the Landolt-C charts. Patients were grouped by the presence or absence of residual distortions. Acuities of both groups were compared at both time points after surgery. At 1–3 months, the groups did not differ significantly on either acuity measure, t(20)=.06, p=ns for ETDRS and t(20)=.08, p=ns for Landolt-C. Beyond 5 months of follow-up, the same pattern was found, t(16)=.53, p=ns for ETDRS and t(16)=.51, p=ns for Landolt-C. Neither visual acuity measure at either time point was able to reflect the presence or absence of metamorphopsia.

4. Discussion

The present study was able to elucidate structure-function relationships in patients with central visual field defects caused by the development of a MH. MH diameter did not accurately predict perception of a vertical line stimulus before surgery. The two key components in explaining this finding may be the choice of fixation target in the stimulus presentation as well as the fixation preferences of MH patients. Various forms of fixation targets have been used in studies involving patients with central scotomas (Bellmann et al., 2004). The most common challenges were related to fixation stability and the ability to find the fixation target (Schuchard & Raasch, 1992). The choice of an incomplete fixation cross in the present study was based on its successful use in previous work with MH patients (Davey et al., 2004; Wittich et al., 2005). In addition, it was assumed that this type of fixation technique would result in placing the center of the line across the center of an absolute scotoma. This assumption may have been incorrect. Previous work by Schuchard and Raasch (1992) evaluated

fixation stability in patients with central scotomas across different types of fixation targets. Their findings indicated that the technique of using peripheral retina for fixation information may not be as efficient as using a small x, which resulted in more stable fixation. In addition, the authors pointed out that a peripheral target, such as the incomplete fixation cross in the present study, still resulted in fixation with the new preferred retinal locus. Even with specific verbal instructions, a large majority of their patients were unable to control their viewing direction in such a way that the center of their scotoma would fall on the fixation target.

When examining the perceptual reports after successful MH closure, it can be assumed that fixation has returned towards the center of the macula (Nakabayashi, Fujikado, Ohji, Saito, & Tano, 2000). At 1–3 months after successful surgery, 13 (59%) eyes perceived an undistorted line while 9 (41%) eyes reported residual distortions. The latter group had significantly larger MH diameter pre-operatively. These results indicate that the extent of residual metamorphopsia may depend on the amount of damage present before surgery. This effect disappeared, however, after at least 5 months, indicating that some type of cortical reorganization may have occurred (Baker, Peli, Knouf, & Kanwisher, 2005) or that the healing process indeed continues well after surgical intervention (Leonard, Smiddy, Flynn, & Feuer, 1997).

The final question to be addressed was whether a link exists between the assessment of metamorphopsia and visual acuity. Contrary to the initial hypothesis, patients with residual distortions in their central visual field did not display differences on the acuity measures compared to patients who perceived the line stimulus to be undistorted. From the psychophysical perspective, this finding is intriguing as the use of this line test revealed perceptual distortions that otherwise remained unnoticed in the clinical setting which relies predominantly on visual acuity. In ophthalmology, metamorphopsia in the context of MH is traditionally detected with the Amsler grid or the Watzke-Allen test (Burke, 1999; Saito et al., 2000; Watzke & Allen, 1969). Both of these tests, however, are presented with unlimited display time and patients are given ample opportunity to scan the stimulus. It is possible that the parameters for the line test, specifically the limited display time of 500 ms, make this measure more sensitive in its ability to detect residual distortions in the central visual field (Wittich et al., 2005). It may, in fact, be sensitive enough to reveal distortions that are so minimal that they do not interfere with the ability to read an eye chart.

In order to explain the type of line distortions described by the participants before as well as after surgery, the question of fixation must be addressed in more detail. The inability to fixate at the center of a scotoma, using information from the peripheral retina had intriguing implications for the perception of the line stimulus. It was initially assumed that the peripheral fixation target would guide the participants' focus in such a way that the line would be viewed across the central scotoma. Unexpectedly though, participants may have used their new fixation area at the edge of the MH in order to fixate at the theoretical intersection of the incomplete fixation target. If that were to be the case, an interesting perceptual change might have occurred, as now the central absolute scotoma may no longer have fallen on the center of the line stimulus but may have been moved off-center. Indeed, some of the participants mentioned that the distortions they perceived looked similar to the options in their display of choices, but were not at the center of the image that they saw. This observation leads to the question of where MH patients actually fixate with the affected eye. Previous work, using a Scanning Laser Ophthalmoscope (SLO), has indicated that, before surgery, patients fixate at or near the edge above the MH (Guez et al., 1998) and that fixation returns towards the central area of the macula after successful closure of the defect (Nakabayashi et al., 2000). As the majority of MH patients have been demonstrated to fixate with the area directly above the MH, the question of whether a line is perceived as distorted or not should be reformulated into whether the line is perceived as symmetrically (fixation above the MH) or asymmetrically distorted (fixation off to either side of the MH). Considering the results of the present investigation from this viewpoint, the percentage of patients with symmetrically distorted line perception was in accordance with previous results (Guez et al., 1998), indicating that most do indeed experience symmetrical line distortions, probably due to fixation above the MH.

Of particular interest is the group reporting thinning of the line preoperatively because, for them, the center should be perceptually missing. Patients seem to fill in the information, resulting in perception of a thinner line at the center. Saito et al. (2000) have previously attempted to explain this phenomenon by examining the perception of the Watzke-Allen Test, whereby a thin white line is projected across the macula, using a slit lamp. They assumed that the photoreceptors, though displaced, were functioning and that the outer edges of the line stimulated the inner edges of the MH. As these cells used to be centrally located, their activity would result in perceptual thinning of the stimulus. In the present sample, this would explain the shape of the perceived line. However, the description of the continuous white central component cannot be explained by this model. The calculation of the line width and MH diameters indicated that the center of the line was not perceived because it was too narrow to be stimulating the edges of the MH in most patients (see Fig. 1). Therefore, the line shape can be explained at the retina, whereas the central line component must be perceptually filled in at the cortex.

The question of activity in the visual cortex in the presence of macular disease is difficult to approach as reports in the literature remain sparse and contradictory. It has been shown that functional magnetic resonance imaging (fMRI) is informative in patients with long-term macular pathology (Sunness, Liu, & Yantis, 2004). However, it remains unclear whether the cortical areas previously stimulated by



Fig. 1. Schematic proportional representation of the mean MH diameter for perception of a broken line (outer circle) and a thinned line at the centre (inner circle). The area within each circle indicates the component of the line stimulus that is lost to perception due to the absolute scotoma within the MH.

the fovea remain active but now only process peripheral information (Baker et al., 2005), or if these areas become silent (Sunness et al., 2004). Some type of cortical reorganization may occur over time, yet, how long the required time span may be or how extensive the damage to the retina can be is not presently established.

The final component of the present study focused on the possible effect of distortions on visual acuity. It was hypothesized that the presence of residual distortions after surgery would be reflected in poorer acuity scores. However, this was not the case. The results indicate that the presented line test may be able to detect distortions that do not interfere with acuity measurement. This finding opens speculations about the type of functional assessment that should be utilized with MH patients. Distortions are generally not quantifiable in the applied clinical context. From the patients' perspective, however, it is the presence of distortions that is more bothersome in their visual experience (Ellis & Baines, 2002; Ellis, Malik, Taubert, Barr, & Baines, 2000). Faces, for example, may appear distorted, making it more difficult to interpret expressions of emotions. From the perspective of structure-function relationships, it is intriguing that an anatomically restored retina looks structurally intact on an OCT scan and allows for acuity within an optimal range on recognition and orientation charts but is unable to perform equally well on a line distortion test. It is likely that this functional discrepancy will motivate

future research regarding the restoration of structure *and* function after the occurrence of retinal disease.

The evaluation of perceptual distortions and the display of the line test encountered a temporal problem. Patients were able to make eye movements across the line during the presentation of 500 ms. Under rigorous psychophysical testing conditions, display time would have to be limited to less than 150 ms. The choice of an extended display time was based on the logistics of applied psychophysical testing with a clinical sample of seniors. It must be pointed out that the participants in this study were recruited in the context of their medical treatment within an ophthalmology department. Their motivation for being present in the clinic was their visual impairment and their need for treatment by a retinal surgeon. Participation in a research project was not their primary concern or interest. The option of participating in a study that did not directly relate to the outcome of their individual treatment required extensive explanation. It was the goal of the research team to create a comfortable environment for the participants and to put them at ease with each task. By extending the display time to 500 ms, the task of "seeing" the line became less frustrating for these participants and they were less likely to discontinue the study. In addition, the extended display time may have allowed participants to compensate for fixation instability, a common phenomenon in patients with macular damage (Bellmann et al., 2004). Therefore, with additional time, they had the opportunity to properly fixate and perceive the line stimulus with their most stable or comfortable fixation location. This stability in fixation would also explain the consistency of the responses over the five trials.

The ideal solution for the problem of fixation instability and exact placement of the line stimulus on the retina would be the use of an SLO. With this technique, a camera and computer screen is connected to the ophthalmoscope, presenting real-time images of the retina to the researcher. The experimenter can then choose, on the computer screen, where on the retina a previously programmed image will be presented. The contribution of SLOs to research with MH has been invaluable, giving insights into fixation patterns (Guez et al., 1998; Hikichi et al., 2000; Nakabayashi et al., 2000), scotoma shape and density (Hikichi et al., 2002; Rohrschneider, Bultmann, Kruse, & Volcker, 2001; Sjaarda, Frank, Glaser, Thompson, & Murphy, 1993a, Sjaarda, Frank, Glaser, Thompson, & Murphy, 1993b), as well as visually evoked potentials (Le Gargasson, Rigaudiere, Guez, Gaudric, & Grall, 1994).

Other investigations of visual function in MH patients have focused on psychophysical techniques such as binocular perimetry (Jensen & Larsen, 1998), spectral sensitivity (Kaur, O'Donaghue, & Murray, 2003), and spatial interval discrimination (Van Baelen, Claessens, Stalmans, & Wagemans, 2005). Each approach will no doubt continue to contribute to the understanding of visual function in patients with MH. In addition to these investigations of visual function, the assessment of structural changes in MH is progressing rapidly, specifically with the development of the next generation of OCT scanners. It is now possible to obtain three-dimensional images at ultra-high resolution which allow for the examination of changes at the cellular level (Schmidt-Erfurth et al., 2005).

The present study was able to contribute to these investigations by exploring perceptual changes after MH surgery. The evaluation of metamorphopsia in addition to visual acuity should be considered more thoroughly in MH patients. More sensitive measures, such as the presented line stimulus, may be able to detect functional deficits that are subject to perceptual filling-in and may otherwise go unnoticed by clinically established measures. The research literature in both areas of acuity thresholds and perceptual filling-in has largely involved healthy observers. Access to a sample of patients with MH provided a unique opportunity. It is questionable whether simulated deficits in younger individuals resemble the visual experience with disease-related vision loss. The key to better understanding of the mechanisms involved in visual perception may, in part, lie in the evaluation of a visual system that is failing or adapting when affected by disease.

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