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#19 Cont

symmetry that is observed in anatomical lattices.

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RECEPTORAL AND NEURAL ALIASING

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Principal Investigator

1 March 1990

Annual Report: Period 11/1/88 -> 10/31/89

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SUMMARY

The major thrust of this project has progressed along three different fronts. 1) The laser interferometer has been constructed and a serious attempt has been made to replicate Williams' studies of aliasing with a similar apparatus. Surprisingly, these results have generally failed to replicate; current investigations center around various avenues which may offer an explanation for this discrepancy. 2) A complementary approach has been started, wherein a small patch of the retinal mosaic is mapped using small points of light. Initial results are quite promising, but it is clear that better control over eye position will be necessary if this is to be a practical technique. The use of video imaging to monitor fixation is under study, with encouraging results. 3) The effect of eye-movements on an aliased image was studied by simulation. Small eye-movements (ocular tremor) will make aliased images move dynamically, but it does not appear that they will render aliasing patterns invisible. Simulations of the embryonic growth of the retinal lattice are being studied, to see if they will produce lattices with the same sort of near-perfect symmetry that is observed in anatomical lattices.

In a brief investigation of a fortuitous observation, the possibility that subjective contours (i.e. without luminance change) could trigger *stereopsis* was studied. It is possible to achieve stereopsis without objective luminance-edges, but the effect is extremely weak.

I. *Outline of Research Activity*

A. *Proposed Research*

Although the proposal does not schedule work on a yearly basis, the following is a reasonable estimate of what we expected to do in the first year.

1. Construct the proposed laser interferometer. This is basic to almost all of the remaining work.

2. Reconcile our earlier results with those of Dave Williams and his co-workers. A major part of this proposal was based on the assumption that by building an apparatus identical to his, we could both replicate his results and -- by simulating our earlier experiments on the new apparatus -- determine the reason for the long-standing discrepancies between our observations.

3. Begin measurements of contrast sensitivity with interference-fringe gratings over a range of retinal eccentricities. This relatively long study would be useful a) as exploratory parametric data in a new area, b) it would contribute to resolving the above-mentioned discrepancy, and c) it would be a first step in demonstrating neural aliasing, which we expect would manifest itself as a particular pattern of sensitivity (described in the proposal).

B. *Research Accomplishments*

1. *The Interferometer*

The first objective has been the construction of the laser interferometer. This was begun in January '89, when the majority of the components had been accumulated, and proceeded rapidly. It was clear within several weeks that we could project fringes on the retina, and that problems of vibration isolation and the like had been adequately dealt with. A plan of the interferometer is shown in Figure 1. The design is a new one, provided to us by Dave Williams, who was building a similar interferometer at about the same time. This design -- though comparable to Dave's earlier device -- offers a distinct advantage in that the two interfering beams traverse exactly the same optical components, only in opposite directions. This cancels out much of the effect of vibration.

The interferometer is built on a 2'x4' optical table which rests on a mattress. This, in turn, rests on a table built of heavy structural aluminum which stands on a concrete floor. The table has wheels for convenience (the device weighs many hundreds of pounds), but these are by far the weakest point in the vibration isolation. In use, therefore, the interferometer table is placed on cement blocks. The subject is stabilized by a bite bar, mounted on a 2"x2" aluminum column. The column is held in a large machinist's vice with two orthogonal lead screws which allow us to precisely position the subject's head. The weakest link in this chain appears to be the subject's dentition; we think a positive forehead rest will substantially improve this, and this is under design.

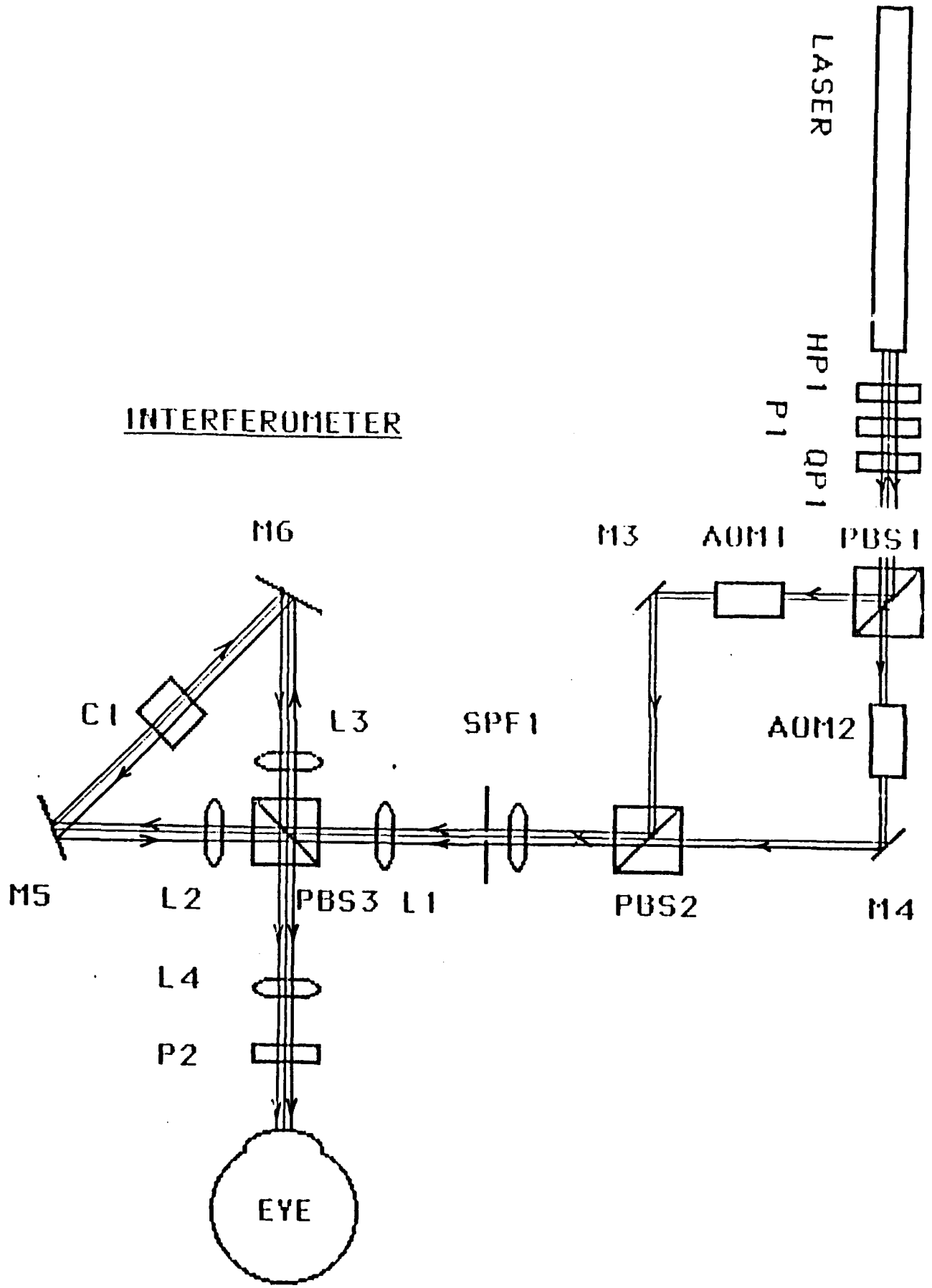

INTERFEROMETER
LASER
HP1
P1
QP1
M6
M3
AOM1
PBS1
C1
L3
SPF1
AOM2
M5
L2
PBS3
L1
PBS2
M4
L4
P2
EYE

Figure 1.

The interferometer is actually assembled on 2" wide bench rails. While not necessary (Dave Williams doesn't use them) these provide easy attachment of devices, with easy motion along the optical axes. The straightness of these rails has proven entirely adequate. We have copied the rails in acrylic plastic (along with their component holders) for use in non-critical parts of the device. The most difficult part of the construction was the motorized mirror-mounts, which tilt the mirrors, varying the orientation and spatial frequency of the grating. While such devices are commercially available, these are typically 1) extraordinarily expensive, 2) several orders of magnitude more accurate than we need, and 3) far too slow to run real-time experimental trials. We removed the stepper motors from two floppy disk-drives, attaching them to the remains of the drives with long cables. The drives remain interfaced to the computer in the normal fashion. This allows us to control the stepper motors using both the hardware and software from the original disk interface; a substantial saving in interfacing effort. The steppers are geared down to run angular mirror positioners. An S-100 computer serves as a dedicated process controller, running both the steppers and the acousto-optic modulators.

Unfortunately, some problems have arisen around the interferometer. First of all, the start of serious research was delayed about three months by an extraordinary delay in the delivery of the acousto-optic modulators. Without these, it was not possible to vary the contrast of the fringes, which is an essential part of our planned experiments. A second problem became apparent simultaneously to us and to Dave Williams; the interferometer depends critically on the ability of polarizing beam-splitter cubes to separate the beam into opposing polarizations with > 99.9% purity. The cubes we are using fall very short of their specifications in this regard. The result of this crosstalk between the polarized beams is that we cannot reduce the contrast of the fringes below about 4%. So far this has actually not affected our experiments, and we have finally located a source of adequate beam-splitters, so this problem is under control.

A more serious problem is apparently not of a technical nature, however. We assumed that when we had duplicated Williams' apparatus, we would be able to replicate his experimental findings, but this is, in fact, not the case. The original discrepancy between our results was this: working with images on a CRT (rather than fringes) we found that orientation discrimination at 7° parafoveal ceased at about 10 c/deg, while Williams was able to discriminate orientation up to about 25 c/deg. The issue is an important one, since the discrimination limit is the operational measure of the onset of aliasing. Thus we appear to be observing with a lattice whose spacing is less than half the spacing of Williams' lattice. How this is possible is by no means clear, but in our proposal, we observed that some important issues hang on this discrepancy, and might be elucidated by a thorough investigation. Even after considerable thought, both in Durham and in Rochester, no one has a very plausible suggestion why the two apparatuses yield such different results.

Despite the use of interference fringes, our measurements of discrimination limit in the parafovea remain quite similar to our earlier measurements (i.e. they are at least a factor of 2 different from Williams'). Moreover, we have been unable to replicate Williams' published results on foveal aliasing ("zebra stripes"). Above about 60 c/deg our fringes become undetectable, and nothing else is seen at any higher frequency. We are not alone in this; at least one other group has seriously tried to replicate Williams and failed (personal communication; researcher wishes to remain anonymous). We have discussed the problem with Dave Williams at some length, but no resolution has come from these discussions. While he acknowledges that the fringes are subtle and hard-to-see, about 80% of his subjects are able to see them. Part of our

problem may be a practical one; to view fringes above about 80 c/deg, it is necessary to dilate the subject's pupil. We do not have available the kind of medical supervision which would permit us to do this with subjects other than the experimenters. Perhaps, by misfortune, Dr. Swift and I are among the 20% of subjects who do not see these phenomena. We are working to get authorization to use other subjects, but permission to administer drugs is not given lightly (or quickly).

Part of our difficulty in seeing aliased patterns surely results from the extreme noisiness of the interferometer's display. An inherent problem with imaging systems using coherent light is that any speck of dirt in the optical path makes a distinct image. This is quite different from conventional imaging systems where the vast majority of such intrusions -- being far from image planes -- are so out of focus as to be invisible. In fact, we have managed to keep the optics of the interferometer quite clean; most of our noise is entoptic, either free-floating in the vitreous humor, or located on the various optical surfaces in the eye. It is possible to suppress the noise from one of these surfaces (the outer surface of the cornea is the worst offender) by focussing the laser beam exactly on that surface, but this still leaves a very noisy image, indeed. The masking effect of visual noise is well-known, and it may be this which is obscuring the relatively faint aliasing patterns. Entoptic noise is believed to become worse with age (this is certainly true for the author), so the use of younger subjects may be helpful. Thibos has done extensive studies of aliasing using the Lotmar white-light interferometer. He has been quite vocal about the advantages of white-light interferometry, precisely because the noise problem is almost entirely avoided. Our experience has made us a good deal more impressed with Thibos' viewpoint; we are considering the purchase of a Lotmar (about $3000) with the express purpose of performing a side-by-side comparison. Although Williams' interferometer may have some notable limitations, it appears to us that entoptic noise, which is primarily high-spatial-frequency, is less of a problem in the parafovea, where acuity is reduced. We are therefore proceeding to take parametric data on contrast sensitivity in the parafovea, albeit with some trepidation, since the unexplained 2-fold difference between our results and Williams' is still present.

2. *Mapping the Retinal Mosaic*

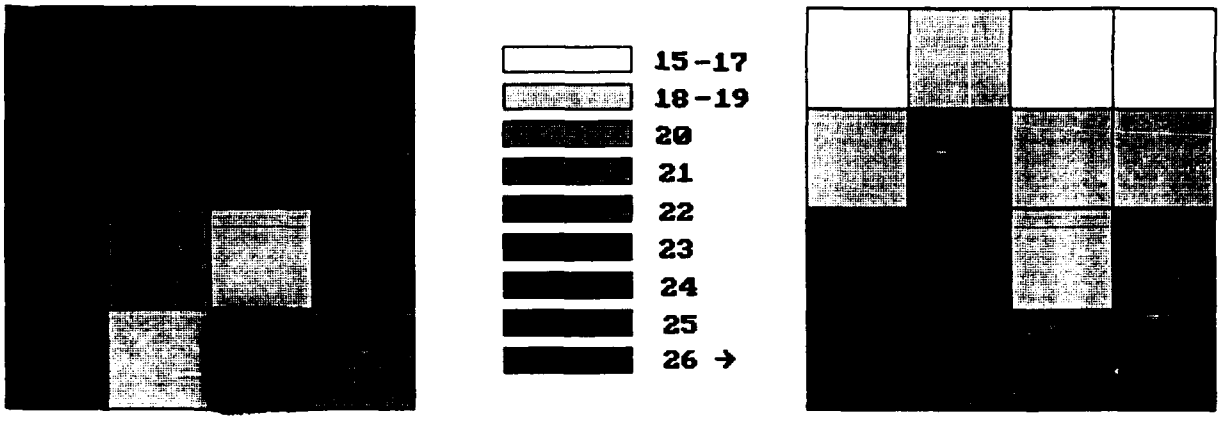
This overall project deals with a variety of indirect methods for studying the retinal mosaic, either receptoral or neural. All of these techniques, however, approach the problem from the spatial-frequency aspect (e.g. the measurement of Nyquist frequencies). Given the difficulties described above, we wondered whether it would be useful to work in the spatial domain instead, by directly mapping the functional mosaic using the detectability of small points of light. The lattice is too dense relative to the large point-spread function to do the mapping in the fovea (Jennings and Charman, 1981), but in the parafovea the lattice density falls very sharply, while optical quality is only slightly reduced. We recently (Smith and Cass, 1989) published data on spatial summation in the parafovea, which suggest that summation areas are about 3' in diameter. Our measurements of the Nyquist limit (Smith and Cass, 1987) offer a direct measurement of parafoveal lattice spacing, which is also about 3'. While these figures are certainly imprecise, they are accurate enough to suggest two things. 1) Both the summation area and the lattice spacing are considerably larger than the optical point-spread function (about 1.2'), suggesting it might be possible to probe these structures with tiny points of light. 2) Since their separation and diameters are about the same, summation areas will be relatively non-overlapping; thus their individual properties might be detectable by such probes. (On the other hand, the parafoveal cone mosaic -- with cone diameters of 1.5' and separations of 2.3' (Hirsch and Miller, 1987) -- is probably too fine for probing in this way.)

If we tentatively accept that a point stimulus can be placed on a summation area with reasonable accuracy, and if we further accept that the summation areas described above have properties similar to ganglion-cell receptive field centers, then some very interesting experiments become possible. The simplest idea is that we could map the sensitivity of a small area of the retina with near-threshold spots. Such an experiment might show a pattern of small, compact areas of high sensitivity, with lower sensitivity between. Some initial experiments with this very simple technique have not yielded statistically significant results, but this does not surprise us The calculations of size and separation given above suggest that the sensitive areas, if not overlapping, are probably too closely adjacent for easy separation. A more sensitive test was devised from the observation that the majority of ganglion cells (the midget ganglion cells, about 85%) are opponent-color-tuned. We changed our task from simple detection to the discrimination of colored spots to effectively "thin out" the mosaic, since a colored stimulus will stimulate only certain retinal areas. Moreover, we asked the subject to discriminate complementary-colored spots (red vs. green). Since the same summation area would presumably not be responsive to both colors, we hoped to find a negative correlation between the sensitivity patterns of the two colors. We have tested three subjects. One appears to lack the fixation ability to perform this experiment (see paragraph below). A second subject typically gives the desired data, at high statistical significance ($p < .001$) for about half of the sessions. A third subject does not produce evidence of "gaps" between receptive fields. However, this was the same subject (PC) who showed the smallest receptive-field separations in our previous measurements of the parafoveal Nyquist limit (Smith & Cass, 1987). This partial success encourages us to think that there is a real effect here, which more refined techniques may reveal. Some representative data are shown in Figure 2.

A major methodological problem with these studies is the questionable ability of our subjects to maintain fixation with the necessary accuracy (perhaps 2'). The subject is provided with a fixation cross, and is allowed to trigger each trial, selecting moments when his fixation seems best. There are no published data indicating how good fixation might be under these conditions, though Riggs, Armington and Ratliff's (1954) data suggest that the desired accuracy is possible. Nonetheless we are certain that fixation error is adding considerably to the noise in our data, and may be accounting for the lack of effect for certain subjects and for certain sessions. We have decided to attack the eye movement problem directly, by monitoring eye position. In extended discussions with Alan Kielar of Iscan Corporation, we find that they are able to track eye position to about 8' accuracy in real time. The limitation on their system is the size of a single pixel. However it is quite possible to accurately estimate the location of an object to a fraction of a pixel (analogous to hyperacuity in vision) using an appropriate algorithm. Using digitized photographic images of the eye (Figures 3 - 5), we have worked out algorithms for tracking both the corneal reflection and the pupil. It is necessary to monitor both, since the corneal reflection is used as a control for small head movements. Both algorithms are stable to about 5" under small perturbations of threshold and other parameters. While this is not a proof that the algorithms will work in an actual experiment, it is most encouraging.

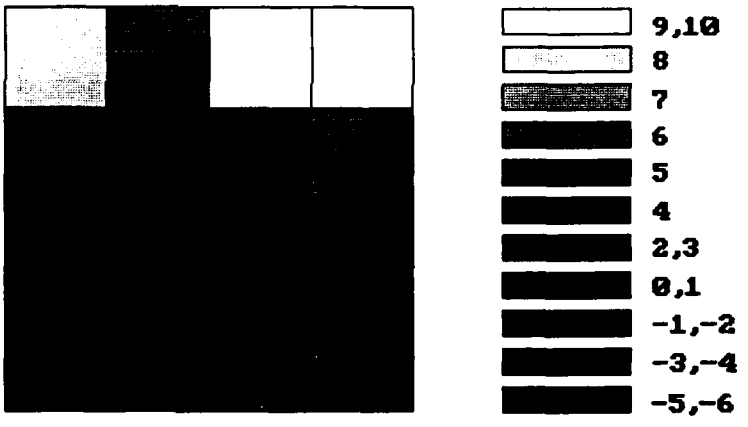
In practice, the experiment we propose is as follows. The subject will perform essentially the same task as in the present situation: fixating a cross while determining the color of a briefly-flashed spot presented 7° in the parafovea. When the spot is presented, a frame-grabber will digitize an image of the pupil, taken in either continuous or strobed infrared illumination, which will then be processed during the inter-trial interval. Note that we do not propose to *track* the eye to high precision in real time; this is probably not possible with current computer technology. Rather we are allowing the computer several seconds to process each frame. With an

accurate localization of eye position, we can calculate our retinal sensitivities in terms of where the spot actually struck the retina, rather than where it was presented on the display screen. We hope that this will dramatically improve our results.



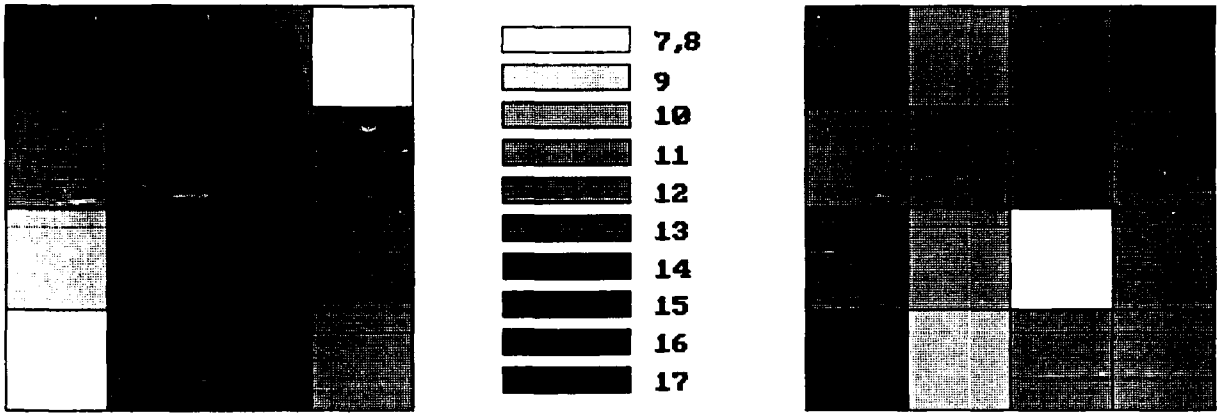
# of Correct *Blue* Responses

# of Correct *Yellow* Responses



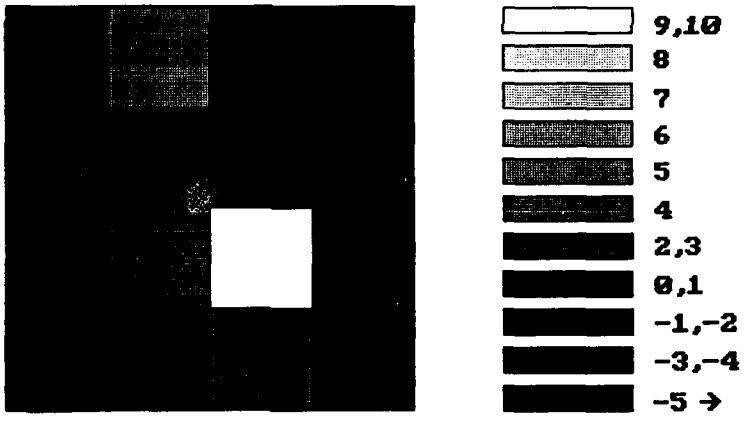
Difference (*Blue* - *Yellow*)

Figure 2a Subject fixated carefully and discriminated between blue and yellow dots presented seven degrees in the superior parafovea. Each square in the matrices represents a single point of light. Center-to-center spacing between points was about four arc-minutes. Blue and yellow spots were each presented 30 times at each location. The squares in the matrices at the top represent the number of correct detections for each color. The matrix at the bottom represents the difference of the two upper matrices. Note that blue is seen more readily in the upper right quadrant; while yellow is seen better in the lower left. Results are highly statistically significant.



# of Correct *Green* Responses

# of Correct *Red* Responses



Difference (*Green - Red*)

Figure 2b Same as Figure 2a, except with green and red spots. Retinal location of spots is similar but not precisely the same as in Figure 2a. Note that there is an area at the bottom middle that seems to more sensitive to green than to red. While this may not seem convincing visually, the correlation between red detections and green detections at each position was *-.81*, and was highly significant.

Figure 3. This grey-scale rendition of an eye shows the corneal reflection (white spot) as well as the pupil (larger dark area).

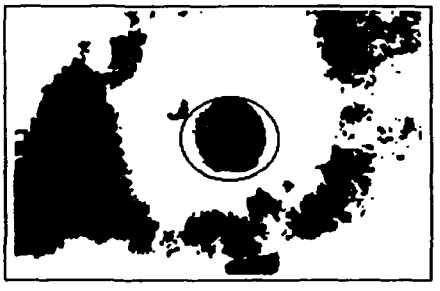


Figure 4. Localization of the corneal reflection. The circle shows the progress of the localization algorithm.

Figure 5. Localization of the pupil. The first estimate of the pupil center is given by the center of a brightness cut.

3. *Modeling the Retinal Mosaic*

We undertook modeling of the retinal mosaic because we were bothered by the following question. Retinal aliasing patterns ("Zebra stripes") are essentially Moiré patterns, and Moiré patterns have the property that a small relative movement of the generating patterns may produce a large movement in the pattern they generate. Specifically if either of the generating patterns moves through one wavelength (or repetition distance), then the Moiré pattern will also move through one wavelength. In the case of aliased interference fringes, the repetition distance will be smaller than the cone separation, while the wavelength of the Moiré fringe may be as much as 2 orders of magnitude larger than that. Thus a small velocity of the fringe will translate into an enormous velocity of the perceived pattern. Since the eye is always subject to small, high-frequency tremors whose size is comparable to the cone spacing, we wondered how the Moiré pattern could ever remain still enough to be seen. We therefore decided to devise a simple model in which we could investigate this question at least semi-quantitatively.

Although there are considerable technical difficulties in assessing fine eye-tremor, the best available data (Eizenman, Hallett & Frecker, 1985) place it in the 40 - 100 Hz frequency range. We are limited in the temporal resolution of our simulation by the 60 HZ frame rate of our CRT. Within these constraints, we decided that a reasonable worst-case scenario was to assume that the spatial phase of the interference fringe with respect to the lattice is random when sampled 60 times per second. We modeled this by generating a perfect triangular lattice of receptors, and projecting on this a vertical grating. The resulting image could actually be viewed, and it displayed aliasing. We calculated a number of these images, of different relative phases, and stored them. The display now selected images at random to present every 1/60 second. Interestingly such a procedure did not produce anything like perfect cancellation of the successive gratings. Although there were brief periods when the stimulus was invisible, there were also periods when the stimulus remained relatively stationary, and the aliased (or Moiré) patterns were quite visible.

While this simulation relies heavily on machine-dependent -- rather than biological -- parameters, we feel that the known parameters of ocular tremor are not so different from our experimental ones as to invalidate our basic conclusion. That conclusion is that rapid involuntary eye-movements are not fast enough to produce cancellation of the image at all times, and so do not seriously disrupt the potential visibility of aliased patterns. As we expected from first principles, however, such movements do cause the image to change rapidly and dynamically.

We were interested in what effect the use of a more realistic lattice would have on this simulation. If we simply allow a small random jitter about the ideal positions of the receptors, this produces noise in the aliased pattern. This is typical of the parafoveal lattice, and is not very surprising. We were more interested in the nearly regular lattice in the fovea. Two questions immediately presented themselves: 1) how do we accurately characterize the almost-regular foveal lattice, and 2) how can we produce similar lattices in our simulation? We attacked the second of these questions first, using a novel approach. We reasoned that the foveal lattice results from a large number of embryonic cone cells growing to fill a basically fixed space. We therefore modeled this growth process (though we found it technically more convenient to keep the cones the same size, and shrink the space within which they were free to move about). A major issue in this simulation turns out to be the boundary condition at the edge of the field of receptors. We have studied rigid and elastic boundaries, and boundaries of different shapes (circular, hexagonal). A hexagonal boundary is much more likely to produce hexagonal packing

than a circular one, for example. We also found that it is necessary to do the calculations to a high precision. If calculations are rounded to the nearest screen-pixel, then the underlying square pixel array influences the simulation, often producing a square lattice! At this point, our general conclusion is that the effect of the boundary is considerably greater than we could wish, given that the boundary constraints on the biological system are by no means clear. We are studying more general and flexible constraints, in the hope that these may prove less troublesome.

4. *What Will Fuse*

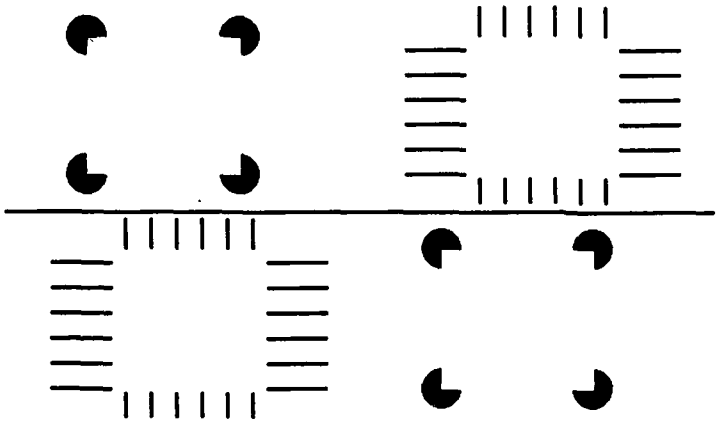
In the course of developing the pcStereoscope™ (which is quite distinct from our AFOSR project), we programmed demonstrations of virtually all of the well-known stereophenomena -- probably more than have ever before been assembled using the same observers and the same apparatus. In the course of this, we inevitably noticed some unexpected phenomena, some of which seemed worthy of purely scientific investigation. One of these is the issue of whether it is possible to fuse subjective (or non-luminance-defined) contours.

The classical theory of stereopsis was that an object was localized by each eye, and the relative difference in position is interpreted as depth. Julesz (1971) showed that this story was backwards. Each point of light to each eye is correlated with points of light to the other eye. The disparity that produces the highest correlation becomes dominant, and all points at that disparity are then seen as a form. Julesz' theory has become well-established, but Julesz never really proved that the old theory could not work -- only that it was unnecessary. The current experiment attempts to answer the question: can form perception be the basis of stereopsis? To do this we must produce stereograms in which the fusion contours are monocularly visible, but have no luminance change associated with them.

Four separate conditions were included. All share the following features: The left eye and right eye each see a square. The two squares are offset slightly. On the left side of the screen the disparity is uncrossed (square should be seen behind the screen); on the right side the disparity is crossed. The squares seen by the left and right eyes share no brightness cues--their only similarity is that they are squares.

Two of the following conditions have been performed before; two are new. A brief description of each follows:

KANIZSA SQUARES - Each eye sees a subjective (or illusory) square that are produced by different inducing figures. On the left side of the screen, one eye gets pac-men figures; the other gets lines. For the other side of the screen, the situation is reversed. Therefore the inducing figures themselves cannot be seen in depth. The only basis for stereopsis is the subjective or illusory squares.



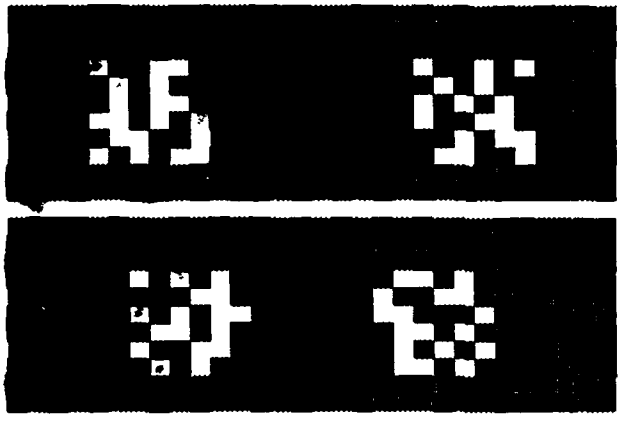
Left Eye

Right Eye

In the above, the square on the left should be seen in crossed disparity (closer to the viewer; the one on the right in uncrossed disparity.

STRUCTURE-FROM-MOTION - Each eye sees a square that is formed solely by motion. At any given instant, each eye is simply seeing a random field of dots. However, a square portion of dots changes position between frames, giving rise to the percept of a moving square. While each eye is seeing the same square, the random dots presented to each eye are completely different. The only basis for stereopsis here is the forms produced by the motion system (Lee, 1971).

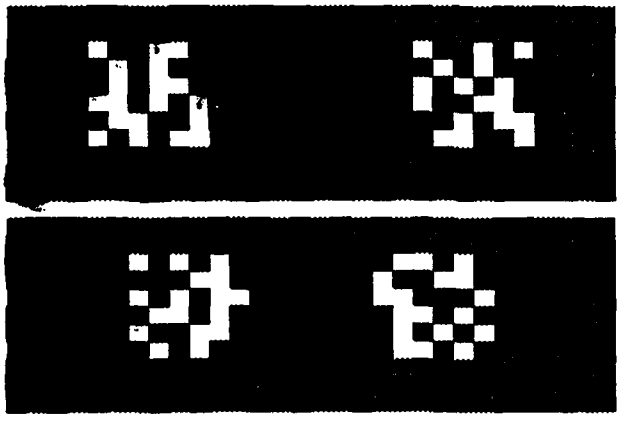
Time 1



Left-eye View

Right-eye View

Time 2



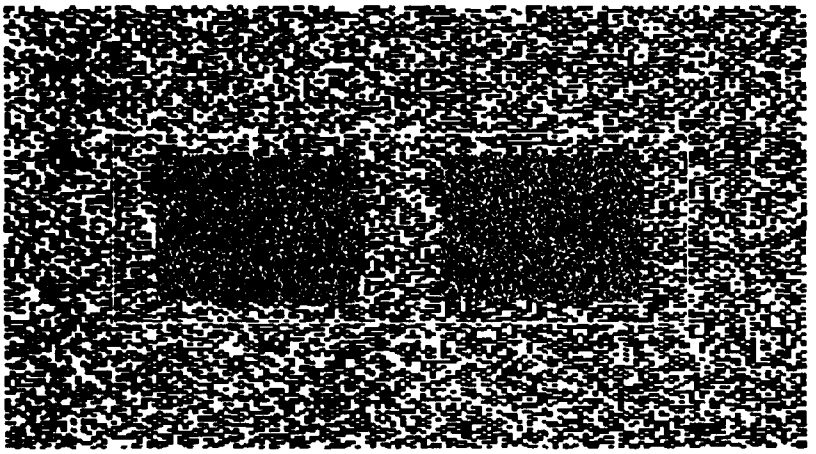
Left-eye View

Right-eye View

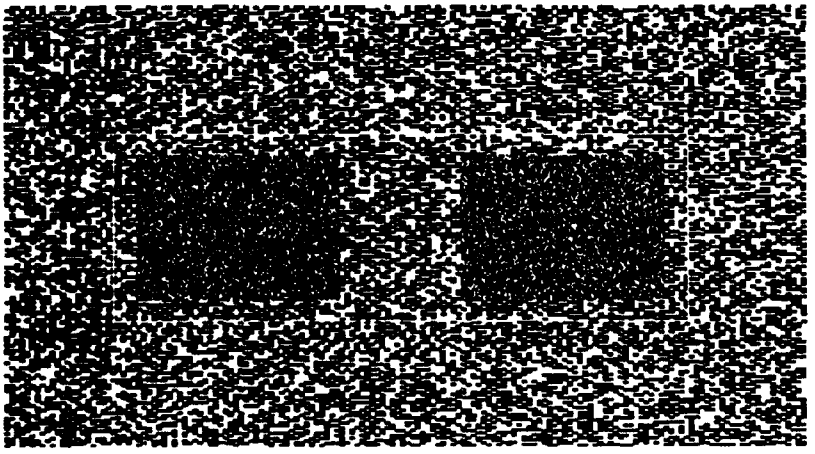
The above four figures represent four frames of the CRT--left-eye frame, right-eye frame, left-eye frame again, and right-eye frame again. The two inner squares on each frame have been highlighted for illustrative purposes only. Note that the inner squares have moved up between Time 1 and Time 2. Each eye therefore sees a square moving upward. Note also that

the right-eye squares and the left-eye squares do not line up in the horizontal domain. This disparity produces the depth effect. This figure is a simplification of the actual stimulus in which approximately 250,000 random dots were used.

TEXTURE DIFFERENCE - The squares are defined by their texture difference with the background (Ramachandran *et al.*, 1973). Once again, however, different random dots are used for each eye, allowing no point-by-point brightness correlation.



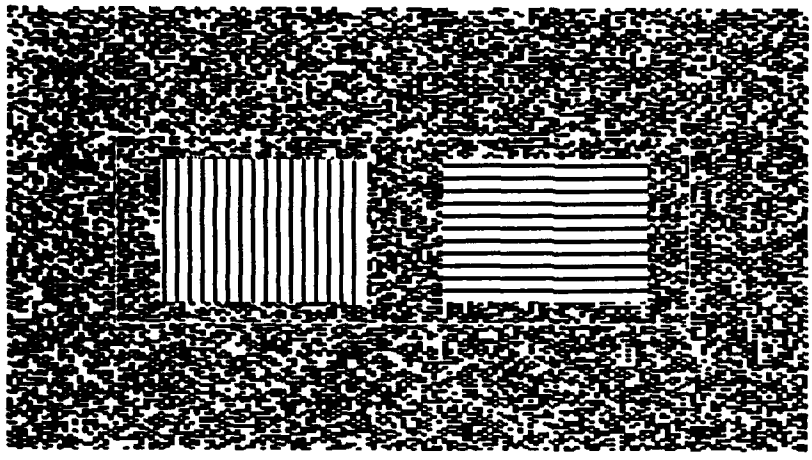
Left-eye view



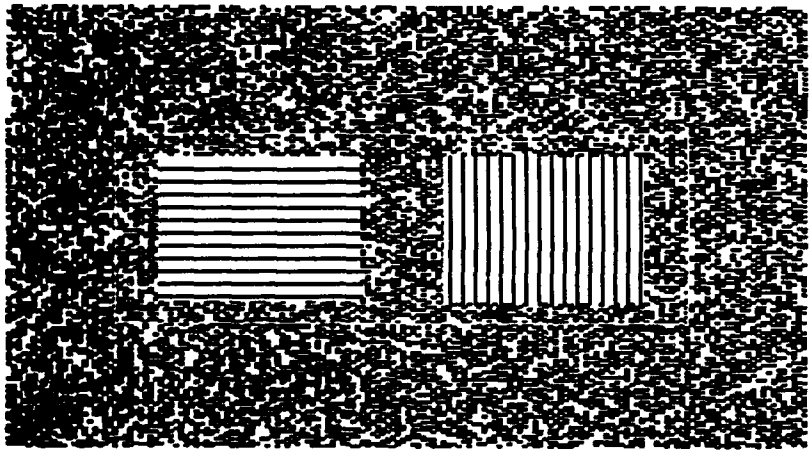
Right-eye view

In the above pair of figures, the square on the left side of the screen will be seen in crossed disparity (closer to the viewer).

VERTICAL/HORIZONTAL - Here the squares are formed by a pattern difference with the background. On the left side of the screen, one eye gets vertical lines and the other gets horizontal lines. On the right side of the screen, the situation is reversed.



Left-eye view



Right-eye view

In the above pair of figures, there is only a small amount of disparity (offset of the squares to the different eyes). The square on the left side of the screen will be seen in crossed disparity (closer to the viewer). In the original version, the mean luminance of the center square and the surround were equal.

The experimental procedure was an interwoven forced-choice staircase. On every trial, the square on one side was presented in crossed disparity, and the square on the other side in uncrossed disparity, under conditions of randomization. Each condition was presented 20 times, and the subjects has to determine the side that contained the "closer" square (i.e. the square that was presented in crossed disparity). Six subjects were run in all, and the experiment was self-paced. No feedback was given. Disparities were approximately 6 arc-minutes in all cases.

The results for the individual subjects are presented in Figure 6. There were significant differences, both between individuals and between conditions. The combined results can be seen in Figure 7. The results for the vertical/horizontal lines produced the best depth effects, though not by a huge margin. This may be due to the fact that the assimilation phenomenon associated with thin lines produces an additional possible cue--a perceived brightness difference between the squares and the background.

It should be noted, however, that all conditions produced results that were significantly above chance. The major conclusion, therefore, is that the form system can feed the stereopsis system, albeit weakly.

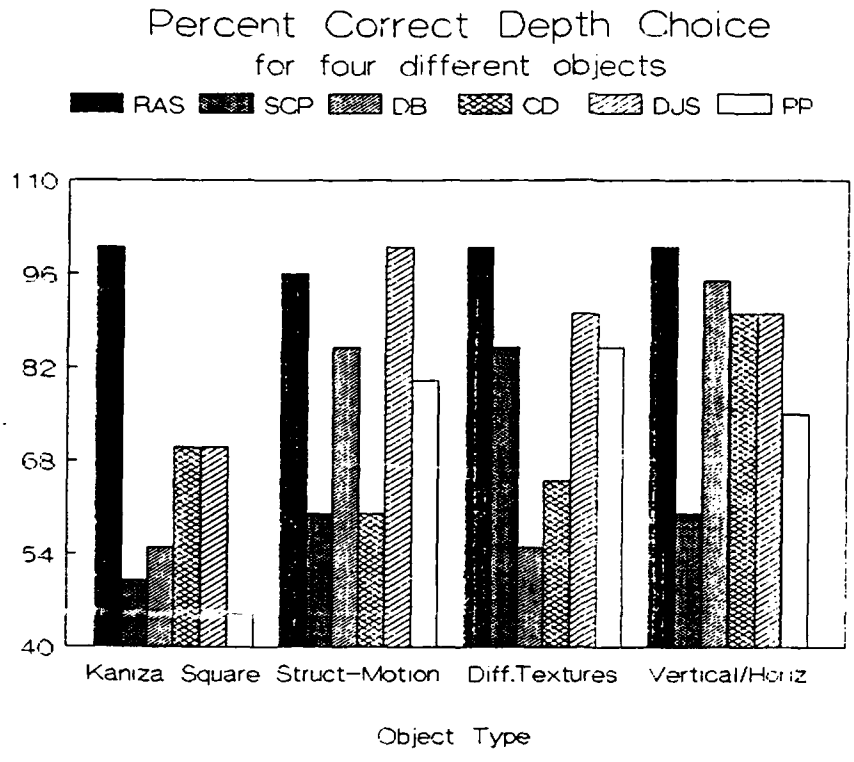


Figure 6. Individual data from "What will Fuse?" See text for details.

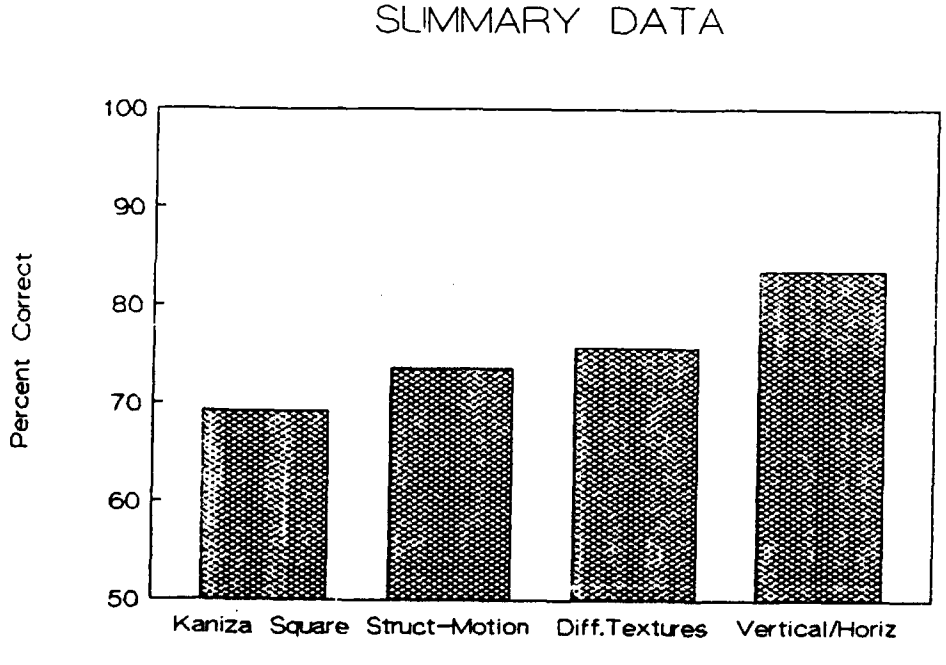


Figure 7. Summary data from "What will fuse?" See text for details.

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Smith, Robert A. and Cass, Peter F. "Effect of eccentricity on spatial summation and acuity." *J. Opt. Soc. Amer. A* **6**, #10, 1633-1639 (1989).

Smith, Robert A. And Cass, Peter F. "Orientation and motion effects in neural aliasing." Submitted to *J. Opt. Soc. Amer. A*

III. *Professional Personnel*

Robert A. Smith, PhD.
Dan J. Swift, PhD.

IV. *Professional Interactions*

Smith, Robert A. "Neural aliasing in the parafovea" presented to ARVO, May 1989.

Swift, Dan J. and Smith, Robert A. "What will fuse?" post-deadline poster at OSA, October 1989.

Smith, Robert A. "Mapping the fine-grain sensitivity of the parafoveal retina." to be presented to ARVO, May 1990.

Swift, Dan J. "Encoding for stereoscopic depth determined from perceived disparity shift" to be presented to ARVO, May 1990.