EVIDENCE OF FOVEAL SPLITTING IN A COMMISSUROTOMY PATIENT

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Abstract—A bilateral projection of the central fovea, produced by naso-temporal overlap at the retinal vertical meridian, has been proposed as the anatomical basis of macular sparing. To evaluate this claim, a commissurotomy patient was required to compare target figures presented 1° or less from the retinal midline with reference figures presented 2.5° from the midline in the same or opposite visual field. The subject judged whether the target and reference were the same or different. It was found that the subject's fovea was effectively split with respect to the cerebral hemispheres; targets in the same visual field as the reference were readily matched with the reference, but accuracy dropped to chance for targets in the opposite field. Ways of reconciling this data with anatomical evidence of naso-temporal overlap and reports of macular sparing are discussed.

IT IS characteristic of primates and other mammals that the left hemiretina of each eye projects to the left hemisphere of the brain while the right hemiretina of each eye projects to the right hemisphere. Each hemisphere of the brain is therefore the direct recipient of information from the contralateral visual field. What happens at the vertical meridian, where the hemiretinas meet, has been the subject of some interest and controversy. Is there a zone of overlap where visual information is sent in tandem to both hemispheres, producing a bilateral representation?

Substantial support for the idea that a strip at the vertical meridian produces a bilateral representation has come from anatomical data. In both the cat [28] and monkey [3, 29] there is a 1° wide strip at the vertical meridian of the retina where ganglion cells projecting to the two hemispheres intermingle. BUNT *et al.* [3] report that in the monkey this "median strip of overlap" splits at the fovea into two 1/2° strips which surround the foveal pit. BUNT and MINCKLER [2] propose that an analogous median strip of overlap in man could form the anatomical basis of "foveal" or "macular sparing", a phenomenon characterized by the preservation of a small pool of central vision in a visual field rendered otherwise blind by unilateral damage to the visual pathway.

Grounds exist, however, for questioning the attribution of macular sparing to such a double projection of the fovea. Unilateral damage to the visual pathway can also result in "macular splitting" [30]. Moreover, experimental attempts to detect the functional consequences of a midline overlap in normal subjects have uniformly failed to do so. Manual reaction times to visual stimuli are slowed when the responding hand is contralateral to visual field of the stimulus, even if the stimuli are presented less than 1° from the midline [11, 18]. Similarly, reaction time delays in a letter naming task which occur when letters are presented to a subject's non-verbal hemisphere are not diminished when the letters are

presented 30' from the midline [12]. These outcomes suggest that stimuli close to the retinal midline do not have direct access to the hemisphere normally tied to the opposite hemifield.

Several studies on patients lacking a corpus callosum bear on the question of midline overlap, but none appears to allow a definitive conclusion. In a subject with callosal agenesis, LINES [17] found a large delay in manual responses to flashes of light that were presented 30' from the retinal midline, when the visual field of the flash was contralateral to responding hand. However, significantly larger delays occurred with larger stimulus eccentricities. Lines points out this finding could be attributed to a weak bilateral midline projection or to erratic fixation by the subject. MITCHELL and BLAKEMORE [20] failed to find stereoscopic depth perception in a commissurotomy patient when disparate stimuli were presented on opposite sides of the vertical meridian, but the $2°$ disparity employed in this experiment may have placed the disparate stimuli outside any zone of overlap. SPERRY [27] and GAZZANIGA [7] report that when commissurotomy patients were briefly shown rows of dots that crossed the vertical meridian, they indicated manually that they saw only the number of dots presented to the hemifield ipsilateral to the responding hand. The placement of stimuli relative to the midline was not well controlled in these experiments, however, and it is not clear whether partial or degraded visual representations were counted by the subjects.

It therefore seemed desirable to assess the presence of naso-temporal overlap in the fovea of a commissurotomy patient using a more precise and sensitive methodology than that previously employed. To accomplish this, a commissurotomy patient was required to compare "target" figures that were presented $1°$ or less from the retinal vertical midline with "reference" figures that were presented distal to the midline in either the same or opposite visual field. The subject's task was to indicate if the target and reference were the "same" or "different". It is well established that commissurotomy patients normally cannot compare stimuli presented to their opposing visual hemifields [7]. However, if a band exists at the vertical meridian which projects to both cerebral hemispheres, a stimulus presented sufficiently close to the midline ought to be represented in both the hemispheres of such a patient. It was therefore predicted that if there was naso-temporal overlap within the subject's fovea, targets presented close enough to the midline would be matched accurately to reference figures in either visual field. The "between field" trials, in which the target and reference were presented to opposing visual fields, allowed for a direct evaluation of this prediction. The "within field" trials, in which the target and reference were presented to the same visual field, provided a baseline against which the between field data could be evaluated.

Since stimulus presentations close to the retinal midline allow for serious artifacts due to fixation errors, the subject was run monocularly with her right eye and that eye was monitored with a high resolution eyetracker.* Trials were initiated only if the subject's fixation met with a strict criterion of accuracy.

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*Although the two eyes are normally tightly yoked with respect to the microsaccades that occur during fixation, there is some independence with respect to the small drifts that occur between those microsaccades [31], and the tightness of the interocular yoking in commissurotomy patients has not been investigated. The Purkinje image eyetracker used in the present experiment to monitor the subject's fixation is only capable of monitoring the right eye. It was therefore deemed essential to restrict the subject's vision to that eye, in order to ensure the validity of the experiment's fixation control procedures. At the time this research was conducted, the authors knew of no reason to suspect that any difference in the outcomes might have resulted if the left eye had been tested. However, see the footnote attached to the discussion section.

METHOD

Subject

V.P., a 33-year-old female commissurotomy patient, served as the subject. Two stage commissurotomy with sparing of the anterior commissure was performed on V.P. in 1979 for the treatment of intractable epilepsy (see SIDTIS *et al.* [26] for a detailed history of this patient). V.P. was alert and co-operative at the time of testing. Two characteristics made V.P. well suited for the present experiment: (1) her well developed right-hemisphere cognition allowed for a ready comprehension of the experimental task by both her cerebral hemispheres and thus allowed the balanced testing of both her visual fields, and (2) her ability to fixate steadily facilitated the accurate monitoring of her eye motions, and permitted a large number of trials to be run in an efficient manner. In one respect V.P. was not ideal as a subject: MR imaging has revealed a small region of fibre sparing in both the splenium and rostrum of her corpus callosum [9]. However, during previous investigations V.P. was not able to compare figures presented to her two hemifields distal from the vertical retinal midline [8, 13].

Apparatus

All stimuli were presented to the subject on a Hewlett–Packard Model 1311A large screen oscilloscope with a fast phosphor (P15) CRT. Displays were generated and controlled by an IBM PC-AT microcomputer using a Kinetic Vision Systems vector generator board. The CRT screen resolution was 300 pixels per degree on both the X and Y axes. The subject's horizontal right eye position was monitored with an SRI double Purkinje image eyetracker, which has a resolution of 1 min of arc [5]. Output from the eyetracker was sampled using a Data Translation Model DT2821 analog to digital converter (ADC), with the eyetracker gain set so that one ADC digit corresponded to 1 min of arc of eye displacement. Display refresh and eye position sampling were synchronous at a rate of 250 Hz. In tandem with the computer sampling of the eyetracker output, an analog record of the subject's eye position was obtained on a strip chart recorder. The subject responded on each trial by pressing one of two buttons on a small box situated on the table in front of her to indicate whether the stimuli presented were the same or different; these buttons were monitored by two digital input channels on the ADC board.

Displays, design and procedure

The subject viewed the displays monocularly with her right eye from a distance of 1 m in a darkened viewing booth, with her head positioned by a bite plate. An eyepatch covered her left eye. A single luminous point on the CRT screen positioned at the subject's subjective straight ahead was always displayed and served as the fixation point. Four outline geometric figures served as the display stimuli: a square, a bisected triangle, an asterisk, and an hourglass-like shape. These are shown in Fig. 1. All four figures were constructed of four straight lines of similar length. On each trial, one of these figures served as the reference and was presented for a minimum of 1 sec prior to the onset of the target, 2.5° to the left or right of the fixation point on the horizontal meridian. The target figure was then presented for 200 msec with the reference remaining on the screen. The target was either the same figure as the reference or one of the three alternative figures, and was displayed on the horizontal meridian in one of five positions: 15′, 30′ or 1° from the fixation point in the visual field opposite to the reference, or 15′ or 1° from the fixation point in the same visual field as the reference. (Trials with the target 30′ from fixation in the same visual field as the reference were eliminated to reduce the trial load on the subject.) The height and width of the figures was 30′ of arc when they served as the reference and 15′ of arc when they served as the target. The larger size was used for the reference figures to insure their easy discriminability despite the fact that they were presented parafoveally. The luminance of the lines forming the stimuli was approx. 4 cd/m² against a nominally dark background. Following the target presentation, both the reference and target vanished, signalling the subject to respond. The subject responded by pressing one of the two buttons on the response box to signify whether the reference and target had been the same or different. The hand used by the subject to respond was always ipsilateral with the visual field of the reference. Since the trials were blocked with respect to the field of the reference (see below), the subject was able to keep the appropriate hand poised on the response box during each session.
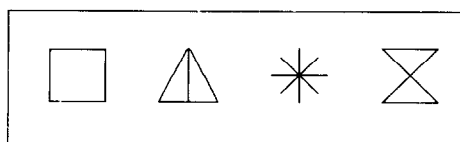
Stimulus Figures

FIG. 1. The four stimulus figures are presented. Figures subtended 30′ of arc when they served as the reference and 15′ when they served as the target.

A total of 480 trials were run in six blocks of 80 trials each. In three of the blocks the reference figure was presented to the subject's right visual field, and in the other three blocks to her left visual field. Each block was made up of 40 Same and 40 Different trials. The probability of a Same presentation was therefore 0.5 on each trial. Within each block, there were eight same presentations (two presentations each of the four possible same pairings) and eight Different presentations (consisting of a random subset of the 12 possible different pairings) for each of the five target positions. Altogether, 48 trials were run for each target position with the reference in each visual field; this yielded a total of 192 within field trials and 288 between field trials, half with a left field reference and half with a right field reference. The 80 trials in each block were presented in a random order with the constraint that 20 Same and 20 Different trials were in the first and second halves of each block. The first four blocks were run on four successive days in an abba order, with a right field reference block first. The remaining two blocks were run on two successive days about 4 months later, with the right field reference block first. Running each block took between 60 and 90 min. Several short rest breaks were taken in the course of each block.

To permit the calibration of the eyetracker at the start of each experimental session, a row of five points was displayed on the CRT screen. The points in the row were separated by 1°, and the position of the row's center point matched the position of the fixation point during the experimental trials. During calibration, ADC readings were printed to the computer console screen while the subject fixated the various points. This allowed the eyetracker output to be centered around zero during fixation of the center point, and for the tracker's gain to be set for an increment or decrement of 60 for a 1° shift in fixation. Only horizontal eye movements were monitored. Since the experiment only required the accurate measurement of small deviations from central fixation, corrections for the nonlinearities in the trackers output were not deemed necessary.

During each experimental trial, several steps were taken to control for errors in fixation.

(1) At the beginning of each trial, the subject fixated the central point and the eyetracker was locked on the subject's eye. ADC values read from the tracker's horizontal output were printed to the investigator's computer console. This allowed the investigator to verify correct operation of the tracker, and if necessary make small offset adjustments so that the tracker output stayed centered on zero as the subject fixated this point. The investigator then initiated the onset of reference display.

(2) During the initial 1 sec reference display period (and during any subsequent delay prior to the onset of the target), if the subject shifted her gaze more than 30′ from the fixation point, the reference figure was blanked (with a worst case delay of 4 msec) until the eye was found to be less than 30′ from the fixation point again.

(3) After the 1 sec reference display, the target was displayed only if the eye was found to be within 6′ of the fixation point, and remained within 6′ of it for a period of 20 msec. Otherwise, the reference display remained on and eye position sampling continued until this condition was met. The 20 msec requirement was imposed to minimize the possibility that the eye would be caught crossing the 6′ fixation window in the course of a saccade.

(4) Finally, if the subject's eye did not remain within the 6′ fixation window while the target was being displayed, an error message was printed to the computer console at the end of the trial. Trials flagged by an error message were rerun at the end of each experimental session.

Despite the fact that V.P.'s fixation stability generally appeared to be quite good, approx. 20% of the trials had to be rerun because her eye left the 6′ fixation window during the target display interval. This can be attributed to the very narrow size of the window. The use of this narrow window, however, ensured that all the target stimuli were in fact presented on the retina to the intended side of the subject's normal retinal fixation locus. Since the target figures were 15′ wide, when targets were flashed 15′ from the fixation point the edge of the target closest to the fixation point was 7.5′ from it. Therefore, even if the eye deviated from perfect fixation by the full 6′ allowable, the target remained correctly lateralized.

The experimental task was explained to the subject at the start of the first session (and again at the start of the fifth session), and illustrated by training presentations in which both the reference and target remained on screen until the subject responded. Following this, a series of practice trials were run for both the left and right visual fields. In all of the training and practice trials, the reference and target figures were presented to the same visual hemifield, with the target 1° from the midline. The subject responded accurately during these practice trials on both left and right field presentations, demonstrating that both her cerebral hemispheres understood the task. At the start of each subsequent session, a few additional practice trials were run with the reference presented to the hemifield in which it would be presented during that trial block.

RESULTS

A graph of the outcomes for the various target positions is presented as Fig. 2. Two tailed binomial tests were conducted to evaluate if the observed accuracy rates differed significantly from a chance value of 50%.

Initially, it should be pointed out that the general pattern of outcomes in the data is commensurate with the assumption of foveal fixation. If the subject had biased her gaze to the left, changes in the accuracy of her responses that were associated with the vertical

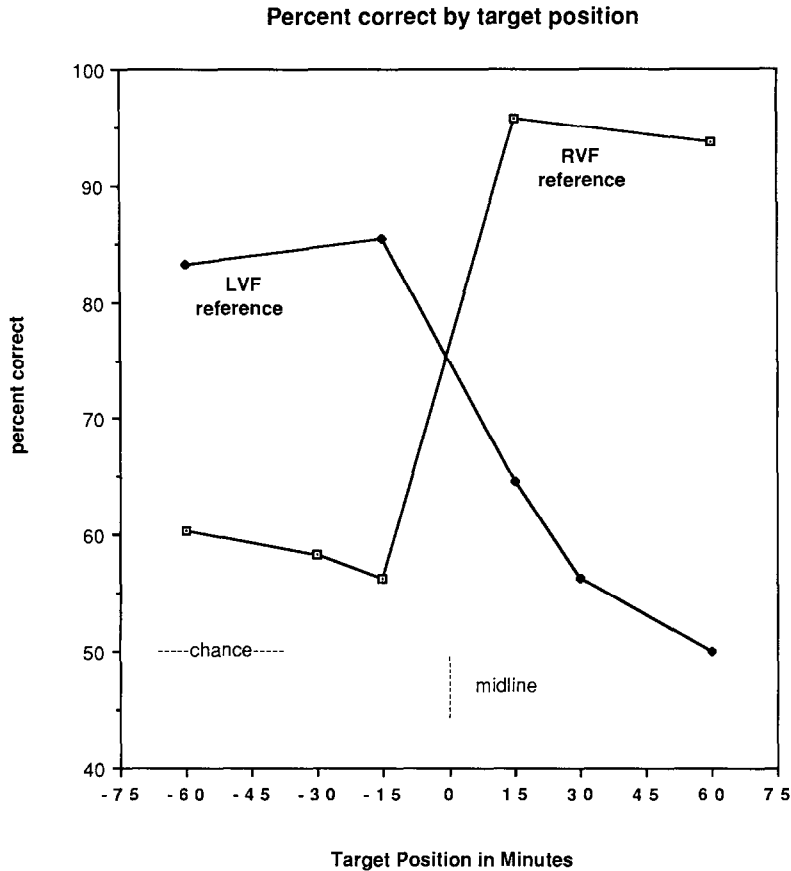## Percent correct by target position

FIG. 2. Data for all stimulus conditions are given as the percentage of the responses that were correct. Each data point is based on 48 responses. Target positions are in minutes of arc from the fixation point, with positions to the left expressed as negative values.

meridian would have been centered around a position to the left of the fixation point. Similarly, if she had biased her gaze to the right, changes in accuracy associated with the vertical meridian would have been centered around a position to the right of the fixation point. It can be seen in Fig. 2 that the two lines depicting V.P.'s accuracy for trials with a right and left field reference descend symmetrically with respect to the fixation point; no apparent shift of the distributions to the right or left actually occurs. This pattern indicates that the vertical meridian of the subject's retina was positioned at or very close to the fixation point.

Turning to the data for trials with a right field reference, the most striking feature of this data is the dramatic drop in V.P.'s accuracy rate that occurred when the target position was shifted across the fixation point. This can be readily seen in Fig. 2. With the target offset 1° to the right of the fixation point V.P. responded accurately on 93.7% of the trials ($P < 0.0001$), and with the target offset 15' to the right of the fixation point she was correct on 95.8% of the trials ($P < 0.0001$). Thus, as expected, V.P. performed quite well on the within field trials. However, when the target was presented 15' to the left of the fixation point, V.P.'s accuracy dropped precipitously to 56.2% ($P > 0.1$). A change from near perfect accuracy to near

chance accuracy was therefore produced by a one half degree shift in target position across the center of the subject's fovea. V.P.'s accuracy remained low at 58.3% ($P > 0.1$) for targets offset 30' to the left and 60.4% ($P > 0.1$) for targets offset 1° to the left.

On trials with a left field reference, V.P.'s accuracy was 83.3% ($P < 0.0001$) with targets 1° to the left of the fixation point and 85.4% ($P < 0.0001$) with targets 15' left of the fixation point. With targets 15', 30' and 1° to the right of the fixation point, her accuracy rates were 64.6% ($P > 0.05$), 56.2% ($P > 0.1$), and 50% respectively. Again, shifting the position of the targets across the vertical meridian caused V.P.'s accuracy to plummet. With a left field reference, however, this drop in accuracy is less steep than the corresponding drop with a right field reference. This is in part attributable to the fact that V.P.'s within field accuracy was not as good in her left visual field as it was in her right visual field, and in part attributable to a trend toward increased accuracy with between field targets 15' from the midline in the right visual field. While the subject's accuracy failed to reach the 0.05 level of significance with these targets, it did attain significance at 0.07 level. A possible implication of this trend will be addressed in the discussion section.

In sum, the data fail to confirm the prediction that figures within the fovea close to the vertical midline would be capable of being matched to reference figures in either visual field, and thus fail to provide evidence for a bilateral representation of the fovea. V.P.'s fovea is effectively split with respect to the cerebral hemispheres. The data therefore point to the conclusion that the functional break at the vertical meridian, at least for stimuli of the type employed in this experiment, is in fact very sharply defined.

DISCUSSION

The present experiment fails to provide evidence for a dual projection of the fovea to the cerebral hemispheres: figures presented to the subject's left and right visual fields less than 1° from the vertical meridian were not conveyed to the ipsilateral hemisphere. This finding is in agreement with previous research with normal and commissurotomized subjects [7, 11, 12, 17, 18, 27]. However, it appears to conflict with the anatomical findings of midline overlap [3, 28, 29] and needs to be reconciled with clinical reports of macular sparing.

To account for the anatomical data, one could speculate that the "median strip of overlap" found in the cat and monkey is absent or largely absent in man, or that any ganglion cells in the left and right human hemiretinas that project to the opposite hemisphere serve only some highly specialized function. Such cells, for instance, might help mediate the perception of forms moving across the vertical midline. A role in stereopsis also seems plausible [1]. The failure of MITCHELL and BLAKEMORE [20] to find midline stereopsis in a commissurotomy patient argues against this, but, as earlier noted, the 2° disparity employed by these investigators may have placed their stimuli outside any zone of overlap.

It has been argued that macular sparing should be attributed to either residual function in the damaged visual pathway or to eccentric fixation on the part of the hemianopic observer [10, 19]. To rule out residual function, HUBER [14, 15] performed perimetry on 11 subjects with unilateral occipital lobectomies. In every case Huber found a 1° or narrower band sparing along the vertical meridian. However, in investigations such as Huber's, limitations inherent in standard perimetric instruments (such as the Goldmann perimeter which Huber used) make the accurate appraisal of foveal fixation virtually impossible [20]. To eliminate fixation errors, FISHER et al. [6] and PERENIN and VADOT [23] employed entoptic retinal phenomena in investigations of macular sparing. Fisher et al. found macular splitting in a

single patient. Perenin and Vadot found splitting in two patients with pregeniculate lesions and sparing in five with postgeniculate lesions. However, in all cases where sparing was found there was some residual vision in the blind hemifield. In at least two of these patients, the residual vision cannot be attributed to the presence of spared cortex, since both of these patients were hemidecorticated during childhood. PERENIN [21] has argued that the residual pattern vision in these hemidecorticate patients may be mediated by the superior colliculus, which has been proposed as the likely anatomical substrate of the "blindsight" localization abilities found in such patients [22]. Whether or not this is the case, the presence of any residual ability to discriminate patterns distal from the midline in the patients studied by Perenin and Vadot must render the interpretation of their findings in terms of midline overlap suspect, especially since, as Perenin and Vadot note, the spatial extent of the apparent sparing found in these patients was well in excess of the extent which the anatomical data on overlap would lead one to expect. An explanation of macular sparing in terms of the combined effects of residual function and eccentric fixation therefore remains viable. To the extent that the present study is not compatible with an explanation of sparing based on a dual representation of the midline, it favors this alternative.

Other approaches to resolving the discrepancies in the data on midline overlap can be found, however. COLENBRANDER [4] argued that the central retina projects bilaterally to the cortex, but that via the corpus callosum the brain hemisphere dominant for each side of the retina inhibits the representation of the overlapping region in the other hemisphere. This inhibition prevents a dual representation from manifesting itself when both hemispheres are functional. When function is lost in the dominant hemisphere, the inhibition is released, allowing the normally nondominant hemisphere to mediate vision. The present experiment weighs against Colenbrander's proposal, since in commissurotomized subjects the inhibition ought also to be released, but the possibility of inhibition via a subcortical pathway or V.P.'s surviving splenial fibers remains.

It may also be possible to reconcile some of the discrepancies in the data on midline overlap by assuming that the retinal ganglion cells projecting to the "inappropriate" hemisphere are at best capable of providing only degraded visual information. Since the figures in the present study differed mainly in their high spatial frequencies, good visual resolution was required to distinguish between them. Standard perimetric techniques, on the other hand, require only that a subject detect the presence of a small spot of light. A degraded representation of the contralateral hemiretina within each cerebral hemisphere might be evident with standard perimetry but not in a more demanding task like the present one. If such a degraded representation exists, evidence of overlap might be obtained if the present experiment were repeated with figures that differed more in their low spatial frequency content.

This degraded representation hypothesis is concordant with the fact that the density of the contralaterally projecting cells found by BUNT et al. [3] was quite low; these cells constituted only 7% of the cells in the median strip of overlap. It also accords with reports of decreased sensitivity and acuity in spared regions [16]. It does not seem to accord with the failure of HARVEY [11] and LINES and MILNER [18] to find a reaction time benefit for flashes of light presented close to the midline when subjects responded with a hand contralateral to the stimulus field. However, Lines and Milner note that since the intensity of their stimulus was low, an attenuated representation of it in the "wrong" hemisphere might have been too weak to elicit a rapid response. When LINES [17] repeated the Lines and Milner procedure with an acallosal subject he did find an advantage for the flashes presented closest to the midline.

In the present data, the trend toward increased accuracy for targets 15′ from the midline in the right visual field when there was a left field reference might be accounted for by the presence of such a degraded representation: one can speculate that this trend reflects the availability of some minimal information regarding the target's shape to the right hemisphere. No comparable trend is observable for targets 15′ from the midline in the left visual field when there was a right field reference, but this difference could be attributed to the putative advantage of the right hemisphere in processing dim or blurred visual inputs [24, 25].*

However, in the present data the trend toward increased accuracy in the right visual field when there is a left field reference is apparent only for targets 15′ from the midline; it is not present for targets 30′ from the midline. If this trend is taken to suggest of a degraded midline projection of the hemiretinas to the contralateral brain hemispheres, it must also be taken to suggest that the width of the band projecting any usable shape information is extremely narrow. The existence of such a narrow band of degraded information would hardly seem to warrant a claim that there is a double projection of the fovea. The need for an alternative explanation of clinical reports of macular sparing is therefore indicated.

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*An alternative explanation of why this trend is unilateral is provided by a paper by LEVENTHAL, AULT and VITEK [*Science* 240, 66–67, 1988], published just after this paper was completed. Leventhal *et al.* report that in both New and Old World monkeys, contralaterally and ipsilaterally projecting ganglion cells intermingle at the vertical midline only in the nasal hemiretina. They argue that a similar pattern in the human eye would lead one to expect macular sparing in the eye contralateral to the lesioned hemisphere but macular splitting in the eye ipsilateral to the lesion. In the present case, viewing was restricted to the subject's right eye. If one assumes that with the present subject testing with a reference in the right visual field was functionally equivalent to lesioning the right hemisphere, while testing with a reference in the left visual field was equivalent to lesioning the left hemisphere, it would follow from the Leventhal *et al.* hypothesis that evidence of naso-temporal overlap should have been found only when a left field reference was employed. While the present data provides little evidence of functional naso-temporal overlap, the observed asymmetric trend is commensurate in its direction with the Levanthal *et al.* prediction. Conceivably, then, if the subject's left eye were tested, a similar trend would be found that was reversed with respect to the visual fields.

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