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Spatial distortions in localization and midline estimation in hemianopia and normal vision

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ABSTRACT

Studies have shown that individuals with hemianopia tend to bisect a line toward their blind, contralesional visual field, termed the hemianopic line bisection error (HLBE). One theory proposes that the HLBE is a perceptual distortion resulting from expansion of the central region of visual space. If true, perceptual expansions of the central regions in the *intact* hemifield should also be present and observable across different tasks. We tested this hypothesis using a peripheral localization task to assess localization and midpoint estimation along the horizontal axis of the visual field. In this task, participants judged the location of a target dot presented inside a Goldmann perimeter relative to their perceived visual field boundary. In Experiment 1, we tested neurologically healthy participants on the peripheral localization task as well as a novel midpoint assessment task in which participants reported their perceived midpoint along the horizontal axis of their left and right visual fields. The results revealed consistency in individual biases across the two tasks. We then used the peripheral localization task to test whether two patients with hemianopia showed a selective expansion of central visual space. For these patients, three axes were tested: the spared temporal horizontal axis and the upper and lower vertical axes. The results support the notion that the HLBE is due to expansion of perceived space along the spared temporal axis. Together, the results of both experiments validate the use of these novel paradigms for exploring perceptual asymmetries in both healthy individuals and patients with visual field loss.

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1. Introduction

Hemianopia, or a binocular loss of vision in one half of the visual field, occurs following unilateral damage to the optic tract, optic radiations, or striate and/or extrastriate cortical areas (Blumenfeld, 2002). It is most often caused by stroke or trauma (Zhang et al., 2006). One characteristic of acquired hemianopia is the Hemianopic Line Bisection Error (HLBE), or the tendency to bisect lines in the direction of the *impaired* (contralesional) hemifield. This tendency is the opposite to that commonly observed in patients with unilateral visual neglect, who tend to bisect lines away from the impaired hemifield, showing an ipsilesional bias (Barton & Black, 1998; Liepmann & Kalmus, 1900).

Though the HLBE is well documented, there are several unresolved issues that have inspired recent research in this area (Kerkhoff & Schenk, 2011; Kuhn et al., 2012; Mitra et al., 2010; Ogun, Viswanathan, & Barton, 2011; Schuett, Dauner, & Zihl, 2011; Zihl et al., 2009). Some studies have reported that the HLBE is found only in patients with lesions in extrastriate visual areas (Schuett, Dauner, & Zihl, 2011; Zihl et al., 2009), although other research that simulated hemianopia in neurologically healthy participants suggests that the HLBE results from loss of vision within a large region of visual space, and does not only arise with hemianopia due to extrastriate lesions (Mitra et al., 2010; Ogun, Viswanathan, & Barton, 2011). Other work has investigated the development of a "pseudo-fovea" (i.e., eccentric fixation) in hemianopia, similar to those observed in patients with central field loss following macular degeneration (Cheung & Legge, 2005; Crossland et al., 2005), and the role that shifts in spatial attention

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play in the HLBE (Kuhn et al., 2012). While spatial cueing has been shown to modulate line bisection errors in neurologically healthy individuals, with the perceived midpoint of a line shifted toward the cue location (Harvey et al., 2000; McCourt, Garlinghouse, & Reuter-Lorenz, 2005; Nichelli & Rinaldi, 1989; Toba, Cavanagh, & Bartolomeo, 2011), a spatial cueing study in patients with hemianopia failed to find significant modulations in the direction or magnitude of the HLBE (Kuhn et al., 2012). The results of Kuhn et al. (2012) also provide evidence against a possible contribution of a preferred eccentric retinal locus to the HLBE.

By definition, patients with hemianopia are only able to perceive lines within one hemifield. Thus, in order to assess the midpoint of a line, patients with hemianopia must either be able to scan a line over time or the entirety of the line must be presented to the intact hemifield. If patients scan across a line, they will view all or part of the line within the intact hemifield at a given moment. If fixation is attempted toward the middle of the line, then patients must maintain and utilize a short-term representation of the line length that is no longer visible within the area of field loss. Alternatively, patients could fixate one end of the line, allowing them to perceive the line entirely within the intact hemifield and perform calculations on line length and midpoint based on this viewpoint. If this latter approach is taken then one potential complication that arises is differences in perceptual sensitivity and potential size asymmetries that may exist as a function of eccentricity. This possibility was assessed by Nielsen, Intriligator, and Barton (1999) in a study of neurologically healthy participants who were asked to judge the midpoint of horizontal and vertical lines while fixating on one end or the other. Results of three experiments showed a centripetal bias, or a tendency to perceive the midpoint closer to the point of fixation than it actually was by approximately 2.6% of the line length. This finding suggests a relative expansion of visual space in the central versus peripheral regions of the visual field. Further analysis suggests that the pattern of results is more consistent with participants determining the midpoint of lines through "angle bisection" rather than line bisection as the true angular midpoint is located more peripherally, though a central expansion was still present even when the midpoint was calculated in terms of degrees of eccentricity. While the centripetal bias is directionally consistent with the over-representation of the central visual field observed in early retinotopic visual areas (Horton & Hoyt, 1991), the magnitude of the bias observed in this sample suggests that cortical magnification in early retinotopic visual areas alone cannot predict the magnitude of bias that was observed. Indeed, it has been suggested by other researchers that differences in attentional distribution or attentional scanning over a large region of space contribute to the centripetal biases observed when lines are presented within one hemifield (McCourt, Garlinghouse, & Slater, 2000).

The presence of a space-based central bias in neurologically healthy participants has been confirmed in another series of studies that manipulated the relative position of greyscale stimuli (Nicholls et al., 2004; Orr & Nicholls, 2005). Greyscale stimuli have been increasingly used instead of line bisection stimuli to assess "pseudoneglect", which refers to the tendency for neurologically healthy individuals to bisect lines slightly to the left of center (or in this case perceive the same gradient stimulus as "darker" when presented on the left side). Interestingly, the results of the study by Orr and Nicholls (2005) dissociated a leftward bias, pseudoneglect, from the foveal bias, suggesting that the foveal expansion observed in the study by Nielsen, Intriligator, and Barton (1999) is distinct from the leftward biases observed in most bisection studies of pseudoneglect.

One of the goals of the present study was to determine the degree to which the two tasks used are sensitive to perceptual distortions that vary across individuals and hemifields in neurologically healthy participants (i.e. pseudoneglect). We used both a peripheral localization task as well as a novel bisection task that measures the degree to which individuals can locate the midpoint of their right or left visual field (Visual Axis Midpoint Assessment task, VAMA). We then compared estimated midpoints across the peripheral localization and VAMA tasks to determine whether they were measuring similar localization abilities. These tasks were then used to study spatial biases in patients with hemianopia.

Although studies of spatial biases in hemianopia have focused primarily on line bisection tasks, numerous other paradigms have been developed to study peripheral localization (Adam et al., 1993; Fortenbaugh & Robertson, 2011; Fortenbaugh et al., 2012; Müsseler et al., 1999; Temme, Maino, & Noell, 1985; van der Heijden et al., 1999) and the application of these paradigms may help to provide further insight into the perceptual processes leading to the HLBE. In particular, given the existence of perceptual biases in neurologically healthy individuals that may be object-based (Orr & Nicholls, 2005), it is of interest to employ other paradigms that assess perceived location in the absence of external objects to determine whether the HLBE represents an expansion of central visual space beyond that observed in neurologically healthy participants under similar experimental conditions.

In a previous series of experiments (Fortenbaugh et al., 2012), we demonstrated that in the absence of any external object boundaries, neurologically healthy individuals mislocalize briefly-presented target dots toward the periphery of their visual field, indicating an expansion of central visual space similar to that observed by Nielsen, Intriligator, and Barton (1999). We also found greater expansion of central visual space at near compared to far eccentricities. We measured peripheral localization of target dots presented in a Goldmann perimeter by collecting verbal magnitude estimates in relation to perceived visual field extent (see also Temme, Maino, & Noell, 1985). The Goldmann perimeter is a self-illuminated half-dome that allows manual presentation of targets at locations up to 90° of visual angle in any direction and has several advantages for peripheral localization studies, including (1) the absence of any external object boundaries, such as the edges of a computer monitor, (2) the ability to present targets at any visual field location while simultaneously visually monitoring the fixation of participants, and (3) the use of the same visual environment and stimuli to measure peripheral localization as well as visual field extent. In the present study we address two questions. In Experiment 1 we test the degree to which our peripheral localization task is sensitive to hemifield asymmetries in neurologically healthy individuals. In Experiment 2 we assess peripheral localization performance in two patients with hemianopia and show spatially specific distortions that are consistent with the HLBE.

2. Experiment 1: peripheral localization in neurologically healthy participants

2.1. Methods

2.1.1. Participants

Eleven neurologically healthy normal-vision undergraduate volunteers completed the experiment (7 females; mean age: 21.2 ± 2.4 years). All participants reported 20/20 visual acuity, either without optical correction or with optical correction by contact lenses. Participants were excluded if they wore eyeglasses, as these artificially restrict the visual field (Steel, Mackie, & Walsh, 1996). All participants reported no history of eye diseases or neurological disorders of any kind. All procedures were approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley, and followed the tenets of the

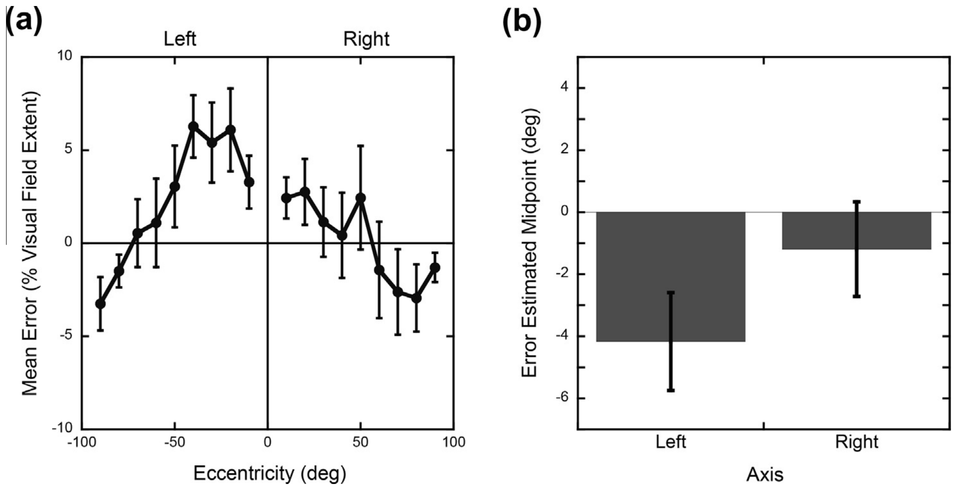

Fig. 1. Experiment 1 peripheral localization task. (a) Mean errors in percentage of visual field extent for the left and right axes as a function of target eccentricity. Positive values indicate a peripheral bias while negative values indicate a foveal bias. Error bars represent ±1 SEM. Solid horizontal lines at zero represent no perceptual distortion. (b) Mean errors in estimated midpoints of the left and right visual axes in degrees of visual angle. Error bars represent ±1 SEM.

Declaration of Helsinki. All participants provided signed informed consent before the study began.

2.1.2. Materials and procedure

Testing was conducted in a Goldmann perimeter, a self-illuminated half-dome with a uniform white background that is used for kinetic perimetry (see Fig. 1, Fortenbaugh et al., 2012). We first measured the binocular visual field extent along the horizontal meridian using the III4e test target (0.44° test spot at a viewing distance of 30 cm; 318 cd/m^2 on a background luminance of 10 cd/m^2). Briefly, the participants maintained fixation on a dot located in the opening of the telescope at the center of the half dome while the experimenter projected the target light in the far periphery and then slowly moved it toward the fovea. Participants pressed a button that elicited a tone as soon as they detected the light in the periphery. Upon hearing the tone, the experimenter, situated on the other side of the perimeter, marked the location of the target on a chart. Participants then completed the two behavioral tasks described below, and task order was alternated across participants.

2.1.2.1. Peripheral localization task. The procedures for measuring peripheral localization are identical to those previously described (Fortenbaugh et al., 2012), with the exception that only the horizontal meridian was tested here. Before beginning behavioral testing, the experimenter briefly flashed the target at the boundary location along the left and right horizontal axes to remind participants of the locations of the edges of their visual field (that had been determined previously in the session).

The same III4e test target used in the perimetry measurements was briefly flashed (~175 ms) at various eccentricities along the left and right horizontal axes, with locations along the two axes intermixed within the block of trials. Target locations were tested in 10° increments from 10° to 90° (or as far into the periphery as possible while remaining within the subject's visual field). Each target location was tested 5 times in random order. A unique random sequence was generated for each participant prior to testing. Fixation was continually monitored throughout each trial by the experimenter via the small telescope located in the center of the perimeter, which provided a magnified view of the eye being tested. Targets were not presented until stable fixation at the center was achieved. On each trial, participants provided a verbal magnitude estimate of how far the target location was from fixation. Target estimates could be any whole number from 0 to 100, where 0 indicated that the target was presented in the center of the visual field (i.e., fixation) while 100 indicated that the target was presented as far as they could see along that axis (i.e., at the boundary of their visual field). Participants performed 5 practice trials to familiarize them with the task.

2.1.2.2. Visual Axis Midpoint Assessment task (VAMA). The VAMA task was modeled on landmark tasks that have been used to assess perceptual distortions in perceived length or size in patients with unilateral neglect (Milner, Brechmann, & Pagliarini, 1992; Milner et al., 1993). Testing was conducted in the Goldmann perimeter using the same III4e test target as the visual field measurements and the localization task. Here, targets were presented at one of seven eccentricities (25°, 35°, 40°, 45°, 50°, 55°, and 65°) in the left and right visual field, resulting in a total of 14 target locations. This large range of eccentricities was tested to accommodate differences in visual field extent across participants, as this shifts the true midpoint of each axis. Each target location was tested 10 times in random order. A unique random sequence of test locations was generated for each participant prior to testing. On each trial, participants reported whether the target had appeared closer to fixation ("inside") or closer to the edge of their visual field ("outside") than their perceived midpoint along the axis being tested. Participants performed 5 practice trials with the targets in random locations to familiarize them with the task.

2.2. Results

2.2.1. Peripheral localization results

The mean horizontal binocular visual extents of the participants were: left axis: 86.4° ± 3.0°, right axis: 85.1° ± 4.1°. For the localization task, data were analyzed in the same manner as previously described (Fortenbaugh et al., 2012). First, given the visual field extent along each axis for each individual, the true percentage of visual field extent was calculated for each target location. Errors were then quantified by subtracting the true percentage of visual field extent from the magnitude estimate made by the participant. Thus, positive values indicate a peripheral bias, or a mislocalization of targets toward the boundaries of the visual field, while negative values indicate a foveal bias. Fig. 1a shows the mean errors in percentage of visual field extent for the left and right axes as a function of target eccentricity. A 2 (Axis) × 8 (Eccentricity) repeated-measures ANOVA was calculated on the localization

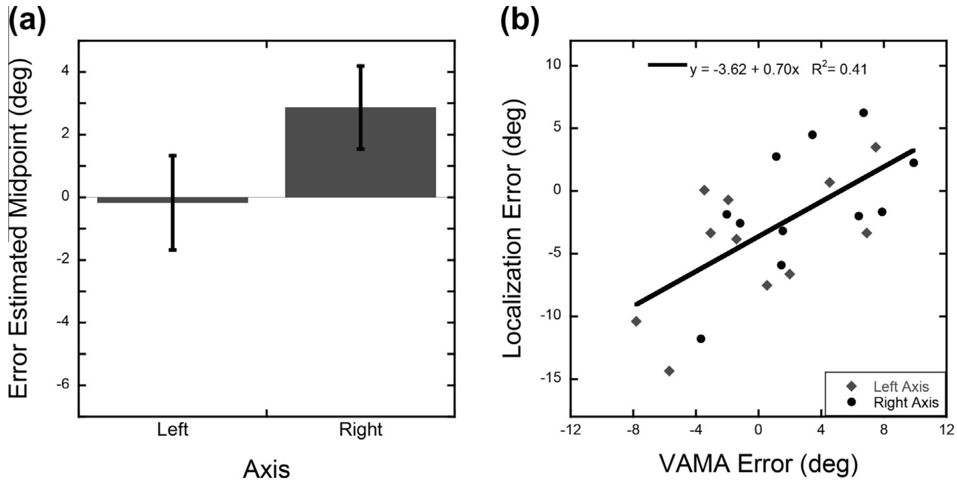

Fig. 2. Experiment 1 Visual Axis Midpoint Assessment (VAMA) Task. (a) Mean errors in estimated midpoints of the left and right visual axes in degrees of visual angle. Error bars represent ±1 SEM. (b) Scatterplot of the errors in estimated midpoint from the peripheral localization task as a function of the errors in estimated midpoint from the VAMA task in degrees of visual angle. Data from the left axis are shown as diamonds and data from the right axis are shown as circles. Each participant contributes two points to the plot. The black line displays the regression line calculated from data combined from both axes.

errors as these eccentricities were tested for all participants on both axes. Results show a main effect of Axis, $F(1,10) = 9.72$, $p = 0.01$, indicating greater peripheral biases in localization along the left axis than the right axis, and a significant main effect of Eccentricity, $F(7,70) = 3.58$, $p = 0.002$, indicating greater errors for near compared to far eccentricities. The Axis $\times$ Eccentricity interaction was not significant, $F(7,70) = 1.36$, $p = 0.24$. These eccentricity results replicate the finding of peripheral biases for targets within the central regions of the visual field, resulting in an inverted-U shape in the error versus eccentricity plot (Fortenbaugh et al., 2012).

One goal of the first experiment was to directly compare estimates of the perceived midpoint of the left and right axes for both the localization and bisection tasks within the same individuals. We estimated perceived midpoints for the localization task by modeling the scaling patterns across eccentricity. Specifically, for each participant and axis separately, power functions (Eq. (1)) were fit to the raw magnitude estimates for all eccentricities tested:

$$J = \lambda D^{\alpha} \tag{1}$$

In this equation, J is the estimated target magnitude, D is the actual target magnitude, λ is the slope parameter that represents a global scaling factor that compresses or expands all values by a constant amount proportional to the actual target magnitude, and α is the exponent parameter (with $\alpha = 1$ indicating a linear relationship between actual and perceived target eccentricity). Raw magnitude estimates were well fit by this power function (average $R^2 = 0.93$, range = 0.86–0.96).

Given the best fitting slope and exponent parameters for each participant and axis, we then determined the target magnitude, D_{midpoint}, that would predict a response of $J = 50$ (i.e., the perceived midpoint). Errors in perceived midpoint were then calculated by subtracting the true midpoint from the estimated midpoints, with positive values indicating a peripheral shift and negative values indicating a foveal shift in perceived midpoint. Fig. 1b shows the mean errors in estimated midpoints from the localization task for the left and right axes. One-sample t-tests of mean error in estimated midpoints show a significant foveal shift (consistent with expansion of visual space at near eccentricities) for the left axis, $t(10) = -2.64$, $p = 0.02$, but not for the right axis, $t(10) = -0.78$, $p = 0.45$. A paired-sample t-test of mean errors shows that the foveal shift is significantly greater for the left axis than the right axis, $t(10) = -3.55$, $p = 0.005$.

2.2.2. VAMA results

For the VAMA task the proportion of "outward" or peripheral responses was calculated for each target eccentricity. Cumulative Gaussian distribution functions were then fit to the data for each participant and axis separately. This allowed an estimate of the point of subjective equality (PSE), or in this case, the perceived midpoint of each axis. The data were well fit by the cumulative Gaussian distributions (average $R^2 = 0.99$, range = 0.95–1.00). For each participant and axis we then calculated the errors in estimated midpoints by subtracting the true midpoint from the estimated midpoint, with positive values indicating a peripheral shift and negative values indicating a foveal shift (Fig. 2a). A paired-sample t-test was calculated on the error scores, with results again showing a significant difference across the left and right axes, $t(10) = -2.31$, $p = 0.04$. One-sample t-tests were then calculated on the errors in estimated midpoints against a hypothetical mean of zero in order to determine whether the errors represent significant shifts. The results show a trend toward a peripheral shift in estimated midpoints for the right axis, $t(10) = 2.17$, $p = 0.06$, but not for the left axis, $t(10) = -0.17$, $p = 0.91$.

2.2.3. Comparison across tasks

In order to determine whether performance on the peripheral localization task reflects individual biases in perception or if individual differences reflect cognitive factors related to the generation of magnitude estimates we compare midpoint estimates across the two tasks. If biases in the peripheral localization task are primarily due to perceptual distortions of visual space, performance in the peripheral localization and VAMA tasks should be correlated across subjects. However, if cognitive processes underlying magnitude estimation contribute to the biases in the peripheral localization task, these processes presumably would have little effect on VAMA task performance, as this task only requires a binary response without assignment of a specific magnitude value.

We computed correlations in estimated midpoints across the two tasks using Pearson's r (Fig. 2b). In order to increase power, errors from both axes were pooled, with each participant contributing two points. We observed a significant correlation ($R = 0.64$, $p = 0.04$), with errors in estimated midpoints from the VAMA task accounting for 41% of the variance in estimated midpoint errors in the localization task (Fig. 2b). Interestingly, when linear regressions were separately calculated for the left and right visual field axes, similar regression slopes were found (left: $y = 0.65x - 4.06$; right: $y = 0.68x - 3.15$). Thus, while errors in estimated midpoints differed across the left and right axes for both the localization and VAMA tasks, the differences were consistent across tasks for individual participants. Moreover, differences in performance across the two tasks are well accounted for by additive shift reflected in the intercept.

In order to examine the relationship between the new tasks reported in this experiment and more traditional measures of hemifield asymmetries in neurologically healthy individuals, we further asked whether differences across the left and right axes were similar to those observed in landmark/line bisection tasks assessing pseudoneglect (Jewell & McCourt, 2000). To this end, we used the errors in estimated midpoints for each axis to derive an estimate of the shift in the midpoint of the horizontal meridian. Specifically, for both the peripheral localization and VAMA tasks, we first calculated the percentage of central visual field expansion along the left and right axes by the equation: %Expansion = 100 * (Error in Midpoint/Visual Field Extent). This measure represents the extent to which midpoints were shifted centrally or peripherally in degrees of visual angle, normalized by the total length of each subject's visual axis in degrees of visual angle. The normalization controls for differences in visual field extent across axes and across individuals.

The perceived midpoint was then defined as: $(\%\text{Expansion}_{\text{right}} - \%\text{Expansion}_{\text{left}})/2$. This score quantifies the expected shift in the midline of the horizontal meridian, with negative values representing a shift toward the left and positive values indicating a shift to the right. One-sample *t*-tests revealed significant leftward biases in the perceived midline of the horizontal meridian for both the localization, $t(10) = -3.531$, $p = 0.005$, and VAMA tasks, $t(10) = -2.28$, $p = 0.046$ (Fig. 3a). A paired-sample *t*-test showed no significant difference between the two tasks in calculated horizontal midline shift scores, $t(10) = 0.14$, $p = 0.89$. Finally, midline biases were significantly correlated between the two tasks across subjects, $R = 0.84$, $p = 0.001$ (Fig. 3b).

2.3. Discussion

2.3.1. Shifts in localization in a normal population: replication and extension

The results of the peripheral localization task showed a similar overall pattern to that observed in the binocular viewing condition of our previous study (Fortenbaugh et al., 2012), with participants overestimating the eccentricity of targets within the central 50° of the visual field. This resulted in the characteristic inverted-U shape pattern of localization errors that was previously observed and a foveal shift in the estimated midpoint of the left axis that was computed from power functions fit to the raw magnitude estimates, consistent with the centripetal bias found in other studies (Nielsen, Intriligator, & Barton, 1999).

Importantly, errors in estimated midpoints on the VAMA task predicted 41% of the variance in the errors from the peripheral localization task. Though the bias in estimated midpoint varied across the two tasks, the positive correlation across tasks suggests that errors observed in target localization using verbal magnitude estimates are capturing individual differences in the perception of space across the visual field and do not simply reflect response biases specific to the generation of magnitude estimates. These findings provide support for the hypothesis that, when applied to individuals with visual field losses, significant deviations from normative errors observed in the magnitude estimates reflect perceptual distortions in the representation of visual space.

2.3.2. Hemifield differences in peripheral localization

Both the peripheral localization and VAMA tasks showed a central shift in estimated midpoints along the left axis relative to the right axis, consistent with distances from fixation on the left side of space appearing longer than equal distances on the right side of space. These findings are consistent with the well-known asymmetries in length, size, and interval judgments, termed pseudoneglect, in which lines on the left side are perceived as longer than equivalent lines presented on right side (Jewell & McCourt, 2000; McCourt, 2001; McCourt & Jewell, 1999; Milner, Brechmann, & Pagliarini, 1992; Porac, Searleman, & Karagiannakis, 2006). Pseudoneglect has been attributed to a differential distribution of attention across the left and right side of space (Charles, Sahraie, & McGeorge, 2007). While attention was not directly manipulated in the present experiment, it is possible that testing target locations along only the horizontal meridian altered the distribution of attention, thereby revealing intrinsic biases in the representation of visual space across the left and right hemifields not previously observed with this peripheral localization task (Fortenbaugh et al., 2012).

Utilizing the errors in perceived midpoint estimated for the left and right axes within each task, we calculated an estimate of the

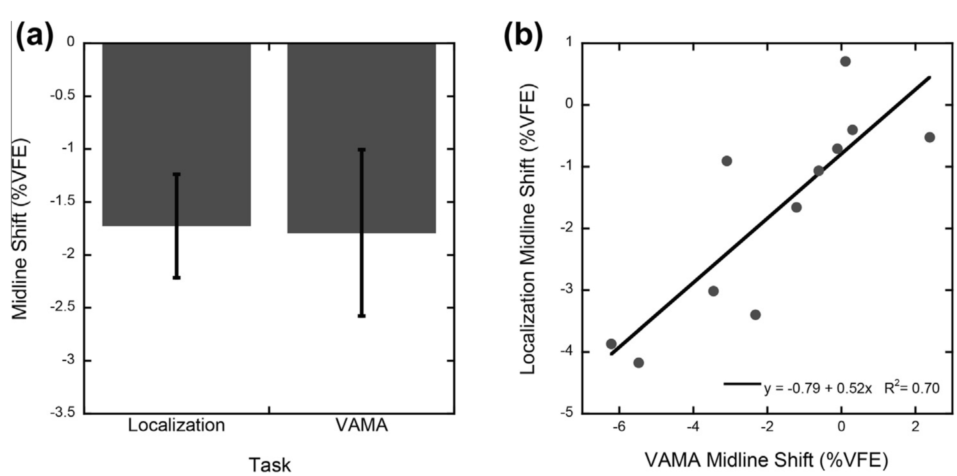

Fig. 3. Experiment 1 hemifield asymmetries. (a) Mean errors in estimated horizontal meridian midline in units of percentage of visual field extent for the localization and VAMA tasks. Error bars represent ±1 SEM. (b) Scatterplot of the errors in estimated horizontal meridian midline from the VAMA task as a function of the same errors estimated from the localization task. Each participant contributes one point to the plot. The black line displays the regression line.

relative imbalance in eccentricity perception across the two hemifields. For both the localization and VAMA tasks, this measure of horizontal midline shift was roughly −1.7% of visual field extent, indicating a perceived expansion of the left hemifield relative to the right hemifield (as in pseudoneglect). Not only were the average deviations found to be equivalent across the two tasks, but there was also a strong correlation across individuals, with hemifield asymmetries on one task predicting 70% of the variance on the other task.

These results are consistent with previous studies of pseudoneglect that used variants of the landmark task and fixed target durations (Jewell & McCourt, 2000; McCourt, 2001). In particular, in a group of 22 neurologically healthy individuals, McCourt (2001) reported an average leftward deviation of −0.26°, or −1.15% of the line length, with an effect size of −2.52. In a meta-analysis of 73 studies of pseudoneglect, Jewell and McCourt (2000) found an average effect size of −1.32 for studies utilizing forced-choice methods. Calculating effect sizes (d') for the horizontal midline shift results of the present experiment using the same formulation as these studies (Keppel & Wickens, 2004; Rosnow, Rosenthal, & Rubin, 2000), we find effect sizes of −2.23 for the Localization task and −1.44 for the VAMA task. Together, both the degree of hemifield asymmetry and the estimated effect sizes suggest that the two tasks utilized in Experiment 1 are sensitive to intrinsic hemifield asymmetries that have been extensively studied in neurologically healthy individuals using variants of the line bisection task.

3. Experiment 2: peripheral localization in patients with hemianopia

Given the results of the first experiment we wondered whether the performance of two of our patients with hemianopia would show a selective expansion of visual space. As noted in the Introduction, line bisection tasks in hemianopia have demonstrated systematic errors in perceived midpoint that are shifted toward the region of visual field loss (Barton & Black, 1998; Liepmann & Kalmus, 1900). One theory has proposed that the HLBE is related to differences in distance perception as a function of eccentricity (Nielsen, Intriligator, & Barton, 1999), a question that the peripheral localization task is well suited to address. Using the peripheral localization task, we tested whether the patients with hemianopia show a selective expansion of the central region of their visual fields beyond that observed in neurologically healthy observers with normal-vision.

3.1. Methods

3.1.1. Participants

Our recruitment procedures yielded two participants with diagnosed hemianopia. Both patients had sufficient postural stability and mobility to sit in a chair with their head centered on a chinrest for approximately one hour of testing, including breaks. Both patients were also able to maintain stable fixation during the perimetry and localization testing.

3.1.1.1. P01. Patient participant P01 (26 year old, male; see Table 1) exhibited a stable, right-sided dense hemianopia resulting from a motor vehicle accident suffered approximately ten years prior to enrollment in the current study (i.e., closed head traumatic brain injury). Neuroimaging at the time of injury (CT scan) revealed left occipital lobe hypodensity consistent with evolving infarction, encephalopia in left temporal-parietal area (posterior and lateral in distribution), and serpiginous calcifications in the gyral distribution in the occipital lobes, that were more marked on the left than the right and consistent with infarction in the region of the optic radiations. A follow-up CT scan one-month later revealed small bilateral hemorrhagic infarcts in frontal, parietal, and right temporal lobes, with a small anterior intra-hemispheric subarachnoid hemorrhage, bilateral cerebral edema and infarction in the left occipital lobe. Gyral calcification had resolved from previous scan.

At the time of injury, cognitive screening revealed a 30% error-rate in executing two-step commands and perseverative errors related to acute, injury-induced aphasia that resolved following speech therapy. Cognitive screening (mental control portion of the SCAN, McGlinchey-Berroth et al., 1996) at the time of enrollment in the current study (status post ~10 years) failed to reveal residual cognitive deficits. Neither the SCAN battery nor a computerized conjunction search task (see Table 1, List et al., 2008) revealed evidence of visual neglect. P01 reported no cognitive problems and was gainfully employed at the time of enrollment.

A visual exam at the time of injury showed 20/20 acuity with dense hemianopia. Evaluation at the time of enrollment in the current study showed a stable dense right hemianopia (see Fig. 4). In addition, performance on the line bisection task portion of the SCAN (McGlinchey-Berroth et al., 1996) showed an ipsilateral spatial bias consistent with the HLBE; with the following errors (expressed as percentage of line length): 3 cm:+5%; 6 cm:+2.5%; 11 cm:+2.72%; 22 cm:+3.41%: average of long lines (11 cm and 22 cm):+3.07%.

3.1.1.2. P02. Patient participant P02 (56 year old female; see Table 1) exhibited left sided hemiparesis, reduced balance, left hemi-inattention and left visual field loss resulting from an acute CVA (i.e., basal ganglia hemorrhage) six months prior to enrollment in the current study. MRI at the time of injury revealed right basal ganglia hypodensity consistent with evolving infarction extending into the region of the optic radiations.

At the time of injury, cognitive screening revealed generalized slowing in speed of processing consistent with acute stroke. Prior to the event, P02 had worked as a book editor. Cognitive screening (mental control portion of the SCAN, McGlinchey-Berroth et al., 1996) at the time of enrollment in the current study (status post ~6 months) failed to reveal residual cognitive deficits.

A visual exam conducted three months post injury showed 20/20 binocular acuity and non-homogenous dense left hemianopia. Ophthalmological report indicated normal eye alignment, with binocular depth perception moderately reduced to 70 arcsec (20–40 arcsec is normative). Eye movements were full and unrestricted,

Table 1
Description of the two patients with hemianopia. Spatial Search Latency is the time to detect a conjunction target in a radial multi item array presented via computer.

Patient	Sex	Age	Time post injury	Etiology	Lesion	Vision	Spatial search latency: left	Spatial search latency: right
P01	M	24 yr	10.2 yr	CHTBI	Bilateral frontal, parietal; R temporal; L occipital; optic radiations	Right dense hemianopia (ou)	514 ms (SD = 90)	510 ms (SD = 160)
P02	F	56 yr	6mn	CVA	R basil ganglia; R optic radiations	Left dense hemianopia (od); partial left hemianopia (os)	1104 ms (SD = 138)	126 ms (SD = 102)

Abbreviations: CHTBI, closed-head traumatic brain injury; od, right eye; os, left eye; ou, both eyes; ms, milliseconds; SD, standard deviation.

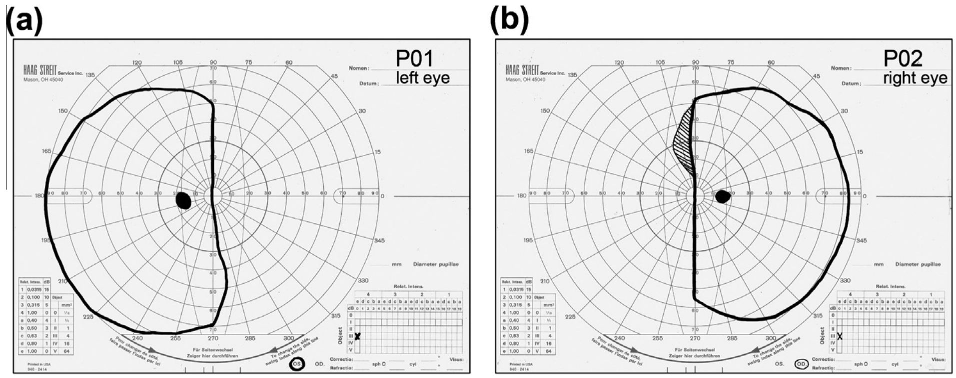

Fig. 4. Experiment 2 perimetry results. The solid outline shows the results of kinematic perimetry indicating the outer boundaries of the *intact* visual field for the tested eye using the III4e test target. The filled region near the horizontal meridian corresponds to the blind spot. (a) Patient P01 left eye. (b) Patient P02 right eye. The hashed area along the superior vertical axis shows a region of decreased sensitivity and inconsistent detection ability.

but jerky throughout the range. The anterior segments of both eyes were healthy, with the presence of beginning cataracts. Dilated retinal exam showed healthy fundus and optic nerve, with a c/d ratio of .2 OU. Tangent screen visual fields indicated a complete left hemianopia in the right eye (see Fig. 4) and a partial left hemianopia in the left eye; P02 did respond to targets in the left superior field up to 12° left of midline. When reading text, she exhibited a midline shift to the right that enabled her to consistently find the beginning of the next sentence.

Performance on measures of primary vision and attention at the time of enrollment in the current study revealed evidence for left-sided visual neglect on a computerized conjunction search task (List et al., 2008). However, performance on a computerized landmark task with a 10 deg line showed a −5.0% leftward (ipsilesional) deviation in perceived midpoint, consistent with the HLBE and inconsistent with the errors typically observed in patients with visual neglect and no primary visual field deficit (Barton & Black, 1998).

Both patients completed signed informed consent before beginning any testing. All experimental procedures were approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley and followed the tenets of the Declaration of Helsinki.

3.1.2. Materials and procedure

3.1.2.1. Visual field assessment. Immediately prior to experimental testing, visual fields were measured monocularly by kinetic perimetry with a Goldmann perimeter using the III4e test target (0.44° test spot at a viewing distance of 30 cm; 318 cd/m^2 on a background luminance of 10 cd/m^2). Each eye was tested separately to allow detection of any monocular scotomas in the ipsilesional hemifield and islands of spared vision, although for both patients, neither was present. Fig. 4 shows perimetry results for the eye tested for each patient in the experiment.

3.1.2.2. Experimental testing. Data for the peripheral localization task were collected monocularly for both patients, while the other eye was patched throughout the testing session. As there can be differences in visual field boundaries between the two eyes in patients with acquired visual field loss, monocular testing assured alignment between the measured and true visual field extents during testing. The left eye of patient P01 and the right eye of patient P02 were tested, resulting in data from the temporal axis of the spared hemifield in each patient and therefore allowing better comparison with monocular data that has been previously collected in neurologically healthy participants (Fortenbaugh et al., 2012). Before beginning behavioral testing, the experimenter briefly flashed the target at the boundary location along each of the three cardinal axes tested (superior, inferior, and temporal) to remind participants of the locations of the edges of their visual field.

As in Experiment 1, the same III4e test target used in the perimetry measurements was briefly flashed (∼175 ms) at various eccentricities along the superior, inferior, and temporal axis, with locations along the three axes intermixed within the block of trials. For both patients, the target eccentricities spanned the full length of the intact visual field across a particular axis in 10° increments with an additional target at 5° eccentricity. For patient P01 targets spanned the following range of eccentricities: Superior: 5°–50°; Inferior: 5°–70°; Temporal: 5°–90°. This led to a total of 24 target locations tested across the three axes. For patient P02 targets spanned the following range of eccentricities: Superior: 5°–50°; Inferior: 5°–50°; Temporal: 5°–80°. Given the smaller visual field extent along the inferior and temporal axes, for patient P02 targets were additionally presented at 15°, 25°, and 35° along the Superior axis, 15° along the Inferior axis, and 25° and 35° along the Temporal axis. This led to a total of 27 target locations tested across the three axes. Every target location was tested four times in a randomized sequence that was pre-generated before the testing session. Five practice trials were completed before beginning the experiment in order to familiarize the patients with the task.

3.2. Results

As in Experiment 1, for each target location, degrees of eccentricity were converted to percentage of visual field extent for each axis. Error scores were then calculated by subtracting the true percentage of visual field extent from each magnitude estimate. Figs. 5 and 6 show the mean errors in units of percentage of visual field extent for the spared temporal and vertical axes as a function of target eccentricity for patient P01 and P02, respectively. For comparison, mean errors and 95% confidence intervals were calculated for the temporal, superior and inferior axes (Figs. 5 and 6) for the data from the right eye monocular condition of the twelve neurologically healthy participants in our previous study (Experiment 2, Fortenbaugh et al., 2012). As seen in Figs. 5 and 6, both patients show larger peripheral biases than the normal-vision group, and in particular, expansions are seen along the temporal axis at the eccentricities closest to fixation. While both patients show the same inverted-U shape pattern along the superior and inferior vertical axes, the degree of overestimation varied with patient P02 showing peripheral biases on average equal to or less than the normal-vision group while patient P01 tended to show larger peripheral biases.

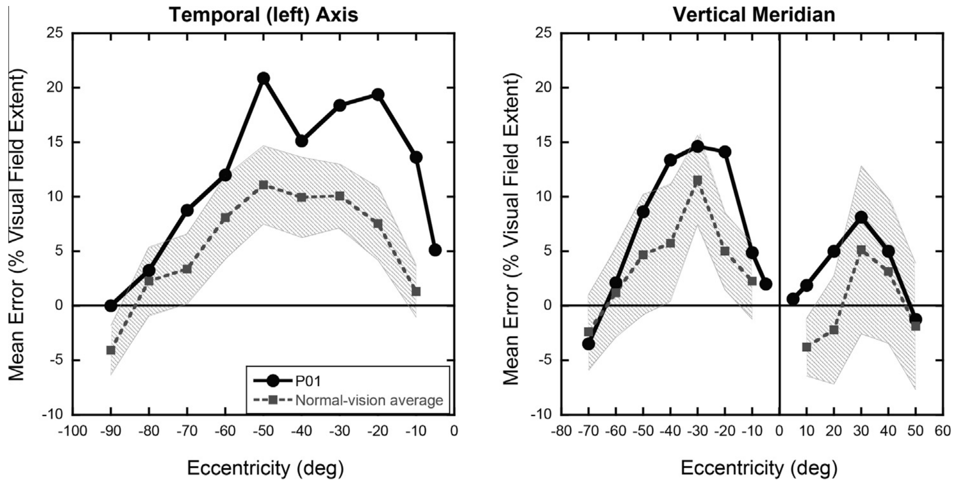

Fig. 5. Experiment 2 patient P01 localization errors: mean errors in percent of visual field extent for the spared horizontal (temporal = left) and vertical meridians as a function of target eccentricity for patient P01 are shown as circles and solid lines. The mean errors for the normal-vision participants from Fortenbaugh et al. (2012) are shown as squares and dotted lines with the shaded regions representing the 95% confidence intervals. Solid horizontal lines at zero represent expected performance is no distortion exists.

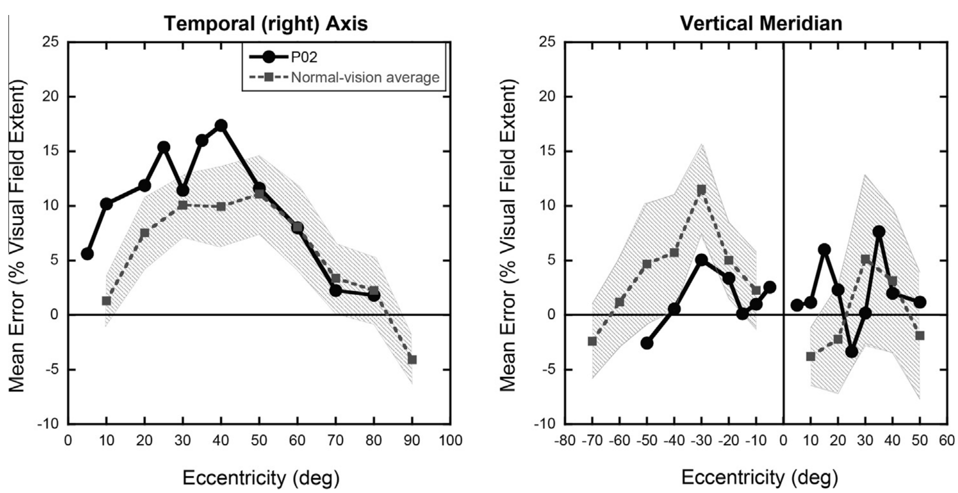

Fig. 6. Experiment 2 patient P02 localization errors: mean errors in percent of visual field extent for the spared horizontal (temporal = right) and vertical meridians as a function of target eccentricity for patient P02. The same formatting from Fig. 5 is used.

As some of the tested eccentricities differ across the two patients as well as the normal-vision group, we analyzed the pattern of target scaling across eccentricity to provide a common measure that would allow for statistical inference. To assess the scaling patterns, for both patients and all axes separately, power functions (Eq. (1)) were fit to the raw magnitude estimates for all eccentricities tested. Fig. 7 shows the estimated slope (λ) and exponent (α) parameters for patients P01 and P02. For comparison, the means and 95% confidence intervals of the estimated parameters for the neurologically healthy comparison group are also plotted (Fortenbaugh et al., 2012).

The estimated slope and exponent parameters along each axis for patient P01 and P02 were compared to the normal-vision group using modified two-tailed *t*-tests and estimates of effect sizes reflecting the deviation from the mean of the normal-vision group in units of standard deviation, z_{cc} (Crawford, Garthwaite, & Porter, 2010; Crawford & Howell, 1998). The modified *t*-test provides a more conservative estimate of the rarity of a single patient's performance than standard *z*-scores when comparing these data with smaller comparison group sizes (Crawford & Howell, 1998). Table 2 presents the results of these modified *t*-tests along with estimates of the proportion of the comparison population that is estimated to have a lower case score (i.e. parameter estimate) than the patient, estimated effect sizes, and the corresponding 95% confidence intervals for these measures (Crawford & Garthwaite, 2002; Crawford, Garthwaite, & Porter, 2010).

3.3. Discussion

In our previous study (Fortenbaugh et al., 2012) and in Experiment 1 we found that, in the absence of external visual boundaries, neurologically healthy individuals with full visual fields tend to show a peripheral bias when localizing targets in eccentric locations. Importantly, the degree of peripheral bias depends on the eccentricity of the target and reflects a relative expansion of the central region of the visual field compared to more peripheral regions. The results for both of the patients show the typical perceived expansion of the central region of the visual field as well as an additional expansion of the central region, primarily along the spared temporal axis. As seen in Table 2 and Fig. 7 the spatial specificity of this expansion is reflected in the larger slopes and smaller exponents for these patients relative to the

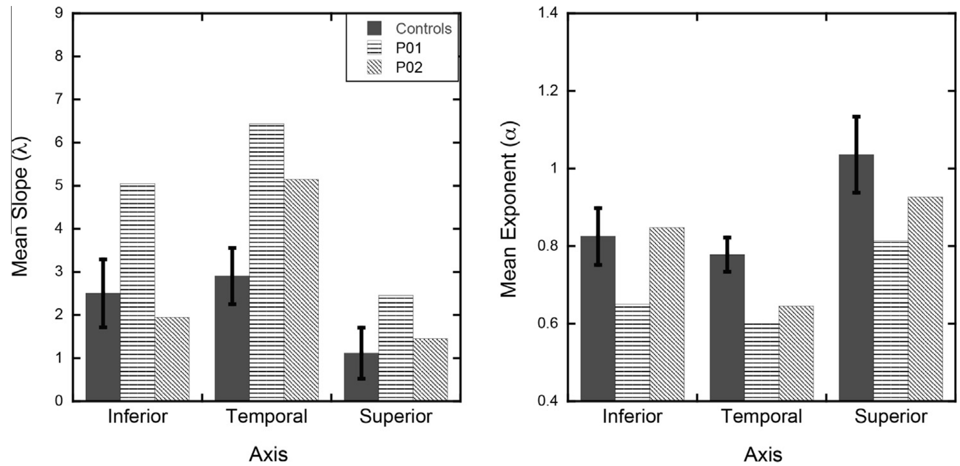

Fig. 7. Experiment 2 power function parameters. Mean estimated slope (left panel) and exponent (right panel) parameters as a function of axis and participant. The grey gray solid bars represent the normal-vision means from the monocular condition in Fortenbaugh et al. (2012) and the error bars represent 95% confidence intervals.

Table 2
Descriptive and inferential statistical results comparing the power function parameter estimates for the two patients with the normal-vision control sample for each of the three axes tested.

Case	Parameter	Axis	Control Sample			Case's score	Significance test		Estimated percentage of the control population obtaining a lower score than the case		Estimated effect size (z_{cc})	
			N	Mean	SD		*t*	*p*	Point (%)	(95% CI)	Point	(95% CI)
P01	Slope	Inferior	12	2.50	1.24	5.05	1.97	0.07	96.27	(84.59 to 99.89)	2.05	(1.02 to 3.05)
		Temporal	12	2.91	1.03	6.43	3.29	0.007	99.64	(97.08 to 99.99)	3.42	(1.89 to 4.93)
		Superior	12	1.11	0.93	2.45	1.38	0.19	90.32	(72.74 to 98.77)	1.44	(0.61 to 2.25)
	Exp	Inferior	12	0.82	0.11	0.65	−1.48	0.17	8.30	(0.86 to 24.91)	−1.55	(−2.38 to −0.68)
		Temporal	12	0.78	0.07	0.60	−2.47	0.03	1.55	(0.01 to 8.72)	−2.57	(−3.76 to −1.36)
		Superior	12	1.036	0.15	0.81	−1.43	0.18	9.08	(1.07 to 26.26)	−1.48	(−2.30 to −0.64)
P02	Slope	Inferior	12	2.50	1.24	1.95	−0.43	0.68	33.91	(15.17 to 56.36)	−0.44	(−1.03 to 0.16)
		Temporal	12	2.91	1.03	5.15	2.09	0.06	96.96	(86.46 to 99.94)	2.18	(1.10 to 3.22)
		Superior	12	1.11	0.93	1.45	0.35	0.73	63.39	(41.00 to 82.73)	0.36	(−0.23 to 0.94)
	Exp	Inferior	12	0.82	0.11	0.85	0.26	0.80	60.09	(37.83 to 80.06)	0.27	(−0.31 to 0.84)
		Temporal	12	0.78	0.07	0.65	−1.85	0.09	4.59	(0.20 to 17.50)	−1.92	(−2.88 to −0.94)
		Superior	12	1.036	0.15	0.93	−0.70	0.50	24.88	(8.72 to 46.96)	−0.73	(−1.36 to −0.08)

normal-vision group. This led to a greater expansion of the more central region of the visual field with little bias for the most peripheral target locations as seen in Figs. 5 and 6. For patient P01 there is also evidence of a higher slope value along the inferior axis ($p = 0.07$) without corresponding changes in the exponent parameter of a similar magnitude ($p = 0.17$). For both patients, scaling along the superior axis was not found to differ from the normal-vision population ($p \geqslant 0.19$ for both parameters).

These results are consistent with the findings of previous studies showing a relative expansion of central space, leading to a centripetal bias, for bisection of lines presented within one hemifield (Nielsen, Intriligator, & Barton, 1999). However, the comparison of the two patients with the normal-vision group further suggest that the HLBE observed in patients with hemianopia is not solely due to differences in perception across the central and peripheral visual fields that are observed in normal-vision neurologically healthy participants. In addition to this central-peripheral difference there is evidence for a selective expansion of space that stretches the central region of the spared temporal axis beyond that expected in full intact visual fields.

The two patients tested differ from one another along several dimensions including age, area of damage to the visual system, time since injury, and clinical presentation. Yet, despite these differences both patients show similar expansions along the temporal axes relative to the normal-vision group. The fact that only 2 patients were tested certainly limit the extent to which the current results can be generalized to all patients with hemianopia, but the findings are the first indication that spatial representation can be affected across a large region of the "intact" hemifield. Also, despite all of the differences across these two participants, perhaps most notably that one patient also showed mild signs of visual neglect while the other patient showed none, both patients had a bias toward the contralesional hemifield when completing line bisection tasks consistent with the HLBE. Finally, the perceived expansion of the central eccentricities was larger in patient P01, who was best matched in terms of age to the normal-vision sample and was over a decade past the time of injury. Together, these findings support a perceptual origin for the HLBE that may be rooted in a perceived horizontal expansion of visual space for the central regions nearest to the boundary of the visual field loss.

4. General discussion

The findings of the present two experiments support the assertion that errors observed in the two patients with hemianopia reflect a selective perceptual distortion of visual space along the temporal axis. How can such a perceptual process be understood given the extensive work that has been completed examining the HLBE in patients with hemianopia and other perceptual distortions that occur following loss of part of the visual field? One interpretation is that such a distortion might be considered a perceptual "filling-out" of space toward the region of visual field loss akin to the perceptual "filling-in" observed in patients with scotomas (Wittich et al., 2006; Zur & Ullman, 2003) and for the physiological blind spot (Dilks et al., 2009). While the perceptual distortion reported here occurs over distances far larger than those observed in perceptual filling-in (and we do not suggest that the same physiological mechanisms underpin these effects) evidence for "filling-out" or perceived expansion of space following peripheral visual field loss due to retinitis pigmentosa has been suggested by previous studies (Temme, Maino, & Noell, 1985). This finding, in conjunction with the present results, poses the interesting possibility that when the visual field one grows up with is reduced due to retinal or cortical trauma there exists a mismatch between the amount of space the visual system believes it is sampling in a given instance and the true visual field extent. How the visual system compensates or adapts to such a mismatch may include a stretching of perceptual space toward the expected field size. In the case of hemianopia, where the width of the binocular visual field is halved while the vertical height remains unchanged, the expected expansion would be along the horizontal dimension with the central region of the visual field compensating or expanding into the lost part of the visual field.

While the automatic process of filling-in across scotomas has been linked with short-range cortical reorganization of horizontal connections of cells in V1 (Darian-Smith & Gilbert, 1994; Das & Gilbert, 1995; Kaas et al., 1990), distortions in the perception and representation of visual space can result from processes occurring at multiple levels within the visual system. For instance, for perceptual mislocalizations induced by moving stimuli in neurologically healthy individuals, fMRI responses in area V1 are better correlated with the actual object location, while responses in higher-order occipital, ventral, and dorsal visual areas are more correlated with the perceived location of targets (Fischer, Spotswood, & Whitney, 2010). These results are consistent with the neuropsychological literature documenting a broad array of perceptual distortions in object size or location in patients with lesions outside of striate cortex, such as those observed in patients with hemimicropsia following occipital lesions (Cohen et al., 1994; Frassinetti, Nichelli, & di Pellegrino, 1999; Park et al., 2007) and patients with visual neglect following temporal and parietal lesions (Kerkhoff, 2000; Milner & Harvey, 1995; Milner, Harvey, & Pritchard, 1998). The extent to which the encoding of perceived location within a given visual area is determined by the incoming visual input, the attentional state of the observer, or factors such as context and expectation remains an active area of research that is far from settled. However, the results of Fischer, Spotswood, and Whitney (2010) and case-reports of patients with occipital, parietal and temporal lesions and varying perceptual distortions suggest an evolving representation and provide evidence that perceptual distortions in perceived location or size observed behaviorally need not be tied to changes in visual processing at the earliest levels of the visual system.

Measurements of line bisection errors using traditional paper-and-pencil tasks or more controlled forced-choice versions of these tasks provide an practical means for measuring deviations in length perception in patients with hemianopia, and they have provided a framework for assessing the roles of attentional focus, eccentric fixation and lesion location on the development and magnitude of the HLBE (Barton & Black, 1998; Kerkhoff & Schenk, 2011; Kuhn et al., 2012; Mitra et al., 2010; Schuett, Dauner, & Zihl, 2011; Zihl et al., 2009). However, bisection tasks are generally not well suited for characterizing distortions in perception that occur across large portions of the visual field. The tasks and results of the current study provide a new approach for studying changes in perception across the entirety of the remaining intact visual field in patients with hemianopia.

More generally, the present tasks provide a new means to assess spatial distortions that may occur following a variety of visual field losses. For example, it has been shown that patients with quadrantanopia, particularly in the lower visual field, due to extra-striate lesions show both horizontal and vertical distortions in the visual subjective straight ahead (VSSA), toward the region of vision loss (Kuhn, Heywood, & Kerkhoff, 2010). In the present study, patient P01 showed some evidence of expansion along the lower vertical meridian while patient P02 did not. Given the present data it is not possible to determine whether differences in lesion locations across the two patients might contribute to this difference and whether the performance differences would generalize to other tasks, such as vertical bisection or VSSA. However, we note that upper/lower hemifield differences in visual processing have been shown for a variety of perceptual tasks (Fortenbaugh, Silver, & Robertson, 2015; Previc & Intraub, 1997; Skrandies, 1987) and neurophysiological distinctions across the retinal and cortical regions that process information from the upper and lower hemifields have been found (Curcio & Allen, 1990; Curcio et al., 1987; Previc, 1990, 1998; Silver, Ress, & Heeger, 2005; Van Essen, Newsome, & Maunsell, 1984). Moreover, the lower peripheral visual field has been shown to play an important role in balance and postural control (Black et al., 2008), consistent with the correlation observed in the patients with quadrantanopia between shifts in the VSSA and reported problems in walking up/down stairs (Kuhn, Heywood, & Kerkhoff, 2010). Future research examining perceived locations across a larger range of radial directions and patient groups (e.g. quadrantanopia) may therefore provide greater insight into the different perceptual distortions that occur following loss of vision to specific regions of the visual field and the functional impact such distortions may have on activities of daily living.

The current results also support a role for such tasks in understanding intrinsic biases that are present in neurologically healthy individuals with normal vision. Recent findings have suggested that the leftward error found in bisection tasks (i.e. pseudoneglect) may be object-based, reflecting distortions in the perception of a line that are independent of visual field location (Nicholls et al., 2004; Orr & Nicholls, 2005). In Experiment 1, neurologically healthy participants were asked to make judgments about target locations in relation to their own perceived visual field extents in the absence of any external object boundaries. Under these conditions we observed both a perceived expansion of the central regions of the visual field as well as an asymmetry in perceived location across the left and right visual axes that was similar in magnitude to measures of pseudoneglect using line stimuli (Jewell & McCourt, 2000; McCourt, 2001). These results suggest that left–right asymmetries in perceived length may well have a space-based component.

There are also several factors that have been shown to modulate bisection performance in neurologically healthy individuals that would be of interest to study using the present tasks. For example, studies have shown that pseudoneglect is modulated by attentional cueing (Harvey et al., 2000; McCourt, Garlinghouse, & Reuter-Lorenz, 2005; Nichelli & Rinaldi, 1989; Toba, Cavanagh, & Bartolomeo, 2011). The degree to which attentional manipulations alter the hemifield asymmetries observed in the present study is an area for future research. Studies have also shown that handedness can influence the magnitude of pseudoneglect in neurologically healthy individuals (Jewell & McCourt, 2000). We note that the handedness of participants was not measured in Experiment 1. Thus, future studies examining the variable of handedness may be able to determine whether handedness helps to account for some of the individual differences in the biases observed across participants.

In conclusion, despite the recent advances in understanding the neural basis of distance and size computations in neurologically healthy normal-vision individuals and the origin of the HLBE in patients with hemianopia, there remains much to be learned. We have shown that behavioral measures that allow for measurements of perceived location across the expanse of the visual field in the absence of external objects can provide unique information that will aid in the understanding of inherent biases in space perception. These, in turn, allow for a more complete characterization of the distortions that are induced when part of the visual field is lost due to brain injury.

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