PAPER

"Bottom-up" and "top-down" effects on reading saccades: a case study

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Objective: To investigate the role right foveal/parafoveal sparing plays in reading single words, word arrays, and eye movement patterns in a single case with an incongruous hemianopia.
Methods: The patient, a 48 year old right handed male with a macular sparing hemianopia in his left eye and a macular splitting hemianopia in his right eye, performed various reading tasks. Single word reading speeds were monitored using a "voice-trigger" system. Eye movements were recorded while reading three passages of text, and PET data were gathered while the subject performed a variety of reading tasks in the camera.
Results: The patient was faster at reading single words and text with his left eye compared with his right. A small word length effect was present in his right eye but not his left. His eye movement patterns were more orderly when reading text with his left eye, making fewer saccades. The PET data provided evidence of "top-down" processes involved in reading. Binocular single word reading produced activity in the representation of foveal V1 bilaterally; however, text reading with the left eye only was associated with activation in left but not right parafoveal V1, despite there being visual stimuli in both visual fields.
Conclusions: The presence of a word length effect (typically associated with pure alexia) can be caused by a macular splitting hemianopia. Right parafoveal vision is not critically involved in single word identification, but is when planning left to right reading saccades. The influence of top-down attentional processes during text reading can be visualised in parafoveal V1 using PET.

During left to right text reading, identification of words is dependent on the high visual acuity afforded by foveal vision extending 1° either side of fixation. Simultaneously, an implicit spatial attentional window, which extends asymmetrically into right parafoveal vision, serves two purposes, providing preparatory partial word identification as well as assisting the planning of reading saccades to the next viewing point in the sentence.[1–4] Thus, word identification and the planning of reading saccades occur in parallel during normal reading.[5]

For over a century it has been known that normal subjects can recognise single words as fast as single letters,[6] and more recently it has been discovered that single words can be read with exposure times as short as 50 ms.[7] Fixation times during text reading average about 250 ms per word, many times longer than would be expected if the rate limiting step in reading was word recognition. Therefore, an appreciable proportion of fixation time during text reading is presumably devoted to planning reading saccades.

Some authors have argued that the pattern of each reading scanpath is mainly dictated by the visual characteristics of the text, such as the length of the next word and the distance from one optimal viewing point to the next;[8–10] while others have stressed linguistic factors such as sentential meaning.[11–13] It is likely that both "bottom-up" (visual) and "top-down" (linguistic and attentional) factors modify reading scanpaths.[5 14]

The presence of an incongruous homonymous hemianopia in a single patient afforded us the opportunity to investigate the role that right foveal and parafoveal vision play in reading. Finding a patient with this rare visual impairment allowed us to design a series of experiments to investigate the relationship between foveal/parafoveal vision, single word and text reading, and regional cerebral blood flow in primary visual cortex, by comparing the performance of each eye in turn. Because the patient's visual impairment results from a tumour in the left lateral geniculate nucleus (LGN), his primary visual cortex is undamaged.

We report three experiments: the first two examine single word reading speeds using a voice trigger and eye movement scanpaths while reading text. The third experiment examines the differences in neural responses during reading using PET. All experiments were conducted monocularly contrasting the patient's reading with his left (macular vision is spared) versus his right eye (macular vision is split).

CASE HISTORY

The patient, a 48 year old, right handed male, was found to have a right sided visual field defect. Subsequently, a cystic lesion was demonstrated on MRI (fig 1), located between the left optic tract and lateral geniculate nucleus, which affects the function of the left visual tract. Visual acuity was N6, corrected in both eyes.

Table 1 shows the results of the patient's neuropsychological tests. On reading tests (reading single words (3, 5, and 7 letters), non-word reading (3, 4, 5, and 6 letters), and whole number reading), he made only one error. Using the final three passages from form 2 of the Neale Analysis of Reading Ability, reading speed was 114.5 wpm and accuracy was 99/100 (ie a reading age of >13 years, the upper limit covered by the Neale test).[15]

A Humphrey perimeter was used to assess his visual fields. He has a macular splitting, right hemianopia in his right eye, and a right hemianopia in his left eye, which spares 3–4° of central vision (fig 2).

METHODS

The project was approved by the Hammersmith Hospital Ethics Committee and permission to administer radioisotopes

Abbreviations: LGN, lateral geniculate nucleus; SEM, saccadic eye movement; RT, response time

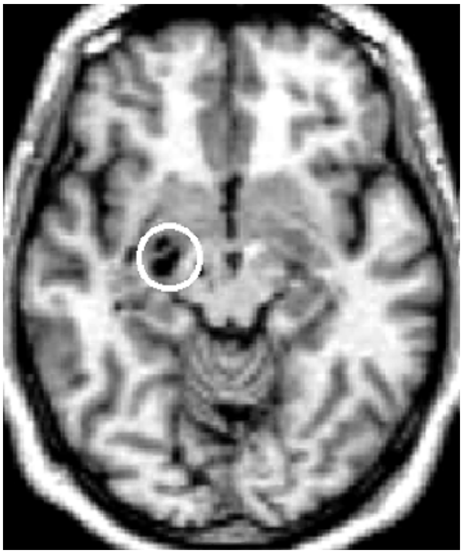

Figure 1 Axial view of the patient's T1 MRI scans (lesion circled).

Table 1 The results of the patient's neuropsychological tests

Task	Score		Test
Pro-rated verbal IQ	97		WAIS-R[16]
Pro-rated performance IQ	108		WAIS-R[16]
Full scale IQ	101		WAIS-R[16]
Predicted IQ	92–94		National Adult Reading Test[17]
Word recognition	47/50	High average	Warrington's Recognition Memory Test[18]
Face recognition	37/50	Defective	Warrington's Recognition Memory Test[18]
Graded naming	26/30	Superior	Graded Naming Test[19]
Graded spelling	15/30	Low average	Baxter's Graded Spelling Test[20]
Visual perception:		Normal	Visual Object and Space Perception Battery[21]
Fragmented letters:	19/20		
Position discrimination:	20/20		
Cube anaylsis:	10/10		

The patient showed no signs of either a generalised language disorder (aphasia) or other forms of peripheral alexia (pure, attentional, or neglect alexia). We can only speculate that his hemianopia affects face recognition, as he shows no evidence of right temporal lobe pathology commensurate with prosopagnosia. His word recognition was in the high average range and this, taken with his accurate reading, suggests that any deficiencies in simple reading tasks, such as the ones used in the experiments detailed here, are unlikely to be due to a failure of memory or word recognition processes. The patient also showed no sign of visuospatial neglect (star cancellation, line bisection, copy drawing, and clock face with numbers were all performed normally). WAIS-R, Wechsler adult intelligence scale: revised.

was given by the UK Department of Health. The patient gave informed consent to participate in the study.

Single word reading speeds

Twenty five words (all nouns) for each of the three word length groups (3, 5, and 7 letters long) were obtained from the MRC Psycholinguistics database,[22] and were matched for both frequency and imageability. The words were selected randomly by PsyScope software[23] and presented in the centre of an AppleMac PowerBook 540c screen in lower case, 42 point Helvetica script, with a crosshair appearing at the centre of the screen between each stimulus. The screen was viewed from 50 cm. A microphone, connected through a button box to the laptop computer, acted as a voice-key trigger for the stimuli so that reaction times were measured from the time the word was presented to the time the subject began articulating his response. The experimenter controlled the rate of word presentation.

He read the full set of stimuli with each eye individually, twice. An eye patch worn under the subject's normal reading glasses covered the eye not being studied. The stimuli were randomised for each presentation and balanced across eyes.

Eye movement recordings

The patient read three short passages taken from British tabloid newspapers. These were presented on a 19 inch computer monitor and saccadic eye movement (SEM) data were recorded using the EyeLink system (Sensorimotoric systems GMbH, Teltow, Berlin, Germany), a video based pupil tracker with a head movement compensation system, sampling at 250 Hz. The data collected by this system were analysed offline using custom software written in "C" on the Macintosh. Individual saccades were identified, using a semi-automated procedure, as periods when the eye position signal's absolute velocity rises above 30° per s for more than two data samples. Fixations were identified as pauses between saccades longer than 50 ms in duration. Any fixations contaminated by eye blink, eyelid clipping artefacts, or those fixations felt to be too short to count as useful reading fixations (~100 ms) were rejected from further analysis.

PET scanning

The patient performed three separate tasks during a total of 16 scans: reading single words, each presented for 500 ms, at the very slow rate of 1–5 per min (three scans: "anticipation"); reading single words, each also displayed for 500 ms, at 20–80 words per min (five scans: "single words"); and reading horizontal arrays of 5 words, presented at a mean rate of 60 per min (eight scans: "text"). The anticipation and single word conditions were viewed binocularly, while the word arrays were viewed with either his left or right eye covered (four scans each). All stimuli were single syllable English words (nouns and verbs) with mean length 4.5 characters (range 4–5), mean imageability rating 511 (range 353–647)[22] and mean log frequency 1.5 (range 10–99 words per million).[24] The five word arrays were selected randomly from the same list and did not form meaningful phrases. The stimuli were presented in the same manner as the single word reading speed task. The angles subtended at the retina for single words and five word arrays were ~1° and ~6°, respectively. A central crosshair appeared between each stimulus, and the patient was asked to fixate on this while awaiting the next stimulus. He was instructed to read each word silently and understand it. The order of scans was randomised. The five word arrays were presented for 3.5 s and he was asked to read each array once only, returning to

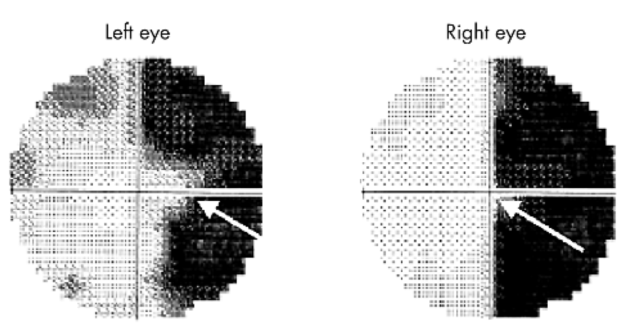

Figure 2 Humphrey perimeter, 10° plots, of the patient's visual fields, showing 3-4° in the left eye and no sparing in the right eye.

the centre of the stimulus for the next crosshair if he finished before the stimuli disappeared.

The PET camera used was the CTI-Siemens ECAT EXACT HR++/966 PET scanner operated in high sensitivity 3D mode. H_2O^{15} was administered intravenously.[25] SPM99 software (Statistical Parametric Mapping, Wellcome Department of Cognitive Neurology) was used to realign and spatially normalise the scans into standard Montreal Neurological Institute (MNI) space.[26] Normalisation of the PET data was guided by a high resolution T1 weighted MRI of the patient's brain, which was normalised into MNI space using a programme that utilises a hand drawn mask of the abnormal area, to prevent the normalisation algorithm from defining the edge of the infarct as part of the brain surface.[27] All scans were smoothed using an isotropic 16 mm full width, half maximum Gaussian kernel to account for variation in gyral anatomy and to improve the signal to noise ratio.[28] The scans were entered into a single subject design matrix with four conditions: anticipation, single words, word arrays (right eye), and word arrays (left eye). The analyses included a blocked AnCova with global counts as confound to remove the effect of global changes in perfusion across scans. The threshold for significance for a change of activity in the peak voxel of an activated region in the grouped analyses was set at $p<0.05$, corrected for analyses across the whole volume of the brain for areas outside the occipital lobe. A small volume correction[29] was applied to activations within the occipital lobe.

RESULTS

Single word reading

Fig 3 shows the patient's overall mean reaction times, when reading the 3, 5, and 7 letter words with each eye. A paired samples t test revealed a significant reaction time difference between the two eyes ($t_{(74)} = 10.262$, $p<0.001$).

He was quicker reading with his left eye than his right eye for all word lengths. A linear regression revealed a significant linear increase in average response times with increasing number of letters per word when reading with the right eye ($F_{(1,73)} = 4.478$, $p<0.05$), but not the left ($F_{1,73} = 0.202$, NS), that is, he shows a word length effect (~16 ms per letter) when reading with his right eye only.

Text reading

Two scanpaths generated by reading the same piece of text with each eye in turn are shown in fig 4.

Four scores were calculated from the scanpaths generated by reading each of the three stimuli with each eye (table 2):

- the mean number of fixations per word for each line of text
- the average reading time per line of text
- the mean fixation time
- the position (x coordinate) of the first fixation on each line (all the stimuli were left margin adjusted, see appendix).

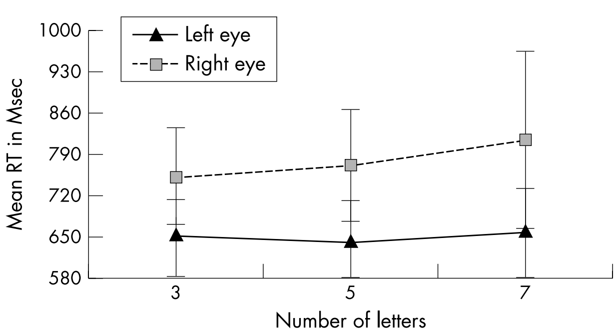

Figure 3 Plot of mean response time (RT) by number of letters for single word reading, showing linear increase in RT for right eye but not the left (error bars show SD).

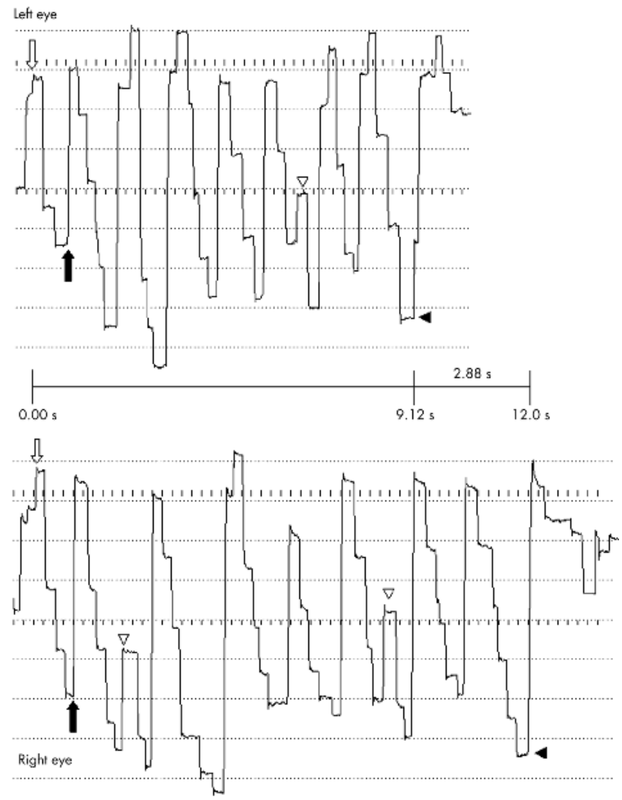

Figure 4 Two of the scanpaths generated by the patient when reading the stimulus "News 1" (see appendix), with each eye. Time is depicted on the horizontal axis, with the bars indicating 240 ms. Distance is on the vertical axis with the left of the stimulus at top and right at bottom. Fixations (horizontal portions of the trace) lasting between 150 and 350 ms are interrupted by saccades (vertical portions) lasting ~20 ms. The start of the first fixation onto the first word of the opening line, "There is a significant", is shown as an open arrow, with the end of the final fixation marked by a closed arrow. Regressive saccades occur in both traces (open arrowheads) but the patient clearly takes longer to get to the last word of the 8th line (closed arrowhead), when reading with his right eye.

Pairing by line, paired samples t tests revealed that when reading with his left eye, he made significantly fewer fixations per word, per line of text ($t_{(25)} = 2.198$, $p<0.05$), than with the right; and that when reading with the left eye, he was also significantly faster per line ($t_{(25)} = 3.698$, $p<0.001$). However, there was no significant difference between the two eyes for the mean length of each fixation ($t_{(25)} = 0.864$, NS). A paired samples t test revealed no significant difference in the position of the first fixation per line, between the two eyes ($t_{(25)} = -0.141$, NS).

Functional imaging

Two contrasts were entered into the design matrix: the first was aimed at identifying foveal activity within primary visual

Table 2 Mean values of the four scores calculated from the eye movement data, for each eye

	Left eye mean (SD)	Right eye mean (SD)
Fixations per word	1.07 (0.46)	1.21 (0.31)
Time per line (ms)	955.77 (209.61)	1155.23 (290.21)
Fixation time (ms)	221.40 (26.55)	228.50 (33.00)
First fixation	143.08 (37.01)	143.88 (23.44)

cortex and the second aimed at identifying attentional modulation of parafoveal V1 during reading text. The results for these contrasts are shown in fig 5.

The first contrast compared activity between the three anticipation scans, when the patient read single words at 1–5 per min binocularly, with all the other scanning conditions (the five scans reading single words with both eyes, and the four each of text arrays with each eye independently). This contrast identified bilateral foveal activity in primary visual cortex during reading. The peak voxel on the left had MNI coordinates of −20, −104, and −2 (x, y, and z), with a z score of 3.41. The peak voxel on the right was at 18, −106, and −4 with a z score of 4.15. Both activations survived a small volume correction for primary visual cortex ($p = 0.05$ on the left, $p = 0.02$ on the right). Because of the low number of degrees of freedom in a design matrix containing only one subject (DF = 11), no activations outside the occipital lobe survived correction for the multiple comparisons made over the whole brain volume.

The second contrast was more complex. Left eye text reading was contrasted with the single word and anticipation conditions, and was exclusively masked by the first contrast (reading conditions *v* anticipation). The use of the mask was to remove any areas of foveal activation already identified in this patient, with the contrast giving any remaining activation unique to reading text with the left eye. This contrast identified significant parafoveal activation in left V1 (bottom fig 5). The peak voxel had MNI coordinates of −8 −96, and 0, with a z score of 3.37. This activation survived a small volume correction for parafoveal V1 ($p = 0.023$).[30] No significant activation was found in right parafoveal V1.

DISCUSSION

As far as can be ascertained, the patient was originally right eye dominant (he is right handed and used to fire a rifle sighting with his right eye). However, he is now a quicker and more efficient reader with his left eye compared with his right for both single word and text reading.

In monocular single word reading tests, he reacted over 100 ms faster, to words of any length, with his left eye compared with his right, although reading accuracy with each eye was identical (one error in each eye, from 150 words). This result suggests that this absolute difference is due to visual field advantage. A right visual field advantage has been found for a variety of tasks including word recognition[31] and lexical decision tasks.[32] Such experiments are carried out using tachistoscopic methods to present stimuli very briefly to the left or right of fixation, the stimuli disappearing before the subject can make a lateral saccade to foveate them.[33] The mechanism for right visual field advantage is uncertain, but may relate to the different language processing abilities of the two hemispheres with the right visual field having a more direct route, in neural terms, to left hemisphere language output structures. Attentional as well as structural models have also been suggested[34 35] to explain this finding. The single word reading result in the patient can be explained by the complete absence of a right visual field in his right eye, therefore identification must be taking place through the less efficient (that is longer) route from left visual field → right visual cortex → left hemisphere language systems via the corpus callosum.

While there is a clear difference between the eyes in terms of absolute reaction times in initiating articulation of single words, a more subtle effect is also present. He exhibits a small but significant linear increase in reading time, when reading single words of increasing length, with his right but not his left eye. This effect has been described as one of the behavioural hallmarks of "pure" alexia (a form of peripheral alexia where subjects fail to identify word forms, but can recognise letters, resorting to a reverse spelling strategy in order to identify words, so called "letter by letter" reading[36]). However, an impaired foveal/parafoveal field to the right of fixation can cause problems with word identification in words with ambiguous prefixes, as the subject has to make a rightward saccade in order to complete word identification.[37] Although we were unable to measure the patient's eye movements during the single word reading tests due to technical limitations, it is also possible that the word length effect demonstrated when reading single words with his right eye is due to his inability to identify some 5 and 7 letter words without making an extra saccade to the right of fixation. This is supported by the range of the mean reading speeds of the 3 and 7 letter words. The mean reading speed for 3 letter words was 750 ms, while the range was 630–935 ms. For 7 letter

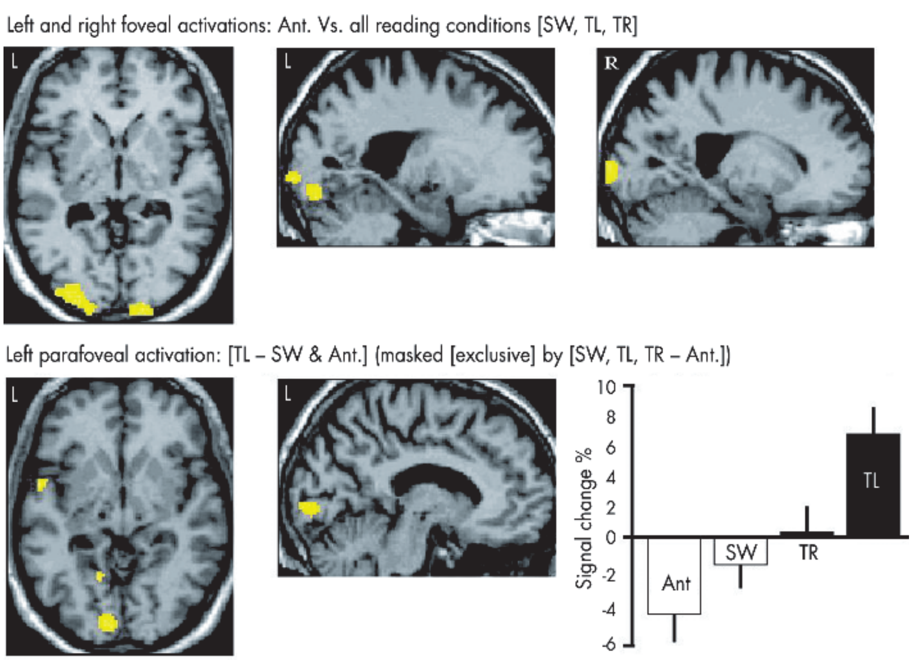

Figure 5 Areas of significant occipital activation from the two contrasts of the PET study are shown in yellow, superimposed onto the patient's MRI scan, which has been spatially normalised into MNI space. The foveal activations generated by the first contrast are shown in the top half of the figure with axial and saggital sections taken in planes that include the peak voxels for left and right foveal activity. The parafoveal activation is shown in the lower half of the figure in the same way. The data from the peak parafoveal voxel have been displayed as a bar graph with mean and standard error of the mean error bars. SPM99 displays voxel values as a percentage change in signal from the average voxel value within the brain blood flow image. The four conditions are: Ant, anticipation; SW, single word; TR, text read with right eye; TR, text read with left eye.

words the mean reading speed was 814 ms with a range of 648–1313 ms. The distribution in the 7 letter words is strongly skewed compared with the 3 letter words, compatible with him needing to make an extra saccade within a few of the 7 letter words in order to identify them, and not by using a letter by letter strategy adopted by pure alexics.

Although he recognises single words faster with his left eye, his slower text reading speed with his right eye is due to inefficient reading saccades. When reading text monocularly, the patient was slower with his right eye, although not by as much as patients with similar homonymous field defects caused by a stroke,[38] perhaps because his loss of visual field has evolved very slowly, allowing him time to adjust to its absence. He was slower across identical pieces of text, making more saccades (and thus more fixations) when reading with his right eye. However, there was no difference between his eyes for the duration of the fixations, suggesting that his increased reading speed is not due to a deficit of word form recognition per se, but to problems with visuomotor coordination of each scanpath. When deprived of useful visual information to the right of fixation, his text reading becomes slowed, a so called bottom-up effect: in this sense the behavioural data presented here serve to confirm the findings of Rayner and McConkie in their parafoveal masking experiments in normal subjects.[39]

As would be expected by his having normal left visual fields, there was no difference in the position of his initial fixation on a line.

Although the behavioural data recapitulates the importance of bottom-up or early perceptual processes involved in text reading, the PET data advance our understanding of the top-down effects, as evidenced by the left parafoveal V1 activation present when the patient reads with his left eye. Two critical issues relating to this observation are the anatomical location of the left parafoveal activation and its function.

The first contrast functionally identified the patient's foveal representation in primary visual cortex (V1). These paired activations were at the occipital poles where previous anatomical and functional imaging studies have located foveal V1.[40–43] The strict retinotopic organisation of V1 dictates that cortex medial and anterior to the occipital pole represents ever more peripheral vision. Allied to this is the bias in the amount of V1 area given over to various parts of the visual field, with mammals in general, and humans in particular, having large portions of V1 devoted to central vision. Studies on cortical magnification factor (the linear extent of cortex in mm corresponding to one degree of visual angle at various eccentricities) have shown that approximately one third of human V1 is concerned with mapping foveal vision; the second third is devoted to parafoveal vision, 2–5° eccentric to fixation; and the last third with peripheral vision (5° and beyond).[44–46] As unfolded human V1 is between 50–60 mm long, the activation seen in the second contrast is in an anatomically plausible location for left parafoveal V1: the peak voxel was 12 mm medial and 8 mm anterior to the foveal activation on that side, deep in the patient's calcarine sulcus when co-registered with his high resolution MRI scan. The spatial resolution of areas of peak rCBF activity between contrasts in a single individual in PET studies on vision has been reported as 3 mm on scanners with less precise spatial resolution than the one used in this study.[47]

When reading text with his left eye, he perceived objects in both left and right parafoveal space as he viewed several word arrays over a minute, and they conveyed as much visual information to the left as to the right of fixation. However, activity was observed only in left parafoveal V1 (corresponding to right parafoveal space), suggesting that the additional effect of directed visuo-spatial attention in response to the presence of words in right parafoveal space was responsible for the observed activation. That this left parafoveal activation is due to top-down (attentional) rather than bottom-up (perceptual) effects is borne out by the lack of a right parafoveal activation in this contrast. Other studies have shown attentional modulation of blood low changes in V1.[48–50] However, they have tended to employ stimuli that would not be encountered in everyday life, often displayed in a contrived manner in order to manipulate visual attention. Text reading is, by contrast, an everyday experience where visual attention is constantly being directed to the right of fixation without the reader's awareness of this or their own eye movements. As such, text is an ecologically valid stimulus, well suited to the investigation of attentional modulation of visual experience.

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APPENDIX

News 1:
There is a ''significant minority'' of criminals serving in the Metropolitan Police, Sir Paul Condon, the force's Commissioner, said last night. Some use violence and intimidation against fellow police officers to avoid detection.

News 2:
The city dubbed it Brown Monday as the markets tumbled in response to Gordon Brown's uncertain position on the European single currency.

News 3:
A Swedish woman is taking a pet shop to court because a parrot they sold her for £400 died a couple of days later. After she got the bird home, it became apathetic and fell off its perch. Later it died and she buried it. The shop owner says she was wrong to bury it because it could have just been sleeping.

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