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ASSESSING THE ROLE OF HEMISPHERIC SPECIALISATION, SERIAL-POSITION PROCESSING, AND RETINAL ECCENTRICITY IN LATERALISED WORD RECOGNITION

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The advantage for words in the right visual hemifield (RVF) has been assigned parallel orthographic processing by the left hemisphere and sequential by the right. However, an examination of previous studies of serial position performance suggests that orthographic processing in each hemifield is modulated by retinal eccentricity. To investigate this issue, we presented words at eccentricities of 1, 2, 3, and 4 degrees. Serial position performance was measured using the Reicher-Wheeler task to suppress influences of guesswork and an eye-tracker controlled fixation location. Greater eccentricities produced lower overall levels of performance in each hemifield although RVF advantages for words obtained at each eccentricity (Experiments 1 and 2). However, performance in both hemifields revealed similar U-shaped serial position performance at all eccentricities. Moreover, this performance was not influenced by lexical constraint (high, low; Experiment 2) or status (word, nonword; Experiment 3), although only words (not nonwords) produced an RVF advantage. These findings suggest that although each RVF advantage was produced by left-hemisphere function, the same pattern of orthographic analysis was used by each hemisphere at each eccentricity.

INTRODUCTION

The arrangement of the human visual system is such that nerve fibres carrying information about stimuli falling in the left visual hemifield (LVF) project to the right cerebral hemisphere while fibres carrying information about stimuli falling in the right visual hemifield (RVF) project to the left cerebral hemisphere. Thus, provided a person's point of fixation can be determined and stimulus presentations are sufficiently brief to prevent eye movements necessary to bring lateralised stimuli into foveal vision, stimuli can be projected to whichever visual hemifield (and, therefore, whichever cerebral hemisphere) is chosen by the experimenter.[1] Numerous studies have used this approach

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[1] In this article, when we refer to stimuli presented to one hemisphere in a divided field task, we are identifying the hemisphere that received the stimulus initially (i.e., stimuli in the RVF were presented initially to the left hemisphere). We do not assume that only one hemisphere has access to this information, simply that the contralateral hemisphere receives the information before the ipsilateral hemisphere. Thus, participants should show a performance advantage if the hemisphere that processes the stimulus more effectively receives the stimulus initially.

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to compare the abilities of the left and right cerebral hemispheres. Indeed, presenting words in the left and right visual hemifields provides one of the few effective ways of investigating hemispheric asymmetries in written word perception in normal intact brains (see Posner & Raichle, 1994, for a review).

One major finding using briefly presented lateralised words is that perceptual accuracy is greater for words presented in the RVF than for the same words presented in the LVF (see, e.g., Bradshaw & Nettleton, 1983, for a review). The predominant interpretation of this RVF advantage is that written language is processed more efficiently in the left cerebral hemisphere. Precisely why this greater efficiency occurs has yet to be discovered, but many have argued that the left hemisphere can process words by mapping orthographic information in parallel onto lexical entries whereas the right hemisphere has a more rudimentary process that can only map orthographic information sequentially (e.g., Babkoff, Faust, & Lavidor, 1997; Bradshaw, Bradley, Gates, & Patterson, 1977; Brand, Van Bekkum, Stumpel, & Kroeze, 1983; Bruyer & Janlin, 1989; Bub & Lewine, 1988; Chiarello, 1988a; Ellis, Young, & Anderson, 1988; Lavidor, Babkoff, & Faust, 2001; Reuter-Lorenz & Baynes, 1992; Young & Ellis, 1985). This difference between the ways in which the two hemispheres process words is supported by evidence from lexical decision and naming studies where increasing the length (number of letters) of words is more likely to affect performance in the LVF than in the RVF (e.g., Bruyer & Janlin, 1989; Bub & Lewine, 1988; Chiarello, Maxfield, Richards, & Kahan, 1995; Ellis et al., 1988; Eng & Hellige, 1994; Eviatar & Zaidel, 1991; Iacoboni & Zaidel, 1996; Young & Ellis, 1985). However, other studies have failed to replicate this length effect (e.g., Eviatar & Zaidel, 1991; Schwartz, Montagner, & Kirsner, 1987), indicating that this parallel-sequential distinction between the two hemispheres requires further investigation.

Serial-position analyses

Assessing the perceptibility of letters in different serial positions in briefly-presented words provides a relatively direct method of assessing the pattern of orthographic processing available in each visual hemifield. Specifically, if the left hemisphere processes orthographic information in parallel while the right hemisphere processes orthographic information sequentially, evidence to support this processing distinction may be derived from patterns of orthographic analysis across different letter positions (see also Jordan, Patching, & Milner, 2000). For example, to take a fairly simple scenario, identical levels of letter perception across all serial positions for RVF stimuli would imply parallel orthographic analysis, whereas a monotonic drop in letter perception from first to last positions for LVF stimuli would imply sequential orthographic analysis. Support for just this distinction between the orthographic processing of words in each hemifield comes from a study by Brand et al. (1983) in which pairs of words that differed at one variable serial position were presented simultaneously for same/different judgements in either the LVF or RVF, at an eccentricity (from a central fixation point) of 1.7 degrees to their inner edge. Response times for "different" judgements for RVF stimuli were unaffected by the serial position of the difference but increased linearly from first to last position for LVF stimuli, suggesting that orthographic information in words is processed in parallel by the left hemisphere and sequentially by the right. However, this distinction may not be present in the same task at smaller retinal eccentricities. Bradshaw et al. (1977) used a similar (same/different) paradigm to that used by Brand et al. but presented words at an eccentricity of 1.0 degree to their inner edge. In contrast to the findings of Brand et al., Bradshaw et al. found that response times for "different" judgements produced a skewed U-shaped function for each visual hemifield. Specifically, for each hemifield, differences were detected fastest of all in first letter positions and differences in last letter positions were detected faster than in medial positions. A similar pattern of effects of retinal eccentricity on serial position performance can be observed in another paradigm. Reuter-Lorenz and Baynes (1992) presented words to a callosotomy patient (JW) at an eccentricity of 2.75 degrees to their inner edge and tested accuracy of report using a two-alternative forced-choice task in which alternatives differed at just one serial position. Accuracy of report was distributed equally across serial positions for RVF stimuli but declined sequentially from first to last position for LVF stimuli. However, when Jordan et al. (2000) used a similar (two-alternative forced-choice) paradigm to that used by Reuter-Lorenz and Baynes but with a smaller eccentricity (2.0 degrees to the inner edge of word items), accuracy of report produced U-shaped functions across serial positions that did not differ between LVF and RVF stimuli.

The different patterns of serial position performance observed in these studies suggest that, rather than the overall parallel-sequential distinction previously drawn between the abilities of the two hemispheres to process orthographic information, the precise pattern of processing inspired by each task depends on the retinal eccentricity at which words are presented. In particular, within each task, similar "outside-in" processing was produced for each hemifield when smaller eccentricities were used whereas parallel processing of RVF stimuli and sequential processing of LVF stimuli appear to have been inspired as eccentricities increased.

Task-specific demands (e.g., Santee & Egeth, 1982) may have affected the absolute amounts of retinal eccentricity at which changes in serial position performance were observed in these studies. However, findings from a study by Bouma (1973) in which changes in retinal eccentricity (from 1–4 degrees to stimuli inner edges) were made within the same task (whole-word report) add support to the notion that retinal eccentricity affects the pattern of orthographic processing in each visual hemifield. Bouma found that, for RVF stimuli, accuracy of report for the first and last letters of words (the only serial position performance measured) was equal up to an eccentricity of 2 degrees; at greater eccentricities, accuracy of report was greatest for last letters. In contrast, for LVF stimuli, accuracy of report for the first and last letters of words was equal only up to an eccentricity of 1 degree; at greater eccentricities, accuracy of report was greatest for first letters. Unfortunately, no measure of the perceptibility of letters in other (medial) serial positions was reported. However, these findings are consistent with the use of "outside-in" processing in each hemifield at smaller eccentricities (up to 2 degrees for RVF stimuli and up to 1 degree for LVF stimuli). Moreover, as eccentricities increased, performance with LVF stimuli showed evidence of left–right orthographic analysis that was not evident for RVF stimuli, even when eccentricity increased to 3 and 4 degrees (Bouma, 1973; see also Schiepers, 1980).

The picture developing from the findings of previous research, therefore, is that retinal eccentricity modulates serial position performance with lateralised words, indicating changes in orthographic processing at different eccentricities in each visual hemifield. Moreover, the effects of eccentricity differ for LVF and RVF displays, indicating that empirical and theoretical contrasts in orthographic analysis made between hemifields depend on stimulus eccentricity. Many researchers have argued that distance from point of fixation is a major determinant of the information encoded from words (see, e.g., Rayner & Pollatsek, 1987). For example, it is well established that visual acuity declines rapidly outside foveal vision (generally regarded as extending about 1 degree either side of the point of fixation) and this has a substantial effect on letter identification (e.g., Anstis, 1974). Consequently, as the eccentricity at which words are presented increases, identification of letters in general and, in particular, those furthest away from the point of fixation, may become impaired in each visual hemifield. Moreover, letter perception in nonfoveal vision is affected substantially by inter-letter interference, acting predominantly towards the point of fixation (e.g., Bouma, 1973, 1978; Chastain, 1981; Chastain & Lawson, 1979). For example, a parafoveally-presented letter is identified less accurately when a nontarget letter is presented to its peripheral side rather than closer to the point of fixation. The precise effects of these and other factors on processing orthographic information in complete words are likely to be highly complex and have yet to be determined (e.g., Bouma, 1978; Hagenzieker & Van der Heijden, 1990; Hagenzieker, Van der Heijden, & Hagenaar, 1990; Van der Heijden, 1987, 1992). Nevertheless, the evidence to date suggests that changes in retinal eccentricity selectively change the quality of visual information in different serial positions in each hemifield which, in turn, would provide conditions well-suited to inspiring changes in the orthographic processing performed by each hemisphere.

However, the precise effects of retinal eccentricity on serial position performance for words in each visual hemifield are not yet known. In particular, the evidence so far has been gleaned from different eccentricities across a small number of studies encompassing a range of procedural variations. Moreover, as we shall discuss, the procedures adopted by most of these studies have not provided the most appropriate measures of retinal eccentricity or serial-position performance.

Assessing performance in each hemifield

The left hemisphere of most individuals plays a special role in perception of written language (e.g., Knecht et al., 2000), but many researchers have addressed the possibility that differences in performance between LVF and RVF words are produced merely by the favourable position of letters relative to the point of central fixation (e.g., see Babkoff & Faust, 1988; Babkoff et al., 1997; Boles, 1985; Bradshaw, Nettleton, & Taylor, 1981; Bryden, Mondor, Loken, Ingelton, & Bergstrom, 1990; Chiarello, Nuding, & Pollock, 1988; Faust, Kravetz, & Babkoff, 1993; Hellige & Sergent, 1986; Kirsner & Schwartz, 1986; Schwartz et al., 1987; White, 1969). More specifically, because visual acuity drops off rapidly as stimuli are moved laterally from the centre of the fovea (e.g., Hilz & Cavonius, 1974; Østerberg, 1935), letters at the beginnings of words in the RVF fall in an area of higher visual acuity than letters at the ends of these words. Conversely, when words are presented in the LVF, letters at the ends of words now enjoy an acuity advantage over letters at the beginnings. Following the arguments of Jordan et al. (2000), this asymmetry in visibility of beginning letter information across the two hemifields presents two problems for determining differences in hemisphere processing, especially as retinal eccentricity increases. The first problem (*covert bias*; Jordan et al., 2000) is that differences in the visibility of initial letters across the two hemifields may inspire artefactual differences in the influences exerted on orthographic analyses by processes normally involved in word recognition. For example, attempts to identify the perceptual units responsible for word recognition emphasise the role of letters from the beginnings of words (e.g., Beauvillain, Doré, & Baudouin, 1996; Jordan, 1986, 1990, 1995; Jordan & Bevan, 1994, 1996; Jordan & de Bruijn, 1993; Lima & Inhoff, 1985; McClelland & Johnston, 1977; Postman & Rosenzweig, 1956; Rapp, 1992; Stanners & Forbach, 1973; Taft, 1979, 1987, 1992). As differences in the visibility of beginning letter information between the two hemifields increases with greater eccentricities, differences in the perception of these units is likely to increase, producing spurious differences between the perceptibility of words in the LVF and RVF and, in particular, spurious influences on the patterns of serial position performance observed in each hemifield. This problem may be exacerbated by a second problem (*overt bias*; Jordan et al., 2000), where differences in performance for LVF and RVF words are contaminated by overt guesswork based on partial word information. Here, performance with words in the LVF and RVF, and the patterns of serial-position performance produced in each hemifield, may reflect processes more suited to crossword completion than word recognition. Thus, unless appropriate precautions are taken, performance with words presented at different retinal eccentricities in each visual hemifield may reflect differences in the influence of covert and overt bias rather than the patterns of orthographic processing used by each hemisphere. Indeed, a particular concern is that covert and overt bias have the potential not only to enhance overall performance for RVF words but also to inspire spurious "parallel" processing of RVF words (but not LVF words) by providing artefactual cues to orthographic information that would not otherwise be identified.

Arguments against the influence of overt bias have been made, usually based on the apparent informativeness of the beginnings and endings of words (e.g., Batt, Underwood, & Bryden, 1995; Bradshaw et al., 1981; Bryden et al., 1990; Chiarello, 1988a, 1988b; Eviatar & Zaidel, 1991;

Hellige & Sergent, 1986). However, arguments against the influence of covert bias are difficult because the contribution normally made by beginning letters to visual word recognition is not yet known (see Jordan et al., 2000, for further discussion). Indeed, not knowing which elements of words normally play a critical role in visual word recognition and how asymmetries in the visibility of beginning letters in lateralised displays affect perception of these elements is a major obstacle to determining not only the effects of covert bias on LVF and RVF performance but also the information available for use in overt guesswork. Consequently, a crucial aspect of assessing the nature of orthographic processing for words at different retinal eccentricities in each visual hemifield is to determine serial position performance under testing conditions that suppress influences of both types of bias.

A technique well suited to this purpose is the *Reicher-Wheeler task* (after Reicher, 1969; Wheeler, 1970; see also Johnston, 1978; Jordan, 1995; Jordan & Bevan, 1994, 1996; Jordan & de Bruijn, 1993; Jordan, Patching, & Milner, 1998, 2000; McClelland & Rumelhart, 1981, 1988; Reuter-Lorenz & Baynes, 1992). In this procedure, stimuli are presented briefly and followed by a forced choice between two alternative letters whose serial position and probability of occurrence cannot be predicted from any other letters in the stimulus display. For example, following presentation of the stimulus *work*, perception of the final letter can be tested by requiring participants to choose between the letters *k* and *d*, where both letters are consistent with the remainder of the word, where *work* and *word* are equally likely to have been presented in the experiment, and where any serial position may be tested on a trial. Using this technique, the identity of the "critical" letter cannot be identified using information from other letter positions; accurate performance requires perception of the critical letter that cannot be uniquely determined by other letters in the stimulus. Indeed, following the findings of Johnston (1978), the task appears to rule out influences of bias not only during the overt selection of a response but at *any* stage of processing (e.g., during early processing of features where covert bias may exist; see Bjork & Estes, 1973; Rumelhart & Siple, 1974; Thompson & Massaro, 1973). Consequently, the Reicher-Wheeler task is ideal for measuring serial position performance at different retinal eccentricities without contamination from asymmetries in the perceptibility of partial word information.

Ensuring accurate retinal eccentricity

Inferences about effects of retinal eccentricity on hemispheric processing are more likely to be accurate if the retinal eccentricities at which stimuli are presented are precisely determined and matched across each visual hemifield. Of particular concern is that cone receptor density changes rapidly over the central 2 degrees, falling approximately five-fold (Østerberg, 1935), with inevitable effects on visual acuity (Hilz & Cavonius, 1974). Consequently, even small shifts in fixation away from centre may influence performance and contaminate differences in performance between the two hemifields (and exacerbate the problems of perceptual asymmetries in partial word information already discussed; for further discussions, see Jordan et al., 1998, 2000; Patching & Jordan, 1998; Sugishita, Hamilton, Sakuma, & Hemmi, 1994). All but one (Jordan et al., 2000) of the previous studies that provide information on serial position performance in lateralised displays have relied on instructions alone to ensure central fixation (e.g., Bouma, 1973; Bradshaw et al., 1977; Brand et al., 1983; Reuter-Lorenz & Baynes, 1992). However, several studies suggest that instructions alone are insufficient for this purpose (e.g., Batt, Underwood, & Bryden, 1995; Findlay & Kapoula, 1992; Jones & Santi, 1978; Jordan et al., 1998; Sugishita et al., 1994). For example, Jordan et al. (1998; see also Patching & Jordan, 1998) found that when instructions to fixate centrally were used, central fixations occurred on only 23% of trials, 12% were between 0.5 and 2 degrees away from centre, and the majority (64%) of noncentral fixations fell to the right of centre. Consequently, while previous findings suggest that serial position performance varies with retinal eccentricity, the actual retinal eccentricities used in these studies, in each visual field, are far from certain. Although the effects of inaccurate fixations on overt performance with lateralised displays have yet to be revealed and may be complex (see Jordan et al., 1998, for discussions), there is now ample evidence to suggest that it would be unwise not to control fixation location in divided visual field studies using an eye-tracking device.

Accordingly, the experiments reported in this article assessed effects of retinal eccentricity on the relative perceptibility of words in each visual hemifield and on the patterns of serial position performance produced at these different retinal eccentricities in order to reveal the processes of orthographic analysis present in each hemisphere. However, these experiments used procedures more stringent than applied in previous research in this area; that is, the Reicher-Wheeler task coupled with stimulus manipulations to test the presence of overt and covert bias and an eye-tracking procedure to ensure central fixation on each trial.

EXPERIMENT 1

Experiment 1 presented four-letter words unilaterally such that the horizontal distance from the central point of fixation to the nearest edge of each word was 1, 2, 3, and 4 degrees in each visual hemifield. These values were chosen because they encapsulate the range of eccentricities used in previous studies of serial position performance (Bouma, 1973; Bradshaw et al., 1977; Brand et al., 1983; Jordan et al., 2000; Reuter-Lorenz & Baynes, 1992). Performance in this experiment was examined under two conditions. In one condition (controlled), central fixation was ensured using an eye-tracking device. In another condition (uncontrolled), fixation location was monitored but participants were merely instructed to fixate centrally. This condition was included to provide a measure of the validity of previous studies that indicate different patterns of serial position performance but in which fixation location was not controlled with an eye-tracking device. In line with previous research (Jordan et al., 1998; Patching & Jordan, 1998), we anticipated a substantial number of inaccurate fixations to occur following instructions alone, leading to words in this condition being presented at a range of inappropriate retinal eccentricities.

Method

Participants. Sixteen paid undergraduate students (eight males and eight females) participated in two sessions in the experiment. All participants reported normal (i.e., not corrected-to-normal) vision, were native speakers of English, and were classified as right-handed by self-report and by administration of a revised version of the 12-item Annett Handedness inventory (Annett, 1967).

Stimuli. Testing was achieved using the Reicher-Wheeler two-alternative forced-choice task. One hundred and twenty-eight matched pairs of four-letter words were selected as experimental stimuli, with a mean frequency of written occurrence of 210 per million (Carroll, Davies, & Richman, 1971). The members of each word pair differed by just one letter (e.g. s*h*ow, s*n*ow) and these differences occurred equally often at each of the four letter positions. An additional 48 matched pairs of four-letter words provided 96 practice stimuli at the beginning of each session.

Visual conditions. Words and masks were presented on a dark-grey oscilloscope screen. Background illumination of the screen was approximately 1 cd/m^2 and the luminance of word stimuli and masks was approximately 25 cd/m^2. Words were presented in a lower-case font in which four letters subtended a horizontal visual angle of approximately 1.20 degrees. Words were presented so that their inner edges were 1.00, 2.00, 3.00, or 4.00 degrees to the left or right of the central fixation point.

Design. All participants took part in the controlled and uncontrolled conditions, one condition in each session. Participants were instructed emphatically to fixate centrally in both conditions and their eye fixations were monitored throughout. However, in the controlled condition, participants could initiate each stimulus display only when fixating the central fixation point. In the uncontrolled condition, participants could initiate each stimulus display irrespective of where they were fixating. The order in which participants took part in the controlled and uncontrolled conditions was counterbalanced across sex. Each word target was presented at each retinal eccentricity in each visual hemifield in a pseudorandom order. Half the male participants and half the female participants used the index finger of their right (preferred) hand to respond while the remainder used the index finger of their left (nonpreferred) hand. Stimuli were shown in cycles of 32 items, counterbalanced across visual hemifield, retinal eccentricity, and critical letter position.

Apparatus. The position of each eye was monitored using an infra-red ACS Applied Research Developments EM 130 eye tracker which emits low levels of (invisible) infra-red light into each eye and detects changes in the angle at which this light is reflected. The output of the eye tracker was recorded through the ADC input of a Cambridge Research Systems D300 interface, which also controlled each visual display. The sampling rate of the eye-tracking system was 1000 Hz and input conversion time was approximately 25 μs.

Stimuli were plotted through the DAC output of the Cambridge Research Systems D300 interface on a Hewlett Packard 1332A oscilloscope equipped with rapid decay P4 phosphor with a spot persistence time of 10 μs to 10%. The screen of the oscilloscope was completely covered with matt black card except for an area at its centre measuring 14 degrees horizontally and 1 degree vertically. The oscilloscope had been modified to provide a higher-resolution display and precise control over the visual angle of stimuli (Jordan & Martin, 1987). The experiment was conducted in a darkened booth, and participants entered their responses via two illuminated keys interfaced with the computer.

Fixation monitoring. The eye tracker was clamped to the head of each participant and its emitters and sensors were positioned a short distance (10 mm) from participants' eyes. The head of each participant was clamped in a head brace throughout the experiment to avoid head movements. This arrangement allowed accurate and consistent measurement of fixation location to within 7.5′ of arc (for further details, see Patching & Jordan, 1998). The eye-tracking equipment was calibrated for each participant by presenting a single pixel at a series of unpredictable horizontal distances (up to 5 degrees), left and right, from a single central pixel (the central fixation point). Participants fixated each noncentral pixel while the output from the eye-tracking equipment was monitored and adjusted such that a change in eye position registered an equivalent change in the value returned from the eye-tracking device. This calibration procedure has considerable empirical support and is widely used in eye-movement research (e.g., Beauvillain & Beauvillain, 1995; Brüihl & Inhoff, 1995; Eden, Stein, Wood, & Wood, 1994; Inhoff, 1989; Jones & Santi, 1978; Rayner & Inhoff, 1981). Calibration continued until the numerical values returned from the eye-tracker showed the same values when participants fixated previously monitored locations. Calibration checks made throughout the experiment showed no deviation in accuracy.

Procedure. At the start of the first session, each participant was familiarised with all 26 letters of the character set used in the experiment. At the start of each trial, the fixation point appeared at the centre of the screen. In the controlled condition, stimulus presentation was inhibited by testing the values returned from the eye tracker at 1 ms intervals to ensure that they were central within the prespecified range (7.5′) continuously for at least 1 s. When this criterion was satisfied, participants could initiate a stimulus presentation by pressing either of the response keys. All fixations remained constant throughout each stimulus display. However, if the value from the eye-tracker fell outside the prespecified range before the presentation of the stimulus, stimulus presentation was immediately inhibited until accurate fixation again occurred for at least 1 s (see Patching & Jordan, 1998, for further details of this procedure). In the uncontrolled condition, fixation location was monitored in precisely the same way but stimulus presentation could be initiated even when noncentral fixations occurred. When participants initiated a trial, the fixation point was immediately replaced by the following display sequence: target; 500 ms blank; two forced-choice alternatives. Target exposure durations were determined individually for each participant. To present the forced-choice alternatives, four dashes were shown in the centre of the screen, corresponding to the four letter positions in a four-letter word. At one of these dashes, two letters were shown, one above the dash and one below (randomly determined) and participants decided which of these two letters had been shown in the serial position indicated by the dash. For example, the target *work* was followed by the two alternative letters *k* and *d*, positioned above and below the final dash. To make their choice, participants pressed one of the two response keys to select either the upper or lower alternative.

Throughout the practice and experimental sections, exposure durations were re-assessed for each participant after each cycle of 32 trials. Exposure duration was increased (by 4 ms) if the number of correct responses in a cycle was below 20 (62.5%) and was decreased (by 4 ms) if the number of correct responses in a cycle was above 28 (87.5%). Within each cycle, all words were shown for the same exposure duration. Thus, when adjustments to exposure duration were made at the end of a cycle, the same adjustment was made for all critical letter positions at all retinal eccentricities in both visual hemifields. This procedure ensured that overall performance fell in the mid-range of the performance scale (75%) and that each critical letter position × retinal eccentricity × visual hemifield condition was represented at the same exposure durations. Average exposure duration for targets was 64 ms.

Results

Central fixation occurred on 100% of trials in the controlled condition. However, in the uncontrolled condition and in line with the findings of previous research (e.g., Jordan et al., 1998), participants accurately fixated (i.e., to within 7.5′) on only 29% of trials. Indeed, while the majority of noncentral fixations fell within 1 degree either side of the fixation point, 10% of fixations were between 1 and 3 degrees from centre (comparable deviations were found by Jordan et al., 1998). Moreover, the total number of noncentral fixations was not divided equally between the two visual hemifields; fixations fell to the right of centre on 51% of trials but to the left of centre on only 20% of trials. Of the 16 participants, 14 fixated more to the right than to the left ($p < .0001$ by the binomial test).

The report accuracy data obtained in the uncontrolled condition are shown in Figure 1. These data (and, by implication, the data obtained in previous studies that did not ensure central fixation) cannot subserve meaningful analysis of the influence of retinal eccentricity on serial position performance in each visual hemifield. However, whilst acknowledging this caveat, we examined the patterns of performance produced in the uncontrolled condition more closely. The data were submitted to an analysis of variance (ANOVA) with two between-subjects factors (sex, response hand) and three within-subjects factors (visual hemifield: nominally left, right; retinal eccentricity: nominally 1, 2, 3, 4 degrees; and critical-letter position). Main effects were found for visual hemifield, $F(1, 12) = 24.77$, $p < .001$, retinal eccentricity, $F(3, 36) = 16.24$, $p < .0001$, and critical letter position, $F(3, 36) = 5.85$, $p < .01$. Interactions were found between visual hemifield and retinal eccentricity, $F(3, 36) = 26.32$, $p < .0001$, and, critically, between visual hemifield and critical letter position, $F(3, 36) = 19.28$, $p < .0001$. Newman-Keuls tests revealed a significant decrease in accuracy of report for each increase in retinal eccentricity for each visual hemifield (all ps < .01) although each decrease was greater for LVF stimuli (all ps < .01). At each eccentricity, accuracy of report was greater for RVF stimuli (all ps < .01). For LVF stimuli, identification of critical letters was more accurate for position 1 than for any other position (all ps < .01) and more accurate for position 2 than position 4 ($p < .01$); no other comparisons were significant. In contrast, the pattern of critical-letter identification in RVF stimuli was relatively flat across serial position, showing only marginally higher levels of accuracy for positions 1 and 4 than for other positions (ps < .06); no other comparisons were significant.

The report accuracy data obtained in the controlled condition (Figure 2) were submitted to an

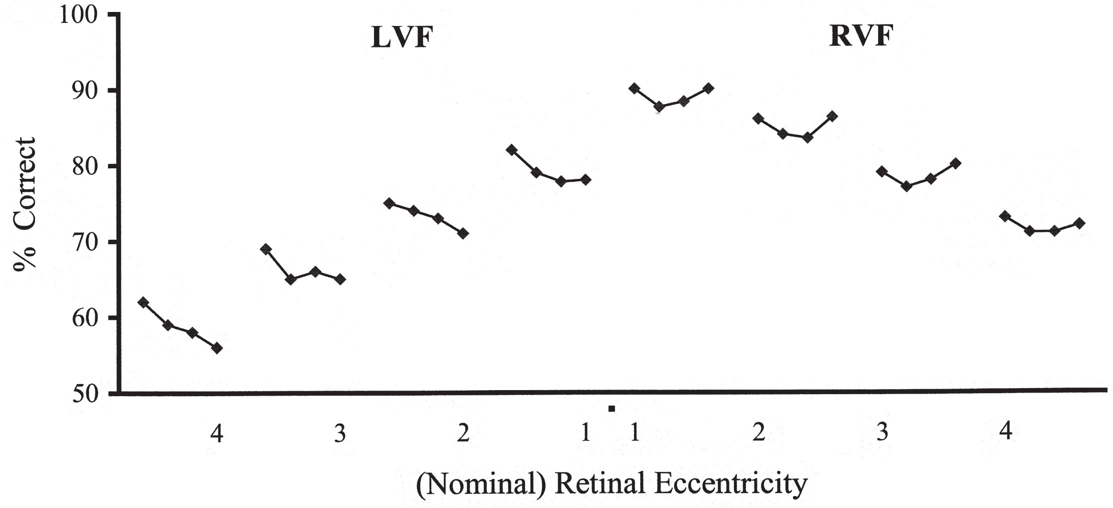

Figure 1. *Mean percentage of critical letters correctly reported (% correct) for words in the left visual field (LVF) and right visual field (RVF) at each (nominal) retinal eccentricity in the uncontrolled condition of Experiment 1.*

analysis of variance (ANOVA) with two between-subjects factors (sex, response hand) and three within-subjects factors (visual hemifield: left, right; retinal eccentricity: 1, 2, 3, 4 degrees; critical-letter position). Main effects were found for visual hemifield, $F(1, 12) = 19.33, p < .001$, retinal eccentricity, $F(3, 36) = 26.24, p < .0001$, and critical letter position, $F(3, 36) = 14.85, p < .0001$. An interaction between visual hemifield and retinal eccentricity was also present, $F(3, 36) = 15.29, p < .0001$. However, no other interactions were found, $F\text{s} < 1.30$, including any interaction involving critical-letter position, indicating no change in serial-position processing across visual hemifield or retinal eccentricity. Newman-Keuls tests revealed a significant decrease in accuracy of report for each increase in

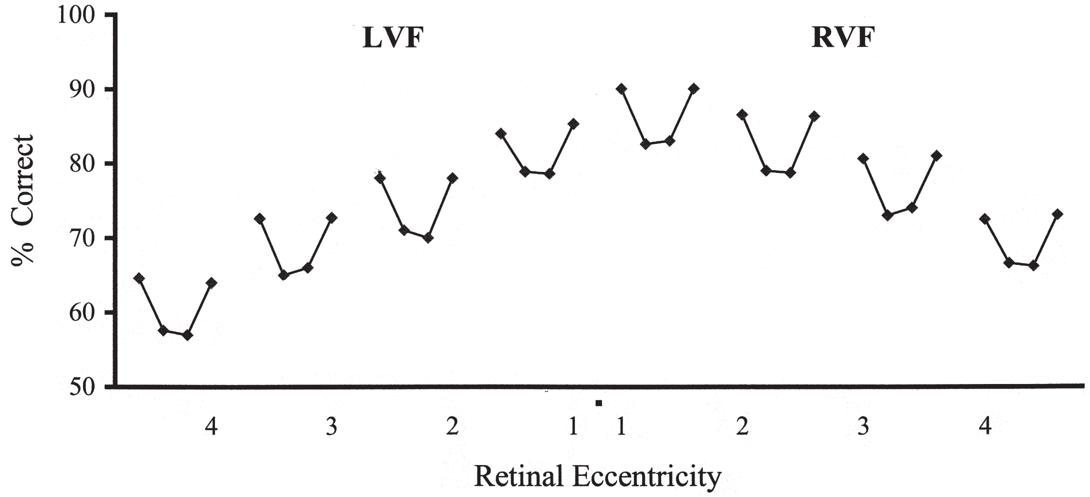

Figure 2. *Mean percentage of critical letters correctly reported (% correct) for words in the left visual field (LVF) and right visual field (RVF) at each retinal eccentricity in the controlled condition of Experiment 1.*

retinal eccentricity for each visual hemifield (all *p*s < .01) although each decrease was greater for LVF stimuli (all *p*s < .01). At each eccentricity, accuracy of report was greater for RVF stimuli (all *p*s < .01). Further tests revealed that exterior letters were identified significantly better than interior letters (all *p*s < .01); no other comparisons were significant.

The finding that the pattern of serial position performance remained essentially constant across visual hemifield and retinal eccentricity has important implications for revealing the orthographic analysis used by each hemisphere. To ensure that this constancy was not merely the result of using an insensitive, omnibus ANOVA, performance was examined further by a series of 10 subsidiary ANOVAs, conducted for pairs of retinal eccentricities between and within each visual hemifield. Specifically, performance at each retinal eccentricity (1, 2, 3, and 4 degrees) in the RVF was compared with performance at the same eccentricity in the LVF. In addition, the effect of each increment in retinal eccentricity on performance in the RVF and LVF was investigated by comparing performance between each pair of adjacent eccentricities (1 and 2 degrees, 2 and 3 degrees, 3 and 4 degrees) within each hemifield. Each between-hemifield ANOVA (with factors sex, response hand, visual hemifield, and critical-letter position) produced a main effect of visual hemifield, $F(1, 12) = 12.73$, $p < .001$, and critical letter position, $F(3, 36) = 14.54$, $p < .001$, and no other main effect or interaction (Fs<1.35). Each within-hemifield ANOVA (with factors sex, response hand, retinal eccentricity and critical-letter position) produced a main effect of retinal eccentricity, $F(1, 12) = 13.87$, $p < .005$, and critical letter position, $F(3, 36) = 20.28$, $p < .001$, and no other main effect or interaction (Fs < 1.20). Newman-Keuls tests of the main effect of serial position for each analysis showed that exterior letters were identified significantly better than interior letters (all *p*s < .01) and no other differences.

Discussion

Experiment 1 provided four important findings concerning effects of retinal eccentricity on orthographic processing. First, it now seems unlikely that accurate assessment of influences of retinal eccentricity on orthographic processing can be achieved using instructions alone to control fixation accuracy. In Experiment 1, stimuli in the uncontrolled condition were presented at a range of inappropriate retinal eccentricities because participants failed to fixate centrally on 71% of trials. Under these conditions, differences in serial position performance were observed across the two hemifields. Moreover, the patterns produced are broadly consistent with left-to-right processing in the LVF and near-parallel processing in the RVF and resemble the findings reported in previous studies where fixation location was also not controlled (e.g., Brand et al., 1983; Reuter-Lorenz & Baynes, 1992). However, rather than supporting the view that different patterns of serial position analysis exist for each hemifield, these findings from Experiment 1 highlight the dangers associated with investigating hemispheric function using lateralised displays without adequate fixation control. The precise effects of noncentral fixations on performance were not the focus of this study. Indeed, the effects are likely to be highly complex (e.g., involving a range of perceptual and cognitive influences; Jordan et al., 1998), and determining these effects will require experiments designed specifically for the purpose. Nevertheless, from the fixation data and accuracy data of Experiment 1, it seems likely that the contrasting patterns of serial position performance observed for RVF and LVF stimuli were inspired by the numerous and variable rightward biases in fixation that diluted performance differences across letter positions in RVF stimuli and produced strategic emphasis on the beginning letters of LVF words to compensate for their disadvantaged retinal placement.

Second, when fixation location was controlled in Experiment 1, changes in retinal eccentricity from 1–4 degrees had no effect on serial position performance in either visual hemifield. This finding contrasts with the indication from previous research that serial position curves are modulated by retinal eccentricity (Bouma, 1973; Bradshaw et al., 1977; Brand et al., 1983; Jordan et al., 2000; Reuter-Lorenz & Baynes, 1992), although the validity of most of these findings is now drawn into doubt by the inappropriate use of instructions alone to control fixation accuracy.

Third, when fixation location was controlled in Experiment 1, no evidence of a parallel/sequential distinction was apparent between the orthographic processing of words in each hemifield at any retinal eccentricity. Indeed, serial position performance was strikingly similar across the two visual hemifields and across retinal eccentricity. Moreover, the U-shaped function observed at each retinal eccentricity indicates a general outside-in orthographic analysis across the visual field, rather than one that is purely parallel or purely sequential. This pattern of serial position performance resembles that previously observed by Jordan et al. (2000), and has resonance with some previous findings (Bouma, 1973; Bradshaw et al., 1977; Reuter-Lorenz & Baynes, 1992) but little resonance with others (Brand et al., 1983). However, in contrast to the variable findings produced by these studies, controlling fixation accuracy and using the Reicher-Wheeler task to suppress covert and overt guesswork revealed a symmetrical U-shaped serial position curve at each eccentricity in each visual hemifield.

Fourth, when fixation location was controlled in Experiment 1, increases in eccentricity produced a greater drop in performance accuracy for LVF stimuli, indicating that perception of words presented in the RVF (and, therefore, to the left hemisphere) is less susceptible to decreases in visual acuity produced as stimuli are presented further from the point of fixation.

EXPERIMENT 2

Our reason for using the Reicher-Wheeler task is that, following the logic of Johnston (1978), the task suppresses influences of overt and covert bias on word perception (see also Jordan et al., 2000). However, Johnston's findings relate to perception of foveal words and it remains to be seen whether performance with the type of lateralised displays used in Experiment 1 is also free from the more subtle effects addressed by Johnston's study.

According to Johnston's (1978) logic, critical-letter performance with words in the Reicher-Wheeler task may be enhanced artefactually by noncritical (context) letters even though both forced-choice alternatives match this context. For example, consider the stimulus word *raid* and a subsequent forced-choice between *d* and *n*. Now suppose that information has been extracted to identify all the context letters but only the upright feature of the critical letter *d*. If letter feature information decays very rapidly unless a more permanent *letter* code is established using contextual information from the remainder of the word, this more permanent code may enhance forced-choice performance (Johnston, 1978). In our example, the contextual information from *rai*-, combined with the upright feature from the critical letter, excludes all letter codes except *d* and *l* and either code may be used to guide the accurate forced-choice response. Indeed, even if the wrong letter code were formed, featural overlap with the critical letter may produce a correct response (e.g., the incorrect letter code *l* may produce the correct choice between *d* and *n* because *d* provides more featural overlap). Thus, although both alternatives in the Reicher-Wheeler task are selected to fit the context provided by the rest of the word, this context may still artefactually affect critical letter identification.

This view of the effect of partial information on word performance centres on the notion that critical-letter report is affected by information from the critical letter and by the context provided by the remaining letters in the word (Johnston, 1978; see also Jordan et al., 2000). Thus, if the amount of information in the critical letter were held constant (by using the same letter in the same serial position), accuracy of report for this letter should be affected by the context provided by the remaining letters in the word. Jordan et al. found little effect of contextual constraint on performance with lateralised words presented at a constant eccentricity of 2 degrees. However, the effect of contextual constraint at other eccentricities is not known and is difficult to predict without knowing how changes in eccentricity affect the relative contributions made by information from context and critical letters. On the one hand, because information from critical letter positions becomes more difficult to encode as eccentricity increases (as the findings of Experiment 1 suggest), critical-letter report may be more susceptible to the degree of constraint provided by context letters in words at greater eccentricities. On the other hand, because information from *all* letter positions becomes more difficult to encode as eccentricity increases (as the findings of Experiment 1 also suggest), the degree of constraint provided by context letters in words may be no more influential at greater eccentricities than at the 2 degrees eccentricity used by Jordan et al. To investigate these possibilities, and following Johnston's approach, Experiment 2 used a new set of word stimuli in which the same letters and forced-choice alternatives were used in high constraint (highly constraining) and low constraint (lowly constraining) contexts. For example, the letters *rai-* provide considerable constraint on the identity of the critical letter *d* whereas the letters *bea-* provide less constraint since many other letters fit this context. If performance at any of the eccentricities used in Experiment 1 in either visual hemifield reflects bias produced by word context at any level of processing, critical-letter report should be more accurate with high constraint contexts.

Method

Participants. Sixteen paid participants, eight males and eight females from the same population as Experiment 1, took part in Experiment 2. All had normal vision, were native speakers of English, and were classified as right-handed by self-report and by a revised version of the 12-item Annett Handedness inventory.

Stimuli. Ninety-six matched pairs of four-letter words were selected from Johnston's (1978) stimulus set, with a mean frequency of written occurrence of 147 per million (Carroll et al., 1971). The members of each pair differed by just their critical letter, with critical letters occurring equally often at each of the four serial positions. Experimental stimuli were divided into sets of four by matching a pair of low constraint words (e.g., *date*, *gate*, where the *-ate* context is compatible with 10 letters in the critical position) to a pair of high constraint words (e.g., *drip*, *grip*, where the *-rip* context is compatible with only three letters in the critical position). In each matched, four-word set, high and low constraint words had the same critical letters in the same serial positions and were followed by the same forced-choice alternatives (in this case, *d* and *g*).

The 48, four-word sets used in the experiment were selected from Johnston's (1978) list to maximise the difference in constraint between high constraint and low constraint items. Twelve word sets were selected for each critical-letter position. Over the entire stimulus set, the mean number of words sharing the context letters of each word but containing different letters in each critical letter position was 8.57 for low constraint words and 2.38 for high constraint words. For the majority of high constraint words, the alternative letter presented for forced-choice testing after target presentation was the only letter (other than the critical letter actually presented) that fitted the context provided by the rest of the word. An additional 96 matched pairs of four-letter words provided 96 practice stimuli at the beginning of each session.

Design. Stimuli were shown in cycles of 64 items, counterbalanced across visual hemifield, constraint (high, low), retinal eccentricity, and critical letter position. Average exposure duration for high and low constraint words was 54 ms. All remaining aspects of this experiment were identical to those of the controlled condition of Experiment 1.

Results

The data (see Figure 3) were submitted to an ANOVA with two between-subjects factors (sex, response hand) and four within-subjects factors (visual hemifield: left, right; constraint: high, low; retinal eccentricity: 1, 2, 3, 4 degrees; and critical-letter position). Main effects were found for visual hemifield, $F(1, 12) = 22.53, p < .001$, retinal eccentricity, $F(3, 36) = 28.30, p < .0001$, and critical letter position, $F(3, 36) = 13.69, p < .0001$. An interaction between visual hemifield and retinal eccentricity was also present, $F(3, 36) = 9.72, p < .0001$. No other main effect or interaction was found, *F*s <

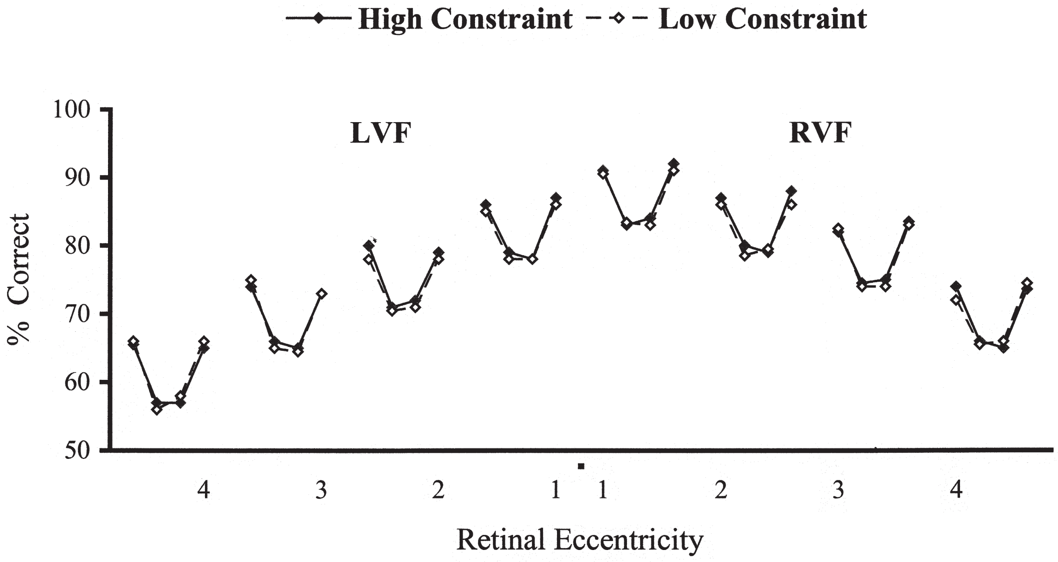

Figure 3. *Mean percentage of critical letters correctly reported (% correct) for high constraint and low constraint words in the left visual field (LVF) and right visual field (RVF) at each retinal eccentricity in Experiment 2.*

1.40. Newman-Keuls tests revealed a significant decrease in accuracy of report for each increase in retinal eccentricity for each visual hemifield (all ps < .01) although each decrease was greater for LVF stimuli (all ps < .01). At each eccentricity, accuracy of report was greater for RVF stimuli (all ps < .01). Newman-Keuls tests of the main effect of serial position showed that exterior letters were identified significantly better than interior letters (all ps < .01).

Ten subsidiary ANOVAs compared performance at each retinal eccentricity in the RVF and LVF and between each pair of adjacent eccentricities within each hemifield. Each between-hemifield ANOVA (with factors sex, response hand, visual hemifield, constraint, and critical-letter position) produced a main effect of hemifield, $F(1, 12) = 10.22$, $p < .001$, and critical letter position, $F(3, 36) = 19.16$, $p < .001$, and no other main effect or interaction (Fs < 1.20). Each within-hemifield ANOVA (with factors sex, response hand, retinal eccentricity, constraint, and critical-letter position) produced a main effect of retinal eccentricity, $F(1, 12) = 9.39$, $p < .01$, and critical letter position, $F(3, 36) = 26.18$, $p < .001$, and no other main effect or interaction (Fs < 1.35). Newman-Keuls tests of the main effect of serial position for each analysis showed that exterior letters were identified significantly better than interior letters (all ps < .01).

Discussion

The findings of Experiment 2 replicated the findings obtained in the controlled condition of Experiment 1. In particular, serial position performance was similar across the two visual hemifields and at each eccentricity in each visual hemifield, irrespective of the constraint provided by the noncritical letters of words. Indeed, the similar U-shaped patterns of serial position report observed for high and low constraint words endorse the view that this pattern of performance reflects hemisphere functions of orthographic analysis rather than influences of bias (covert or overt). The indication remains, therefore, that each hemisphere uses the same serial position processing for words at different retinal eccentricities (1–4 degrees) in each visual hemifield. However, increases in eccentricity again produced a greater drop in performance accuracy for LVF stimuli, underscoring the notion that, despite similarities in serial-position performance, processing words in the RVF (and, therefore, the left hemisphere) is less susceptible to decreases in visual acuity as stimuli are presented further from the point of fixation.

EXPERIMENT 3

Finally, we wanted to establish whether the patterns of performance obtained so far with words reflected processes also available for other types of string, particularly nonwords. This was for three reasons. First, several researchers have argued that, whereas orthographic information in words is processed in parallel in the RVF and sequentially in the LVF, orthographic information in nonwords is processed sequentially in both hemifields (e.g., Bruyer & Janlin, 1989; Bub & Lewine, 1988; Ellis et al., 1988; Lavidor et al., 2001; Young & Ellis, 1985). Previous serial position data obtained using a single retinal eccentricity provide no evidence of this difference between words and nonwords. For example, Jordan et al. (2000) found no evidence of different patterns of serial position processing for words and nonwords in either hemifield and Reuter-Lorenz and Baynes (1992) do not report data on this serial position distinction between words and nonwords. However, if lateralised words and nonwords do inspire different patterns of serial position processing, especially in the RVF, this difference may be more likely when multiple eccentricities are used as these provide a more comprehensive assessment of performance in each hemifield.

Second, it was important to establish whether the pattern of serial position performance observed so far with words reflected access to processes normally involved in word perception or merely processing at a more basic level where words are perceived only as disjoint strings of letters. If the latter, the U-shaped pattern of serial-position performance observed for words may reflect irrelevant spatial nonuniformity in letter perception (e.g., caused by lateral interference; Bouma, 1970, 1973, 1978; Estes, 1978; Estes, Allmeyer, & Reder, 1976; Haber & Standing, 1969; Hagenzieker & Van der Heijden, 1990; Hagenzieker et al., 1990; Loomis, 1978; Van der Heijden, 1987, 1992) rather than a pattern of orthographic analysis that subserves access to lexical processes. One way to reveal the involvement of processes of word perception is to contrast performance between words and nonwords. Many studies using foveal displays have shown that letters in words are perceived better than letters in illegal strings containing minimal orthographic structure (the *word–nonword effect*; e.g., McClelland & Rumelhart, 1981; Reicher, 1969; Rumelhart & McClelland, 1982; Wheeler, 1970) and that this superiority reflects the ability of words to access processes of word perception. Jordan et al. (2000) and Reuter-Lorenz and Baynes (1992) observed effects for lateralised words and nonwords comparable to those obtained previously with foveal displays, indicating that access to processes of word recognition for lateralised stimuli can be revealed by the word–nonword effect. Consequently, if processes of word perception are accessed at a particular retinal eccentricity, patterns of serial-position performance observed for words at that eccentricity should be accompanied by a word–nonword effect.

Third, the use of nonwords permitted a further test for bias (overt or covert) in the Reicher-Wheeler task. If bias contributed to the patterns of serial position performance observed so far with words, these patterns should differ for nonwords in which the potential for bias to enhance performance is reduced by the removal of legal orthography. Accordingly, Experiment 3 investigated the effects of retinal eccentricity on performance in each hemifield using word stimuli and illegal nonword stimuli containing minimal orthographic structure.

Method

Participants. Sixteen paid participants, eight males and eight females from the same population as Experiments 1 and 2, took part in Experiment 3. All participants had normal vision, were native speakers of English, and were classified as right-handed by self-report and a revised version of the 12-item Annett Handedness inventory.

Stimuli. One hundred and twenty-eight matched pairs of four-letter words (including the 96 used in Experiment 1) were used in Experiment 3. Matched nonword stimuli were constructed for each pair using custom software (Jordan & Monteiro, in press) to rearrange the three noncritical letters in each word to form unpronounceable nonwords with minimal orthographic structure but which shared the same critical letter in the same serial position (e.g., the words s*h*ow and s*n*ow formed the nonwords *ohsw* and *onsw* respectively). An additional 64 matched pairs of four-letter words and nonwords were constructed to provide 128 practice stimuli at the beginning of each session.

Design. Stimuli were presented in pseudorandomly constructed cycles of 64 items, counterbalanced across visual hemifield, stimulus type, retinal eccentricity, and critical letter position, with no obvious transition from one cycle to the next. Average exposure duration for words and nonwords was 86 ms. All remaining aspects of this experiment were identical to those of the controlled condition of Experiment 1.

Results

The accuracy data (see Figure 4) were submitted to an ANOVA with two between-subjects factors (sex, response hand) and four within-subjects factors (visual hemifield; stimulus type: word, nonword; retinal eccentricity: critical-letter position). Main effects were found for visual hemifield, $F(1, 12) = 9.46, p < .01$, retinal eccentricity, $F(3, 36) = 12.97, p < .0001$, and critical-letter position, $F(3, 36) = 20.82, p < .0001$. Interactions were found between visual hemifield and stimulus type, $F(1, 12) = 16.54, p < .01$, visual hemifield and retinal eccentricity, $F(3, 36) = 13.02, p < .0001$, and visual hemifield, stimulus type, and retinal eccentricity, $F(3, 36) = 5.63, p < .005$. No other main effects or interactions were significant. Newman-Keuls tests showed that exterior letters were identified significantly better than interior letters (all *p*s < .01). In addition, words were reported more accurately than nonwords at each retinal eccentricity in the RVF (all *p*s < .01) but no word nonword effect was found in the LVF. Moreover, for RVF stimuli, the word-nonword effect increased with increased eccentricity, such that the word–nonword effect observed at 4 degrees was greater than that observed at 1 degree ($p < .05$). As in the two previous experiments, a significant overall decrease in accuracy of report was found for each increase in retinal eccentricity, in each visual hemifield (all *p*s < .01). However, for words, each decrease was greater for LVF stimuli than for RVF stimuli (all *p*s < .01) whereas, for nonwords, decreases did not differ between the two hemifields. At each eccentricity, accuracy of report for words was greater for RVF stimuli than for LVF stimuli (all *p*s < .01) whereas performance for nonwords did not differ between the two hemifields.

Twenty subsidiary ANOVAs, 10 for words and 10 for nonwords, compared performance at each retinal eccentricity in the RVF with performance at the same eccentricity in the LVF and compared performance between each pair of adjacent eccentricities within each hemifield. For words, each between-hemifield ANOVA (with factors sex, response hand, visual hemifield, critical-letter position) produced a main effect of visual hemifield (all *p*s < .01) and critical letter position (all *p*s < .01) and no other main effect or interaction. For nonwords, between-hemifield ANOVAs produced only main effects of critical-letter position (all *p*s < .01) and no other main effect or interaction. For words and nonwords, each within-hemifield ANOVA produced a main effect of retinal eccentricity and critical letter position (all *p*s < .01) and no other main effect or interaction. Newman-Keuls tests of the main effect of serial position for each analysis showed that exterior letters were identified significantly better than interior letters (all *p*s < .01).

Discussion

The serial position data for nonwords at each retinal eccentricity in each visual hemifield in Experiment 3 resemble closely the U-shaped function observed for words in this and the two previous experiments reported in this article and offer no support for the notion that words and nonwords produce different patterns of serial position processing in lateralised displays. Indeed, the essen-

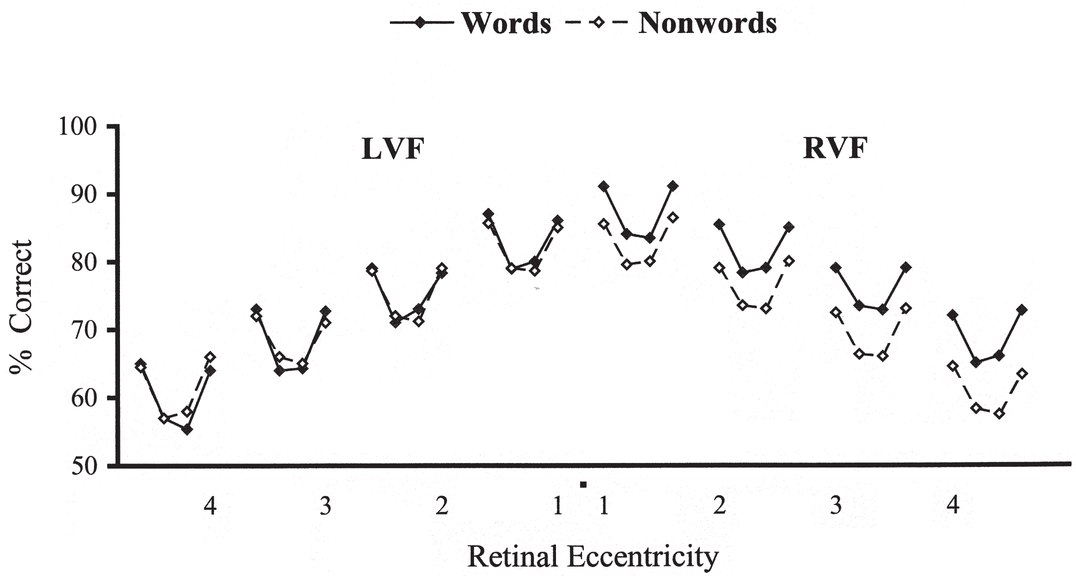

Figure 4. *Mean percentage of critical letters correctly reported (% correct) for words and nonwords in the left visual field (LVF) and right visual field (RVF) at each retinal eccentricity in Experiment 3.*

tially identical serial position curves produced by words and nonwords across Experiments 1–3 underscore the view that performance in each experiment at each eccentricity was unaffected by influences of perceptual asymmetry or bias. However, in contrast to the findings obtained with words, nonwords produced no RVF advantage and showed similar effects of increased retinal eccentricity in each visual hemifield. In addition, stimuli presented to the left hemisphere showed substantial word–nonword effects (which actually increased with retinal eccentricity) whereas the same stimuli presented to the right hemisphere did not show a word–nonword effect at any eccentricity. Thus, whereas the U-shaped pattern of serial-position analysis was observed for words and nonwords at each retinal eccentricity and in both visual hemifields, this pattern of serial-position analysis subserved processes of lexical activation only when presented to the left hemisphere.

GENERAL DISCUSSION

The first major point to emerge from the findings of this study is an RVF advantage for words obtained at all eccentricities, even under the stringent testing procedures adopted in these experiments. This suggests that, for normal right-handed individuals, recognition of written words in the RVF not only benefits from access to processes in the left hemisphere but also that access to these processes is available even when words are presented 4 degrees away from the point of fixation. However, our findings suggest these left-hemisphere processes were available only for words. In particular, whereas presenting stimuli to the right hemisphere produced very similar levels of accuracy for words and nonwords, presenting stimuli to the left hemisphere did not change nonword performance but improved word performance sufficiently to produce a word–nonword effect at each eccentricity.

This difference between words and nonwords is consistent with the view that performance with briefly presented word stimuli benefits from the ability of words to activate lexical processes (e.g., Grainger & Jacobs, 1994, 1996; Jacobs & Grainger, 1994; Johnston & McClelland, 1980; Jordan et al., 2000; McClelland & Rumelhart, 1981, 1988; Paap, Newsome, McDonald, & Schvaneveldt, 1982; see also Carr & Pollatsek, 1985). In particular, the activation produced by words in lexical representations provide an additional source of stimulus information for words over nonwords, which may also feed back to lower levels of representation (e.g., for individual letters; Johnston & McClelland, 1980; McClelland & Rumelhart, 1981, 1988; Paap et al., 1982). Consequently, when words are presented briefly, observers are more likely to encode orthographic information from words than nonwords which, in turn, produces a processing advantage for word stimuli. Following this logic, in view of the controlled assessment of hemifield performance used in this study, and assuming that briefly presented words are more likely to activate lexical representations when presented directly to the hemisphere in which these representations exist, the improved performance accuracy observed for words presented in the RVF and the absence of any improvement for nonwords indicates that only the left hemispheres of our participants contained visual lexical representations.

The slower decline in performance for RVF words as retinal eccentricity increased can also be explained by access to left-hemisphere processes of word recognition. Here, access to lexical processes in the left hemisphere may have offset effects of reductions in the quality of visual information produced as eccentricity increased. In contrast, access to lexical processes would not have been available for words presented in the LVF, and nonwords presented in either hemifield. This would account for the greater decline in performance observed for LVF words, the absence of a slower decline in performance for LVF and RVF nonwords, and the increased word–nonword effect, as eccentricity increased.

The second major point to emerge from our findings is that, in contrast to the findings of previous research in which serial position performance appeared to be modulated by retinal eccentricity, the patterns of serial position performance observed across Experiments 1–3 indicate the same pattern of orthographic processing occurred in both visual hemifields at all retinal eccentricities (1, 2, 3, and 4 degrees). Moreover, this similarity between the two hemifields was unaffected even when different stimulus sets were used (Experiment 1 vs. Experiment 2 vs. Experiment 3). This suggests that the U-shaped pattern of serial-position performance observed is not specific to a particular set of stimulus characteristics. However, this pattern of serial-position performance (see also Jordan et al., 2000) does not support a parallel-sequential distinction between the ways in which the two hemispheres process orthographic information (e.g., Bruyer & Janlin, 1989; Bub & Lewine, 1988; Ellis et al., 1988; Lavidor et al., 2001; Young & Ellis, 1985). Rather, the U-shaped serial-position curves we obtained indicate that both hemispheres process orthographic information in the same way and that this information is processed in parallel from exterior letters and from interior letters but sequentially with regard to the order in which all serial positions are eventually processed (i.e., exterior letters are processed before interior letters).

The similar patterns of serial position performance observed for words and nonwords at each eccentricity suggest that the processes underlying the U-shaped functions we observed operate at a relatively low level, before representations specific to words are activated (see also Jordan et al., 2000). As we pointed out in the Introduction, explanations of U-shaped curves obtained with foveal displays draw on interactions between the basic, psychophysical properties of letter strings. For example, many researchers have addressed the notion that information from exterior letters is perceived more easily due to reduced lateral interference from neighbouring characters (e.g., Bouma, 1970, 1973, 1978; Estes, 1978; Estes et al., 1976; Haber & Standing, 1969; Hagenzieker & Van der Heijden, 1990; Hagenzieker et al., 1990; Loomis, 1978; Van der Heijden, 1987, 1992). Indeed, psychophysical factors may play a major role in determining the pattern of serial-position processing in each visual hemifield, which then forms the basis of orthographic analysis in each hemisphere. However, the RVF advantages observed for words in each experiment and the word superiority effects observed in Experiment 3 suggest that the U-shaped functions do not reflect psychophysical processes in letter perception that are irrelevant for word recognition but rather a pattern of orthographic analysis that subserves access to lexical processes. Thus, while the relative perceptibility of orthographic information in each visual hemifield is likely to be influenced by psychophysical factors in any string of letters (words or nonwords), processes of word recognition appear to have developed (in the left hemispheres of our participants) to make use of this pattern of input. The precise nature of the processes underlying U-shaped patterns of orthographic analysis is the focus of further research.

The overall levels of performance accuracy observed for words and nonwords at different eccentricities underscore the findings of previous research (e.g., Anstis, 1974; Bouma, 1973; Hilz & Cavonius, 1974; Schiepers, 1980) that the accuracy with which orthographic information is encoded in each visual hemifield becomes substantially less as retinal eccentricity is increased. Consequently, the strikingly similar patterns of serial-position processing observed across the retinal eccentricities used in this study suggest that similar orthographic processing occurred at each eccentricity despite changes in the quality of information available at each increment. In line with our views on the relevance of relating psychophysical processing to word recognition, one explanation of this constancy is that it reflects a fundamental aspect of word recognition that is available across different retinal eccentricities. Specifically, orthographic information in the exterior positions of words may be relatively easy to locate and therefore is available for processing ahead of orthographic information in other positions (e.g., Jordan, 1990, 1995; Jordan, Smith, & Phillips, 1995). According to this view, a cursory (e.g., coarse scale) analysis of a word may normally be sufficient to reveal its horizontal extent although insufficient to reveal the identities of its individual letters. However, the exterior letters of words are invariably present at word boundaries and so an early analysis of the horizontal extent of a word could provide important information for the localisation and subsequent processing of exterior letter pairs, which then provide crucial information for lexical activation and further orthographic analyses. The importance of boundary information in perceiving exterior letter pairs (Jordan, 1990, 1995; Jordan et al., 1995) and the importance of boundary information in reading text (e.g., Pollatsek & Rayner, 1982; Rayner, 1978) has previously been reported in the literature. Indeed, several investigators posit a system of word recognition in which coarse scale information plays an important role alongside individual letter identities (e.g., Allen & Emerson, 1991; Allen, Madden, Weber, & Groth, 1993; Allen, Wallace, & Weber, 1995; Healy, Oliver, & McNamara, 1987; Jordan, 1990, 1995; Rudnicky & Kolers, 1984). For example, the hybrid PISA model (Allen et al., 1995) incorporates whole-word information in an input channel to supplement the high spatial frequency information (letter level) channel to account for lexical decision performance. In addition, although increases in retinal eccentricity produce substantial deficits in visual acuity, coarse visual cues survive more readily and so provide cues to the location of exterior letters that are relatively stable across different eccentricities (e.g., Rayner, 1998). Consequently, while letter perception overall may decrease as eccentricity increases, the presence of a U-shaped function across all eccentricities may reflect orthographic analysis inspired by coarse visual cues to the boundaries of strings that can be encoded across different retinal eccentricities. Indeed, a pattern of orthographic analysis that is common to both hemispheres and across a range of retinal eccentricities is likely to be particularly beneficial for processing words as they move across our visual field (e.g., when reading text).[2]

A privileged role for exterior letter pairs in word recognition at a range of eccentricities remains to be interpreted within the constraints of conceptualisations of hemispheric processing that contain no provision for the influence of this perceptual unit (e.g., Babkoff et al., 1997; Bradshaw et al., 1977; Brand et al., 1983; Bruyer & Janlin, 1989; Bub & Lewine, 1988; Burgess & Skodis, 1993; Chiarello,

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[2] The results of the experiments reported in this article do not support models that stress the role of visual quality in hemispheric asymmetry for alphabetic stimuli (e.g., Sergent, 1982, 1987). In particular, these models suggest that information from locations distant from the point of fixation lack the spatial resolution and acuity necessary to produce an RVF advantage for words. In contrast, our results show that an RVF advantage for words obtained at all eccentricities and was actually larger when eccentricity was greatest.

1988a; Ellis et al., 1988; Koenig, Wetzel, & Caramazza, 1992; Reuter-Lorenz & Baynes, 1992; Young & Ellis, 1985; although see the discussion by Ellis et al., 1988). At the very least, the privileged status of exterior letter pairs we observed indicates that letters in the exterior positions of words constitute a critically important orthographic unit that plays a major role in lexical activation (see also Forster, 1976; Humphreys, Evett, & Quinlan, 1990; Jordan, 1990, 1995; Jordan et al., 2000; Jordan & Thomas, 2002; Jordan, Thomas, & Scott-Brown, 1999; Jordan, Thomas, Patching, & Scott-Brown, in press; McCusker, Gough, & Bias, 1981). For example, it has been argued that the information value of exterior letter pairs is such that they provide considerable orthographic cues to word identity, particularly when accompanied by other information (e.g., boundary information, word shape; Jordan, 1990, 1995). In addition, Forster (1976) argues that exterior letters are used as an access code to partially activate a subset of word entries and that full lexical access takes place only when sufficient information from the remainder of the word has been extracted to specify one member of this subset. Although the precise role of exterior letter pairs in word recognition has yet to be fully revealed, the evidence provided in this article indicates that models of hemispheric processing of orthographic information would do well to incorporate influences of exterior letter pairs in their functioning.

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