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A longitudinal investigation of the relationship between crowding and reading: A neurodegenerative approach

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ABSTRACT

We have previously documented two patients (FOL and CLA) with posterior cortical atrophy who achieved accurate and rapid reading despite deficits in ten measures of visual processing, with two notable exceptions: (1) a measure of visual acuity, (2) a measure of visual crowding. Subsequent longitudinal investigation of these patients was carried out, involving annual tests of early visual, visuoperceptual and visuospatial processing and assessment of reading ability. Follow-up assessments identified the evolution of a particular early visual processing deficit, excessive visual crowding; this deficit has been previously implicated in forms of dyslexia. Consistent with the link between crowding and reading dysfunction, follow-up assessments also revealed deterioration in both patients' reading ability. The current findings demonstrate a neurodegenerative approach towards understanding the relationship between visual crowding and the reading system, and suggest possible mechanisms for how excessive crowding may disrupt word recognition.

1. Introduction

Visual crowding describes the inhibition of the identification of a target stimulus by the presence of flanking stimuli. This effect is primarily determined by the spacing between target and flanker stimuli, with reduced spacing leading to greater suppression of target identification; greater visual similarity between target and flankers also increases this suppression. In healthy individuals, crowding effects tend to be largely restricted to peripheral vision (with the critical spacing being proportional to the eccentricity; Bouma, 1970). However, in individuals with posterior cortical atrophy (PCA), a neurodegenerative condition characterised by progressive visual impairment, prominent effects have been observed in central vision (Crutch and Warrington, 2007, 2009, Yong et al., 2014a).

The occurrence of crowding when target stimuli and flankers are separately presented to different eyes indicates a cortical locus (Flom et al., 1963; Tripathy and Levi, 1994). Previous studies have placed this locus within the occipital cortex (Levi, 2008; Bi et al., 2009; Fang and He, 2008; Anderson et al., 2012), with functional localisation varying among V1 (Blake et al., 2006), V2 (Freeman and Simoncelli, 2011) and V4 (Liu et al., 2009). Functional imaging studies have identified an increase in crowding-modulated activation in the lateral occipital cortex (Chicherov et al., 2014) or from early to late visual areas (Anderson et al., 2012). Such findings have interpreted later visual areas being particularly involved in integrating or grouping features (Gori and Spillmann, 2010), and support crowding as a process that cannot be fully attributed to early visual areas such as V1. Correspondingly, there have been proposals of crowding as a multistage process, involving a lower-level feature detection stage, possibly in V1, and a higher-level integration of features downstream from V1 (Levi, 2008). In PCA, patterns of performance indicative of crowding when naming centrally-presented flanked stimuli have been associated with lower grey matter volume in the collateral sulcus (Yong et al., 2014a). While crowding tends to be considered a preattentive process, spatial attention may modulate crowding-related activation in early visual areas (Chen et al., 2014) and there have been suggestions that crowding itself arises from poor resolution of attention (Intriligator and Cavanagh, 2001).

Crowding is a promising candidate for a visual deficit that may fundamentally limit reading ability. Our uncrowded vision corresponds to the visual span (Pelli et al., 2007): the visual span is the extent to which we can read without moving our eyes, and has been proposed as a particularly significant factor in limiting our reading rate (Chung, 2004; Legge et al., 2001). Crowding might

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inhibit word recognition, parallel or serial letter processing through the interaction between the low-level features of words (Yu et al., 2012) such as letters (Martelli et al., 2005) or features of letters themselves (Fiset et al., 2008; Zhang et al., 2009). Excessive visual crowding has been proposed as a possible cause of developmental dyslexia, along with deficits in temporal and visuospatial attention (Franceschini et al., 2012) and diminished integrity of the magnocellular pathway (Gori et al., 2014); for a review of how these deficits relate to dyslexia including their neural and genetic bases, see Gori and Facoetti (2015). Developmental dyslexics have been found to exhibit particularly prominent crowding effects (Martelli et al., 2009; Pelli and Tillman, 2008) and increased interletter spacing has resulted in improved text reading performance of children with dyslexia (Zorzi et al., 2012).

Excessive crowding has previously been suggested to underlie a form of acquired dyslexia (Crutch and Warrington, 2009) and likely contributes to characteristic deficits in word recognition and text reading in PCA (Yong et al., 2014b; 2015). Two factors in the expression of crowding, spacing between target and flanker stimuli and visual similarity, may relate to specific reading deficits in peripheral dyslexia. One previously reported alexic PCA patient has been found to achieve optimal reading with words of moderate interletter spacing and lower letter confusability, a measure of the visual similarity of letters (Crutch and Warrington, 2009), while there have been suggestions of length effects in letter-by-letter (LBL) readers being artefacts of high letter confusability (Arguin et al., 2002; Fiset et al., 2005a, 2005b).

We previously identified two patients (FOL and CLA) who maintained rapid and accurate reading despite impairments on ten measures of early visual, visuoperceptual and visuospatial processing (figure-ground discrimination, shape discrimination, hue discrimination, number location, dot counting, object decision, fragmented letters, canonical and non-canonical view perception, chequerboard experiment), establishing that such deficits were not sufficient to impair to reading dysfunction (Yong et al., 2013). These findings present a compelling challenge to general visual accounts of letter-by-letter (LBL) reading, which propose that reading is crucially undermined by even the most subtle visual deficits (Friedman and Alexander, 1984; Farah and Wallace, 1991; Price and Devlin, 2003; Behrmann et al., 1998). Exactly where such deficits might arise remains underspecified, with general visual accounts citing impaired peripheral, prelexical, early or general visual processing underlying LBL reading.

We proposed that FOL and CLA's efficient reading was maintained due to three factors: (i) their intact visual acuity; (ii) the relative preservation of the left fusiform gyrus, a region instrumental for orthographic processing (Roberts et al., 2012) and critically, (iii) an absence of crowding deficits when identifying centrally-presented flanked letter stimuli. Regarding condition (iii), neither patient made any errors on tests of centrally-presented flanked letter identification; furthermore, while both patients were slower than their respective control groups, neither showed the hallmark spacing effects, consistent across different flankers, that are characteristic of crowding.

The current study presents longitudinal data showing deteriorating reading speed and accuracy in both FOL and CLA. The main aim of this study was to investigate the evolving relationship between word recognition and crowding. It was hypothesised that any emergence of crowding effects with centrally-presented flanked stimuli would be associated with a deterioration in reading ability. Both patients began to exhibit flanked letter identification deficits consistent with excessive crowding at follow-up; the relationship between these deficits and reading is described below.

2. Methods

2.1. Participants

The study participants were the same two individuals with PCA as in Yong et al. (2013); FOL, a right-handed retired NHS administrator, and CLA, a right-handed retired classics teacher. At first assessment, FOL and CLA were 58 and 86 years old respectively. Nine control participants were administered the same tasks as FOL and CLA. The controls were split into two groups for each patient, matched for age, gender and years of education (FOL controls [N=4]: mean age 58.4 yrs [range 56–60], all female, mean education: 16 yrs; CLA controls [N=5]: mean 83.5 yrs [range 81–84], all female, mean education: 14.8 yrs).

2.1.1. Imaging

Fluid-based non-rigid image registration (Freeborough and Fox, 1998) was used to identify local volumetric changes in grey matter, white matter and cerebrospinal fluid between paired images from different time points (Baseline scans from FOL/CLA and follow-up scans at 25 and 24 months respectively). A viscous fluid model was used to calculate the warping or deformation needed to achieve correspondence of both images at the voxel level (Scahill et al., 2002). The Jacobian determinants of the deformation fields represent the location and extent of warping, and can be displayed as voxel-compression maps which show longitudinal expansion and contraction of local brain regions. The Medical Information Display and Analysis System (MIDAS) was used to overlay voxel-compression maps on rigidly aligned MRI scans for visualisation. Non-linear registrations of follow-up scans to baseline scans were performed for both patients; the resultant voxel-compression maps (Freeborough and Fox, 1998) are shown in Fig. 1. The white arrow indicates the mean activation peak of the visual word form area ($x=-44$, $y=-58$, $z=-15$) constituted from 17 functional imaging studies (Jobard et al., 2003).

FOL: Maps indicate relative sparing of left posterior fusiform (iii) and more extensive involvement of the right than the left occipital lobe.

CLA: While maps indicate diffuse atrophy, with extensive involvement of the occipital lobe, they also indicate the relative preservation of the left relative to the right inferior temporal lobe (iii).

2.1.2. Background neuropsychology

FOL and CLA completed a battery of tests including a background neuropsychological assessment of memory, language, spelling and arithmetic and an assessment of early visual, visuoperceptual and visuospatial processing (see Sections 2.2.1 and 3.1: Visual assessment). Scores on each test are shown in Table 1. FOL was assessed 13 and 25 months after her initial visit, while CLA was assessed 17 months after her initial visit. CLA was due for a follow-up assessment at 31 months after her initial visit but was no longer suitable for testing due to a sharp deterioration in her condition, she did, however, complete the reading and crowding assessments at 27 months after her initial visit (see Section 2.2: Experimental procedures).

Across visits, FOL consistently demonstrated good performance on the concrete synonyms and spelling tasks. CLA also performed well on concrete synonym and spelling tasks for visits where background neuropsychological tests were administered (see Table 1).

2.2. Experimental procedures

Subsequent to the initial baseline assessment reported in Yong et al. (2013), the patients each completed two follow-up