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The effects of crowding on eye movement patterns in reading

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ABSTRACT

Crowding is a phenomenon that characterizes normal periphery limiting letter identification when other letters surround the signal. We investigated the nature of the reading limitation of crowding by analyzing eye-movement patterns. The stimuli consisted of two items varying across trials for letter spacing (spaced, unspaced and increased size), lexicality (words or pseudowords), number of letters (4, 6, 8), and reading modality (oral and silent). In Experiments 1 and 2 (oral and silent reading, respectively) the results show that an increase in letter spacing induced an increase in the number of fixations and in gaze duration, but a reduction in the first fixation duration. More importantly, increasing letter size (Experiment 3) produced the same first fixation duration advantage as empty spacing, indicating that, as predicted by crowding, only center-to-center letter distance, and not spacing per se, matters. Moreover, when the letter size was enlarged the number of fixations did not increase as much as in the previous experiments, suggesting that this measure depends on visual acuity rather than on crowding. Finally, gaze duration, a measure of word recognition, did not change with the letter size enlargement. No qualitative differences were found between oral and silent reading experiments (1 and 2), indicating that the articulatory process did not influence the outcome. Finally, a facilitatory effect of lexicality was found in all conditions, indicating an interaction between perceptual and lexical processing. Overall, our results indicate that crowding influences normal word reading by means of an increase in first fixation duration, a measure of word encoding, which we interpret as a modulatory effect of attention on critical spacing.

1. Introduction

The relationship between eye-movements and reading has been studied for a long time. At the beginning of the 20th Century, Huey calculated that, while reading a text, the eyes move across the page (saccadic eye movements) at a nearly constant rate and that fluent adult readers make about four fixations per second (Huey, 1908). As a consequence, the reading rate was thought to be the product of the number of fixations and the number of letters that could be acquired in each fixation (Woodworth, 1938). Subsequently, O'Regan (1980) suggested that the amplitude of saccades in reading should be expressed as a number of characters rather than as degrees of visual angle, and Morrison and Rayner (1981) showed that the average saccade amplitude remains constant at 5–6 characters with increasing character size.

Recently, it has been shown that crowding, a decoding impairment limiting the number of letters that can be processed in parallel in a glimpse, predicts reading rate (Pelli, Tillman, Su, Berger, & Majaj, 2007). Crowding is a well-studied operationally defined psychophysical phenomenon, whereby a letter is hardly identified when surrounded by nearby letters. The aim of this study is to show the eye-movement marker of crowding in functional reading.

1.1. Crowding

Beyond acuity, letter recognition is impaired by crowding (for a review see Pelli, Palomares, & Majaj, 2004; Levi, 2008; Whitney & Levi, 2011). This phenomenon, first named by Stuart and Burian (1962), has been explained in terms of the failure of the feature integration process within a spatial window (e.g. Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004). This window has been variously termed recognition span, perceptual span, visual span or uncrowded window (Legge, Mansfield & Chung, 2001; O'Regan, 1990; Pelli et al., 2007; Rayner, 1986).

Pelli et al. (2007) showed that the visual span (i.e., the number of letters that can be processed in a glimpse) corresponds to the size of the uncrowded window, namely, the letters that escape crowding at a given retinal eccentricity. The crowding effect is in fact related to the critical spacing between letters that is needed to restore

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recognition. This spacing is roughly equal to half of the target viewing eccentricity (Bouma, 1970). Bouma's proportionality of critical spacing with eccentricity means that feature integration failure is present almost always in the periphery. In fact, for the identification of a foveal letter, the integration field extends only through a few minutes of arc, which is close to the acuity threshold (Latham & Whitaker, 1996), while the amplitude of the integration field increases together with eccentricity but independently from visual acuity.

Critical spacing is not linked to letter size per se nor to empty spacing per se, but it is center-to-center letter distance which limits letter recognition in crowding (Arditi, Knoblauch, & Grunwald, 1990; Pelli et al., 2004; Strasburger, Harvey, & Rentschler, 1991). With this in mind, we examined whether the effect of interletter spacing on eye movements during reading could be attributed to crowding.

Indeed, when reading a text, some letters fall in the fovea, but most letters are located in the periphery. Since critical spacing scales with eccentricity, there will be a point beyond which it will not be possible to identify the letters. The size of the uncrowded window for reading shrinks as it moves away from the foveal region (Chung, Mansfield, & Legge, 1998; Legge, Ahn, Klitz, & Luebker, 1997; Legge, Mansfield, & Chung, 2001; Legge et al., 2007; Pelli et al., 2007). In a fixed gaze condition, a proportional increase in spacing starting from fixation allows crowding to be avoided because the letters pushed further into the periphery have proportionally increasing spacing needs. On the other hand, this proportional increase in spacing starting from fixation is not feasible in an ecological reading context in which the eyes move continuously. Because of this, up to now, crowding has been studied almost exclusively with fixed gaze.

We aimed to study the direct effect of crowding on the efficiency of reading by measuring eye movements in conditions of free viewing. In this condition, one possibility for partially reducing crowding is constant spacing. Indeed, while reading, some of the words will be seen parafoveally and increasing spacing at a constant rate would slightly move the crowding impairment towards the letters more in the periphery. Accordingly, it could be predicted that, in functional reading, when the eyes are free to move, an increase in letter spacing or letter size may similarly improve eye movement guidance by reducing the number of fixations or/and the fixation duration. Two studies suggested the involvement of crowding in the effect of spacing on eye movements measures. McDonald (2006) found that a reduction of letter spacing, keeping constant the spatial width of word stimuli, increased fixation duration. Hautala, Hyona, and Aro (2011) compared two different spacings given by proportional font and monospaced font. They found that the former, where an increase in the number of letters did not widen the word's spatial extent, induced an increase in fixation duration and gaze duration with respect to the latter. Although Hautala et al. (2011) attributed this effect to the number of letters, both studies suggested a role of crowding in fixation duration.

1.2. Visual span, perceptual span, and the lexicality status of the stimuli

The visuo-spatial distribution of characters is relevant for the calculation and the programming of sacades, and the manipulation of both interletter and interword spacing greatly influences reading and saccadic eye movements (e.g., Paterson and Jordan, 2010; Pollatsek & Rayner, 1982). McConkie and Rayner (1975) elegantly demonstrated that the amount of information that is used by the observer to guide saccades while reading extends for up to 10 characters to the right of fixation. However, when random letters are used, the span size is considerably lower than McConkie and Rayner's (1975) estimate. O'Regan (1990) proposed a distinction between the perceptual span that is obtained with words and that might be influenced by the lexical knowledge of the stimuli, and the visual span that is obtained with random letters (see Rayner, 1986 but also Legge et al., 1997, 2001; Chung et al., 1998; Legge et al., 2007; Legge & Bigelow, 2011).

This suggests an interaction between perceptual and lexical components, during eye-movement guidance in reading. The first step in reading aloud consists of the mapping of visual features onto representations through the computation of a set of letters that are displayed in a horizontal spatial orientation (McClelland & Rumelhart, 1981, Rumelhart & McClelland, 1982). This computation is probably achieved in parallel and represents a major challenge for word recognition models that need to incorporate visual limitations, such as crowding (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996). In accordance to the dual route model of word recognition (DRC) proposed by Coltheart et al. (2001), while pseudowords are read via a slow grapheme-to-phoneme conversion strategy (GPC route), words can be read with both the GPC route and a less slow direct lexical matching (lexical route). According to the DRC model, reading aloud would be achieved in parallel using the lexical route and serially using the grapheme-to-phoneme conversion rule (but see Zorzi, Houghton, & Butterworth, 1998). The lexicality advantage may thus suggest that during reading, acquisition letter processing is optimized through a reduction in the size of the integration fields with a consequent increase in the uncrowded window size expressed by a reduction in number of fixation. However, if the perceptual limitation set by crowding constitutes a rigid bottleneck one might expect the same number of letters to be uncrowded when words and pseudowords are presented (Levi, 2008; Pelli & Tillman, 2008).

In this case subjects may use a guessing strategy for words (e.g., Paap, Newsome, McDonald, & Schvaneveldt, 1982), producing different decoding times. In this vein, differences may be found in the fixation duration for these types of stimuli when crowding is relieved by increasing the spacing or size of letters.

In the present study, we conducted three experiments in order to analyze the effects of interletter spacing, lexicality and number of characters on eye movements during reading. We developed a new two items reading task that allowed the testing of the effects of center-to-center letter distance (either by manipulating the letter spacing within a word or the font size). As in functional reading, in this task the reading pattern of the second item (the only one analyzed) is influenced by a previous similar item and not by a fixed starting point (as in a single item reading task).

In the first experiment, we recorded eye movements in normal readers by manipulating spacing and stimulus length while observers read words and pseudowords aloud. Although investigation of the complexities of oral compared to silent reading is out of the scope of the present paper, in the second experiment, in order to exclude the interference of time consuming articulatory processes, which could have slowed visual scanning, we asked new participants to perform the same task reading silently. The third experiment used the same stimuli and procedures as Experiment 2, but manipulated character size rather than spacing. We hypothesized that if the observed changes are due to crowding and not to the insertion of empty interletter spacing per se, then manipulating size or spacing should lead to similar results.

In particular, it has been shown that increasing spacing induces more fixations, reduces fixation duration and does not influence gaze duration (e.g., Slattery & Rayner, 2013). We hypothesized that the number of fixations depends mostly on the string spatial extension. Thus, we predicted obtaining similar results on this parameter by increasing the number of letters or the spaces between them. In contrast, we conjectured that the decrease in fixation duration may reflect encoding and may be due to a release from crowding. In this vein, we predicted the same reduction in fixation duration when increasing letter size or letter spacing. On the other hand, if the increase in the number of fixations and the decrease in fixation duration are due to spacing per se, the manipulation of size should not induce the same effects as the introduction of empty spacing.

2. Experiment 1: oral reading

The first experiment was designed to study the effect of interletter spacing on eye movements. We required participants to read aloud.