Holistic Word Processing Is Involved in Fast Parallel Reading

Article · April 2019

CITATIONS
13

READS
798

7 authors, including:

Paulo Ventura
University of Lisbon
81 PUBLICATIONS **2,892** CITATIONS
SEE PROFILE

Miguel Domingues
University of Lisbon
14 PUBLICATIONS **72** CITATIONS
SEE PROFILE

Inês Ferreira
University of Lisbon
5 PUBLICATIONS **23** CITATIONS
SEE PROFILE

Mariana Madeira
University of Lisbon
2 PUBLICATIONS **18** CITATIONS
SEE PROFILE

Journal of Expertise
2019. Vol. 2(1)

ISSN 2573-2773

Holistic Word Processing Is Involved in Fast Parallel Reading

Paulo Ventura, Miguel Domingues*, Inês Ferreira*, Mariana Madeira*, Ana Martins*, Maria Neto*, and Marta Pereira*
CICPSI, Faculty of Psychology, University of Lisbon, Portugal
*These authors contributed equally to this work.

Correspondence: Paulo Ventura, paulo.ventura@gmail.com

Abstract
Holistic processing of words has been previously observed. When readers have to decide whether the target part of a study and test words are the same, their performance is affected by the irrelevant part. The goal of the present study was to provide an empirical test of the idea that holistic word processing is involved in expert reading (fast and parallel letter reading pattern) by exploring the perceptual expertise limits of the neuronal systems dedicated to reading. We presented adult readers with words in the composite paradigm that were degraded by word rotation (22.5º and 67.5º). Rotations were applied clockwise or counterclockwise. A word rotation of 22.5º is below the threshold of the perceptual expertise of the Visual Word Form (VWF) System, while a rotation of 67.5º is above the threshold of the perceptual expertise of the VWF system. The word composite effect was found only for a degree of rotation within the field of expertise of the ventral visual system, thus within the limits for fast, parallel-letter reading. We thus showed that word holistic processing occurs within the functional, fast, and parallel reading route.

Keywords
perceptual expertise, visual word recognition, holistic effect, composite tast, parallel reading pattern

Introduction

In modern societies people may have expertise in two visual categories: faces and objects, which include words. Face processing differs from that of other visual objects. Whereas the latter are usually identified at the basic level (e.g., dog and not chihuaha, the breed, or Snoopy, a name (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), such identification would be barely useful for faces as all have eyes, nose, and mouth, and in the same general configuration. Identification of a face (e.g., a person named Paulo) is done at an individual level and depends on fine, subordinate-level discrimination based on subtle differences in configuration, which explains the preponderance of *holistic* processing (Diamond & Carey, 1986; Gauthier and Tarr, 2002; McKone, Crookes, Jeffery, & Dilks, 2012). This type of processing can be defined as the simultaneous integration of the multiple features of the stimulus into a *Gestalt* (Rossion, 2013), or as a perceptual strategy of processing all parts together that becomes automatized due to extensive individuation of members of a particular category (Wong & Gauthier, 2010; for a discussion, see Richler, Palmeri, & Gautier, 2012). Holistic processing is inferred from an

inability to ignore one half of a face as being irrelevant. This is a failure of selective attention (cf. Harrison, Gauthier, Hayward, & Richler, 2015): The irrelevant part affects performance on the critical part because the face (the composite constituted by the top and bottom halves) is processed as a whole (but see Rossion, 2013). Regardless of the interpretation, holistic processing is critical for faces; consequently, the perception of one part is deeply influenced by the other parts of a face.

Experts in a non-face category also identify the objects of expertise at a subordinate level (Bukach, Gauthier, & Tarr, 2006), and this seems to be critical for the emergence of holistic processing (Wong, Palmeri, & Gauthier, 2009). Indeed, Wong, Palmeri, and Gauthier (2009) showed that such hallmarks of face processing can also be found for novel, artificial, nonface objects as people develop expertise in individuating specific objects. Considering naturally occurring objects, although these objects do not bear any low-level, physical resemblance to faces (e.g., X-rays: Bilalic, Grottenthaler, Nagele, & Lindig, 2014; chessboards: Bilalic, Langner, Ulrich, & Grodd, 2011; fingerprints: Busey & Vanderkolk, 2005; cars: Gauthier, Curran, Curby, & Collins, 2003), experts have been found to show holistic processing of these objects.

Chess is an interesting example because expertise varies from expert to truly novice players, with recreational players in between. Chess experts study and remember precise positions from specific games, an individuation experience which is considered critical for face-like processing (Boggan, Bartlett & Krawczyk, 2012). Boggan et al. (2012) examined the face processing hallmark of expertise—holistic processing as indexed by the congruency effect (congruency between the responses to relevant and irrelevant parts in a sequential matching task)—in chess. They found that the congruency effect was equally strong with chessboards and faces. The task Boggan et al. (2012) used was an interleaved procedure in which participants viewed interleaved chess composites and face composites. They found that chess expertise was positively related to the congruency effect with chess yet negatively related to the congruency effect with faces, suggesting that face and expert chess processing share common processes (see Gauthier, Curran, Curby, & Collins, 2003, for a similar conclusion regarding faces and cars in car experts).

Although some authors claim that the brain has evolved a specific module for faces (the fusiform face area—FFA; Kanwisher et al., 1997), many argue that the FFA is actually an area that enables differentiation between exemplars within the same category, regardless of the kind of stimulus, and which is responsible for holistic processing (Gauthier et al., 1999). Bilalic et al. (2011) used thorax X-rays that do not share any obvious features with faces and in which skill in medical image perception can be compared. They demonstrated that the sensitivity of the FFA to X-rays was significantly better in experienced radiologists than in medical students with limited radiological experience.The holistic processing in radiological expertise may be one of the underlying factors behind the FFA sensitivity to X-rays (Bilalic et al., 2011). Sheridan and Reingold (2017) review the evidence of holistic processing in the field of medical image perception and point to the aspects that support this holistic perspective: Expertise in medical image perception is domain-specific (not found for example, in a “looking for Wally” visual search task), medical experts use parafoveal and/or peripheral vision to process large regions of the image in parallel, and experts may need only a single glance at the image. Also, radiological images, like faces, are made up of variable elements situated in fixed locations (Bilalic, 2018). For a recent example of the sensitivity of the FFA to expert perception see the work, with cars, of Ross, Tamber-Rosenau, Palmeri, Zhang, Xu, and Gauthier (2018) showing that the neural representation of cars in right anterior FFA is more holistic for car experts than car novices, consistent with the idea of common mechanisms of neural selectivity for faces and other objects of expertise in this area. The interest one may have in individuating objects from various categories may be very fine-grained and is shown in how we process

objects. For example, modern-car experts showed expert discrimination and holistic processing of modern cars but not of antique cars (Bukach, Phillips, & Gauthier, 2010).

Holistic processing has thus been regarded as a marker of perceptual expertise for many objects. Although word recognition is among the most prevalent forms of expert object recognition observed in the population (Wong & Gauthier, 2007), there is no consensus yet on whether expert word recognition involves holistic processing (Wong, Wong, Lui, Ng, & Ngan, 2019). For example, there is the well-known word superiority effect (Reicher, 1969; Wheeler, 1970) which suggests that whole-word representations can have a top-down influence on the letter level (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). However, other authors argue for part-based recognition of visual words (Pelli, Farell, & Moore, 2003). In this vein, Farah and colleagues (e.g., Farah, 1991, 1992; Farah et al., 1998; Tanaka & Farah, 1993) conceived word and face recognition as relying on different representational capacities (part-based vs. holistic-based).

In recent years, some researchers investigated holistic word processing using a task called the composite paradigm: For example, participants are asked to decide whether the left part of words is the same (for an illustration, see Figure 1). The composite task thus provides a stringent test of holistic processing: Any interference in performance from the irrelevant part on the relevant part indicates automatic and compulsory processing of all parts of the stimuli. In the complete version of this task (for a recent meta-analysis and review see Richler & Gauthier, 2014), there are four conditions, including "same" and "different" trials (the critical halves of the two stimuli being same or different) with irrelevant face halves that are different or the same. One can thus define "congruent" and "incongruent" trials depending on the relation between the correct response for the target part and the same/different status of the task-irrelevant part (Richler & Gauthier, 2014). The complete paradigm usually involves an aligned (parts are aligned) and a misaligned (parts are misaligned) condition. Holistic processing is inferred from a better performance on congruent than incongruent trials that is reduced in misaligned trials.

Using this paradigm, researchers observed holistic processing in both English words (Wong et al., 2011) and Chinese characters (Wong et al., 2012). This holistic effect was larger for words in one's familiar writing system, and larger for words than pseudowords, suggesting that the holistic processing style is acquired with perceptual experience (Ventura et al., 2017; Wong et al., 2011).

Nevertheless, it is unclear where in the word processing system holistic word processing occurs (Wong et al., 2019). Indeed, Chen et al. (2013) showed in an event-related potential (ERP) study that holistic processing of words has an earlier neurophysiological correlate (P1) than that (N170) commonly found for face holistic processing (e.g., Jacques & Rossion, 2009), suggesting involvement of the early visual processes. Recently, Ventura et al., (2017) have shown that the congruency effect was immune to surface features as it was similar for words printed in a typical, courier font, in aLtErNaTiNg-case, or in a handwriting font, suggesting an involvement at the level of abstract lexical representations. The objective of the present investigation is to give an experimental test of the possibility that holistic word processing is associated with expert reading with quick and parallel processing of letters.

We will explore the effect of word rotation on holistic word processing. Several behavioral studies have explored the impact of rotation on holistic word processing. The study of Koriat and Norman (1985) suggested that words are read holistically at orientations at or close to the upright but in a more piecemeal or analytical fashion when rotated by 180 degrees (see also Pashler, Ramachandran, & Becker, 2006): Recognition times for words are independent of word length between 0º and ~60º, increasing with increased word length suggesting bit-by-bit reading of sub-lexical units, with a last shift to very slow letter-by-letter reading beyond ~120º

(cf. Conway, Brady, & Misura, 2017). This "word inversion effect" holds for words presented in their familiar format—not for words written backwards or for mirror rotated words (Bjornstrom, Hills, Hanif, & Barton, 2014). A study which employed upright and inverted words showed that holistic word recognition is impaired in dyslexia (Conway et al., 2017): While stimulus inversion leads to an increase in RTs in controls and dyslexic participants, this increase is greater for control than for dyslexic participants. Dyslexics are less hindered by changes in orientation.

Another rotation study suggests that handwritten word perception requires greater holistic processing, relative to computer print, because handwritten words are variable and ambiguous (Barnhart & Goldinger, 2013). Although these studies point to the importance of holistic processing for word recognition, other studies claim the unimportance of holistic information for word recognition (e.g. Ge, Wang, McCleery, & Lee, 2006). Indeed, Ge, Wang, McCleery, & Lee (2006) used a contextual priming paradigm. Participants were first engaged in processing either faces or non-faces (Chinese characters) and then were tested using ambiguous stimuli that could be perceived as faces or non-faces (Chinese characters) depending on the priming condition. After the face priming task, participants showed a significant inversion effect when processing the ambiguous stimuli. However, after the character priming task, the same ambiguous stimuli did not produce a significant inversion effect. Thus, the literature on rotation and holistic processing of faces, reviewed above and which used the inversion effect, is not conclusive. However, many authors explicitly state that the inversion effect is merely indirect evidence for holistic processing (e.g., Michel, Rossion, Han, Chung, & Caldara, 2006), and Maurer, Le Grand, and Mondlach (2002) explicitly noted that the mere presence of an inversion effect is not diagnostic of holistic processing in the absence of more direct evidence.

Word rotation has also been manipulated in the neuroimaging/neuropsychological literature which is more directly relevant for the purposes of our study. Fast, parallel (letter processing) word recognition in expert readers relies on sectors of the left ventral occipito-temporal pathway collectively known as the Visual Word Form (VWF) system (e.g., McCandliss, Cohen, & Dehaene, 2003). Expertise is reached only after years of practice. Children initially decipher words slowly and letter by letter, as indexed by a large effect of word length on reading latencies (Aghababian and Nazir, 2000). Over years of practice, speed increases and the length effect eventually disappears, at least for words of about 3 to 6 letters (e.g., Barton, Hanif, Bjornstrom, & Hills, 2014), demonstrating a parallel processing of letters. This expertise, arising from perceptual learning mechanisms, enables the VWF system to become attuned to the regularities of the writing system (Dehaene et al., 2005). Perceptual learning mechanisms can ensure only that the visual system of the expert reader is attuned to the perception of normal print: horizontally aligned words presented in the foveal region in a usual font (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008). "Parallel word recognition, based on the ventral visual system, should be limited to words displayed in this familiar format; words displayed in formats outside this field of expertise should be read serially, under supervision of dorsal parietal attention systems" (Cohen et al., 2008).

Vinckier et al. (2006) studied a simultagnosic patient with bilateral parietal atrophy. The patient was excellent at reading normally printed words presented foveally, but reading was severely disrupted with "words which were mirror reversed, or rotated by angles larger than 50º, or whose letters were separated by at least two blank spaces, or words displayed in her left hemifield." Vinckier et al. (2006) and Cohen et al. (2008) proposed that those are basic cutoff points/limits of the perceptual expertise of the VWF system which is tuned to process optimally words underneath certain levels of rotation, spacing, and displacement. Above the limits of the perceptual expertise of the VWF system, reading requires the mediation of the parietal lobes. Therefore passing these limits is related with a change from a generally automatic

and (letter) parallel word identification procedure to an attention based serial reading procedure

We explored in the present study whether holistic processing of words is involved in expert reading (fast and parallel) by taking into consideration the perceptual tolerance of the VWF system. More specifically, we presented adult readers with words in the composite paradigm that were degraded by word rotation (22.5º and 67.5º). Rotations were applied clockwise or anticlockwise. A word rotation of 22.5º is below the threshold of the perceptual expertise of the VWF system, while a rotation of 67.5º is above the threshold of the perceptual expertise of the VWF system (Cohen et al. 2008; Vinckier et al., 2006). If holistic word processing is involved in expert reading (fast and parallel), the word composite effect should be observed for a 22.5º rotation. The word composite effect is verified as a better performance on congruent than incongruent trials that is reduced in misaligned trials. For a 67.5º rotation, which is beyond the limits of the perceptual expertise of the VWF system, one would predict a piecemeal reading of sub-lexical units. In this case, the pattern of results would parallel those for pseudowords (Ventura et al., 2017), a congruency effect not modulated by alignment. Thus, we explored word expertise effects, and the role of holistic processing in those effects, testing undergraduate students (supposedly, all experts) by exploring the perceptual expertise limits of the neuronal systems dedicated to reading.

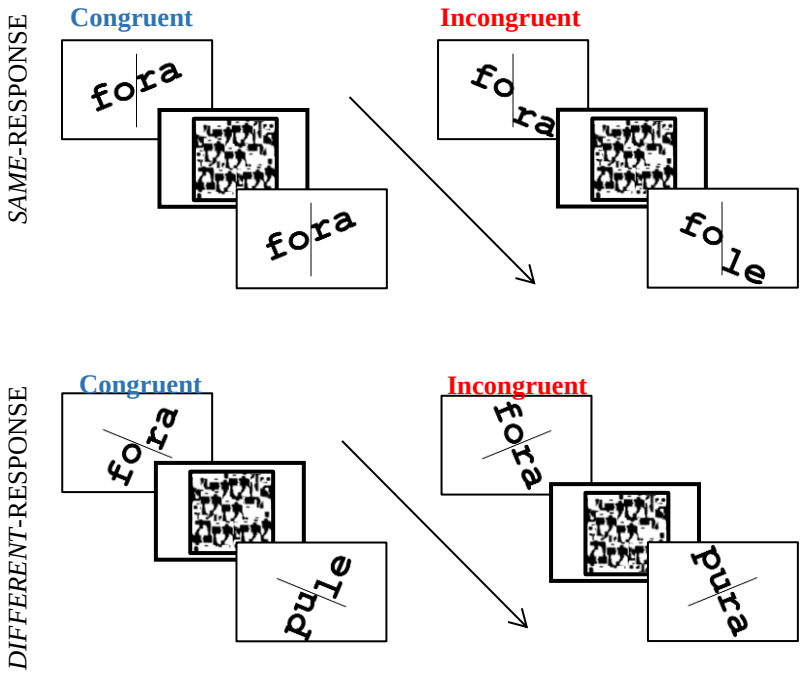

Figure 1. Illustration of the composite task with Portuguese words. Sequence of events in the same-different matching composite task (Response x Alignment x Congruency). Rotation was manipulated between-participants (for details see General Method): small rotation (illustrated in the same-congruent aligned condition at the top and in same-incongruent and misaligned condition at the top) and big rotation (illustrated in different-congruent and misaligned at the bottom and different-incongruent and aligned condition at the bottom). In the experiment, we ensured that material was presented in the center of the screen.

Method

Participants

All participants were native Portuguese readers with normal or corrected-to-normal vision and no known history of a reading disorder. They were undergraduate students of psychology at the University of Lisbon and participated voluntarily in exchange for course credits or a bookstore voucher. Participants were randomly assigned to one rotation condition: small (n = 59), and big (n = 59) rotation.

This study followed the Declaration of Helsinki, the Portuguese deontological regulation for Psychology, and was approved by the Deontological Committee of Faculty of Psychology of the University of Lisbon. All participants provided informed consent.

Material and Procedures

Twenty-four sets of four consonant-vowel.consonant-vowel (CV.CV) Portuguese words were used as stimuli (presented in the supplemental material; cf. Ventura et al., 2017). Each word was divided into a left and a right half as illustrated in Figure 1: The left half was always the critical one. Some authors that investigated word holistic processing in the composite task (Wong et al., 2011, 2012) used a version of the task in which a cue (presented between study and test stimuli) signaled which part of the word, left or right, was relevant. However, using the left half always as the critical one, we replicated the word composite effect in Portuguese (Ventura et al., 2017). We thus decided to keep the same task format. Within each set, words were arranged to allow for the manipulation of the same/different status and congruent/incongruent status. Each word appeared four times as study and test stimuli in the experimental trials.

For each word, four stimuli with 20-point size were prepared: small rotation version (5º x 4.12º at a viewing distance of 90 cm), both clockwise and anticlockwise; big rotation version (3.82º x 4.78º at a viewing distance of 90 cm), both clockwise and anticlockwise. The left and right halves of each word were separated by a vertical line. As shown in Figure 1, in the misaligned condition, the right half of the word (for both the study and the test words) was moved down by 100 pixels (5º x 4.73º for small rotation, 3.82º x 5.22º for big rotation; at a viewing distance of 90 cm). Stimuli were presented in the aligned and misaligned condition in different blocks (8 blocks). Each block comprised six sets of words (96 trials). Participants in the small rotation condition saw half the stimuli clockwise (4 blocks—2 aligned, 2 misaligned) and half anticlockwise (4 blocks—2 aligned, 2 misaligned). Similarly, participants in the big rotation condition saw half stimuli clockwise (4 blocks,—2 aligned, 2 misaligned) and half anticlockwise (4 blocks—2 aligned, 2 misaligned). Congruent and incongruent trials were distributed randomly in each block.

Presentation of stimuli and data collection were controlled by E-Prime 2.0[1]. Stimuli were presented on the center of a 17" CRT monitor, first, a fixation cross (500 ms), followed by the study stimulus (400 ms), then a mask (1 s), followed by the test stimulus, which remained on the screen until response or for a maximum of 2.5 s. Participants were asked to perform as quickly and as accurately as possible a same-different judgment on the left part of the test stimulus by key presses. Before the experimental trials, they were first presented with four examples on paper, for which they received feedback on the correct response; next, they performed 32 computerized practice trials on different stimuli but with the same procedure as that on experimental trials.

Direction of rotation was blocked and since all words in a block had the same direction of rotation, participants could tilt their heads to facilitate perception. To avoid this possibility, the chair was in a fixed position and participants were instructed not to move their body or head during the experiment. The experimenter verified compliance with these instructions.

Results

Due to excessive error rate (> 25%), 3 participants were removed from the analyses in small rotation condition, and 2 participants in big rotation condition. The average global error rate was of ~ 4% in small rotation condition, and of ~ 4% in big rotation condition. Data analyses

were run on mean S*ignal Detection Theory* (SDT) *A* scores (Zhang & Muller, 2005), with alignment (aligned; misaligned) and congruency (congruent; incongruent) as within-participants factors and rotation (small, big) as between-participants factors. *A* scores were computed as shown in Figure 2, with *hits* (H) corresponding to the proportion of correct responses in *different*-response trials and *false alarms* (F) to incorrect responses in *same*-response trials. *A* was the SDT measure adopted because, in contrast to *d'*, it is a nonparametric measure of sensitivity that does not assume normality or equal variances (Zhang & Mueller, 2005). Data analyses were also run on mean *Reaction Time* (RT) for correct responses. Effect sizes were analyzed according to partial eta square (ηp^2) values (Cohen, 1988).

$$A = \begin{cases} \frac{3}{4} + \frac{H - F}{4} - F(1 - H) & \text{if} \quad F \leq 0.5 \leq H\,; \\ \frac{3}{4} + \frac{H - F}{4} - \frac{F}{4H} & \text{if} \quad F \leq H < 0.5\,; \\ \frac{3}{4} + \frac{H - F}{4} - \frac{1 - H}{4(1 - F)} & \text{if} \quad 0.5 < F \leq H\,. \end{cases}$$

Figure 2. Formula used to compute the SDT *A* scores.

Participants were quite accurate on same-different judgments of the critical part of Portuguese words, with overall mean *A* scores of .98 (*SEM* = .005) for small rotation condition and of .98 (*SEM* = .004) for big rotation condition, in line with the results found previously with this task (cf. Ventura et al., 2017; Wong et al., 2011, 2012). No significant effects were found in the mixed 2 (rotation: small, big) x 2 (alignment: aligned, misaligned) x 2 (congruency: congruent, incongruent) ANOVA run on A scores (all *p*s > .09). The lack of effects on the A measure was already observed by us in our previous study with Portuguese words (Ventura et al., 2017) and is probably the result of overall high values of A.

In the mixed 2 (rotation: small, big) x 2 x 2 ANOVA run on mean correct RTs (cf. Figure 3), the main effect of rotation was not significant, $F(1, 111) = 2.22$, $p = .14$. The main effect of alignment was also not significant, $F < 1$. The main effect of congruency was significant, $F(1, 111) = 66.54$, $p < .0001$, $\eta p^2 = .37$, with faster RTs in congruent, $M = 598.86$ ($SE = 19.92$), than incongruent trials, $M = 609.58$, $SE = 20.51$). The interaction between alignment and congruency was significant, $F(1, 111) = 5.35$, $p < .05$, $\eta p^2 = .05$. Indeed, the congruency effect found in the aligned condition (on average, participants were 13 ms faster in congruent than in incongruent trials) was significantly reduced in the misaligned condition (average congruency effect of 8 ms,), $t(112) = 2.24$, $p < .05$.

Crucially, rotation modulated the word composite effect, $F(1, 111) = 5.9$, $p = .017$, $\eta p^2 = .05$. The word composite effect was significant for the small rotation condition, $F(1, 55) = 10.39$, $p < .002$,but not for the big rotation condition, $F < 1$. No other effects were significant, all *p*s > .37.

We did not use a degree of rotation of zero, but it would be important to show that the small degree of rotation (22.5º) did not differ from a normal upright word in terms of the word composite effect. We built a data file including data from the small rotation condition and data for the "courier" condition in Experiment 1A of Ventura et al. (2017) which is equal to small rotation condition except for the fact that words were presented in normal upright position. The critical interaction of degree of rotation x alignment x congruency was not significant $F(1, 99) = 1.19$, $p = .28$.

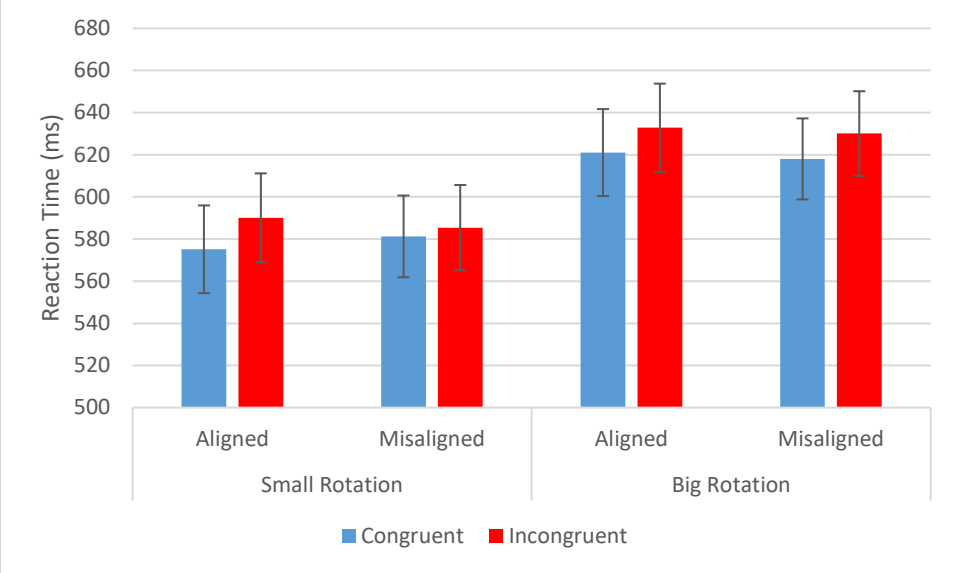

Figure 3. Mean RTs (in ms) separately by rotation in the aligned and misaligned blocks with congruent trials in blue and incongruent trials in red. Error bars represent standard error of the mean.

Discussion

At what stage of processing does the holistic processing of words take place? The VWFA is generally agreed to intervene in the efficient identification of orthographic stimuli (Dehaene et al., 2001) and to enable quick association of such stimuli with phonological and lexical information (Hashimoto & Sakai, 2004). In the present study we provided an empirical test of the idea that holistic word processing is involved in normal fast and parallel reading pattern, supported by the VWFA system, by presenting Portuguese readers with written words in the composite task. We thus explored word expertise effects—and the role of holistic processing in those effects—testing expert readers, but exploring the perceptual expertise limits of the neuronal systems dedicated to reading. Specifically, we investigated whether the word composite effect occurs for words rotated by 22.5º or rotated by 67.5º. The word composite effect was found only for a degree of rotation within the field of expertise of the ventral visual system (Cohen et al., 2008; Dehaene, Vinckier, Jobert, & Montavont, 2008; Vinckier et al., 2006), thus within the limits for fast, parallel reading. We thus showed that holistic word processing occurs within the functional, fast and parallel reading route. The role of holistic processing may be to "bind together individual letters that activate the posterior part of the VWFA providing the input that activates more anterior parts of the VWFA, responsive to whole words" (Ventura et al., 2017). Holistic processes are thus an integral part of normal, fast, and parallel (letter) reading.

As discussed in the Introduction, experts in several visual categories (including faces and objects that do not bear any low-level, physical resemblance to faces) identify the objects of expertise at a subordinate level (Bukach, Gauthier, & Tarr, 2006), and this seems to be critical for the emergence of holistic processing. For readers, letters and written words are also a category of perceptual expertise. However, in contrast to faces, visual word recognition seems to rely more on part-feature processing (e.g., Pelli, Farell, & Moore, 2003): It depends on number, sequence, and identity of constituent parts (Grainger, 2017), with the detailed spatial relationships between parts (e.g., the distance between components) being less relevant than for face recognition. There is however also the need for a subordinate level identification in the case of words. Indeed, words are composed of a limited and highly similar (compare "c" and "e") set of letters, and fine-grained distinctions are

needed. Holistic processing, a hallmark of visual expertise, has indeed been shown for written words, signaled by the word composite effect (Ventura et al., 2017; Wong et al., 2011, 2012): Fluent readers find it difficult to focus on just one half of a written word while ignoring the other half, especially when the two word halves are aligned rather than misaligned. We had, however, no demonstration that holistic processing is an intrinsic part of expert reading. The present study showed precisely that word holistic processing occurs within the expert, fast, and parallel reading route.

One limitation of the present study was that we could have included more rotations (e.g. 45º, and 90º). Note, however, that we were interested in degrees of rotation within and outside the field of expertise of the ventral visual system, and not on word rotation per se. Also, we could have made rotation angle a within-participants variable, thus another limitation of the present study.

The composite task has been the most commonly used paradigm in the study of holistic face processing (for a discussion, see e.g., Fitousi, 2015; Richler & Gauthier, 2014; Rossion, 2013). Although the same composite paradigm has been used to reveal holistic processing for faces and words, this does not mean that the same mechanisms underlie the effects for the two domains (Chen, Bukach, & Wong, 2013). Indeed, Chen et al. (2013) showed in an event-related potential (ERP) study that holistic processing of words has an earlier neurophysiological correlate (P1) than that (N170) commonly found for face holistic processing (e.g., Jacques & Rossion, 2009). This suggests potentially different mechanisms behind holistic processing for words and faces. On the other hand, the absence of duration effects for visual words and faces suggest that the holistic processing in these two categories may share some common principles (Chen, Abbasi, Song, Chen, & Li, 2016). In a study on face recognition, Richler, Mack, Gauthier, & Palmeri (2009) parametrically varied the stimulus duration from 17 ms to 800 ms. The holistic effect, as indexed by the congruency effect, was observed for exposure as brief as 50 ms, and from 50 ms onwards it was affected neither by the duration of the study face, nor by the duration of the test face (Richler et al., 2009). Chen et al. (2016) investigated how the holistic word effect might be modulated by stimulus exposure duration. They found that, similarly, variation in the exposure duration did not bring about significant changes in holistic word effect, at least when the stimuli were presented in the range of 170 to 600 ms. The effect of rotation on holistic processing of words shows a dissociation with what happens with faces. Although overall levels of performance differ, processes related to holistic processing may be engaged in holistic processing of faces presented in unusual orientations (inversion; Richler, Mack, Palmeri, & Gauthier, 2011; Sekuler, Gaspar, Gold, & Bennett, 2004). Words presented in unusual orientations, on the contrary, show qualitatively different expertise related processes, failing to show holistic effects.

In conclusion, in the present study we manipulated the perceptual expertise limits of the neuronal systems dedicated to reading by presenting words in the composite task rotated either by 22.5º or 67.5º. We found evidence of holistic processing only when words were presented within the perceptual expertise limits of the VWF system. Holistic processing of words is a thus a characteristic of expert reading.

Footnote

1. Available at www.pstnet.com/eprime.

Acknowledgement

The work presented in his manuscript was supported by the Research Center for Psychological Science (CICPSI) at the University of Lisbon.

Authors' Declarations

The authors declare that there are no personal or financial conflicts of interest regarding the research in this article.

The authors declare that they conducted the research reported in this article in accordance with the Ethical Principles of the Journal of Expertise.

The authors declare that they have reported all measures, condition, and data exclusions. Determination of samples sizes was done by reference to the work of Ventura et al. (2019).

The authors declare that the dataset is publicly available at DOI 10.17605/OSF.IO/VGURC.

References

Aghababian, V., Nazir, T.A., 2000. Developing normal reading skills: aspects of the visual processes underlying word recognition. *Journal of Experimental Child Psychology. 76,* 123–150. DOI: 10.1006/jecp.1999.2540

Barnhart, A. S., & Goldinger, S. D. (2013). Rotation reveals the importance of configural cues in handwritten word perception. *Psychonomic Bulletin & Review*, *20,* 1319–1326. http://doi.org/10.3758/s13423-013-0435-y

Barton, J. J. S., Hanif, H. M., Bjornstrom, L. E., & Hills, C. (2014). The word length effect in reading: A review. *Cognitive Psychology, 31,* 378-412. DOI: 10.1080/02643294.2014.895314

Bilalic, M. (2018). The brains of experts. *Psychologist, 31,* 24-28.

Bilalic, M., Grottenthaler, T., Nagele, T., and Lindig, T. (2014). The Faces in Radiological Images: Fusiform Face Area Supports Radiological Expertise. *Cerebral Cortex, 26,* 1004-1014. doi:10.1093/cercor/bhu272

Bilalic, M., Langner, R., Ulrich, R., and Grodd, W. (2011). Many faces of expertise: fusiform face area in chess experts and novices. *Journal of Neuroscience, 31,* 10206-10214. doi:10.1523/jneurosci.5727-10.2011

Björnström, L. E., Hills, C., Hanif, H., & Barton, J. J. S. (2014). Visual word expertise: A study of inversion and the word-length effect, with perceptual transforms. *Perception*, *43,* 438–450. http://doi.org/10.1068/p7698

Boggan, A. L., Bartlett, J. C., & Krawczyk, D. C. (2012). Chess masters show a hallmark of face processing with chess. *Journal of Experimental Psychology: General*, *141,* 37–42. http://doi.org/10.1037/a0024236

Bukach, C. M., Gauthier, I., and Tarr, M. J. (2006). Beyond faces and modularity: the power of an expertise framework. *Trends in Cognitive Science, 10,* 159-166. doi:10.1016/j.tics.2006.02.004

Bukach, C.M., Phillips, S.W., Gauthier, I. (2010). Limits of generalization between categories and implications for theories of category specificity. *Attention, Perception, & Psychophysics*, *71,* 1865-1874. DOI: 10.3758/APP.72.7.1865

Busey, T. A., and Vanderkolk, J. R. (2005). Behavioral and electrophysiological evidence for configural processing in fingerprint experts. *Vision Research, 45,* 431-448. doi:10.1016/j.visres.2004.08.021

Chen C., Abbasi, NuH., Song, S., Chen, J. & Li, H. (2016) The Limited Impact of Exposure Duration on Holistic Word Processing. *Frontiers in Psychology, 7,* 646. doi: 10.3389/fpsyg.2016.00646

Chen, H., Bukach, C. M., & Wong, AC-N. (2013). Early Electrophysiological Basis of Experience-Associated Holistic Processing of Chinese Characters. *PLoS ONE*, *8,* 1–10. doi:10.1371/journal.pone.0061221

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: Contribution of the dorsal and ventral visual pathways. *NeuroImage*, *40,* 353–366. http://doi.org/10.1016/j.neuroimage.2007.11.036

Conway, A., Brady, N., & Misra, K. (2017). Holistic word processing in dyslexia. *PLoS ONE, 12,* 1–20. https://doi.org/10.1371/journal.pone.0187326

Diamond, R., & Carey, S. (1986). Why faces are and are not special: an effect of expertise. *Journal of Experimental Psychology: General*, *115,* 107-117.

Dehaene, S., Cohen, L., Sigman, M., Vinckier, F., 2005. The neural code for written words: a proposal. *Trends in Cognitive Science*, *9,* 335–341

Dehaene, S., Naccache, L., Cohen, L., Bihan, D., LeMangin, J.-F., Poline, J.-B., & Rivière, D. (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Reviews Neuroscience , 4,* 752.

Farah, M. J. (1991). Patterns of cooccurrence among the associate agnosias: implications for visual object representation. *Cognitive Neuropsychology, 8,* 1-19. doi:10.1080/02643299108253364

Farah, M. J. (1992). Agnosia. *Current Opinions in Neurology, 2*, 162-164. doi:10.1016/0959-4388(92)90005-6

Farah, M. J., Wilson, K. D., Drain, M., & Tanaka, J. N. (1998). What is "special" about face perception? *Psychological Review, 105,* 482-498.

Fitousi, D. (2015). Composite faces are not processed holistically: evidence from the Garner and redundant target paradigms. *Attention, Perception, & Psychophysics,* 77, 2037-2060. doi:10.3758/s13414-015-0887-4

Gauthier, I., Curran, T., Curby, K. M., and Collins, D. (2003). Perceptual interference supports a non-modular account of face processing. *Nature Neuroscience, 6,* 428-432. doi:10.1038/nn1029

Gauthier, I., & Tarr, M.J. (2002). Unraveling mechanisms for expert object recognition: Bridging brain activity and behavior. *Journal of Experimental Psychology: Human Performance and Perception,* 28*,* 431-446. doi:10.1037//0096-1523.28.2.431

Gauthier, I, Tarr, M. J., Anderson, A.W., Skudlarski, P., & Gore, J. C. (1999). Activation of the middle fusiform "face area" increases with expertise in recognizing novel objects. *Nature Neuroscience, 2,* 568–573.

Ge, L., Wang, Z., McCleery, J. P., & Lee, K. (2006). Activation of face expertise and the inversion effect. *Psychological Science*, *17*, 12–16. http://doi.org/10.1111/j.1467-9280.2005.01658.x

Grainger, J. (2017). Orthographic processing: A "mid-level" vision of reading. *Quarterly Journal of Experimental Psychology, 5,* 1-72. doi:10.1080/17470218.2017.1314515

Harrison, S. A., Gauthier, I., Hayward, W. G., & Richler, J. J. (2015). Other-race effects manifest in overall performance, not qualitative processing style. *Visual Cognition*, *22*, 843–864. doi: /10.1080/13506285.2014.918912

Hashimoto, R., & Sakai, K. L. (2004). Learning letters in adulthood: direct visualization of cortical plasticity for forming a new link between orthography and phonology. *Neuron, 42*, 311-322.

Jacques, C., & Rossion, B. (2009). The initial representation of individual faces in the right occipito-temporal cortex is holistic: electrophysiological evidence from the composite face illusion. *Journal of Vision, 9,* 1–16. doi:10.1167/9.6.8

Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience, 17,* 4302–4311.

Koriat, A., & Norman, J. (1985). Reading Rotated Words. *Journal of Experimental Psychology: Human Performance and Perception*, *11*, 490–508. http://doi.org/10.1037/0096-1523.11.4.490

Pashler, H., Ramachandran, V. S., & Becker, M. W. (2006). Attending to a misoriented word causes the eyeball to rotate in the head. *Psychonomic Bulletin & Review, 13,* 954–957. http://doi.org/10.3758/BF03213908

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition. *Nature, 423,* 752-756.

Maurer, D., Le Grand, R., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences*, *6*, 255–260. doi: 10.1016/S1364-6613(02)01903-4

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Science, 7,* 293-299.

McClelland, J. L., & Rumelhart, D. L. (1981). An interactive activation model of context effects in letter perception. Part 1. An account of basic findings. *Psychological Review, 88,* 375-407.

McKone, E., Crookes, K., Jeffery, L., & Dilks, D.D. (2012). A critical review of the development of face recognition: experience is less important than previously believed. *Cognitive Neuropsychology, 29,* 174–212. doi:10.1080/02643294.2012.660138

Michel, C., Rossion, B., Han, J., Chung, C.-S., & Caldara, R. (2006). Holistic processing is finely tuned for faces of one's own race. *Psychological Science, 17,* 608–615. doi: 10.1111/j.1467-9280.2006.01752.x

Reicher, G. M. (1969). Perceptual recognition as a function of the meaningfulness of the stimulus material. *Journal of Experimental Psychology, 81,* 275-280.

Richler, J. J., & Gauthier, I. (2014). A meta-analysis and review of holistic face processing. *Psychological Bulletin, 140,* 1281-1302. doi:10.1037/a0037004

Richler, J. J., Mack, M. L., Gauthier, I., & Palmeri, T. J. (2009). Holistic processing of faces happens at a glance. *Vision Research, 49,* 2856-2861. doi: 10.1016/j.visres.2009.08.025

Richler, J. J., Mack, M. L., Palmeri, T. J., & Gauthier, I. (2011). Inverted faces are (eventually) processed holistically. *Vision Research, 51,* 333–42. http://doi.org/10.1016/j.visres.2010.11.014

Richler, J.J., Palmeri T. J., and Gauthier, I. (2012). Meanings, mechanisms, and measures of holistic processing. *Frontiers in Psychology, 3.* doi: 10.3389/fpsyg.2012.00553

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8,* 382-439. doi:http://dx.doi.org/10.1016/0010-0285(76)90013-X

Ross, D.A., Tamber-Rosenau, B.J., Palmeri, T.J., Zhang, J., Xu, Y. Gauthier, I. (2018). High Resolution fMRI Reveals Configural Processing of Cars in right anterior Fusiform Face Area of Car Experts. *Journal of Cognitive Neuroscience, 30,* 973-984.

Rossion, B. (2013). The composite face illusion: A whole window into our understanding of holistic face perception. *Visual Cognition, 21,* 139-253. doi:10.1080/13506285.2013.772929

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: Part 2. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review, 89,* 60-94.

Sekuler. A. B., Gaspar, C. M., Gold, J. M., & Bennett, P. J. (2004). Inversion leads to quantitative, not qualitative, changes in face processing. *Current Biology, 14,* 391-396.

Sheridan, H., & Reingold, E. M. (2017). The holistic processing account of visual expertise in medical image perception: A review. *Frontiers in Psychology, 8.* DOI: 10.3389/fpsyg.2017.01620

Tanaka, J. W., & Farah, M. J. (1993). Parts and wholes in face recognition. *Quarterly Journal of Experimental Psychology Section A, 46,* 225-245. doi:10.1080/14640749308401045

Ventura, P., Fernandes, T., Leite, I., Almeida, V. B., Casqueiro, I., & Wong, A.C-N. (2017). The word composite effect depends on abstract lexical representations but not surface features like case and font. *Frontiers in Psychology, 8,* 1036. doi: 10.3389/fpsyg.2017.01036

Vinckier, F., Naccache, L., Papeix, C., Forget, J., Hahn-Barma, V., Dehaene, S., & Cohen, L. (2006). "What" and "where" in word reading: ventral coding of written words revealed by parietal atrophy. *Journal of Cognitive Neuroscience, 18,* 1998–2012. http://doi.org/10.1162/jocn.2006.18.12.1998

Wheeler, D. D. (1970). Processes in word recognition. *Cognitive Psychology, 1,* 59-85. http://dx.doi.org/10.1016/0010-0285(70)90005-8

Wong, A. C.-N., Bukach, C. M., Hsiao, J., Greenspon, E., Ahern, E., Duan, Y., & Lui, K. F. H. (2012). Holistic processing as a hallmark of perceptual expertise for nonface categories including Chinese characters. *Journal of Vision, 12.* doi:10.1167/12.13.7

Wong, A. C.-N., Bukach, C. M., Yuen, C., Yang, L., Leung, S., & Greenspon, E. (2011). Holistic Processing of Words Modulated by Reading Experience. *PLoS One, 6,* e20753. doi:10.1371/journal.pone.0020753

Wong, A. C.-N., Palmeri, T. J., Gauthier, I. (2009). Conditions for face-like expertise with objects: Becoming a Ziggerin expert – but which type? *Psychological Science, 20,* 1108-1117. DOI: 10.1111/j.1467-9280.2009.02430.x

Wong, A. C.-N., & Gauthier, I. (2007). An analysis of letter expertise in a levels-of-categorization framework. *Visual Cognition, 15,* 854–879. http://dx.doi.org/10.1080/13506280600948350

Wong, A. C.-N., Wong, Y. K., Lui, K. F. H., Ng, T. Y. K., & Ngan, V. S. H. (2019). Sensitivity to configural information and expertise in visual word recognition. *Journal of Experimental Psychology: General, 45,* 82-99. doi: 10.1037/xhp0000590.

Wong, Y. K., & Gauthier, I. (2010). Holistic processing of musical notation: Dissociating failures of selective attention in experts and novices. *Cognitive, Affective, and Behavioral Neuroscience, 10,* 541-551. doi:10.3758/CABN.10.4.541

Wong, A. C.-N., Wong, Y. K., Lui, K. F. H., Ng, T. Y. K., & Ngan, V. S. H. (2019). Sensitivity to configural information and expertise in visual word recognition. *Journal of Experimental Psychology: Human Performance and Perception, 45,* 82-99. doi: 10.1037/xhp0000590.

Zhang, J., & Mueller, S. T. (2005). A note on ROC analysis and non-parametric estimate of sensitivity. *Psychometrika, 70,* 203-212. doi:10.1007/s11336-003-1119-8

Received: 4 October 2018
Revision received: 23 January 2019
Accepted: 10 February 2019