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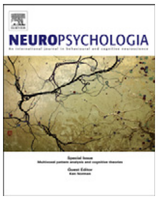

Pre-orthographic character string processing and parietal cortex: A role for visual attention in reading?

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ABSTRACT

The visual front-end of reading is most often associated with orthographic processing. The left ventral occipito-temporal cortex seems to be preferentially tuned for letter string and word processing. In contrast, little is known of the mechanisms responsible for pre-orthographic processing: the processing of character strings regardless of character type. While the superior parietal lobule has been shown to be involved in multiple letter processing, further data is necessary to extend these results to non-letter characters. The purpose of this study is to identify the neural correlates of pre-orthographic character string processing independently of character type. Fourteen skilled adult readers carried out multiple and single element visual categorization tasks with alphanumeric (AN) and non-alphanumeric (nAN) characters under fMRI. The role of parietal cortex in multiple element processing was further probed with *a priori* defined anatomical regions of interest (ROIs). Participants activated posterior parietal cortex more strongly for multiple than single element processing. ROI analyses showed that bilateral SPL/BA7 was more strongly activated for multiple than single element processing, regardless of character type. In contrast, no multiple element specific activity was found in inferior parietal lobules. These results suggests that parietal mechanisms are involved in pre-orthographic character string processing. We argue that in general, attentional mechanisms are involved in visual word recognition, as an early step of word visual analysis.

1. Introduction

A large body of evidence, both behavioral and neuronal, shows that orthographic processing of letter strings involves specialized perceptual processes (Aghababian & Nazir, 2000; Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011; Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Maurer, Brandeis, & McCandliss, 2005, 2006; Schlaggar & McCandliss, 2007). Studies comparing letter-string processing to other stimuli types have underlined the highly reproducible involvement of a specific area of ventral occipito-temporal (vOT) cortex for orthographic processing (Visual Word Form Area Cohen & Dehaene, 2004; Dehaene & Cohen, 2011, but see Price & Devlin, 2011). There is however mounting behavioral and neural evidence pointing towards the importance of pre-orthographic visual processing mechanisms for efficient reading (Korinth, Sommer, & Breznitz, 2011; Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005). In contrast to orthographic processing, little is known of how the neural underpinnings of pre-orthographic visual processing relate to character string processing and reading.

Different tasks have been used to assess pre-orthographic processing performance and its putative relationship to reading efficiency. These tasks usually involve either illegal (unreadable) consonant strings, digit strings or unknown character strings. Symbol string processing capacity was assessed in a series of studies using a two-alternative forced choice string matching task (Pammer, Lavis, Hansen, & Cornelissen, 2004, 2005; Jones, Branigan, & Kelly, 2008). A string of five unknown letter-like symbols was flashed during 100 ms and followed by a mask. Two alternative symbol strings were then displayed and participants were asked to pick which one had been previously displayed. Symbol string sensitivity predicted reading performance in normal-reading adults and children (Pammer et al., 2004, 2005) and was reduced in dyslexic children (Jones et al., 2008). Hawelka and Wimmer (2005) and Hawelka, Huber, and Wimmer (2006) used partial report tasks to compare letter and digit string processing capacity in normal-reading and dyslexic adults and teenagers. Performance in these tasks was lower for dyslexic participants than for normal readers. A formal measure of pre-orthographic processing capacity has been put forth: the visual attention (VA) span (Bosse, Tainturier, & Valdois, 2007; Bosse &

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Valdois, 2009). Defined as the number of individual visual elements that can be processed simultaneously, it is assessed using a five-consonant report task. VA span predicts reading performance in normal-reading elementary school children (Bosse & Valdois, 2009) and is reduced in a subset of reading impaired (dyslexic) children (Valdois, Bosse, & Tainturier, 2004; Bosse et al., 2007). On the whole, these data speak for an impact of pre-orthographic processing capacity on reading performance.

In contrast, neuroimaging studies have extensively explored the specificity of orthographic processing while overlooking the generality of multiple character processing. A number of studies have used symbol strings as stimuli (Appelbaum, Liotti, Perez, Fox, & Woldorff, 2009; Levy et al., 2008; Tagamets, Novick, & Chalmers, 2000; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999; Vinckier, Dehaene, Jobert, & Dubus, 2007; Woodhead, Brownsett, Dhanjal, Beckmann, & Wise, 2011), but little information on pre-orthographic multiple character processing can be taken from them. First, symbol strings were usually considered not as the stimuli of interest but as a control for low level visual activations (Levy et al., 2008; Woodhead et al., 2011). Furthermore, many studies used tasks that required no explicit processing of symbol strings. Indeed, whilst reading is an automatic process that is nearly impossible to inhibit, as shown by the well-known Stroop interference effect, nothing suggests that other types of character strings are processed automatically. Thus, neural activity during passive viewing (Levy et al., 2008) or target detection (Appelbaum et al., 2009; Levy et al., 2008) of letter or symbol strings does not necessarily relate to processing of individual string elements as it would in reading. In contrast, Tagamets et al. (2000) used a one-back repetition detection task of briefly presented (200 ms) stimulus strings made up of words, pseudo-words, consonant strings or pseudo-letter strings. Task demands promoted individual processing of elements regardless of stimuli type. On the whole, their results suggest stronger involvement of parietal and visual areas for non-word like stimuli. However, in order to control for the cognitive demands of their one-back repetition task, their baseline task was a one-back repetition detection task with geometric-shape strings. Since this baseline task also required individual processing of several visual elements, using it as a baseline may very well have canceled out any brain activity specific to pre-orthographic processing.

Alternatively, the specific neural correlates of pre-orthographic letter string processing were studied in normal reading and VA span impaired children using a letter categorization task in two conditions: flanked and isolated (Peyrin, Démonet, N'guyen-Morel, Le Bas, & Valdois, 2011). A categorization task was preferred to a letter report task to minimize verbal report and phonological processing. Normal readers activated a broad parietal network for multiple letter processing, including posterior parietal cortex (PPC). The contrast between flanked vs. single letter categorization was used to isolate neural processes more specifically involved in multiple letter processing. Flanked categorization activated left superior parietal lobule (SPL) more than isolated categorization. Furthermore, this multiple character specific SPL activation was absent in VA span impaired children. Taken together, these results suggest a specific involvement of the parietal cortex and more specifically of SPL in multiple character, pre-orthographic processing.

Further research is however necessary to resolve whether this parietal involvement is truly related to our process of interest. By using a categorization task, Peyrin et al. (2011) sought to eliminate reading specific processes. However since the task used letter stimuli, it is not possible to completely rule out a putative involvement of orthographic processes. In this study, we use a novel categorization task with both alphanumeric and non-alphanumeric character strings under fMRI. We show that pre-orthographic processing of multiple character strings is subserved by superior parietal lobules, regardless of character type.

2. Methods

2.1. Participants

Fourteen healthy, right-handed French adults (seven males, mean age: 24.4, range: 19–30) with normal or corrected to normal vision took part in this study. All participants gave informed consent and received 60 Euros for their participation. They were screened for previously diagnosed learning disabilities and carried out a simple reading test to ensure that they had normal adult reading ability. No participants had previously studied Japanese scripts, ruling out any spurious effects of unequal stimulus familiarity between subjects. This study was approved by the local ethics committee.

2.2. Stimuli

Four different character categories were used: letters, digits, Japanese Hiragana and pseudo-letters, with five different characters in each category. While participants had extensive multiple character processing experience with two categories (letters and digits), the other two were completely novel. The font used for letters and digits was Arial. Digits were drawn from the following set of five digits 3, 5, 6, 8 and 9. Letters were drawn from the following set of five consonants: D, F, K, M and V. Pseudo-letters were created by cutting and rearranging the visual features of letter set characters (as created by Hawelka & Wimmer, 2008). Hiragana characters were chosen amongst the 48 possible characters of the syllabary so that their mean perimetric complexity as defined by Majaj, Pelli, Kurshan, and Palomares (2002) was similar to that of the other character sets. Character perimetric complexity is a reliable predictor of character recognition efficiency (Pelli, Burns, Farell, & Moore-Page, 2006): character sets with similar average perimetric complexity are recognized with similar efficiency. For the multiple element task, strings of five characters were builtup from these sets. There were 48 alphanumeric strings and 48 non-alphanumeric strings. Out of the 48 alphanumeric strings, 24 were consistent and 24 were inconsistent. Consistent strings were made up exclusively of letters and digits. Twelve of the consistent strings contained three letters and two digits and the other 12 contained two letters and three digits. Inconsistent strings were made up of letters, digits and one inconsistent character, either Hiragana or pseudo-letter. Twelve of the inconsistent strings contained two letters, two digits and one inconsistent character and the other 12 contained three letters, one digit and one inconsistent character. The position and choice of the inconsistent character was controlled across trials. Similarly, individual character positions were counterbalanced across consistent and inconsistent trials. The 48 non-alphanumeric strings were builtup the same way as the alphanumeric ones, with pseudo-letters and Hiragana replacing letters and digits. The inconsistent characters were then letters and digits. For the single element task, stimuli were made up of one central character surrounded by four pound (#) signs. There were 48 strings: 24 with a central alphanumeric character (12 letters, 12 digits) and 24 with a central non-alphanumeric character (12 pseudo-letters, 12 Hiragana). For all stimulus strings, characters subtended a visual angle of 0.7°, and the distance between adjacent characters was of 0.57° in order to minimize crowding. The entire string subtended a visual angle of 5.4° and was drawn in white on a black background.

2.3. Procedure

A task requiring visual categorization of characters was carried out in two conditions: multiple element (ME) and single element (SE) (see Fig. 1). Stimuli were displayed during 200 ms to avoid useful ocular saccades and serial visual processing. Stimulus display was driven by E-Prime software (E-Prime Psychology Software Tools, Inc. Pittsburgh, USA). Synchronization between scanner and paradigm was ensured by a trigger pulse sent from the scanner to the computer on which E-Prime was running. The paradigm was presented using a video projector (Epson EMP 8200), a projection screen situated behind the magnet and a surface mirror centered above the participant's eyes. A response key was used to collect participant responses. Response accuracy and reaction times (RT, in milliseconds) were recorded.

Our experimental task was designed to isolate the processes involved in individual processing of multiple characters displayed in a horizontal string, regardless of stimulus type. The task relied on visual categorization of individual characters in two conditions: a multi-element (ME) condition of interest and a single-element (SE) control condition. Both task conditions were carried out with either alphanumeric (AN) or non-alphanumeric (nAN) characters. Our task was designed with several constraints in mind. First, in order to avoid interference with the reading network, alphanumeric strings included both letters and digits. While it has been shown that reading processes are activated in mixed letter–digit strings (Molinaro & Duñabeitia, 2010; Perea, Dunabeitia, & Carreiras, 2008), this is only the case when letters are replaced with visually similar digits in a real word. Since none of our stimulus strings resembled real words, we do not expect reading processes to be activated. Second, we designed our SE condition to control for effects of general attention, response motor execution, visual input and higher-order cognitive demands. While both the experimental and control conditions require visual categorization of the attended stimuli, only the experimental condition requires processing of several characters. We expect contrasts between neural activations from these conditions to highlight those that are specific to multiple character processing demands. Third, we chose a categorization task rather than an identification task so that it could be carried out in the same way with either alphanumeric or non-alphanumeric characters. Indeed, memory span limits constrain performance on non-alphanumeric string processing (Pelli et al., 2006). These constraints should not be relevant in a task that does not require character identity recall.

In the ME condition, visual categorization of individual characters of a string is required. Performance was monitored by asking participants to report the number of characters of a target category present in the stimulus string. In the alphanumeric condition, participants were asked to report the number of letters present in a character string made up of letters and digits. In the non-alphanumeric condition, participants were asked to report the number of Hiragana characters in a character string made up of Hiragana and pseudo-letters. All participants pressed the index finger button for two target category characters and the middle finger button for three target category characters. They carried out 48 trials for each condition, half with two target characters and half with three target characters. Trial order was pseudo-randomized.

In the SE condition, visual categorization of a single character flanked by pound signs is required. In order to monitor performance, participants were asked to report whether or not the single stimulus character belonged to either one of two target categories (alphanumeric condition: letters or digits, non-alphanumeric condition: pseudo-letters or Hiragana). All participants responded by pressing the index finger button if the stimulus character belonged to either target categories and by pressing the middle finger button otherwise. They carried out 48 trials for each condition, half of which contained a target category character. Trial order was pseudo-randomized. This condition was designed to control for three important task characteristics. First, low-level visual stimulation was similar to the ME condition since five characters were displayed (four pound signs and a central stimulus character). Second, motor response was the same for both tasks. Last, both tasks required character categorization, controlling for higher-level categorization processing.

Immediately before the scanning session, participants took part in a 45 min training session. Participants first performed two character identification tasks in order to familiarize themselves with the two unknown character types. Only visual recognition was trained and no verbal labels were assigned to characters. During the second part of training, participants were familiarized with the experimental tasks. For each task and each condition (alphanumeric and non-alphanumeric), they first carried out five training trials followed by a sequence of 48 trials with the same timing as the experimental sequence (but different stimulus strings).

2.4. Event-related fMRI experimental design

Each participant carried out four event-related-fMRI sessions: two to assess multiple element processing (one for alphanumeric and one for non-alphanumeric characters) and the other two to assess single element processing (one for alphanumeric and one

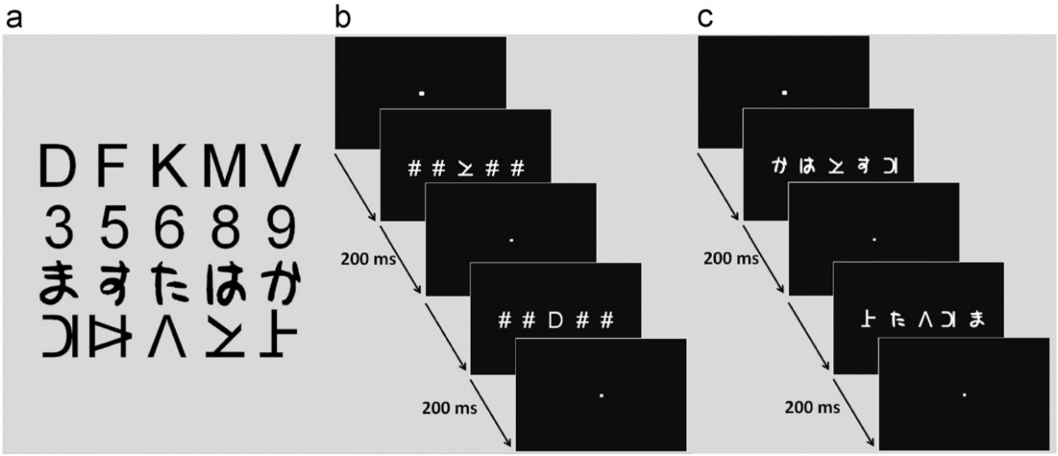

Fig. 1. Stimuli and procedure. (a) Stimuli characters for each category (letters, digits, pseudo-letters, Hiragana). Procedure in the non-alphanumeric. (b) Single element task. (c) Multiple element task.

for non-alphanumeric characters). FMRI session order was counterbalanced across participants. Stimuli onsets were optimized using pseudo-randomized ER-fMRI paradigms (Friston, Zarahn, Josephs, Henson, & Dale, 1999). For each session, 48 trial-events were displayed: 24 consistent strings and 24 inconsistent strings. In order to provide an appropriate baseline measure (Friston et al., 1999), 27 null-events (three of them at the end of the session) were pseudo-randomly included in each session. These null-events comprised a black screen and a fixation dot displayed at the center of the screen. SOA between events was set to 3 s. SOAs between trial-events were of 3, 6 or 9 s, depending on the presence of null-events. To reduce eye movements, the fixation dot was displayed between stimuli and participants were asked to fixate it. In order to stabilize the magnetic field, each functional run started with five dummy scans that were discarded before analysis. After these dummy scans, 90 functional volumes were acquired for each run. Each functional session lasted for 3 min and 45 s.

2.5. MR acquisition

A whole-body 3 T MR scanner was used (Bruker MedSpec S300) with 41 mT/m maximum gradient strength and 120 mT/m/s maximum slew rate. A one-channel quadrature Bruker/Siemens transmit/receive head coil was used. For functional scans, the manufacturer-provided gradient-echi/T2* weighted EPI method was used. Thirty-nine adjacent axial slices parallel to the bi-commissural plane were acquired in interleaved mode. Slice thickness was 3.5 mm. The in-plane voxel size was 3 × 3 mm (216 × 216 field of view acquired with a 72 × 72 pixels data matrix; reconstructed with 0 filling to 128 × 128 pixels). The main sequence parameters were: TR = 2.5 s, TE = 30 ms, flip angle = 80°. To correct images for geometric distortions induced by local B_0-inhomogeneity, a B_0 fieldmap was derived from two gradient echo data sets acquired with a standard 3D FLASH sequence ($\Delta TE = 9.104$ ms). The fieldmap was subsequently used during data processing. Finally, a T1-weighted high-resolution three dimensional anatomical volume was acquired, by using a sagittal magnetization-prepared rapid acquisition gradient echo (MP-RAGE) sequence (field of view: 256 × 224 × 176 mm; resolution: 1.333 × 1.750 × 1.375 mm; acquisition matrix: 192 × 128 × 128 pixels; reconstruction matrix: 256 × 128 × 128 pixels).

2.6. Data processing

Both preprocessing and statistical analyses of the data were performed using the Statistical Parametric Mapping software (SPM5, Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm; Friston et al., 1995). Functional volumes were time corrected using the 20th slice as reference. All volumes were then realigned using rigid body transformations to correct for head movement, using the first ER-fRMRI session as the reference volume. The T1-weighted anatomical volume was co-registered to the realigned mean images and normalized to MNI space using a trilinear interpolation. The anatomical normalization parameters were then used for functional volume normalization. Finally, each functional volume was smoothed by an 8-mm FWHM (full width at half maximum) Gaussian kernel. Time series for each voxel were high-pass filtered (1/128 cut-off) to remove low-frequency noise and signal drift.

2.7. Statistical analyses

2.7.1. Whole-brain analysis

Statistical analyses were performed on the pre-processed functional images for each one of the four sessions. For each session (multiple AN, multiple nAN, single AN and single nAN), two conditions (consistent and inconsistent) were modeled as two regressors convolved with a canonical hemodynamic function. Movement parameters computed during the realignment corrections (three translations and three rotations) were included in the design matrix of each session as additional parameters. Parameter estimates of activity in each voxel were generated using the general linear model at each voxel for each condition and each participant. Linear contrasts between the HRF estimates for the different experimental sessions were used to generate statistical parametric maps. All statistical analyses were carried out with consistent and inconsistent trials separately as well as together. Results did not differ qualitatively between analyses, therefore we chose to present the analysis combining consistent and inconsistent trials due to the greater statistical power afforded by the increased number of scans.

At the individual level, statistical parametric maps were computed for several contrasts of interest. The entire cerebral network associated with multiple element processing was assessed by contrasting the ME condition to baseline (fixation point) conjointly for both character types. The cerebral network associated with single element processing was assessed by contrasting the SE condition to baseline conjointly for both character types. To identify brain regions specifically activated for each character type in each condition (SE and ME), we used the following contrasts: $[ME{-}AN > ME{-}nAN]$, $[ME{-}nAN > ME{-}AN]$, $[SE{-}AN > SE{-}nAN]$ and $[SE{-}nAN > SE{-}AN]$. We identified that the brain regions involved more specifically in attention demanding multiple element processing by contrasting the multiple to the single element condition for each character type: $[ME{-}AN > SE{-}AN]$ and $[ME{-}nAN > SE{-}nAN]$. Finally, we estimated the opposite contrasts $[SE{-}AN > ME{-}AN]$ and $[SE{-}nAN > ME{-}nAN]$. We then performed a random-effect group analysis on the contrast images from the individual analyses (Friston et al., 1998), using one-sample t-tests. Individual contrasts were then entered in a random-effects group analysis. Specific effects were assessed using one-sample t-tests. Clusters of activated voxels were identified for each group, based on the intensity of individual responses. Because main task effects were stronger than between-task effects, two different significance thresholds were applied. For $[Task > Baseline]$ contrasts, areas of activation were considered as significant if they passed a voxel threshold of $p < .0001$, uncorrected with a minimum cluster extent of 50 voxels. For between task contrasts, areas of activation were considered as significant if they passed a voxel threshold of $p < .001$, with a minimum cluster extent of 50 voxels.

Based on results of previous studies (Tagamets et al., 2000; Peyrin et al., 2011), we expect the $[ME > Baseline]$ contrast to activate a broad bilateral cerebral network including the parietal network and more specifically the superior parietal lobules. Furthermore, since our task and stimuli are designed to avoid activating reading-related networks, we expect contrasts between AN and nAN multiple element processing to reveal no significant reading-related activations. In line with results from Peyrin et al. (2011), superior parietal lobules should show significant differential activity for $[ME > SE]$ contrasts if the area drives multiple character processing.

2.7.2. Regions of interest

Analyses were completed by statistically comparing activity within regions of interest (ROIs) for three different factors: attentional demands, character type and consistency. Behavioral deficits in simultaneous visual processing in dyslexia have been linked to lower activation in parietal brain areas, and more specifically in the superior parietal lobule bilaterally and the left inferior parietal lobule (Peyrin et al., 2011). We used *a priori* anatomically defined ROIs to assess the specific role of parietal areas in single and multiple character processing . ROIs were defined using predefined masks from the Wake Forest University (WFU) PickAtlas (Maldjian, Laurienti, Kraft, & Burdette, 2003). These masks were created using jointly the Brodmann area (cytoarchitectonic) atlas and the automated anatomical labeling atlas, which uses an anatomical parcellation of the MNI MRI single-subject brain and sulcal boundaries to define each anatomical volume. The first two ROIs were defined as the intersection of Brodmann area 7 and superior parietal lobule (bilaterally). The next two anatomical ROIs were defined as the intersection of Brodmann area 40 and inferior parietal lobule (bilaterally). Parameter estimates of event-related responses were then extracted from these ROIs for each participant. All ROIs were constructed using the SPM Marsbar toolbox (http://marsbar.sourceforge.net).

Parameter estimates were entered in a $2 \times 2 \times 2$ repeated measures ANOVA with attentional demands (SE/ME), character type (AN/nAN) and Trial consistency (consistent/inconsistent) as within-subject factors. Our two main factors of interest are attentional demands and character type. Trial consistency was also entered in the analysis in order to ensure that differences in neural activity between ME and SE conditions were not due to a spurious interaction effect between consistency and attentional demands. If posterior parietal cortex drives multiple character processing regardless of character type, we expect ROI activity to be modulated by attentional demands but not by character type, with stronger activity for the more demanding ME condition. Furthermore, we expect the activity modulation by attentional demands to be of similar magnitude regardless of character type or Trial consistency.

3. Results

3.1. Behavioral results

Reaction times (RTs) were log transformed to meet parametric assumptions and entered in a 2×2 repeated measures ANOVA with attentional demands (multiple *vs.* single element) and character type (alphanumeric *vs.* non-alphanumeric) as within-subject factors. Main effects of attentional demands ($F(1,13) = 37.0$, $p < .0001$, $\eta^2 = .52$) and type ($F(1,13) = 53.2$, $p < .0001$, $\eta^2 = .22$) were significant while the task × type interaction was not ($F(2,26) = 3.4$, $p = .09$, $\eta^2 = .01$). Participants were slower for non-alphanumeric characters than for alphanumeric ones, and slower for the ME task than for the SE task (Single element, AN $RT = 692 \pm 72$ ms, Single element, nAN $RT = 811 \pm 126$ ms, Multiple element, nAN $RT = 950 \pm 164$ ms, Multiple element, nAN $RT = 1130 \pm 187$ ms). Concerning accuracy (proportion correct), ANOVA parametric assumptions could not be met because of a ceiling effect for the single element task (Single-element, AN accuracy $= .98 \pm .01$ ms, nAN accuracy $= .99 \pm .02$ ms). Multiple element accuracy was transformed to meet parametric assumptions and a paired *t*-test was used to compare accuracy between the AN and nAN conditions. Participants were significantly more accurate ($t(13) = 5.7$, $p < .0001$) in the AN condition (accuracy $= .93 \pm .04$ ms) than in the nAN condition (accuracy $= .79 \pm .12$ ms).

3.2. fMRI results

3.2.1. Task driven brain regions

First, we used contrasts between our task and baseline to identify the main networks of brain regions involved in multi-element or single element processing. Brain activations are illustrated in Fig. 2. (Tables with detailed activation coordinates available on request.) Relative to baseline (fixation) the ME condition activated a broad and bilateral cortical network, including both dorsal and ventral visual areas. Activated visual areas included the extra-striate cortex bilaterally, the right superior occipital gyrus as well as bilateral ventral fusiform gyri. Parietal activations included the superior and inferior parietal lobules bilaterally. Finally, frontal activations included the bilateral supplementary motor areas. Relative to baseline, the SE condition activated a more limited cortical network, including visual and

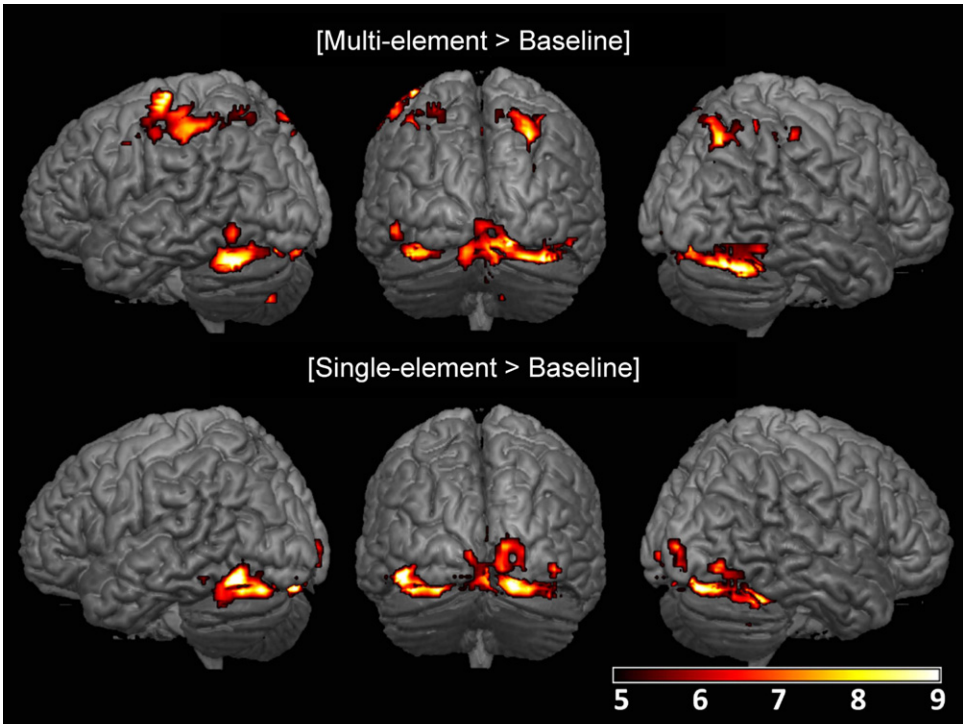

Fig. 2. Whole-brain activations induced by multiple and element processing (AN and nAN conditions connjoined) overlaid on a surface-rendered single subject brain normalized to MNI template. For all contrasts: voxel-wise threshold of $p < .0001$ uncorrected with a minimum cluster extent of 50 voxels.

ventral areas. Visual areas included both striate and extra-striate cortex bilaterally while ventral areas included the fusiform gyrus bilaterally. Contrasts between the AN and nAN conditions revealed no significant activations for either attentional demands condition (ME and SE) at the chosen threshold ($p < .001$ uncorrected and $k > 50$).

Table 1
Cerebral regions significantly more activated for multiple than for single element processing. The statistical significance threshold for individual voxels was set at uncorrected $p < .001$ ($T > 3.85$). For each cluster, peak MNI coordinates (x,y,z), cluster spatial extent k and peak Z-value are indicated. Anatomical labels are based on the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002). Labels represent the first two anatomical regions presenting the largest percentage of overlap with the activation cluster.

	x, y, z	k	Z
[**Multi-element** > **Single-element**]—**Alphanumeric**			
Parietal cortex			
Right superior parietal lobule/angular gyrus	15, −75, 60	118	3.9
[**Multi-element** > **Single-element**] —**Non-alphanumeric**			
Parietal cortex			
Right superior and inferior parietal lobules	33, −42, 42	76	3.8
Left superior and inferior parietal lobules	−30, −54, 49	65	4.0
Frontal cortex			
Right and left supplementary motor areas	9, 18, 49	84	4.0

Contrasts between the multi-element and single element conditions for each character type separately ([$ME{-}AN > SE{-}AN$] and [$ME{-}nAN > SE{-}nAN$]) were used to identify brain regions specific to multi-element processing. Brain areas showing stronger activations for the ME than the SE condition are listed in Table 1 and illustrated in Fig. 3. In the AN condition, a single right hemisphere superior parietal lobule cluster was activated. In the nAN condition, superior and inferior parietal lobules were more activated for multiple than single element processing in both hemispheres.

3.3. Regions of interest

For each of the four *a priori* ROIs (SPL and IPL, left and right hemisphere), extracted parameter estimates were entered into a $2 \times 2 \times 2$ repeated-measures ANOVA with attentional demands (ME *vs.* SE), character type (AN *vs.* nAN) and consistency (consistent *vs.* inconsistent) as within-subject factors. Results are illustrated in Fig. 4. Concerning the right hemisphere SPL ∩ BA7 ROI, the main effect of attentional demands was significant ($F(1,13) = 31.09$, $p < .0001$, $\eta^2 = .20$), indicating that activation was stronger for multiple than for single character processing. The character type and consistency main effects were not significant (character

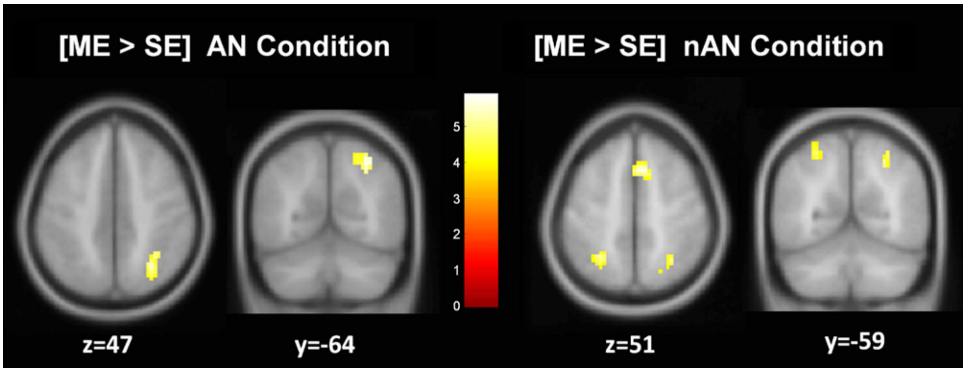

Fig. 3. Cerebral regions significantly more activated for multiple than for single element processing. The statistical significance threshold for individual voxels was set at uncorrected $p < .001$ ($T > 3.85$), with a minimum cluster extent of 50 voxels.

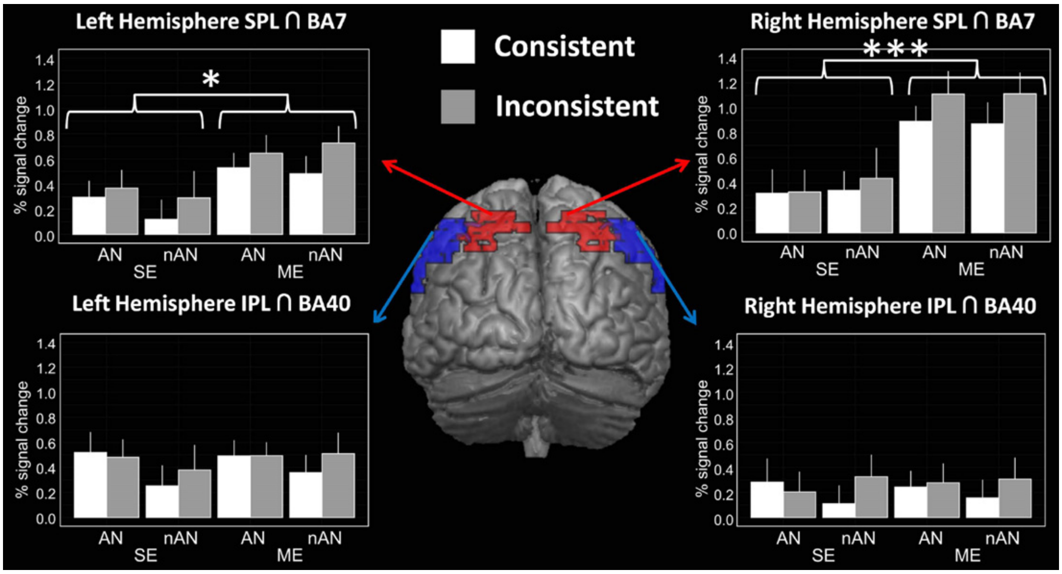

Fig. 4. Percent signal change in SPL and IPL ROIs according to attentional demands, character type and consistency. Error bars indicate 95% confidence intervals. *: $p < .05$, ***: $p < .0001$.

type: $F(1, 13) = 0.05$, *n.s.*, consistency: $F(1, 13) = 2.8$, $p = .12$). No interactions were significant (attentional demands × character type: $F(1, 13) = 0.06$, attentional demands × consistency: $F(1, 13) = 2.1$, character type × consistency: $F(1, 13) = 0.1$, attentional demands × character type × consistency: $F(1, 13) = 0.1$, all *n.s.*). character type modulated neither task-related activity nor attentional demands related differences in activation. Similarly, consistency modulated neither task-related activity nor attentional demands related differences in activation. Right SPL ∩ BA7 activation was stronger for multiple character processing irrespective of character type or consistency. For the left hemisphere SPL ∩ BA7 ROI, the main effect of attentional demands was significant ($F(1, 13) = 8.0$, $p < .05$, $\eta^2 = .08$), indicating that left hemisphere SPL activation was larger for multiple than for single character processing. There was no significant effect of character type ($F(1, 13) = 0.2$, *n.s.*). The main effect of consistency was significant ($F(1, 13) = 5.7$, $p < .05$, $\eta^2 = .02$), indicating that activity was stronger for inconsistent than for consistent trials. No interactions were significant (attentional demands × character type: $F(1, 13) = 0.2$, attentional demands × consistency: $F(1, 13) = 0.2$, character type × consistency: $F(1, 13) = 0.7$, attentional demands × character type × consistency: $F(1, 13) = 0.02$, all *n.s.*). Character type and consistency did not modulate attentional demands related differences in activation. Left SPL ∩ BA7 activation was stronger for multiple element processing irrespective of character type or consistency. Concerning IPL ∩ BA40 ROIs, results were similar for right (attentional demands: $F(1, 13) = 0.1$, character type: $F(1, 13) = 0.1$, consistency: $F(1, 13) = 1.4$, all *n.s.*) and left hemispheres (attentional demands: $F(1, 13) = 0.2$, character type: $F(1, 13) = 1.2$, consistency: $F(1, 13) = 1.2$, all *n.s.*) with no significant main effects. Similarly, no interactions were significant for both hemispheres. IPL does not seem to be specifically involved in multiple element processing.

4. Discussion

Neural activity associated with multiple character string processing was investigated in this study. We used fMRI to record hemodynamic responses associated with visual processing for a categorization task of multiple or single characters. Characters could be either known, alphanumeric or novel, non-alphanumeric. Participants were trained to recognize the visual shapes of non-alphanumeric characters but no verbal names were learned. Our main interest was to identify neural mechanisms involved in visual, pre-orthographic encoding stages of the reading process. Specifically, we aimed to isolate brain areas that subserve the attentional processes necessary to attend to a word's letters, independently from any associated phonological, semantic or orthographical processing. We hypothesized that multiple character processing would selectively activate superior parietal lobules. In order to test this hypothesis, we extracted task related percent signal change from two bilateral anatomically defined regions of interest: the intersection of SPL and BA7 and the intersection on IPL and BA40.

Behavioral performance showed high accuracy in the SE condition regardless of character type. In the ME condition, accuracy was modulated by character type, with higher accuracy for alphanumeric than for non-alphanumeric strings. Reaction times were modulated by both task and type, with slower times for the ME condition compared to the SE condition and for nAN characters compared to AN characters. This consistent pattern of higher performance for the AN conditions can be explained by familiarity. While adults have little opportunity to process strings made up of both letters and digits, they have extensive experience with both stimuli types. Conversely, they had very little experience with nAN characters, making character recognition more difficult, even in the SE condition (longer RTs for nAN characters). This lack of processing efficiency for nAN characters could also explain the performance drop for the nAN ME condition. Following Bundesen's Theory of Visual Attention (Bundesen, 1990), a set amount of attentional resources is available for processing multiple elements. The amount of resources needed to successfully process an element depends on our efficiency for that specific stimulus type. Efficiency for letter and digit recognition is very high whilst efficiency for new, unfamiliar stimuli is lower. Because of this low efficiency, recognition of individual unfamiliar elements requires more resources. The amount of available resources being limited, there may not be enough to process all elements in the 200 ms available, explaining lower accuracy.

Neuroimaging results showed that relative to fixation, visual processing of multiple elements activated a broad neural network including ventral and dorsal brain areas. Involvement of extra-striate cortex is consistent with previous character string studies (Levy et al., 2008; Tagamets et al., 2000), and could relate to feature extraction. Activations of ventral occipito-temporal (vOT) cortex are consistent with studies of character string processing (regardless of character type) (Reinke, Fernandes, Schwindt, O'Craven, & Grady, 2008; Tagamets et al., 2000; Vinckier et al., 2007). These activations could reflect the general role of the ventral visual stream in higher level visual processing of shapes (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2007). Frontal activations can relate to category abstraction (Vogels, Sary, Dupont, & Orban, 2002) and comparisons with long term memory representations (Kosslyn, Alpert, & Thompson, 1995). Activations of superior and inferior parietal lobules are in line with previous studies of both letter and non-letter string processing (Brem et al., 2006; Levy et al., 2008; Peyrin, Lallier, Baciu, & Valdois, 2008; Tagamets et al., 2000). Parietal areas are associated with visuo-spatial attention task demands (Behrmann, Geng, & Shomstein, 2004; Corbetta & Shulman, 2002), and these activations may reflect attentional demands of character string processing. In contrast with this dorsal and ventral network, the SE condition recruited a more limited ventral network. Activations of bilateral fusiform gyri are in line with previous studies of single character (letter or symbol) processing (Flowers et al., 2004) and are consistent with the hypothesis of vOT activity relating to visual complexity (Indefrey et al., 1997). This network suggests that single character processing primarily involves perceptual visual processing and has low attentional demands.

The ME condition was designed to tax general pre-orthographic processes involved in multiple character processing, independently from reading specific networks. In order to verify this, we compared activations for AN or nAN character string processing. There were no preferential activations for processing alphanumeric characters over unfamiliar characters. The absence of preferential activations in the left vOT between the two conditions is consistent with previous studies suggesting that left vOT is sensitive to both letters and symbols (Callan, Callan, & Masaki, 2005; Tagamets et al., 2000; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). While there is substantial evidence for a specific role of vOT for reading (Cohen & Dehaene, 2004), comparing vOT activation between novel character strings and non-lexical, illegal character strings, has previously revealed no clear differences (Vinckier et al., 2007).

Neural correlates specific to multiple element processing were isolated for each character type separately by contrasting neural activity for the ME condition to neural activity for the SE condition. For both character types, a parietal network including SPL, IPL and precuneus was more strongly activated for multiple than single element processing. Additional results from ROI analyses support a specific involvement of SPL in multiple element processing, regardless of hemisphere. In SPL ∩ BA7 ROIs, activation was significantly stronger for multiple than single element processing bilaterally. This difference in activation strength did not differ between character types. In contrast, there was no difference between tasks in IPL ∩ BA40 ROIs. Parietal cortex in general and SPL more specifically are reliably reported as involved in tasks taxing visual attention processes (Behrmann et al., 2004; Kanwisher & Wojciulik, 2000; Wojciulik & Kanwisher, 1999). Previous studies have reported a positive modulation of posterior parietal cortex (PPC) activity by the number of visual objects to be processed (Mitchell & Cusack, 2008; Scalf & Beck, 2010; Xu & Chun, 2009), consistent with increased attentional demands for multiple element processing. These results show that beyond the object-based, perceptual processes of the ventral visual stream, character string processing relies on parietal, dorsal attentional mechanisms.

If attentional mechanisms involved in multiple character processing of alphanumeric strings are indeed pre-orthographic, we expect them to be similar for AN and nAN character strings. In line with this hypothesis, our data suggests that character type does not modulate parietal involvement in multiple character processing. Contrasts between the AN and nAN condition for multiple element processing did not reveal any significant activation differences. Furthermore, bilateral SPL ∩ BA7 ROIs analyses showed that activation was of similar strength for both character types. Previous studies reported similar attention-related parietal activity levels for letter and shape processing (Nebel et al., 2005). Our study extends these results to characters presented in a familiar horizontal format. Character string processing could thus involve a pre-orthographic component related to general attentional parietal mechanisms.

If these parietal mechanisms putatively involved in pre-orthographic processing result from the attentional demands of multiple element processing, we expect PPC activity to be modulated by these attentional demands. Our results consistently associated increased attentional demands with increased PPC activity (in both whole-brain and ROI analyses). Increased SPL activity for multiple character processing is present bilaterally for both AN and nAN characters (ROI analysis), although whole-brain analyses suggest that right SPL could be more sensitive to attentional demands than left hemisphere. As language related processes are generally located in the left hemisphere for right-handed people (as were our participants), one might expect a left lateralization of neural activity for AN character strings at least. However, bilateral and right-hemisphere PPC activity has been previously reported in several studies of multiple letter processing (Cohen et al., 2008; Mayall et al., 2001; Pammer et al., 2006). Furthermore, right hemispheric dominance in parietal cortex for visual attention tasks is often reported (Hodsoll, Mevorach, & Humphreys, 2009; Pourtois, Vandermeeren, Olivier, & de Gelder, 2001; Rushworth & Taylor, 2006).

For our categorization task, posterior parietal activity for character strings is modulated by visual attention demands rather than by character type. In contrast, Brem et al. (2006) report stronger PPC activity for symbol strings than for words in a one-back repetition detection task, suggesting a specific involvement of parietal cortex for symbol strings. The one-back repetition task was most probably carried out with different strategies in each condition (implicit reading for words and shape encoding in visual short-term memory for shapes). Therefore, it is possible that increased PPC activity relates not to stimuli type but implicit task demands. In support of this account, Booth et al. (2004) report results opposite to Brem et al. (2006) (i.e., stronger PPC activity for words than for symbol strings). Adult readers activated bilateral PPC more strongly when asked to carry out a spelling rhyming task (do two words have the same "rhyme" spelling, i.e.: pint and mint) than a repetition detection task with symbols. The visuo-attentional task demands of the spelling rhyming task could here account for increased PPC activity compared to repetition detection.

In our study, we posit that visual attentional demands are responsible for the modulation of parietal activity between the ME and SE conditions. Indeed, our study rationale is that the difference in neural activity between the ME and SE conditions result from increased attentional demands for multiple character processing. A limit to this reasoning is that while the SE condition only requires character categorization, the ME condition requires character categorization as well as numerosity estimation. Increased PPC activity could thus index different cognitive demands rather than different attentional demands. Recent studies investigating the neural basis of subitizing (numerosity estimations for quantities smaller than four) have highlighted the role of the right temporo-parietal junction (Ansari, Lyons, van Eimeren, & Xu, 2007; Vetter, Butterworth, & Bahrami, 2011). It therefore seems more likely that our difference in PPC activity between the ME and SE conditions results from increased attentional demands than from different cognitive demands.

If processing multiple characters relies on similar PPC attentional mechanisms regardless of character type, it is most likely that these mechanisms predate reading acquisition. In previous research, attentional, parietal processes in reading were thought to be present mainly when occipito-temporal, automatic processing of words was impossible. Disrupted word spatial layout has been repeatedly associated to increased parietal activations in word reading (Cohen et al., 2008; Mayall et al., 2001; Pammer et al., 2006; Rosazza et al., 2009). This increase was taken to reflect the spatial shifting of attention necessary to read in those conditions. Similarly, increased parietal activity for reading long compared to short pseudo-words was interpreted as relating to attentional shifts from syllable to syllable (Schurz et al., 2010; Valdois, Carbonnel, Juphard, & Baciu, 2006). In short, parietal areas were mainly associated with serial, effortful reading. In contrast, the current data speaks for a general involvement of PPC attentional mechanism in pre-orthographic processing of character strings.

Letters in a word (Adelman, Marquis, & Sabatos-DeVito, 2010) are processed in parallel. While it is widely accepted that parallel orthographic processing of letter strings is subserved by VWFA (Cohen & Dehaene, 2004; Dehaene et al., 2005; Dehaene & Cohen, 2011), we suggest that parallel pre-orthographic processing of letter strings is subserved by PPC. In this account, PPC would subserve pre-orthographic attentional processes necessary for character individuation and feature binding (Xu & Chun, 2009) and drive further orthographic perceptual vOT processes through PPC-vOT cortical connections (Blankenburg et al., 2010; Zanon, Busan, Monti, Pizzolato, & Battaglini, 2010). The current literature supports this account in several ways. Visual processing capacity for unrelated letter strings (namely, VA span), which can be taken as indexing pre-orthographic constraints, modulates both SPL activity for multiple letter processing tasks (Peyrin et al., 2011) and reading performance (Bosse et al., 2007; Bosse & Valdois, 2009). Being able to correctly identify more letters is associated with both stronger activity in SPL and better reading efficiency, in line with a model where reading specific mechanisms are driven by PPC. Furthermore, several recent studies have shown reading-related connectivity between PPC and vOT. Using resting state connectivity to investigate the network associated with the VWFA, Vogel, Miezin, Petersen, and Schlaggar (in press) identified correlations between superior parietal areas and the VWFA, correlations that increased with age and reading skill. Functional connectivity between different parts of vOT (including VWFA) and other brain areas was evaluated in a group of normal reading and dyslexic children for a reading task (Vandermark et al., 2009). Significant connectivity between VWFA and bilateral SPL was present in normal reading children. This connectivity pattern's relevance to reading ability is underlined by the fact that it was absent in dyslexic children.

5. Conclusions

In this study, we investigated pre-orthographic processing of multiple character strings using fMRI. We showed that posterior parietal cortex is involved in character string processing, with a more specific role for superior parietal lobules for processing multiple elements. Attentional mechanisms did not differ according to character type (alphanumeric or non-alphanumeric), suggesting that PPC subserves character string processing mechanisms that predate reading acquisition. We posit a role for PPC in reading for pre-orthographic attentional processing of letter strings, upstream from VWFA orthographic parallel processing.

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