Can skilled readers perform a second task in parallel? A functional connectivity MRI study

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Abstract

When asked to search for a target letter while reading, the patterns with which people miss the target letter reveal information about the process of reading itself. Questions remain as to whether this paradigm reflects normal reading processes however. We used a novel continuous-performance neuroimaging paradigm to address this question. In separate scanning runs, subjects either read alone, read while searching for a target letter, or searched nonwords continuously. Functional connectivity analysis recovered the full extent of brain areas identified for reading in a localizer scan, with no differences between reading alone and the dual task condition. Differences were found, however, between both reading conditions and the nonword search condition. These results demonstrate that in skilled readers brain activation associated with reading is unaffected by a concurrent letter-search task. They further demonstrate the utility of a naturalistic, continuous-performance paradigm for studying the neural basis of language processing.

Keywords: brain, attention, fMRI, missing letter effect, letter search

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1. Introduction

Investigating reading processes is complex and challenging, as evidenced by the number of paradigms developed for its investigation. In many paradigms, like the lexical decision task, words are presented in isolation in attempts to control various processing factors. However, a number of researchers investigating various topics, such as letter processing within words and morpheme processing, have pointed out the impossibility of extending results obtained in single word paradigms to paradigms involving reading continuous texts (e.g., Hyönä and Laine, 2002; Jordan et al., 2003). Thus while the extensive literature on single-word reading has yielded much important information, they cannot fully inform our understanding of the type of reading that people most often engage in.

Investigating reading processes in connected text brings unique challenges, however. In order to better specify the processes involved in reading, it is common to require participants to engage in a secondary task while reading. The secondary task can be aimed at blocking specific processes, as in the case when readers must constantly articulate an irrelevant word while reading (Eiter and Inhoff, 2010). Alternatively, the secondary task may be used to collect information about word or letter processing. Good examples of the latter usage are proofreading, and letter search tasks. In the letter search task developed by Corcoran (1966), participants are asked to read a prose passage for comprehension while searching for a given letter. The key variable was the rate at which subjects missed the target letter in words in which it was present. For instance, it is very difficult to find all F’s in Read’s (1983) famous sentence “FINISHED FILES ARE THE RESULTS OF YEARS OF SCIENTIFIC STUDY COMBINED WITH THE EXPERIENCE OF MANY YEARS”, The difficulty of finding the 3 F’s in of nicely illustrated the phenomenon: omission rate was sensitive to lexical properties of the reading materials with, for instance, more omissions for grammatical function (closed class) words like of than for content (open class) words like files, a pattern of results known as the missing-letter effect (MLE). This well-replicated effect has been observed in many languages and has been found to be sensitive to numerous reading related factors including word frequency, word function, eye-movement patterns
(Roy-Charland et al., 2007), prosody and stress pattern (Read, 1983), reading level (Saint-Aubin et al., 2005), bilingualism (Greenberg and Saint-Aubin, 2004; Tao and Healy, 2002), and text familiarity (Saint-Aubin and Roy-Charland, 2012). Although a number of reading factors can co-vary like grammatical function, word frequency, phonology, prosody and word length in the example provided above, each of these reading factors have also been nicely isolated in previous experiments.

However, the approach of collecting information about reading continuous texts by means of a secondary task has also been challenged. For example, in 1989 Rayner and Pollatsek stated,

Sometimes proofreading [or a letter search task] is very much like a visual search task (indeed, in many experimental instantiations of proofreading, subjects are asked to search for the presence of certain target letters), and other times it is very much like skimming. While we do not doubt that at times comprehension processes get in the way of proofreading (so that you inadvertently start paying more attention to the meaning of what you are proofreading that the task at hand), we are suspicious about the extent to which results of experiments on proofreading can inform us about reading. (p. 449)

In order to address those criticisms, eye monitoring studies were conducted. Results have shown that the benchmark eye movement effects are observed even when readers engage in a secondary search task (Greenberg et al., 2006; Roy-Charland et al., 2007; Saint-Aubin and Klein, 2001). In addition, behavioural studies have shown that comprehension is almost as good when readers search for a target letter while reading than when they read only (Oliver et al., 2005). Despite these findings, some authors continue to challenge to the usefulness of secondary tasks for understanding reading Rayner et al. (2012). Here a novel approach using neuroimaging (fMRI) was used to provide converging evidence on this question. The purpose of the present study was to determine whether the neural network engaged during reading continuous text under normal reading conditions (i.e., reading for comprehension) was activated similarly or differently during the reading and searching dual-task condition.
The neural network involved in reading has been well-characterized (for a review see Schlaggar and McCandliss, 2007). Single-word reading elicits distributed activation including bilateral ventral extra-striate regions involved in initial visual-orthographic processing, including the visual word form area (VWFA) in the left fusiform gyrus, as well as the classical left peri-Sylvian language network, including inferior parietal (supramarginal gyrus (SMG) and angular gyrus (AG)), posterior and middle segments of the superior temporal sulcus (STS)/middle temporal gyrus (MTG), and anterior regions including the inferior frontal gyrus (IFG), inferior frontal sulcus, and premotor cortex (Turkeltaub et al., 2002). Reading sentences and longer text passages activates additional areas, particularly extending anteriorly along the STS, that is left-lateralized but includes greater activation of right hemisphere homologues of left hemisphere regions than does single word reading (Bavelier et al., 1997; Spitsyna et al., 2006).

Typically, reading is studied using fMRI with block or event-related task designs in which the target stimuli/task (reading text) is alternated with control stimuli and tasks, chosen such that the contrast between target and control stimuli isolates the neurocognitive process(es) of interest. For example, reading text might be contrasted with reading pronounceable pseudowords, to isolate semantic processes while controlling for phonological processes. However, more recently-developed approaches to fMRI task design have sometimes focused on the strength of correlations (functional connectivity) between different brain regions, rather than on within-region, task-related fluctuations in activity (Friston, 2005). This analytical approach, termed functional connectivity fMRI (fcMRI), is commonly used with fMRI data acquired during continuous rest (Fox et al., 2005), but has been applied to other domains, including studies of continuous reading (Hampson et al., 2006). Such an approach allows us to go beyond a “neo-phrenological” brain mapping approach to understand how interactions between different brain regions change with experimental variables. The continuous-performance fcMRI design can be used both to examine patterns of correlations between brain areas under a particular task condition, and to compare how these correlation patterns may differ under different task/stimulus condition (by including
in the experimental design multiple scans across which task/stimuli differ).

Hampson et al. (2006) used the left IFG as a “seed” region of interest (ROI), deriving the time course of fMRI signal from this area during continuous reading of sentences and correlating this time course with that of every other voxel in the brain. This analysis revealed correlations with most of the regions of the reading network described above, including the IFG, premotor cortex, middle/superior temporal lobe, angular gyrus, and occipitotemporal regions, as well as the thalamus. In another study that used a fcMRI approach to study language processing, Stanberry et al. (2006) examined phonological processing in good readers and people with dyslexia. Participants performed a phoneme-mapping task in which they judged whether highlighted letters in pairs of pseudowords could stand for the same sound. ROI analyses based in left and right IFG, as well as the cerebellum, revealed networks involved in phonological processing that were consistent with previous block-design studies using similar tasks, and showed differences between good readers and those with dyslexia. Thus the continuous-performance fcMRI approach has been shown to be an effective means of studying reading, yielding patterns of results that vary between task conditions, and between subjects, consistent with the findings of more established fMRI experimental designs.

We chose a continuous-performance fcMRI design for the present study for three reasons. Firstly, continuous reading of connected text (i.e., stories) created an experimental setting that is more like most non-experimental reading conditions, compared with reading isolated sentences or words in 30 sec blocks alternating with some other task or stimulus. This seems essential to study the processes involved in normal reading. Secondly, previous studies measuring behavior and eye movements during the reading-and-letter-searching task have all used continuous reading of connected text. Thus in order to be able to compare our neuroimaging results with those studies, we required similar experimental conditions. Further, in behavioral pilot testing we found that we could not replicate the MLE (i.e., greater omissions for function than content words) using a standard fMRI block design in which 30 sec periods of reading while searching for a target letter alternated with viewing non-pronounceable letter strings. While it is conceivable that longer blocks might have yielded an MLE, the continuous-performance fcMRI paradigm mimicked the natural reading
environment and parallels the behavioural and eye monitoring studies we wished to relate our neuroimaging data to significantly better than the block paradigm, yielding a robust behavioural MLE.

Adults with no history of reading difficulties participated in this study. After familiarization with the tasks, participants underwent four fMRI scanning runs that were relevant to the questions posed here. Three of these involved continuous performance under different stimulus and task conditions: reading continuous, coherent text for comprehension (READ TEXT); reading coherent text for comprehension while searching for a target letter (READ+SEARCH); and searching scrambled letter strings for a target letter (SEARCH LETTERS). The fourth run employed a block design in which 30 sec periods of reading continuous text for comprehension (without a letter search task) alternated with 30 sec periods of passively viewing uppercase consonant strings. The purpose of this last run was to localize the peak areas of brain activation during reading, for use as seed ROIs in the fcMRI analysis of the other runs.

Consistent with our assertion that the addition of the letter search task does not affect normal reading processes, we predicted that the pattern of functional connectivity among the ROIs of the reading network (as identified by the block design localizer) would not differ between the READ and READ+SEARCH tasks. In contrast, we predicted that the patterns of functional connectivity would differ between the tasks involving reading (READ and READ+SEARCH) and those involving searching non-coherent text (SEARCH LETTERS). Specifically, we predicted greater strength of correlations among the ROIs of the reading network during the tasks requiring comprehension of coherent texts than those not requiring comprehension.

2. Materials and Methods

2.1. Subjects

Nineteen young adults volunteered in this experiment. Four of the first fifteen subjects were discarded due to technical difficulties, errors in stimulus presentation during data collection, or poor MR image quality. These were replaced by four other subjects, and are thus
not included in the analyses reported here. The data reported here are from 15 young adults (9 females, 6 males; mean age = 23.5 years, SD = 4.8 years) who took part in individual three hour testing sessions. All were right-handed (Oldfield, 1971) and reported no history of neurological, psychiatric, attention, or reading disorders. Subjects were recruited via email and received a structural MR image of their brain and $25. All procedures were reviewed and approved by local research ethics boards.

2.2. Stimuli

Four texts were created for assignment to 4 critical conditions, the first three being assigned to the critical conditions, and the fourth to a blocked design localizer scan. Because the MLE is sensitive to word length, the critical comparison was between function and content words of the same length, with the target letter in the same position. In this study, the critical words for analysis of the MLE were 3-letter words beginning with $t$, with the being the critical function word. The specifics of each text are described below with reference to the conditions they were used in.

The presentation of three prose texts, each a separate story, were completely counter-balanced within the READ and READ+SEARCH conditions, along with a third condition (requiring searching but with explicit instructions that reading was not required) that is not reported here. The passages conformed to the following criteria: each word could not contain more than one occurrence of the letter $t$, with a minimum of four words between each $t$-word (to ensure that a response could be unambiguously attributed to the critical word, given the rate of presentation; Saint-Aubin and Klein, 2001); each text contained an equal number of occurrences of the word the and 3-letter content words beginning with the letter $t$ (e.g., tie, tax, and toe); the critical words were never adjacent to a punctuation mark; and critical words were always presented in lowercase letters. These three prose texts contained 1405, 1283 and 1200 words respectively, including 60 critical words (30 instances of the and 30 three-letter content words starting with $t$) and, respectively, 80, 105 and 87 non-critical $t$-words (i.e., more than 3 letters long and/or did not begin with $t$, e.g., pat, director).

For the SEARCH LETTERS condition, a text was generated by first selecting words
randomly from all three coherent texts and randomizing their order, then randomizing the order of letters in each word from the random words text. To randomize the word order, a computer program was used to preserve the same average number of words per sentence, standard deviation, and the minimum and maximum number of words. This text was inspected to detect and eliminate any syntactically coherent groupings of words created by chance, as well as to add punctuation marks at semi-random intervals. The order of the letters within each word were then randomized. Visual inspection was used to identify and remove any valid words that were created by chance; single-letter words (e.g., I, a) were replaced by other letters that were not words (e.g., y, e). In some words that were easily recognizable even when scrambled, letters were changed to create obvious non-words. Further, the word the, which was the critical target function word, was replaced by tef and tfe (because teh is a common mis-spelling we preferred to substitute a different letter to create the nonword). Punctuation was inserted into the text following the procedure described in the previous section. The final length of this passage was 1209 non-words, including 50 critical t-nonwords, and 63 non-critical non-words containing the letter t.

The text used for the block design localizer scan was previously reported in Saint-Aubin and Klein (2001) and Saint-Aubin et al. (2010). It was 513 words long, of which 28 were critical words (14 instances of the and 14 content words), and 7 others were non-critical t-words. This text was broken into blocks that would last between 10.5 – 15.5 s, allowing for presentation of complete, unbroken sentences. A set of 495 control stimuli were generated for the block design scan as well. Each was a string of a single consonant presented in caps, with length varying in the same range as the length of words in the texts used for the critical conditions. The identity of the letter varied randomly across the set of control stimuli.

2.3. Procedures

2.3.1. Presentation order

During the experimental session, subjects performed each critical condition (READ TEXT, READ+SEARCH, SEARCH LETTERS) as well as two additional control conditions which will not be discussed further in the present paper — searching for the letter
t in coherent text with explicit instructions that reading comprehension was not required, and searching for the letter t in the text generated by randomizing word order. The order of these five conditions were counterbalanced using a randomized Latin square. The block design run was always performed last.

2.3.2. Text presentation format

To ensure a consistent rate of reading and condition duration across subjects, rapid serial visual presentation (RSVP — Potter et al., 1980) was used with a rate of 250 msec/word. With the RSVP procedure, readers can achieve as good or even better comprehension than with printed paragraphs (Masson, 1983; Rahman and Muter, 1999; Sloan, 1999). Furthermore, Saint-Aubin and Klein (2004) showed when readers also searched for a target letter, they produced the same pattern of omissions (i.e., MLE) with the RSVP and the usual paper and pencil procedure. In the block design run, blocks of RSVP presentation of words from one of the prose texts alternated with blocks of RSVP presentation of consonant strings. The consonant string blocks were 12 s in length; the duration of the prose blocks varied between 10.5 and 15.5 s to ensure that each block ended at the end of a sentence, while keeping the blocks at approximately 12 s in length.

Words were presented in Courier New 36 point font, in black on a white background. The text was projected onto a white screen mounted at the opening of the MRI bore, about 150 cm from the subjects’ eyes. Subjects read the text through a mirror mounted on the head coil. Stimulus presentation used the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) running in MATLAB R2009b, 32-bit (The Mathworks Inc., Nattick, MA), on a MacBook Pro 2.4 GHz Core 2 Duo processor with 4 GB of RAM running Mac OS × 10.6.2 (Apple Inc., Cupertino, CA).

2.3.3. Behavioural data acquisition

In the READ+SEARCH and block design runs, subjects were instructed to press a button on a fiber optic response box (Current Designs Inc., Philadelphia, PA) whenever they detected the target letter t. For the READ and READ+SEARCH conditions, as well as the block design localizer scan, subjects were told to read the texts for comprehension
as they would be tested on the material after each of these runs. Each test consisted of 5 multiple-choice questions (4 possible answers each) and was presented to subjects on the screen in the MRI immediately following the end of each fMRI scanning run.

2.3.4. MRI acquisition

For BOLD fMRI, images were acquired using a two-shot spiral out sequence on a 4T MRI scanner located at the National Research Council Institute for Biodiagnostics (Atlantic), in Halifax, Nova Scotia, Canada, using a transmit-receive birdcage head coil and parameters as follows: TR = 2 s, TE = 25 ms, flip angle = 90°, voxel size = 3.75 x 3.75 x 4.7 mm³, matrix = 64 x 64 voxels, interslice interval = 0.5 mm, number slices = 23. Low resolution T1 images were obtained co-planar with the functional images (i.e., same dimensions and slice locations) and high resolution T1-weighted images were obtained with voxel size = 0.93 x 0.93 x 4.75 mm³.

2.4. MRI data preprocessing and analysis

The data from each fMRI run were first visually inspected for the presence of any obvious artifacts or reconstruction errors. Preprocessing was then conducted in FEAT (FMRI Expert Analysis Tool) Version 5.98, part of FSL (FMRIB’s Software Library; Smith et al., 2004), including motion correction using MCFLIRT, slice-timing correction using Fourier-space time-series phase-shifting; non-brain removal using BET, spatial smoothing using a Gaussian kernel of FWHM 8 mm, grand-mean intensity normalization of the entire 4D dataset by a single multiplicative factor, and highpass temporal filtering (Gaussian-weighted least-squares straight line fitting, with sigma = 50.0 sec). To identify and remove imaging artifacts (largely caused by the large susceptibility-by-movement artifacts inherent at 4 T), probabilistic independent components analysis (ICA; Beckmann and Smith, 2004) was applied to all runs except the block design runs (ICA for the block design is described below). ICA was implemented in MELODIC (Multivariate Exploratory Linear Decomposition into Independent Components) Version 3.10. The input data were masked to remove non-brain voxels, demeaned voxel-wise basis, and the voxel-wise variance was normalized. Pre-processed data
were then whitened and projected into an n-dimensional subspace using probabilistic principal components analysis where the number of dimensions was estimated using the Laplace approximation to the Bayesian evidence of the model order (Beckmann and Smith, 2004). The whitened observations were decomposed into sets of vectors, which describe signal variation across the temporal domain (time-courses) and across the spatial domain (maps) by optimizing for non-Gaussian spatial source distributions using a fixed-point iteration technique. Estimated component maps were divided by the standard deviation of the residual noise and thresholded by fitting a mixture model to the histogram of intensity values (Beckmann and Smith, 2004). Components with obvious “spikes” (i.e., large fluctuations in intensity over the space of 2 – 6 time points) were removed and the data reconstituted from the ICA mixing matrix without these components, for further analysis. The data from each run were transformed into MNI152 space using linear affine registration as implemented in FSL’s FLIRT (Jenkinson et al., 2002) for the steps described below.

The block design localizer scans were analyzed using tensorial independent component analysis (Beckmann and Smith, 2005), using the same procedures described above with the exception that all individual data sets were represented as a single time × space × subject block of data. Tensor ICA decomposed this block of data into 25 components. A general linear model (GLM), fitted using least squares, was then applied to the time course of each component to identify the component(s) whose shape matched the block-design input convolved with a gamma model of the hemodynamic response function. As well a group-level GLM was fitted to the subject mode of each component to further identify those that had a reliable pattern across subjects. The component(s) significantly activated by reading relative to viewing letter strings were defined a priori as those that achieved significance by both the time series and subject mode tests, with significance defined as a corrected cluster size threshold of \( p < .05 \) after voxelwise thresholding at \( z > 2.3 \). As described below, only one component met both these criteria. From this component, peak \( z \) values were identified (described under Results). This resulted in a set of 13 regions of interest (ROIs). To ensure that only one ROI per anatomically distinct region was used, if two peaks occurred within the same anatomical region, and/or within 6 voxels of each other, only the peak with the
larger \( z \) value was used. These ROIs were then used as the seed regions for the functional connectivity analyses described below. The ROIs was defined as \( 3 \times 3 \times 3 \) voxel cubes centered on each of the 13 peak voxels.

The functional connectivity analysis for each ROI was performed in the manner described by Fox et al. (2005). We first derived the average time course from each of the 13 ROIs, for each subject, under each of the three experimental conditions. Then, a multiple linear regression was performed for each run, for each subject, using each of these ROI seed time courses as the reference time series, with the following time series included as covariates of no interest: the 6 parameters from the motion correction preprocessing step; and the average time courses for that subject/run from the grey matter, white matter, and CSF (each obtained using the templates provided with FSL). This resulted in a set of 13 correlation maps \( \times 3 \) conditions \( \times 15 \) subjects. Higher-level analyses to identify the pattern of reliable correlations among the nodes of the reading network within each of the three conditions were performed in two steps, using linear mixed effects modelling. In the first step (second-level analysis), subject means were estimated for each subject across all seed ROIs, using a fixed effects model with least squares estimation in FLAME (FMRIB’s Local Analysis of Mixed Effects — Beckmann et al., 2003; Woolrich et al., 2004). In other words, the correlation maps for the 13 ROIs were treated as repeated measures for that subject, and we obtained a map that reflects the strength of correlation of each voxel in the brain with the entire set of seed voxels. The third level analysis was used to identify consistent activations across subjects and ROIs, using FLAME stage 1. The functional connectivity maps were thresholded at \( z > 2.3 \), voxel-wise, followed by cluster size thresholding at a corrected \( p < .05 \). Contrasts between conditions were estimated by entering the correlation maps for all ROIs from each subject, for each of the two conditions being contrasted, into a LME model (FSL’s FLAME stage 1) with subjects treated as random effects, and condition treated as a fixed effect. The between-condition contrasts were also thresholded at \( z > 2.3 \), cluster \( p < .05 \), corrected.
3. Results

3.1. Behavioral Data

The results of the multiple-choice comprehension questions are presented first, followed by omission rates and reaction times for the letter-detection task that was performed during the READ+SEARCH and SEARCH LETTERS conditions. For all tests, the $\alpha = .05$ significance level was adopted, with the exception of simple effect tests, where Dunn’s correction is used.

3.1.1. Comprehension Questions

Performance at answering the comprehension questions was similar across conditions, with an average of 4.13 (SD = 0.83), 4.00 (SD = 0.85) and 3.87 (SD = 0.74) correct answers in the block design, READ ONLY and READ+SEARCH conditions, respectively, $F(2, 28) = 0.43, p = .66$.

3.1.2. Omission Rates

Omissions are defined as cases in which no response was made within 1000 ms after the onset of a target $t$-word. This criterion was chosen for the sake of comparability with previous studies (Healy et al., 1987; Saint-Aubin and Klein, 2001). In addition, a target $t$-word is considered omitted when the response occurred up to 200 ms after the onset of the $t$-words, a delay that corresponds to the average simple reaction time (Simpson et al., 2000; Willingham et al., 1989). The group-averaged omission rates are plotted in Figure 1A. As expected, there were more omissions for the frequent function word the than for the less frequent content words, when participants were reading a coherent prose passage while searching for the target letter $t$ (the READ+SEARCH condition), but not when they were searching for the target letter in the SEARCH LETTERS condition. We observed that in the READ+SEARCH condition, this missing-letter effect was present in all subjects (see Figure 1B).

A $2 \times 2$ repeated measures ANOVA with grammatical class (function vs. content) and conditions (READ+SEARCH vs. SEARCH LETTERS) as factors revealed a significant
effect of grammatical class with more omissions for the target letter embedded in the function word the than in control words (+11.2%, $F(1, 14) = 25.07, \eta^2 = .64, p < .001$), and of condition with more omissions in the READ+SEARCH than in the SEARCH LETTERS condition (+18.9%, $F(1, 14) = 22.18, \eta^2 = .61, p < .001$), as well as a significant interaction ($F(1, 14) = 87.37, \eta^2 = .86, p < .001$). Simple main effect tests revealed that there were more omissions of the target letter t embedded in the function word the than in content words in the READ+SEARCH condition (+28.2%, $F(1, 28) = 95.62, \eta^2 = .77, p < .0001$), but not in the SEARCH LETTERS condition (+5.8%, $F(1,28) = 4.01, p = .055$).

3.1.3. Response times

Response times were computed only for the critical targets which were detected. As can be seen in Figure 1A, response times were slower for function than for content words in the READ+SEARCH condition, but not in the SEARCH LETTERS condition. Those trends were confirmed by a $2 \times 2$ repeated measures ANOVA with grammatical class (function vs. content) and conditions (READ+SEARCH vs. SEARCH LETTERS) as factors. There was a statistically significant effect of condition, $F(1, 14) = 15.77, \eta^2 = .53, p < .001$, but the main effect of grammatical class was not significant, $F = 2.43$. Importantly, the interaction between grammatical class and condition was significant, $F(1, 14) = 15.01, \eta^2 = .52, p < .01$. Simple main effect tests revealed that participants were significantly slower at detecting the target letter in function than in content words in the READ+SEARCH condition, $F(1, 28) = 16.90, \eta^2 = .38, p < .001$, but they were significantly faster at detecting the target letter in function than in content words in the SEARCH LETTERS condition, $F(1, 28) = 6.00, \eta^2 = .18, p < .0375$.

3.2. fMRI

3.2.1. Block Design Localizer

[Figure 2 about here.]

The block design localizer scan contrasted reading for comprehension with viewing consonant strings, and served to identify seed ROIs for the functional connectivity analyses.
A single independent component among the 25 identified by tensor ICA showed a significant relationship with the block design time series (p < .00001) that was significant across subjects (p < .00001). The map of this component is shown in the top panel of Figure 2; it includes areas typically involved in reading, including along the superior temporal sulcus/middle temporal gyri, the inferior frontal gyri, and the caudate nuclei and putamen, as well as anterior and posterior regions of the medial aspect of the superior frontal gyrus, and the posterior cingulate cortex. Activations were largely bilateral, though z values tended to be larger in the left than right hemisphere, as can be seen in Table 1.

3.2.2. Functional Connectivity — Individual Conditions

The seed ROIs for the functional connectivity analysis were centered on the subpeaks of each activation cluster identified in the block design localizer. This resulted in a set of 13 ROIs, the locations of which can be seen in the bottom part of Figure 2. fcMRI maps for each continuous-performance condition were created by aggregating the correlation maps from each of these seeds, first within and then between subjects. Thus each functional connectivity map reflects the overall strength with which each voxel is correlated with the 13 nodes of the “reading network” identified by the block design localizer scan.

Figure 3 shows the fcMRI maps for each condition; details are provided in Table 2. Two general features are notable in these. Firstly, the areas of correlation are generally similar across conditions, and secondly they are quite similar to the block design localizer map shown in Figure 2. The bottom part of Figure 2 shows the conjunction of the functional connectivity maps of the three conditions — in other words, areas that showed significant functional connectivity in each of the three conditions. It can be seen that these co-localize with the locations of the ROIs. In all three conditions, activity in the 13 nodes of the reading network were overall correlated with the inferior and middle frontal gyri, the anterior-posterior extent of the superior temporal sulci/middle temporal gyri, the medial superior frontal gyri, the basal ganglia (caudate and putamen), the thalamus, and the posterior cingulate gyrus.
3.2.3. Functional Connectivity — Contrasts Between Conditions

In spite of the overall similarities, some apparent differences between conditions can be seen in Figure 4. We first provide a qualitative description of the apparent differences observable in the figures, followed by reporting of the statistical contrasts. In the READ+SEARCH condition, functional connectivity appeared to extend from the posterior part of the superior temporal sulcus into the angular gyrus in the left hemisphere to a greater degree than in the READ ONLY condition. The SEARCH LETTERS condition showed an apparently even greater area of significant functional connectivity in the left angular gyrus, and in the right angular gyrus as well. It also appeared that the region of significant functional connectivity was also larger in the frontal lobes for both the READ+SEARCH and SEARCH LETTERS conditions relative to READ ONLY; this included an area of the left middle frontal gyrus, dorsal to Broca’s area. As well SEARCH LETTERS showed greater extent of right middle frontal gyrus functional connectivity than either the READ ONLY or READ+SEARCH conditions.

The primary question of this study was whether the addition of a concomitant letter search task disrupted the neural network involved in reading for comprehension. A pairwise statistical comparison of the fMRI maps for the READ ONLY and READ+SEARCH conditions revealed no significant differences in functional connectivity, as can be seen in the top part of Figure 4. As such, we found no evidence that the addition of a letter search task disrupted the neural network engaged during reading alone.

More widespread differences were found between the SEARCH LETTERS condition and the two reading conditions. As can be seen in the bottom sections of Figure 4, both the READ ONLY and READ+SEARCH conditions elicited stronger functional connectivity with the reading network along the superior temporal sulcus/middle temporal gyrus bilaterally (with greater spatial extent in the left hemisphere), and in the superior frontal gyrus/frontal pole. Cluster sizes along with peak locations and z values are provided in Table 3. As well, the READ ONLY condition was associated with greater functional connectivity than the SEARCH LETTERS condition in the thalamus bilaterally and the area of the right nucleus accumbens, while the READ+SEARCH condition was associated with stronger
functional connectivity than SEARCH LETTERS in the posterior cingulate gyrus/precuneus region.

The SEARCH LETTERS condition, on the other hand, elicited stronger functional connectivity than either reading condition in the anterior cingulate gyrus and surrounding regions, as well as in the inferior parietal lobes bilaterally, including the angular and supramarginal gyri.

4. Discussion

We tested the hypothesis that similar interactions occur among brain regions involved in reading continuous text for comprehension, when the task is simply reading alone or when a secondary letter search task is also required. It was motivated by debate in the literature as to whether the addition of a secondary search task disrupts the normal processes of reading. Our fcMRI results were in accord with those of our previous behavioural and eye tracking studies—we found no differences between reading alone and reading plus searching in the pattern of functional connectivity involving the nodes of the brain network for reading. These results were not due to a lack of statistical power nor an inability of the technique to find differences where they exist; both reading alone (READ ONLY) and reading plus searching (READ+SEARCH) had significantly different functional connectivity patterns than a task involving searching for letters in scrambled letter strings (SEARCH LETTERS). In what follows we discuss the implications of these results for other methods of studying reading, the relationship of the fcMRI results to more traditional methods of studying reading with fMRI, and finally a critical discussion of the somewhat novel approach to functional connectivity analysis used here.

Although the reading-and-letter-searching task has a long history in experimental psychology, questions remain as to whether the search task may disrupt the normal processes of reading. The implications of this question are significant, because it calls into question the validity of an extensive literature on reading and a task that allows a simple, inexpensive, and implicit means of potentially understanding the reading process. The weight of
behavioral evidence indicates that comprehension of the text is not impaired when the secondary letter search task is employed, at least in people without reading impairment (see, e.g., Oliver et al., 2005). Such evidence is easily obtained, yet does not rule out the possibility that different processes are employed in achieving the same levels of comprehension. The behavioral data we collected during the fMRI tasks reported here are consistent with this: subjects showed equal levels of recall of story elements in both the READ ONLY and READ+SEARCH conditions, while at the same time manifesting a typical MLE during the READ+SEARCH task (higher rates of omission for closed-class items than open-class words matched in length). Eyetracking data also support the assertion that the search task does not disrupt the normal oculomotor patterns engaged during reading for comprehension alone (Greenberg et al., 2006; Roy-Charland et al., 2007; Saint-Aubin and Klein, 2001). To these lines of evidence we now add neuroimaging data that suggests that the overall pattern of correlations within the neural network engaged in normal reading for comprehension is not altered when people perform a simultaneous letter search task.

The results of the block-design localizer scan were consistent with previous fMRI studies of reading. Areas of activation included the IFG (pars opercularis and triangularis), middle frontal gyri (dorsolateral prefrontal cortex), and the length of the MTG/STS from the temporal pole back to the inferior parietal lobe. These areas were activated bilaterally, though with greater extent of activation in the left hemisphere (roughly 25% greater volume in the temporal lobes, and twice the volume in the IFG). The lateral frontal and temporal areas are the areas typically associated with language processing, including reading (Price and Mechelli, 2005), and it is not uncommon to find this pattern of bilateral activation with greater spatial extent in the left hemisphere in sentence reading tasks (Bavelier et al., 1997; Spitsyna et al., 2006). Right hemisphere activation also increases when the text being read is a story with a rich discourse structure, as used here, relative to a set of sentences that are not thematically connected with each other, which are often used in neuroimaging studies (Beeman and Chiarello, 1997; Newman et al., 2010). Activation was also obtained in midline structures including the superior frontal gyri, anterior paracingulate gyrus, pre-SMA, and the precuneus/posterior cingulate gyrus region, as well as the basal ganglia and thalamus.
All of these regions have previously been implicated in language processing (Friederici et al., 2003; Ullman, 2001; Binder et al., 1999).

The neural network revealed by our functional connectivity analysis of the three experimental conditions yielded maps that were overall similar to each other, and to the network identified using the block design localizer. All of the ROIs derived from the functional localizer were present in the conjunction map showing the overlap of the three conditions. In one respect, this is not surprising — the seed regions for our fcMRI analysis were chosen from the activation peaks in the localizer scan, and so it is likely that they would correlate highly with themselves and other regions that were co-activated. However, if the pattern of correlations derived from the seeds was entirely driven by spatial autocorrelation (i.e., the smoothing applied to the fMRI data, combined with the inherent correlations between adjacent voxels), then we would expect the correlation maps to feature significant areas centered on each of the ROIs extending for a relatively symmetrical distance in each direction (with the possible exception of medially into the white matter). Instead, the patterns of significant correlations followed the same pattern as in the block design localizer, including significant correlations along the entire length of the STS/MTG, and “blobs” in the lateral frontal cortex that had a similarly elongated, rather than spherical shape. Thus the correlation maps accurately reflected the pattern of distributed activation observed in the functional localizer across a total of 3890 voxels, based only on 13 peak areas (totalling 351 voxels, or less than 10% of the original map) within that network.

The pattern of differences in the fcMRI maps between conditions was entirely consistent with our predictions: the lack of differences between the READ ONLY and READ+SEARCH conditions supports our hypothesis that the secondary letter search task does not disrupt the normal pattern of distributed brain activity that occurs during normal reading for comprehension. Although a null result on its own would be difficult to interpret, the fact that both reading conditions showed stronger functional connectivity involving STS/MTG language regions than the SEARCH LETTERS condition supports the contention that this functional connectivity is task-related. Further, it is important to note that not only did we not find changes in the strength of functional connectivity within the reading network
in the conditions with and without the additional letter search task, we also did not find increased functional connectivity in the READ+SEARCH condition between nodes of the reading network and other areas that were not engaged in the READ ONLY condition.

Among the regions that showed stronger functional connectivity during reading than searching scrambled letter strings were the angular gyrus, the middle part of the STS/MTG, and the anterior STS/temporal pole. The angular gyrus is a key area in reading — it is associated with mapping between orthographic and phonological and other linguistic representations, and disruptions in functional connectivity between the angular gyrus and temporal and occipital regions is observed in dyslexia (Horwitz et al., 1998; Shaywitz et al., 1998). The angular gyrus is also implicated in the retrieval and integration of semantic information (Binder et al., 2009). The middle part of the STS/MTG is associated with lexical retrieval and semantic processing (Indefrey, 2006), while anterior temporal regions have been demonstrated to be involved in both sentence-level syntactic processing (Friederici et al., 2000) and the integration of syntactic and semantic information in sentence processing (Humphries et al., 2006). An additional area of stronger functional connectivity was found in the medial superior frontal gyrus — an area that has been associated with semantic retrieval (Binder et al., 2009; Price, 2010).

In addition to the areas that showed stronger functional connectivity during the reading scans, there were regions that showed the opposite pattern, i.e., stronger functional connectivity during the SEARCH LETTERS condition than the reading conditions. These included the inferior parietal lobe bilaterally (including both regions of the angular gyrus dorsal to those showing stronger connectivity during reading, and the supramarginal gyrus), as well as the right middle frontal gyrus and anterior cingulate gyrus. The inferior parietal cortex, including the angular gyrus region identified in this contrast, is a key area involved in visual search tasks, and the functions that have been ascribed to it include directing attention serially to a series of possible targets, deciding on the presence or absence of a target, and making manual responses to targets (Muggleton et al., 2011; Nobre et al., 2003). While searching for the target letter was required for both the SEARCH LETTERS and READ+SEARCH tasks, subjects may have employed a more serial searching procedure
during the SEARCH LETTERS task, in contrast to wholistic word reading and identifying target letters based on word knowledge rather than serial search through letter strings. The angular gyrus is associated with response selection and the monitoring of performance and detection of errors (MacDonald et al., 2000); it may be that when given only the letter search task with material that was not readable, subjects were more attuned to their performance in the search task and thus more closely monitoring for errors. The right dorsolateral prefrontal cortex is associated with visuo-spatial working memory, as well as strategic control and maintaining the attentional demands of a task (MacDonald et al., 2000); again, stronger functional connectivity during the SEARCH LETTERS task may be attributable to a different search strategy (serial scanning through letters) that required different and possibly greater attentional control than during the READ+SEARCH task, including the fact that this task was likely less interesting.

Beyond the findings presented here regarding the nature of functional connectivity during reading and letter searching, the present study makes several other contributions to the literature. Firstly, the impetus for designing the study around continuous performance was the fact that the MLE could not be obtained under the conditions of a typical fMRI block design, in which reading and searching alternated with a control task (in this case, searching for the target letter in scrambled letter strings). Given that MLE may be considered a hallmark of fluent reading, this finding suggests that block designs may not be the ideal way of studying normal reading. As such, our continuous-performance design may have wide utility in future investigations of reading. Following from this, we derived a measure of aggregate functional connectivity within a neural network identified on the basis of a task-specific localizer scan. While this does not supplant the more traditional approach of using a single seed, it allows an alternative and perhaps more wholistic picture of interactions within a pre-specified neural network. Single-seed approaches may be most useful in studies aimed at understanding the function of a particular brain area of interest, and how its activity covaries with other brain regions. Our aggregate measure is better-suited to understanding the overall pattern of functional connectivity between a network of pre-specified regions. At the same time, it must be understood that the aggregate approach does not reveal the entire
pattern of functional connectivity in a given task. Indeed, individual ROIs in this study showed significant correlations with brain regions that did not appear in the aggregate map, because that functional connectivity was limited to only one of the 13 ROIs. This likely explains why certain brain regions that were doubtless activated during the tasks (e.g., visual areas) did not appear in the aggregate connectivity maps — while they fed information forward into the reading network, our results indicate that activation in visual areas does not show a consistent level of correlation with the reading network as a whole. In the future it will be of interest to contrast this aggregate functional connectivity measure with other approaches such as those that apply graph theoretical analysis to a large set of pair-wise (as opposed to aggregate) correlations between a large set of regions (Bullmore and Sporns, 2009).

In summary, our results demonstrated that the pattern of correlations in activity among the network of brain regions involved in reading is not disrupted by the concurrent performance of a letter search task. This finding supports the use of the read-and-search task to study reading.

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