Stroke disconnectome decodes reading networks

Running title: Decoding reading

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Abstract

Cognitive functional neuroimaging has been around for over 30 years and has shed light on the brain areas relevant for reading. However, new methodological developments enable mapping the interaction between functional imaging and the underlying white matter networks. In this study, we used such a novel method, called the disconnectome, to decode the reading circuitry in the brain. We used the resulting disconnection patterns to predict the typical lesion that would lead to reading deficits after brain damage. Our results suggest that white matter connections critical for reading include fronto-parietal U-shaped fibres

and the vertical occipital fasciculus (VOF). The lesion most predictive of a reading deficit would impinge on the left inferior parietal and the three temporal and occipital gyri. This novel framework can systematically be applied to bridge the gap between the neuropathology of language and cognitive neuroscience.

Introduction

This discovery of fire [is] probably the greatest ever made by man, excepting language [...] (Darwin, 1871).

The invention of the written language is a pivotal hallmark in human history, and the mastery of reading and writing (i.e. literacy) requires many years. Written language is critical to society and spans from passing information between individuals to written rules that govern society. In today's world, literacy abilities are indispensable to learning and navigating our social and professional environments.

Reading and writing require the interplay of several processes, including abstraction. For alphabetic language (sound-based, e.g. English), when we write, we graphically encode (grapheme) linguistic utterances (phoneme) with the aim of a reader being able to accurately decode and reconstruct the meaning. For this information transaction to succeed, one must understand the associated spoken language to comprehend the text.

Seminal work on the functional brain activations of proficiency in literacy has shown that reading selectively activates bilateral temporo-occipital areas, including the left visual word form area and right occipital areas. However, a more comprehensive left hemisphere language network is modulated by reading proficiency, suggesting that the acquisition of literacy is tapping into the language circuitry in the brain. This network includes the left temporal cortex, premotor, and supplementary motor area (SMA) (Dehaene et al., 2010). Literacy-related activations also extended to the planum temporale suggesting a

top-down modulation of orthography from spoken inputs. Of note, these changes occur regardless of when literacy was acquired (adulthood vs childhood) (Dehaene et al., 2010).

Literacy, therefore, requires a network of language-processing, auditory, and visual regions to interact. These relevant regions are distant from each other and, as such, rely on a network of connections. Classical language and auditory areas in the frontal and temporal lobes are connected by the arcuate fasciculus, the most prominent pathway for language functions (for review, see (Forkel et al., 2021). The fronto-temporal branch, also known as the long segment of the arcuate fasciculus, has also been shown to be relevant for learning new words via the phonological route (López-Barroso et al., 2013). The long segment is also associated with reading skills in children (Yeatman et al., 2011), while the parietal-temporal branch, also known as the posterior segment, has been associated with reading skills in adults (Thiebaut de Schotten et al., 2014). Another network that connects occipital-temporal-frontal cortices includes the inferior longitudinal fasciculus (ILF, occipito-temporal connection) (Catani et al., 2003), inferior fronto-occipital fasciculus (IFOF, occipital-frontal connection) (Forkel et al., 2014), and the vertical occipital fasciculus (e.g. VOF, intraoccipital connection) (Forkel et al., 2015; Vergani et al., 2014; Yeatman et al., 2014). Longitudinal studies in children acquiring literacy revealed the left IFOF (Vanderauwera et al., 2018) and ILF (Yeatman et al., 2012) as mediators of orthographic (visual) but not phonological (auditory) processes. The VOF has been suggested as the link between the dorsal and ventral visual streams and to contribute to reading through the integration of eye movement with word recognition (anterior branch) and communication with visual processes (posterior branch) (Yeatman et al., 2014). In addition to the intrahemispheric communication between dorsal and ventral networks, information integration between both hemispheres —interhemispheric— is critical to literacy. Reading relies on visual inputs from both eyes that need to be synthesised in the brain. Accordingly, the posterior corpus callosum connects the parietal and occipital

lobes to mediate this integration (Carreiras et al., 2009). While all these studies sporadically highlight pieces of brain networks that orchestrate the language, visual, and auditory processes necessary for reading acquisition, their relationship with the networks whose damage will contribute critically to reading impairment is not unequivocal.

Clinical neuroanatomical studies in patients who temporarily or chronically lost the ability to read after brain lesions only partially overlap with the networks related to literacy acquisition.
For instance, phonological dyslexia, an acquired dyslexia characterised primarily by difficulties in reading pronounceable nonwords, is usually caused by sizeable left hemisphere perisylvian lesions in the middle cerebral artery territory (Luzzatti et al., 2001). Surface dyslexia, the difficulty with whole word recognition and spelling, has been associated with lesions to the anterior lateral temporal lobe (Patterson and Hodges, 1992). While letter-by-letter dyslexia, characterised by prolonged reading and a linear word length effect, presents after lesions to the occipital and inferior temporal regions (Cohen et al., 2004; Fiset et al., 2006). Pure alexia, defined as pure word blindness by Dejerine (1892), has been initially characterised by lesions to the angular gyrus. However, this view has been challenged, and current models suggest an occlusion of the left posterior cerebral artery subserving parietal and occipital-temporal regions to cause the symptom (Cohen et al., 2000; Dehaene and Cohen, 2011; Philipose et al., 2007; Starrfelt and Shallice, 2014) Hence the relationship between the areas functionally activated when reading, the network required for literacy acquisition, and the critical network for reading disorders is missing.

A potential way to fill this gap is to take advantage of recent developments in functional-structural connectivity coupling that provides methods to decode functional MRI activations based on the pattern of brain disconnection derived from stroke – the disconnectome (Thiebaut de Schotten et al., 2020). This

method reveals the white matter circuitry connecting activated areas and typical lesions that should interrupt this circuitry, thereby identifying the critical white matter circuitry for a specific cognitive function - in this case, reading. The disconnectome has never been applied in full to the reading circuitry. Therefore, in the present study, we reanalysed data (Hesling et al., 2019) in light of the disconnectome to reveal the reading circuitry and typical lesions that should impair its functioning.

Methods

A methodological overview is provided in Figure 1. Briefly, We used previously published data (grey boxes) for a functional reading task (Hesling et al., 2019) and the disconnectome maps (Thiebaut de Schotten et al., 2020) to calculate the group-level statistical map for reading and use the disconnectome to decode the critical white matter network for reading.

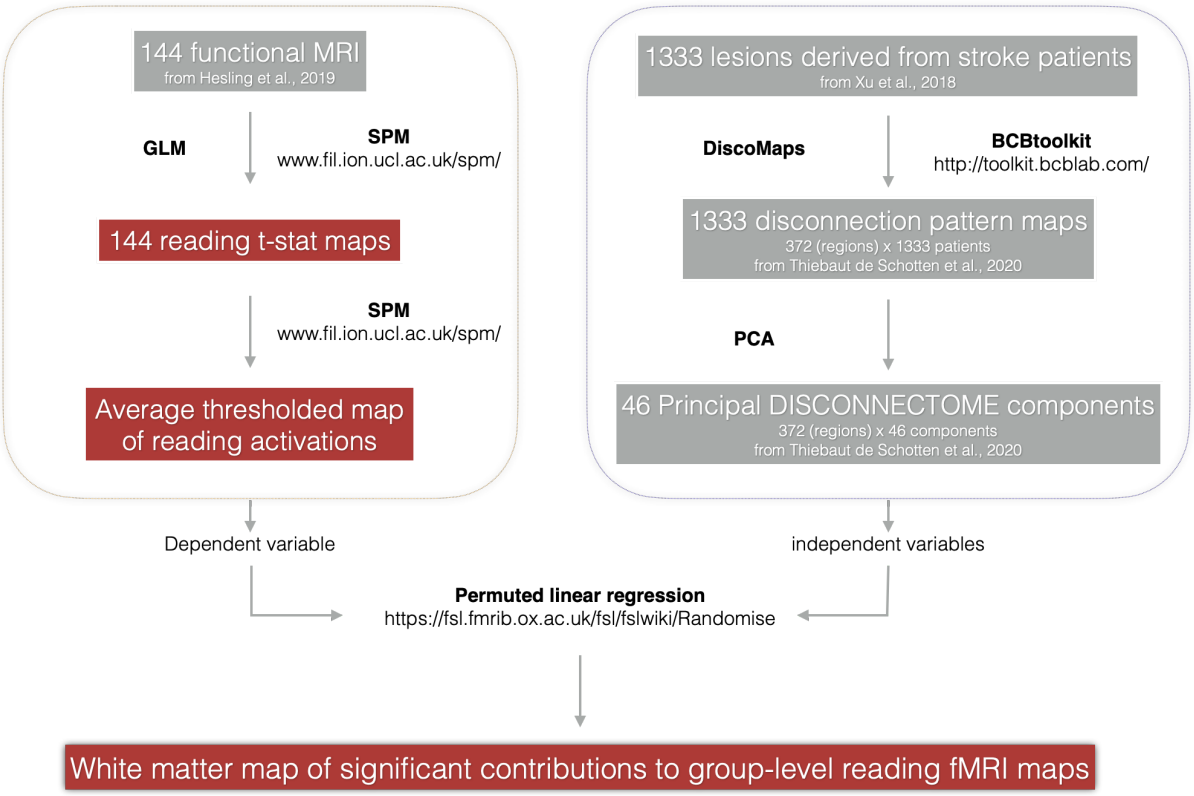

Figure 1. Schematic overview of the processing steps implemented in this study.

Functional MRI

The present study included a sample of 144 healthy right-handed volunteers (72 women, 27±6 years, age range 19–53 years) from the BIL&GIN database (www.gin.cnrs.fr/en/current-research/axis2/bilgin-en/), which is a multimodal database harbouring imaging, psychometric, and genetic data to study the neural correlates of brain lateralisation (Mazoyer et al., 2016). We used the functional MRI data (fMRI) previously published in (Hesling et al., 2019) to generate t-maps of the significant voxels of functional activations during the word-list reading task. For this task, participants were asked to read aloud lists of words. The stimuli were lists of over-learnt words, making it possible to decrease the load of lexico-semantic and syntactic processing. The lists included the days of the week, the months of the year, and the seasons. This task consisted of 13 trials lasting 14 seconds. Response times were recorded during the fMRI experiment.

The fMRI experiment included further tasks not analysed in this study. Participants were shown a scrambled drawing for 1 s, immediately followed by a central fixation crosshair (Fig. 2). During the reading task, participants had to read lists of words flashed on the screen and click the response pad with their right hand afterwards. This was followed by a low-level control task where participants fixated the central cross and pressed the response pad when the cross changed to a square (both stimuli covering a 0.8° × 0.8° visual area). This part of the trial lasted at least half the total trial duration. It was aimed at refocusing the participant's attention to a non-verbal stimulus and controlling for manual motor response activation and lasted 6 - 10 seconds.

For computational purposes, t-maps of functional activations during the reading task were further characterised by measuring the average level of activations in subcortical areas (Catani and Thiebaut de Schotten, 2012) as well as in areas derived from a multimodal atlas of the brain surface (Glasser et al., 2016).

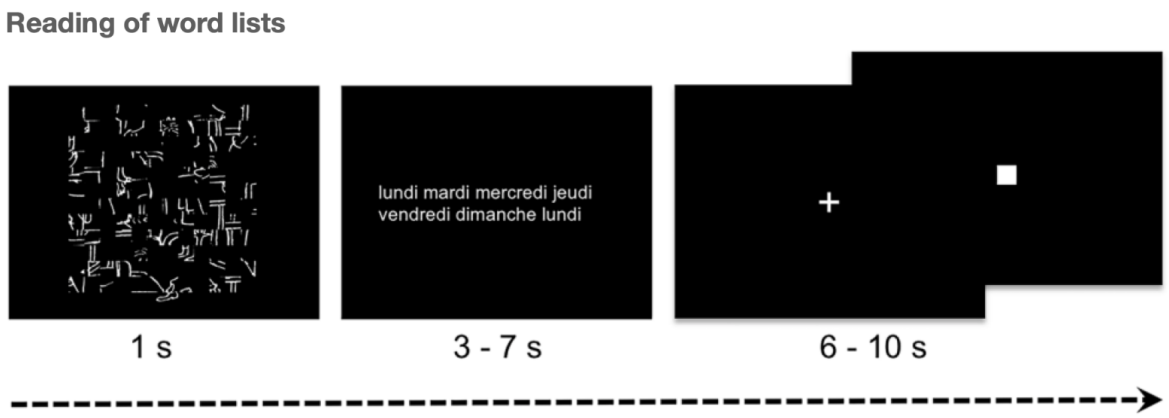

Figure 2. Description of the functional MRI paradigm for word-list reading. An event was initiated by presenting a scrambled picture for one second, followed by the presentation of a list of words (weeks, hours, seasons, days, months) that participants were instructed to read. The participants had to click when they had finished reading, and they subsequently had to indicate by clicking when the central cross that reappeared was changed into a square. In this figure, for reading convenience, the stimuli were zoomed in on compared to the presentation of the stimuli during the scanning session.

T-maps functional MRI activations

The acquisition parameters and the pre-processing steps have been fully described (Hesling & al. 2019). Briefly, the data were acquired on a 3T Philips Intera Achieva scanner. After normalisation to the BIL&GIN template in the MNI space, the T2*-weighted echo-planar images (EPI) (TR = 2 s; TE = 35 ms; flip angle = 80°; 31 axial slices; field of view, 240 × 240 mm2; isotropic voxel size, 3.75 × 3.75 × 3.75 mm3) were initially smoothed using a 6-mm full-width at half-maximum Gaussian filter to each functional volume (194 T2*-weighted volumes). The data were processed using global linear modelling using SPM12 (https://www.fil.ion.ucl.ac.uk/spm/). For each participant, the BOLD variations of the Word-List reading task were contrasted against the cross-change detection task.

The average brain activation map of BOLD signal variations (at the voxel level) during the reading task was calculated. This activation map corresponded to the t-values extracted from the Student's t-test for each voxel across the 144 participants. Finally, the resulting average brain map was thresholded to conserve only the significant and positive t-values (Bonferroni corrected).

The disconnectome components

Disconnectome component corresponds to the 46 principal components explaining > 99% of the variance of the white matter disconnection derived from 1333 patients with stroke lesions (see (Thiebaut de Schotten et al., 2020) for more details). Lesion data were derived from 1333 patients admitted to University College London Hospitals (UCLH) between 2001 and 2014. The study was approved by the West London & GTAC Research Ethics Committee. The data have been previously published (Thiebaut de Schotten et al., 2020; Xu et al., 2018). The lesions used in this research were non-linearly registered to the Montreal neurological institute space (2 × 2 × 2 mm, MNI; http://www.bic.mni.mcgill.ca) to allow direct comparisons amongst individuals. Notably, a second set of disconnectome components exist and can be used to replicate subsequent analyses. The disconnectome components exist as a string of values corresponding to the average level of disconnection in subcortical areas (Catani and Thiebaut de Schotten, 2012) as well as in areas derived from a multimodal atlas of the brain surface (Glasser et al., 2016) as well as neuroanatomical maps in the MNI2152. Two sets of component maps — original and replication for replication convenience of any results derived from the disconnectome.

Lesion identification

1333 ischemic lesions were provided from the authors (NP) and were manually delineated on T1-weighted images. Lesion masks are derived by an unsupervised patch-based lesion-segmentation algorithm followed by manual curation as described in Xu et al. The process yields binary masks non-linearly registered to SPM's TPMs (see (Xu et al., 2018) for details).

Decoding the functional activations with the disconnectome component maps

Permuted linear regression was applied to identify the statistical contribution of each voxel of each component map (i.e. independent variables) to real group-level fMRI maps for reading (i.e. the dependent variable) (see Figure 1). The group-level fMRI maps were derived from a reading task in 144 healthy right-handed participants previously collected (Hesling et al., 2019). The 46 disconnectome components provided in (Thiebaut de Schotten et al., 2020) explained 50% of the variance of reading activation. The linear component provided a loading (Figure 2b) for each component that was subsequently used as an independent variable in a permuted linear regression (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Randomise). Randomise produced a map of the white matter significantly contributing to group-level reading fMRI maps. Since we have two sets of component maps, we replicated the results mapped onto the white matter. The replicability of this analysis was assessed using a Pearson correlation between the results and indicated excellent replicability for fMRI reading mapping onto the white matter with a score (83%).

Anatomical labelling

The white matter and grey matter were labelled manually by expert anatomists (SJF/MTdS) according to the Atlas of Human Brain Connections (Catani and Thiebaut de Schotten, 2012).

Results

The reading task activated a bilateral network of regions in the frontal, temporal, occipital lobe and subcortical areas (Figure 3a). In the frontal lobe, activations are centred on Exner's area (ExA) - located just above the language area in the inferior frontal gyrus and the frontal eye field (saccadic eye movements) at the intersection of the middle frontal gyrus with the precentral gyrus. Previous studies have shown that words in the visual field activate a widespread neuronal network that is congruent with classical language areas (Price et al., 1996). Our results replicate this observation by showing activations in the inferior frontal gyrus and superior temporal gyrus (Figure 3a).

Functional activations are also in the medial superior frontal gyri (SMA). The SMA has been shown to mediate motor speech control, integrate processing between the two hemispheres and interact with subcortical structures (Hertrich et al., 2016). The striatum is a subcortical structure and part of the basal ganglia that has been shown to play a role in sequencing. The frontostriatal circuit may therefore contribute to linguistic sequencing in a domain-specific manner (Chan et al., 2013), and its dysregulation has been linked to reading disorders (Hancock et al., 2017). The superior, middle, and inferior occipital cortices have also been activated bilaterally.

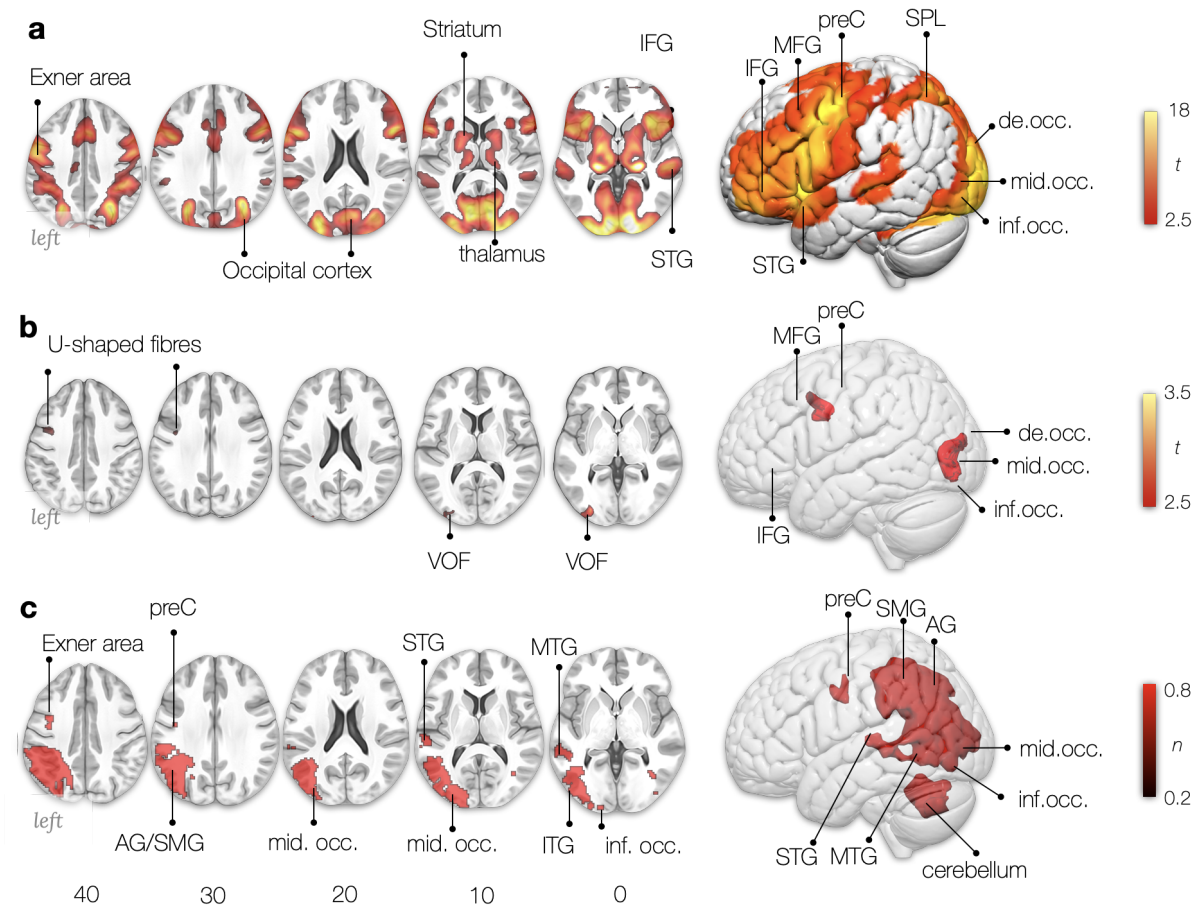

Figure 3. Multidimensionality of the reading network. **a** Average bilateral activation during the reading task (fMRI), **b** Disconnectome components explaining activations during the reading task, **c** Typical lesion causing reading deficits.

IFG: *inferior frontal gyrus*, MFG: *middle frontal gyrus*, preC: *precentral gyrus*, SPL: *superior parietal lobe*, STG: *superior temporal gyrus*, MTG: *middle temporal gyrus*, de.occ: *descending occipital gyrus*, mid.occ.: *middle occipital gyrus*, inf.occ: *inferior occipital gyrus*, SMG: *supramarginal gyrus*, AG: *angular gyrus*, VOF: *vertical occipital fasciculus*.

Mapping the profiles of disconnections identified reading clusters in the occipital lobe centred around the vertical occipital fasciculus (VOF) (Figure 2b).

Finally, a typical lesion was identified that showed that this disconnection profile could explain 33% of the variance in the reading task (Figure 3c, Figure 4). Hence, this lesion is likely to disconnect the white matter pathways 'feeding' into the activation pattern for reading. The typical lesion to cause a reading deficit is

in the left hemisphere and affects Exner's Area and the precentral gyrus in the frontal lobe; the angular gyrus in the inferior parietal lobe; the superior and middle temporal gyri and the superior, middle and inferior occipital cortices (Fig. 3c).

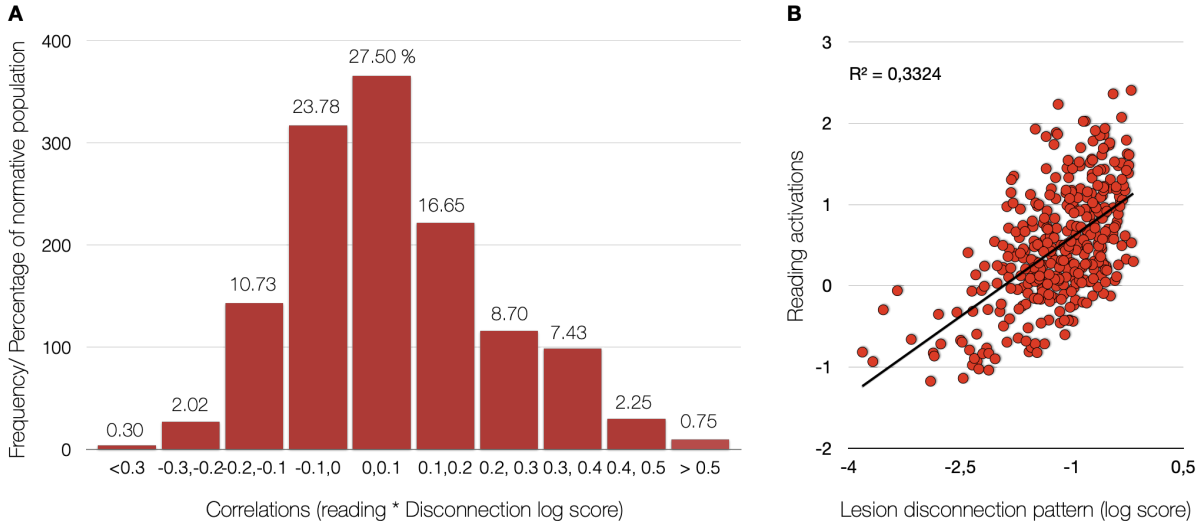

Figure 4. Distribution of reading activation correlations with disconnection pattern maps in 1333 patients (A). According to our experimental framework, a pure lesion to the reading network would only occur in 0.75% of cases. The most representative patient from this sample with a correlation of 0.58 is highlighted for its correlation with functional reading task activations from fMRI explaining 33% of the variance (B).

Discussion

This study combined the latest research in functional MRI of reading with the disconnectome framework to revisit the neurobiology of reading. This approach couples functional MRI and structural connectivity to disentangle the circuitry, supporting a reading network in healthy controls. We propose a new, more comprehensive model of the reading network based on the convergence of functional, structural, and lesion data. First, we confirmed the functional areas activated by reading tasks during fMRI tasks. Second, we identified the critical white matter network supporting reading. Thirdly, we were able to reveal the typical brain areas that are essential for reading deficits if damaged by a lesion

that disconnects a reading circuitry, which putatively would involve phylogenetically recent white matter tracts.

The cortical networks for reading have been studied for over 30 years using functional MRI (Carreiras et al., 2009; Hesling et al., 2019; Labache et al., 2019; McCrory et al., 2005; Price, 2012, 2000; Price et al., 1999; Price and Mechelli, 2005). Multiple cortical and subcortical areas have been identified as relevant for reading processes. For example, the pre-SMA and SMA-proper were associated with sequencing abstract motor plans and with the control of motor output, respectively (Alario et al., 2006; Tremblay and Gracco, 2006). The subcortical structures, for example, the thalamus, may be involved in processes that involve manipulations of lexical information (Llano, 2013). The striatum has been associated with phonological processing and implicit sequence learning relevant to early language reading acquisition and hyperactivation in this network has been linked to reading disorders (Hancock et al., 2017). The network of cortical areas involved in reading as identified by our analysis matches the reading literature. The areas of highest activation were centred in the posterior frontal lobe, anterior insula and the occipital lobes in both hemispheres (Figure 3a).
Reading familiar words, such as in our case the days of the week and months of the year, would not necessitate sublexical assembly as the process is facilitated by lexical knowledge of the whole word. It does, however, rely on the conversion of orthographic to articulatory codes (i.e. spelling to sound conversion). As such, activations in the occipital cortex (visual), the superior temporal gyrus (auditory), and the frontal network of the IFG, MFG, preC and SMA (articulation) are very plausible (Ekert et al., 2021; Kaestner et al., 2021). fMRI does highlight all areas involved in a task by providing correlational evidence for structural-functional relationships. Recent non-invasive and invasive methods of brain stimulation allow disentangling the critical cortical regions by drawing causal inferences. Using such an approach, the precentral gyrus, which is a strongly activated hub in our fmri analysis, has been shown to be relevant for silent reading (Kaestner et

al., 2021). A recent review consolidated the literature and summarised the contributions of the individual areas into a dual stream model where pseudoword reading was propagated along a dorsal parietal-frontal route while reading familiar words was processed along a ventral occipito-temporal-frontal route (Turker and Hartwigsen, 2021). In this model, the frontal areas are relevant for sound and sequencing, parietal regions for grapheme-phoneme conversion and word meaning, and the temporal areas for phonological analyses and match the fMRI result we presented.

Within the large cortical network for reading, another area that stands out is Exner's Area. First postulated as a neuroanatomical 'writing centre' by Exner (Exner, 1881), the posterior part of the middle frontal gyrus (MFG), also known as 'Exner's Area', is one of the regions involved in the writing process that is highlighted in the literature (Anderson et al., 1990; Exner, 1881; Lubrano et al., 2004; Planton et al., 2013; Roux et al., 2009). Despite significant advancements in neuroimaging techniques, there are few studies that describe patients with isolated lesions in 'Exner's Area' or which look at the underlying white matter connections involved in reading and writing processes. The small number of patients in the original description in tandem with the absence of pure agraphia symptoms plus the interindividual variability in the lesion anatomy is partially the reasons why Exner's hypothesis is still debated (Roux et al., 2010). There are isolated reports of Exner's area being involved in reading and writing (Roux et al., 2009), as well as word learning in the blind (Mizuochi-Endo et al., 2021). In our study, Exner's area has been identified as a contributing cortical region in the fMRI analysis, its disconnection from the inferior frontal gyrus and the precentral gyrus has been shown as a critical white matter connection in the disconnectome analysis, and the typical lesion that would explain most the variance in reading has also been identified in the triangle between the IFG/MFG and preC (Figure 3a-c).

Accordingly, the disconnectome analysis revealed connections to Exner's area and the vertical occipital fasciculus (VOF) of Wernicke as essential white matter circuits for reading. The frontal U-shaped fibres of the dorsal precentral gyrus connect the motor cortex and the middle frontal gyrus near Exner's area (Catani et al., 2017), and will be referred to as 'Exner's U-shaped' fibres. The VOF is connecting the dorsolateral and ventrolateral visual cortex (Takemura et al., 2017; Vergani et al., 2014; Yeatman et al., 2014), including the Visual Word Form Area (VWFA), a part of the ventral occipito-temporal cortex specialised in processing visual formation of words and reading (Dehaene et al., 2002; Wandell et al., 2012). A ventral temporal-occipital disconnection by lesions or surgical interventions have been linked to pure alexia (Epelbaum et al., 2008; Ng et al., 2021; Starrfelt et al., 2010). The anatomy of the VOF has been verified using tractography (Briggs et al., 2018; Keser et al., 2016; Panesar et al., 2019; Schurr et al., 2019; Yeatman et al., 2014), post-mortem dissections (Güngör et al., 2017; Palejwala et al., 2020; Vergani et al., 2014), and comparative anatomy (Takemura et al., 2017). These descriptions were scrutinised against historical post-mortem descriptions from Wernicke (Yeatman et al., 2014), Sachs (Forkel et al., 2015; Vergani et al., 2014) and the Dejerine's (Bugain et al., 2021). Anatomically, the vertical occipital fibre system is distinct from the parietal-temporal branch of the arcuate fasciculus (e.g. posterior segment) in its trajectories and cortical terminations. The intralobar vertical occipital fasciculus projects between the ventral and dorsal occipital cortices while the interlobar posterior segment of the arcuate fasciculus connects posterior temporal and inferior parietal regions (i.e. supramarginal and angular gyrus) (Weiner et al., 2017). A recent review identified an association between the VOF and visual tasks, including object recognition and integrating the dorsal and ventral stream during hand actions (Budisavljevic et al., 2018; Forkel et al., 2021). The VOF terminations have also been shown to predict reading-related responses in the human ventral temporal cortex (Grotheer et al., 2021) and early literacy skills in children (Broce et al., 2019). In the clinical setting, the VOF has recently also been associated with

visual scores in assessments in patients with multiple sclerosis (Abdolalizadeh et al., 2022). Hence, the disconnectome identification of U-shaped fibres and the VOF as critical connections supporting literacy is very plausible.

These U-shaped fibres might have evolved later on in the phylogenetic tree. The emergence of literacy necessitated accessing our knowledge of spoken language through a novel modality, one that was never anticipated by evolution: vision. While we as a species have been using representations of visual objects and spoken sounds using visual signs (e.g. hieroglyphs) for a long time, our brains mostly evolved for millions of years in a world where literacy, or any form thereof, did not exist (Hodgson, 2019). It is argued that reading developed some 5000 years ago, a time frame too short for significant evolutionary changes. As a consequence, some say that reading would rely on brain regions that initially evolved to process vision (e.g. VOF) and spoken language (e.g. Exner's U-shaped fibres) (Dehaene et al., 2010) and the connections at their interception (Yeatman and White, 2021). A recently developing field, neuroarchoelogy, compared the neuronal responses to written words and engravings. Engravings were shown to activate the ventral visual stream bilaterally and the left visual word form area (Mellet et al., 2019). However, the specificity of the VWFA has been challenged (Price and Devlin, 2004, 2003). On the other hand, some might argue that the reading brain does not exist but is created as the acquisition of literacy has been linked to brain plasticity both in the grey and the white matter (Carreiras et al., 2009; Dehaene et al., 2010; Thiebaut de Schotten et al., 2014).
This study identified the critical role of fronto-parietal U-shaped fibres underneath Exner's area. The superficial white matter, which includes short-ranged intergyral U-shaped fibres, is more variable between people and associated with higher cognitive functions (Croxson et al., 2018).

If we consider the emergency of literacy as a late appearance in the evolution of the brain, then it would come as no surprise that reading relies on a more adaptable and flexible white matter network, i.e. U-shaped fibres. This is

because there is a gradient of variability where the more superficial white matter is more variable while the deeper white matter is more conserved across individuals. The U-shaped fibres are the most superficial connections in the human brain and might consequently adjust to new arising demands as the most variable areas are associated with higher cognitive functions in humans (Croxson et al., 2018). The VOF is also a short ranging intracortical connection and as such located superficially. The critical involvement of U-shaped fibres and short-range connections in reading may reflect a recent adaptation to the advancement of human skills.

We have demonstrated in this study that the most likely lesion to disrupt the reading circuitry was located in the inferior parietal lobe, the posterior superior, and middle temporal cortex, the superior, middle and inferior occipital cortex, and Exner's area of the left hemisphere (Figure 3c). The typical lesion affected the white matter behind the inferior temporal gyrus in the right hemisphere. As such, this lesion would consist of the language areas identified from the fMRI task and the U-shaped fibres and the vertical occipital fasciculus unifying the results determined by functional imaging and disconnectome mapping. This result is in line with recent neuroimaging studies suggesting that learned orthographic knowledge is associated with the left inferior temporal-occipital cortex and fusiform gyrus (Cohen and Dehaene, 2004). As well as the literature suggesting that lesions to that area should lead to reading impairments. For example, a voxel-based lesion-symptom study in 111 stroke patients, identified the critical lesion areas for reading (left occipito-temporal cortex, and inferior parietal cortex), writing (left inferior parietal lobe, superior temporal cortex including Heschl's gyrus, and sensorimotor cortex), single-word reading (left temporo-occipital cortex, posterior lateral temporal, and inferior parietal cortex), and sentence reading (left temporo-occipital cortex, lateral temporal cortex, superior portion of the temporal pole, inferior and posterior insula) (Baldo et al., 2018). The typical lesion identified from our cohort of 1333 patients

matches these results for single word reading with the addition of Exner's area and the cerebellum.

Decoding task-based functional MRI imaging using a disconnectome framework is a new and promising method to link structural connectivity with function and behaviour using brain disconnections. Although this method has been successfully applied to a range of cognitive functions and behaviours (Dulyan et al., 2021; Thiebaut de Schotten et al., 2020), it offers an indirect measure of the structural connectivity supporting functional activations. To directly predict reading impairments and estimate measures of reading impairments, we provide the maps associated with this study on Neurovault for future research. In addition, this is a cross-sectional study in adults, and results might diverge depending on reading abilities, literacy skills or developmental cohorts. Finally, we used the previously collected data for a reading task based on automatic stimuli and tapped into basic language processes. This task cannot be linguistically loaded and likely bypasses complex language processes. The advantage of this task is twofold. First, complex linguistic fMRI tasks are likely to activate the whole brain. Second, this task involves little engagement and no oral output from participants, making it a suitable clinical task and relevant results for a clinical setting.

Of all human inventions, the ingenuity of the written word has probably been momentous and far-reaching in human evolution. Literacy has enabled a considerable increase in the rate and efficacy of cultural evolution. The cultural evolution of society and individuals relies on knowledge transmission within and across generations, which was greatly facilitated by literacy. Neuroimaging offers the tools to uncover the brain circuitry that enables literacy, and this paper is a novel contribution to decipher the neurobiology of reading. Overall, we demonstrated that the reading circuitry can be decoded in healthy participants' functional activations using a disconnectome approach and

identified Exner's U-shaped fibres and the vertical occipital fasciculus are relevant white matter connections.

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Competing interests: The authors declare no conflict of interest.

Data availability

Disconnectome maps and lesions were downloaded from the supplementary material of Thiebaut de Schotten et al. The two sets of component maps and the atlas of white matter function (original and replication) are available at https://identifiers.org/neurovault.collection:7735. The scatterplot (fmri and disconnectome) was done using the available python code http://www.bcblab.com/BCB/Coding/Entries/2019/3/15_Produce_scatterplots_of_correlation_between_2_.nii_files.html.
Maps associated with this research are available on Neurovault.org (Collection: https://identifiers.org/neurovault.collection:12309.
Individual files: fMRI: https://identifiers.org/neurovault.image:777434; Disco map: https://identifiers.org/neurovault.image:777435; typical lesion: https://identifiers.org/neurovault.image:777436).

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