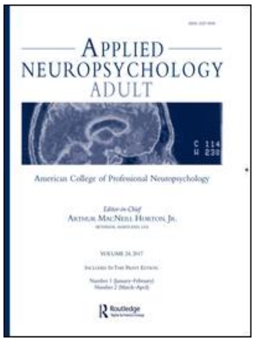

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Acquired reading impairment following brain injury

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ABSTRACT
This large-scale patient study investigated the rate, unique signatures associated with acquired reading impairments, its neurocognitive correlates, and long-term outcome in 731 acute stroke patients using the sentence and non-word reading subtests of Birmingham Cognitive Screen (BCoS). The objectives for the study were to explore the (i) potentially different error patterns among adult patients, (ii) associative relationship between the different subclasses of reading impairment and performance in other cognitive domains, and (iii) recovery rates in patients nine months post-lesion compared with their initial performance. The study revealed distinctive reading impairment profiles in patients with left hemisphere (LH) and right hemisphere (RH) lesions. Some interesting associations between reading disorder and other cognitive functions were observed. Nine months post-lesion, both groups showed some recovery in reading performance compared with their baseline performance, but the rate of improvement was higher for the LH group. The study reveals unique reading profiles and impairment patterns among left and right hemisphere lesions. The findings of the study provide a deeper understanding of reading deficits that will inform clinical practice, planning of rehabilitative interventions of brain injured patients, and the scientific community.

KEYWORDS
Assessment; brain injury; dyslexia; reading impairment; recovery; stroke

Introduction

Proficient reading is a multifaceted neurocognitive skill that requires simultaneous contribution of phonological, orthographic, and semantic processes (Frost, 2012). Moreover, reading demands involvement of several other cognitive and executive functions (perception, attention, working, and long-term memory, to name a few). To read correctly one needs to process visual features of the target words (e.g., their letters—orthography), their sound (input phonology), their meaning (semantics) and to read them aloud,the reader must create the corresponding speech sounds (phonetics) that need to be articulated (output phonology) (Paz-Alonso et al., 2018, p. 433). An acquired brain lesion that disturbs one or more of these contributing functions impairs the ability to read efficiently and can have a large impact on communication and everyday life (Hilari & Byng, 2009). Following a stroke, about one-third of patients show acquired impairments in speech processing and language (e.g., Bickerton et al., 2012; Pedersen et al., 2004). Impaired language is characterized by (i) reduced comprehension and/or production of speech, (ii) trouble with object naming, and (iii) difficulty in reading of visually presented written text. Like other language disorders, acquired reading disorders (dyslexia/alexia) are associated with damage to the left hemisphere of the brain.

Acquired dyslexia and alexia are reading disorders observed in previously literate patients who have suffered a brain injury. A wide variety of the disorders has been documented. More than a century ago, Dejerine (1891, 1892) distinguished between *alexia with agraphia* (writing impairment) and *alexia without agraphia* (or pure alexia) after studying two patients. Shallice and Warrington (1980) presented an improved classification of dyslexias in which they distinguished between (a) *peripheral* dyslexias and (b) *central* dyslexias.

Peripheral dyslexias affect the initial pre-lexical processes of recognition of letters and written word forms, without necessarily affecting central semantic and phonological processes and is attributed to a deficit in the processing visual aspects of the word that prevents matching of word to its stored representation or "visual word form" (Shallice & Warrington, 1980), though deficits in lexical knowledge may also be contributory (Lambon Ralph & Ellis, 1997). Peripheral dyslexias take three forms (i) *pure alexia*, (ii) *neglect dyslexia*, and (iii) *attentional dyslexia*.

Pure alexia is characterized by letter-by-letter reading strategy and a word length effect on single word reading. Hence, pure alexic reading is usually slow and single word reading is distinguished by a pronounced word length effect that increases the time needed to read a word by about hundreds of milliseconds per letter (Behrmann et al., 1998). Essentially, the reader has to identify each letter of the word

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individually in a slow, serial fashion, rather than through a rapid, automatic, and parallel identification. Behrmann and Plaut (2014) argue that even pure alexia not only affects the word recognition, but pure alexic patients have mild but reliable face recognition deficits (p. 1115). A pure alexic patient only shows impaired reading while performance in other language functions (e.g., writing, text comprehension) remains at normal level, except for some difficulties in naming (retrieving) correct words (Starrfelt & Woodhead, 2021). The deficit usually follows damage to the posterior left hemisphere (Johnson & Raphail, 2015; Starrfelt et al., 2013), especially in the visual word form area (VWFA), a region in the posterior left occipitotemporal cortex adjacent to the fusiform gyrus. that seems to mediate word recognition (Turkeltaub et al., 2014). However, using Transcranial Magnetic Stimulation (TMS) on the right hemisphere of the brain, Coslett and Monsul (1994) could simulate similar reading impairment as in pure alexia.

Neglect dyslexia: this second type of peripheral dyslexia is caused by attentional deficits, most commonly following right hemisphere or bilateral lesions. This syndrome is distinguished by failure in explicitly identifying the initial portion of a letter string caused by visuospatial errors in word identification and text reading triggered by neglect syndrome and often more prevalent after right hemisphere (RH) damage to the posterior parietal, superior temporal, and inferior frontal gyri (Chechlacz et al., 2010; Karnath et al., 2002; Karnath & Rorden, 2012; Ptak et al., 2016).

Attentional dyslexia: this third form of peripheral dyslexia was first classified by Shallice and Warrington (1977) who described it as an impairment where the reading is relatively preserved for single words but severely impaired when the word is in the presence of other words and letters (Price & Humphreys, 1993). Another feature of attentional dyslexia is the production of errors that reflects the migration of letters from elsewhere on display (Saffran & Coslett, 1998). These context-based errors are presumably related to an impaired attenuating filter control mechanism that reduces the output from elsewhere in the display (Shallice & Warrington, 1977; Warrington et al., 1993).

Central dyslexias: Shallice and Warrington (1980) describe the impairment as aphasia-related reading impairment. Central dyslexias seem to reflect a disconnection syndrome due to an interruption between the processing of the visual input and higher-level linguistic processing (Schattka et al., 2010). Consequently, those procedures by which visual word forms gain access to meaning or speech production mechanisms are impaired. Shallice and Warrington (1980) suggested three types (i) *surface dyslexia*, (ii) *deep dyslexia*, and (iii) *phonological dyslexia.*

Surface dyslexia is the acquired inability to read words with irregular and unpredictable grapheme-to-phoneme correspondences (e.g., "pleasure" and "mild"), while performing at normal level in reading Regular words and non-words (pseudowords), which indicates that the networks by which words are "sounded out" are relatively preserved (Coslett & Turkeltaub, 2016). Surface dyslexic patients suffer lesions primarily involving the temporal lobe, including both posterior and anterior regions (Ripamonti et al., 2014).

Deep dyslexia is distinguished by production of semantic paralexia (semantic substitution) in which a word related in meaning to the target word is substituted when reading aloud (Coltheart, 1980; Marshall & Newcombe, 1973) for instance the word "talk" is produced as "speak." These patients especially show severe deficits not only in reading non-words but also reading abstract (as opposed to concrete) words, non-imageable words, Function words, producing frequent "visual" errors (e.g., "skate" is read as "scale"). They also make Function word substitution errors (reads "her" as "she"), and morphological errors in which a prefix or suffix is added, deleted, or substituted. Another distinctive feature of deep dyslexia is that nouns are read more reliably than adjectives, adverbs, which in turn, are read more accurately than verbs (Coslett & Turkeltaub, 2016).

Phonological dyslexia is typically associated with impairments in basic language components, such as phonology and semantics. It resembles deep dyslexia in many aspects with one exception; these individuals show signs of semantic paralexia (read "sea" as "lake"). It is associated with disturbed direct activation of phonology from orthography and impaired activation of sound from print via meaning (Lambon Ralph & Graham, 2000). A critical feature of phonological dyslexia is the presence of a lexicality effect on reading accuracy. This occurs when words are read more efficiently than non-words. Friedman (1996), however, argues that deep and phonological dyslexia are two ends of a continuum. Presumably, deep dyslexia falls at one end of this hypothetical continuum. "Pure" phonological dyslexia with impoverished performance for non-words as the only reading deficit at the other end (p. 641). Nevertheless, while the primary symptom for both dyslexias include poor performance in reading non-words, the dominant feature in phonological dyslexia is the presence of a lexicality effect on reading accuracy (word > non-word) (Coltheart & Ulicheva, 2018). Lambon Ralph and Graham (2000) argue that phonological and deep dyslexias occur in the context of non-fluent aphasia following damage to the fronto-temporo-parietal regions of the left hemisphere (p. 142) and suggest that such a lesion is linked to both deep and phonological dyslexias, though, in deep dyslexia the lesion is more extensive and affects the presylvanian areas and often may include much of the left hemisphere.

In their seminal work, Marshall and Newcombe (1973) included acquired deep dyslexia and acquired surface dyslexia in the classification of reading disorders observed in previously literate patients after a brain injury. Later, a new type; "*visual dyslexia*," was also added to the category. *Visual dyslexia* could be identified by "visual confusions" (e.g., reading "dug" as "bug," or "war" as "raw") that could be accompanied by frequency-effect in reading accuracy where common words being read more accurately than rarer words—Regular word > Exception words (Lambon Ralph & Ellis, 1997). This pattern of errors has been identified in surface dyslexia.

Although there are empirical grounds to distinguish the different reading disorders, little is known about their rates of occurrence, the expected trajectory for natural recovery, and their relationship to other cognitive processes including other aspects of language, attention, and executive function. Few large-scale population studies have been conducted into the incidence, longer-term outcome, and cognitive correlates of different dyslexia after brain lesion (though see Ptak et al., 2012, for an exception for neglect dyslexia). The study focuses on acquired reading disorders following stroke in a population of patients who underwent screening on the BCoS battery (Bickerton et al., 2015). The BCoS provides a comprehensive screen of neurocognitive abilities in brain injured adults and covers five primary domains: (i) language (written and spoken), (ii) attention and executive functions, (iii) memory, (iv) praxis, and (v) number processing. The screening battery is designed to be aphasia- and neglect-friendly so that test should be minimally influenced by these common sequelae of brain injury when the tasks are not meant to measure language or spatial attention. By providing a broad analysis of different cognitive abilities, the BCoS battery assesses each specific set of impairments (e.g., reading impairments here) in relation to other potentially important contributory factors, such as the presence of executive and spatial attentional biases or poor phonological word production. For example, several reading disorders have been linked to attentional impairments in patients (e.g., alexia: Behrmann et al., 1998; Caramazza & Hillis, 1990; neglect-dyslexia: Riddoch et al., 1990; and phonological dyslexia: Baylis et al., 1994; Hall et al., 2001; Lambon Ralph & Graham, 2000). The tests of reading used here require patients to read aloud two short sentences containing Regular words, Function words, Exception words, and to read a set of non-words. The use of different word classes and forms enables the examiners to identify the different types of reading impairments (see below methods for details), to inform targeted rehabilitation. Along with assessment of other cognitive domains measured through the battery, the study could evaluate whether the magnitude of each reading impairment in a large patient sample does relate to other problems, such as selective and spatial attention, memory, etc.

The study is sub-divided into three segments; each designed to address one of the study's objectives. The study analyzed the incidence of different forms of acquired reading impairment and their relation to the laterality of the impairment (left or right hemisphere damage) in a large group of stroke patients—though without focusing on the specific lesion itself. It examined their performance on the reading tests in relation to other language functions as well as important neurocognitive abilities. The final segment explores extent and trajectory of recovery for the different dyslexic profiles when performance is measured after nine months post-lesion to differentiate recovery profiles for contrasting forms of impairment and examine whether there is a common recovery pattern determined by, for example, the hemispheric location of a deficit in the first instance and/or the presence of other ancillary impairments?

Part 1: Assessing sub-classes of reading impairment

Material and procedure

The reading tests from the BCoS

The BCoS battery has two reading tasks: the Sentence reading and the Non-word reading task. The Sentence reading task is one of three subtests within the language specific domain of the battery (see Appendix A for an illustration of the BCoS domains). It provides a straight forwards bedside assessment tool to clinically examine the nature and extent of the language impairment in stroke survivors. The Sentence reading task was composed of two sentences. The subject was asked to read each sentence aloud and as quickly as s/he could. The first sentence contained fourteen words, printed on three lines and the second sentence contained twenty-eight words divided into five lines. Of these 42 words, there were seven exception nouns/verbs (with irregular spelling-sound correspondences and word frequencies of >1577/million based on the British National Corpus's word frequency rank; http://www.natcorp.ox.ac.uk/corpus/index.xml); fourteen regular nouns/verbs (with regular spelling-sound correspondences and frequencies of >3029/million). All the remaining words were either prepositions, conjunctions, or definite articles (Function words with frequencies of >4120/million). Another aspect of the word category was how easily that word could be translated into a concrete image. The higher the imageability, the more quickly and accurately the word could be recognized (e.g., Paivio, 1971, 1986; Swaab et al., 2002). Based on available databases (e.g., Gilhooly & Logie, 1980) and the MRC Psycholinguistic Database (Coltheart, 1981) the average imageability value (standardized) for the Function words was 2.6, for the Regular words it was 4.4, and for the Exception words it was 5.2. The average word length for the Regular words was 5.28 letters, for the Function words it was 3.18, and for the Exception words, it was 7.57. In addition, all participants completed a non-word reading task that comprised of six pronounceable non-words (three five-letter long and three six-letter long) non-words.

The reading time and reading errors were recorded (reading times were recorded by stopwatch for the reading of the whole passage and for the reading of all the non-words, respectively). Each word/non-word that was read correctly was credited a one-score point. The maximum accuracy score for the Sentence reading was 42 and it was 6 for the non-word reading task. There was no time limit for completing the tasks, but the time was recorded, nevertheless.

The reading text was "neglect-friendly" as it was printed center-aligned around an imaginary vertical midline on the paper with few words per line. Similarly, the non-words were printed in the center of the page.

In this initial part of the study, reading tests were used on a large cohort of stroke survivors in their early stage of recovery (>100 days since stroke), to assess inter-rater reliability, and the effects of lesion-side and sex on reading performance.

Brain damaged participant

A group of 731 stroke-survivors (407 males, 324 females) participated in the study, who were recruited through the project across 15 different National Health Service (NHS) hospitals. The Mean age (*SD*) of the participants was 69.7 (13.77) with a range between 18 and 95 years, and the Mean (*SD*) for "years in education" was 11.23 (2.8) with a range between 4 and 25 years. All participants were tested within 100 days post-stroke; Mean (SD) = 24.7 (21.44) with a range between 1 and 99. Seventy participants were left-handed, 631 right-handed, 12 ambidextrous and for 18 participants no data on handedness had been collected at the time of screen. Sixty-three participants were not able to complete the Sentence reading task for various reasons.[1]

According to the participants' clinical notes and/or analysis of hospital CT/MRI scans for those who completed the task (668 participants), 197 participants showed signs of left hemisphere (LH) lesion, 253 showed signs of right hemisphere (RH) lesion, 63 participants showed signs of bilateral lesions and for 155 participants, no data were gathered. The administration of the battery was carried out by trained examiners in a quiet area, all following the same standard instructions for testing and scoring.

Healthy age-matched controls

For the reading task, 98 healthy controls (43 females) with no history of neurological disease participated. Their Mean age (*SD*) was 70.8 (11.94), with an age range between 22 and 94 years, and their Mean (*SD*) "years in education" was 10.9 (2.5) with a range between 6 and 19 years. All controls were recruited through personal contact (e.g., relatives of brain-injured participants) and poster advertisement on public notice boards around areas of recruitment. Fifteen participants were left-handed. The performance of the brain-injured participants was regarded as impaired if the scores deviated by 2*SD* or more from the control means (the different cutoff scores for different subtests of BCoS can be found in Bickerton et al. (2015) and Humphreys et al. (2012).

Procedures

Written informed consent was obtained from all participants. For the patients, the UK National Institute of Health Research's (NIHR) recommendations for Good Clinical Practice (GCP) were adhered to. For the control participants, a formal approval for the study was obtained from the University's and the NHS Ethics Committees. All patient-testing took place in hospital, either at bedside or in a room on the ward. All control testing was carried out at the university.

The BCoS Sentence- and Non-word reading tests were used. Alongside the overall measures of reading accuracy and speed, individual scores for each category of words (Exception, Function, and Regular) were retrieved and analyzed. To identify any bias due to visuo-spatial impairment, the total scores for left and right side of the page were scored and analyzed separately (page-neglect).

Throughout this report, unless reported otherwise, the necessary statistical assumptions for every test are met. Where appropriate and necessary, all analyses controlled for participants' education (years in school) and age.

Results

Inter-rater reliability of the sentence reading test

Because all patient data in the study were collected and initially scored by a team of trained examiners at different hospitals, to evaluate the consistency of the initial scoring, two blinded independent judges were asked to carry out a re-scoring of Sentence reading subtest for a sample of 38 anonymized patients. The sample was randomly selected from the database and copies of the scoring sheets were given to the judges for scoring. Both judges were familiar with the scoring procedures and received the same written instructions. High correlations were found between the scores for all aspects of the task indicating satisfactory consistency in the initial scoring of the Sentence reading task. The correlations between different ratings were as follows: between the total scores $r = .99$; between the scores for Regular words and for Function words $r = .99$ and for Exception words $r = 1.0$ (all $p < .001$).

Examination of different reading profiles

There were three types of words presented in the Sentence reading task: Exception (seven words), Regular (14 words), and Function words (21 words). The raw patients-data were analyzed in more detail to isolate the performance across different word-types as well as for the non-words (accuracy & speed). Each individual's raw error score (number of errors on each word type) was converted into a percentage of the total possible errors for each word type. The presence of spatial errors in reading (e.g., lateralized omissions) was also investigated.

Overall reading accuracy and speed

Six hundred and sixty-eight patients completed the Sentence reading task. The reading time data for the patients were as follows: Mean (SD) = 35.26 (42), (ranging between 10.03 and 594 s). The Mean (*SD*) number of accurately read words was =36.65 (10.39) (ranging between 0 and 42). For the controls, the Mean (*SD*) of reading time was 16.64 (7.14) s (with a range between 10.54 and 79.12 s) and the Mean (*SD*) of accuracy score (for reading words) was 41.74 (0.84) (with a range between 35 and 42). Just over half the patients (50.8%) had accuracy scores above the age-appropriate cutoff norms. Reading times for 49.7% of the patients were above their age-appropriate cutoff norm. These norms are available in Humphreys et al. (2012).

[1]The reasons for not completing the task were: refusal, aphasia, visuo-spatial difficulties, physical discomfort/fatigue, confusion, or other external factors beyond the control of the experimenter, such as relatives visiting.

Table 1. Categorization of patients according to whether their performance was impaired (fell inside or outside the control norms) in each type of word, and for each lesion group.

Left hemisphere				Right hemisphere			
Exception	Function	Regular	Frequency	Exception	Function	Regular	Frequency
Intact	Intact	Intact	63	Intact	Intact	Intact	115
Intact	Intact	Impaired	9	Intact	Intact	Impaired	7
Intact	Impaired	Intact	7	Intact	Impaired	Intact	20
Intact	Impaired	Impaired	4	Intact	Impaired	Impaired	20
Impaired	Intact	Intact	25	Impaired	Intact	Intact	21
Impaired	Intact	Impaired	20	Impaired	Intact	Impaired	10
Impaired	Impaired	Intact	8	Impaired	Impaired	Intact	8
Impaired	Impaired	Impaired	61	Impaired	Impaired	Impaired	52
Total			197	Total			253

The effect of lesion site, sex on reading different word types

The Sentence reading accuracy and speed data for 450 patients with confirmed LH or RH lesions were categorized according to whether their scores fell below or above the cutoff score for the controls. These results were entered into a loglinear analysis with the factors patient's sex and lesion site (LH, RH). The analysis showed significant main effects of lesion site; χ^2 (1) = 5.13, $p < .023$, showing better overall reading accuracy for the patients with right side lesions. There was no significant effect of sex and no significant interaction. Neither was there any significant effect for reading speed (all factors, $p > .10$).

Two separate loglinear analyses were conducted on the data for the accuracy and speed of non-word reading with the factors of sex and lesion site. Analysis of the accuracy showed a significant effect of lesion location on non-word reading accuracy; χ^2 (1) = 11.52, $p < 0.001$. There was no effect of sex, and the interaction was not reliable. Overall, there was better performance for the patients with an RH lesion than for those with LH. The analysis of reading speed did not show any significant effect ($p > .10$).

To investigate the effects of lesion site and sex on reading of different word types, a repeated measures ANOVA on the error data for each word type was conducted with the factors being word type, lesion site, and sex. There were reliable effects of lesion [$F(1, 446) = 15.51$, $p < .001$; ${\eta_p}^2 = .034$]; of word type [$F(2, 892) = 31.71$, $p < .001$; ${\eta_p}^2 = .066$]; and an interaction between word type and lesion location [$F(2, 892) = 23.4$, $p < .001$, ${\eta_p}^2 = .050$]. There was neither any reliable effect of sex nor any significant interactions involving this factor. Two similar ANOVAs, but this time by excluding sex as a factor, for each lesion group showed that the reading performance in both groups varied as a function of word type; for the LH group [$F(2, 392) = 45.5$, $p < .001$ ${\eta_p}^2 = .188$]; and for the RH group [$F(2, 504) = 6.9$, $p < .003$, ${\eta_p}^2 = .027$]. Figure 1A illustrates the results.

For the LH patients, performance was better on Function words than for Regular words ($t = 6.32$, $p < .001$), and better on Regular words than on Exception words ($t = 4.28$, $p < .001$), respectively. For the RH patients, the performance was equal on Function and Exception words ($p > .05$) but performance on Regular words was lower compared with both Function words ($t = 4.34$, $p < .001$), and Exception words ($t = -2.62$, $p < .05$).

Next, the nature of patients' performance on different word types were assessed by categorizing patients according to whether their performance was spared or impaired on each word type, relative to the controls. If the performance was inside the control norms (see Humphreys et al., 2012), it was labeled as "Intact," and if it was below the norms, it was labeled as labeled as "Impaired." Table 1 shows the frequencies of errors for each group of patients separately.

In the LH group, more patients performed within control levels on Function words than on Regular and Exception words [χ^2 (1) = 4.45, $p < 0.05$ and 20.64, $p < 0.001$]; and more patients performed better at Regular than Exception words [χ^2 (1) = 8.69, $p < 0.01$]. In contrast, among the RH group, more patients performed at control levels with Exception words than with Function words [χ^2 (1) = 5.92, $p < 0.05$]; and there was also a tendency for Regular words to be read more accurately than Function words [χ^2 (1) = 2.69, $p = 0.06$]. There were no differences in the number of patients who performed normally on Regular words while being impaired on Exception words, or vice versa ($\chi^2 < 1.0$). These error patterns showed a slight disadvantage for the LH patients being affected by the frequency of the words (errors in Exception > Regular > Function).

Non-word reading performance

Two independent sample *t*-tests found that LH group were more accurate and quicker in reading non-words than the RH group [for accuracy t (427) = 5.43, $p < .001$; and for reading time; $t(427)3.19$, $p < .002$].

Discussion

In conclusion, data in part one on the rate of incidence of different error types indicate that reading impairments are relatively prevalent in the current sample of stroke survivors, occurring in 61% of the patients. Perhaps not surprisingly, patients with LH lesions fared worse (68%) than patients with RH lesions, though even with the RH group a substantial proportion fell outside the overall control range (54.5%). On the whole, Exception word errors had higher frequencies of occurrence than Regular words, and these in turn were more frequent than Function words (Exception > Regular > Function). The overall pattern also seemed to reflect the effect of the lesion on the general error frequency of words for LH patients. This group of patients had more errors in reading the Exception words, followed by Regular and Function words (errors in Exception > Regular > Function), indicating deficits seen in surface dyslexia. the RH group showed a different pattern indicating that the proportion of patients failing on the Regular words was higher than for the Exception and Function words but the latter two showed equal rates of error (errors in Regular > Exception = Function). In addition, it was shown that the RH patients fared worse in reading non-words compared with LH group. This finding corroborates previous finding by Weekes et al. (1997). Individuals with phonological dyslexia show this specific pattern of deficit where non-word reading is selectively impaired relative to word reading (Coltheart, 1996; Dérouesné & Beauvois, 1979).

Another element of reading deficit may concern the word length effect. Patients with pure alexia for instance are affected by word length effect so that the reading time for each word increases as a factor of the number of letters in each word. In the Sentence reading task, there were 14 Regular words with an average word length of 5.28 letters, there were 21 Function words with an average of 3.18 letters, and seven Exception words with an average of 7.57 letters. Poorer performances were found with Exception words, which happen to be longer words. Therefore, a note of caution here would be that the observed poorer performance might reflect a contribution of word length effect in addition to the words being irregular and uncommon. To account for each separate effect, recording performance on word-level was required.

In Part two, data were reported that link the problems patients may have on the Sentence reading task with problems in other cognitive domains detected on other components of BCoS.[2] Are the reading problems systematically linked to deficits in particular aspects of attention, to executive functions, and/or to other language processes (e.g., problems in name production, detected through Picture Naming)?

Part 2: Relation between reading and other cognitive functions

In this part of the study, first, the relations between the overall Language domain and other domains assessed by the BCoS battery were investigated. Next, the associations between the subtests Sentence reading and Non-word reading were examined against other domains by using a hierarchical regression analysis method.

Results

The relation between sentence reading and other language subtests

The relation between Sentence reading scores and the Language domain (all language related subtests when the Sentence reading task is excluded) was examined by conducting two separate stepwise linear regression analyses; one for each lesion group. The language subtests that were included in this analysis were sentence construction, Picture Naming, Non-word reading, Word and Non-word writing, Number reading, and Number writing. The final model for the LH group revealed significant predictive values for the following subtests: Number reading, Picture Naming, Non-word reading, and sentence construction [adjusted $R^2 = .443$, $F(4,\ 171) = 56.74$, $p < .001$]. The final model for the RH group indicated the same subtests as above bar Picture Naming [adjusted $R^2 = .336$, $F(3,\ 232) = 70.15$, $p < .001$].

The relation between sentence reading and other cognitive domains in BCoS

Here, the accuracy and speed data from Sentence reading task were pitted against the overall scores from all cognitive domains. The analyses showed the following.

Accuracy of reading. For both hemisphere groups, significant and high correlation was found between reading accuracy with the domains: Language (excluding Sentence reading), Numbers, Praxis, Memory, Spatial bias, and Controlled attention.

Speed of reading. Here, there were some differences between lesion groups. For the RH group, the variables Language (excluding Sentence reading), Numbers, Praxis, Memory, Spatial bias, and Controlled attention correlated with Sentence reading speed. For the LH group, only variables Numbers, Memory, and Spatial bias correlated with reading speed, but not Praxis and Controlled attention.

For the domain-level tests, the number of subtests within the domain that each patient was impaired on were summed together and the new composite score was used for correlations with the reading task. The Spatial bias scores were based on the patients' scores on (i) canceling targets on a page, and (ii) detecting distractors with a gap on one side, when compared with controls.

All domain-level correlations were significant bar those between Sentence reading speed and the Praxis, and between Sentence reading speed and Controlled attention scores, but only for LH patients. Patients who fared worse at reading tended also to fare worse at other cognitive tasks.

Two separate stepwise regression analyses were also conducted on the relation between the reading task performance and all other cognitive domains, one analysis for each lesion group. For both groups domains Language, Spatial attention and Number processing were entered into the final model that showed: for the LH group the adjusted $R^2 = .494$, with $F(6{,}196) = 32.89$, $p < .001$ and for the RH group the adjusted $R^2 = .424$, with $F(6{,}252) = 30.13$, $p < .001$. For the RH group, the Language, Spatial bias, and Number processing domains were all reliable predictors for their performance in Sentence reading task. For the LH group only, the Language and Numbers were reliable predictor but not Spatial bias.

[2]Descriptions of the BCoS tests are provided in the Appendix A.

Overall relation between reading tasks with other BCoS measures

In a similar fashion to the above, the reading data for non-words were correlated with the BCoS domain scores (using Bonferroni adjustments for multiple comparisons). As for the Sentence reading data, the correlations with the other language tests accounted for most of the variance. For non-words, however, the correlation between reading accuracy and the measure of Spatial attention was weak and only reliable for LH patients.

Finally, two separate stepwise regression analyses were conducted on the relation between the non-word reading performance and the other cognitive domains measured by the test battery, one for each lesion group. For both groups, domains Language and Number processing and Spatial attention were entered into the final model. For the LH group the performance in the domains Language and Numbers were reliable predictors of performance in non-word reading, but not the domain Spatial bias [adjusted $R^2 = .637$, with $F(6, 190) = 58.26$, $p < .001$]. For the RH group, only the domain Language could predict non-word performance, but not the domains Numbers and Spatial bias [adjusted $R^2 = .488$, with $F(6, 246) = 40.01$, $p < .001$].

Relation between aspects of reading and other cognitive domains

Finer-grained analyses assessed the relations between the cognitive domains measured using the full test battery and accuracy on certain types of word (i.e., Exception, Function, and Regular words). Here, the percentages of correctly read words, for each class of word were correlated with the other cognitive domains. The levels of significance for correlation coefficients were adjusted for multiple comparisons by Bonferroni's correction. The correlation index revealed significant correlations on at least .01 level between all the three types and the cognitive domains Numbers, Praxis, Memory, Spatial attention, and Controlled attention. The only exception was for the RH group who did not show significant correlation between Spatial attention and the Exception word accuracy.

Performance on each word type was correlated with each domain-level measure in the battery (except for the Spatial bias measure for RH patients). As before, stepwise regression analyses were conducted on the relation between each word type and other cognitive domains for each lesion group. On the Exception words, for the LH group, the model included all the domains [adjusted $R^2 = .532$, $F(6, 190) = 38.12$, $p < .001$]. As shown in Table 2, the significant predictor variables were Language, Number processing, and Spatial attention. For the RH group, only Language and Number processing were included in the model [adjusted $R^2 = .366$, $F(2, 250) = 74.95$, $p < .001$]. On the Function words, similar regression analysis showed that performance of the LH group on reading of Function words is related to Language and Spatial attention domains [adjusted $R^2 = .383$, $F(194) = 80.2$, $p < .001$] but other domains were not entered in the model. For the RH group, the model included all the cognitive domains [adjusted $R^2 = .360$, $F(6, 246) = 24.61$, $p < .001$], but not all of them were significantly related. In the Regular word, the model for the LH group entered Language, Spatial attention, and Number processing into the analysis [adjusted $R^2 = .426$, $F(3, 193) = 59.22$, $p < .001$]. For the RH group, the model entered all the domains but only the Language and Number processing domains were significant predictors of performance on Regular words [adjusted $R^2 = .425$, $F(6, 246) = 31.75$, $p < .001$].

To the extent that the reading of Exception words is dependent on perceiving each word as a single "unit," it can be argued that Exception words (more than Regular words and Function words) might be more dependent on Spatial attention. There was no evidence for this however and, if anything, Exception words showed a weaker correlation with the measures of Spatial attention than Function words.

Lateral asymmetry in errors and relation between reading and spatial attention

Patients with visuo-spatial impairment tend to miss stimuli presented on their contralesional side. To investigate the

Table 2. Relation between word type and other cognitive domains in BCoS, shown as predictor variables for each word type and for each lesion group.

		Left hemisphere		Right hemisphere	
	Predictor variable	Beta	*p*-value	Beta	*p*-value
Exception	Language	**−0.508**	**0.001**	**−0.522**	**0.001**
	Numbers	**−0.178**	**0.037**	**−0.13**	**0.05**
	Praxis	0.035	0.577	N/E	N/E
	Memory	0.027	0.706	N/E	N/E
	Spatial attention	**−0.248**	**0.001**	N/E	N/E
	Controlled attention-WM	0.021	0.746	N/E	N/E
Function	Language	**−0.521**	**0.001**	**−0.463**	**0.001**
	Numbers	N/E	N/E	−0.133	0.094
	Praxis	N/E	N/E	−0.04	0.521
	Memory	N/E	N/E	−0.054	0.423
	Spatial attention	**−0.276**	**0.001**	−0.108	0.058
	Controlled attention-WM	N/E	N/E	0.096	0.153
Regular	Language	**−0.447**	**0.001**	**−0.434**	**0.001**
	Numbers	N/E	N/E	**−0.264**	**0.001**
	Praxis	N/E	N/E	0.018	0.768
	Memory	N/E	N/E	−0.097	0.13
	Spatial attention	−0.193	0.01	−0.075	0.167
	Controlled attention-WM	**−0.178**	**0.035**	0.123	0.054

N/E: some variables were not entered into the model. Not all entered variables were significant though. All correlations are Bonferroni adjusted.

Spatial bias in the distribution of error responses across the visual fields, the accuracy data from each side of the page were entered into an analysis. A repeated measures ANOVA on the percentage of errors made on the left and right side of page was conducted with the factors being visual field (errors on the left or right side of the page) and lesion site. There were reliable effects of visual field [$F(1, 448) = 5.49$, $p < .02$, $\eta_p^2 = .012$], showing slightly more errors made on the left visual field (for the left visual filed = 15.42 *vs.* 14.15% for the right visual field), and lesion site [$F(1, 448) = 9.69$, $p < .002$, $\eta_p^2 = .021$], showing an overall better performance for the RH group (RH = 10.92 *vs.* 18.64% for the LH group). Also, these two factors interacted [$F(1, 448) = 20.04$, $p < .001$, $\eta_p^2 = .043$]. Further *t*-tests showed that, as expected, the LH group had most of their errors when the words appeared on the right visual field [$t(196) = 2.1$, $p < .036$], while the RH group had most errors on the left visual field; $t(296) = 4.24$, $p < .001$. The cross-over interaction indicated that spatial errors in reading reversed according to which hemisphere was damaged. Figure 1B shows the spatial error distribution data.

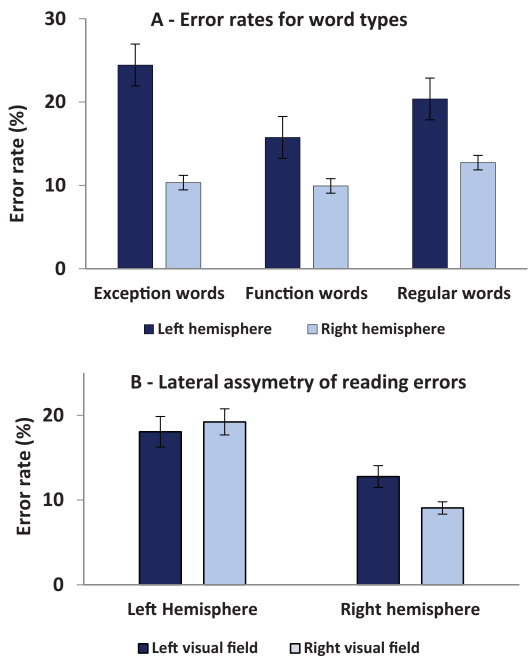

Figure 1. (A) Standardized average error rate (% of total maximum possible error) for each word category as a function of lesion site illustrated separately for LH or RH group; (B) Lateral asymmetry of errors—Percentage of errors as a function of the side of page and lesion site.

In the next step, the relations between Spatial attention data and spatial errors in the Sentence reading data were assessed by calculating the page-based errors (the absolute differences between left- and right-side errors) in the Sentence reading task and correlating these differences with all other measures in the BCoS. For both lesion groups, there were significant correlations on at least .01 level between reading asymmetry and Language, Numbers, and Praxis, respectively, but only patients with RH lesion showed significant correlation with the measure related to Spatial bias.

Finally, the relation between the reading asymmetry and all other cognitive domains which have shown significant correlations with the reading task (i.e., Language, Numbers, Praxis, and Spatial bias) were investigated, on a subtest level. Table 3 shows the data. The analyses revealed fine-grained differences between the two lesion groups. The LH group showed strong correlations with subtests measuring Language and Number processing while the RH group showed stronger correlations with subtests related to visuo-spatial construction and detection skills.

Discussion

In part 2, the relations between the Sentence reading task and performance on other cognitive domains assessed by the screening battery were examined. There were reliable correlations between Sentence reading and all other cognitive domains, with performance on the language sub-tests (not including the Sentence reading) accounting for all the variance, and variations in other domains failing to add to the account of performance. Thus, there were no grounds here to argue that reading was affected by problems in

Table 3. The correlations between reading asymmetry of the related cognitive domains measured with the BCoS.

Domain	Subtest	Left hemisphere	Right hemisphere
Language	Picture naming	−0.152	−0.118
	Sentence construction	−0.098	**−.198***
	Non-word reading	**−.431***	**−.200***
	Word/non-word writing	**−.370***	−0.14
Praxis	Figure copy	**−.187***	**−.401***
	Multiple object use	−0.13	**−.174***
	Gesture production	−0.096	−0.016
	Gesture recognition	**−.217***	−0.05
	Gesture imitation	−0.094	**−.207***
Numbers	Number reading	**−.345***	**−.306***
	Number writing	**−.365***	−0.099
	Calculation	**−.329***	−0.11
Spatial bias	Asymmetries in egocentric visual attention	**0.188***	**.478***
	Asymmetries in allocentric visual attention	.041	**.328***
	Visual unilateral detection	−0.159	**−.554***
	Visual extinction	−0.125	**−.426***
	Tactile unilateral detection	−0.002	−0.081
	Tactile extinction	−0.075	**−.289***

*Correlation is significant at the 0.01 level (two-tailed). All correlations are Bonferroni adjusted.

Memory, Attention, measures of Gesture recognition and Gesture production, and even Number processing over and above the problems in language. The exception to this was in terms of the spatial errors made in reading, which did relate to the presence of visual spatial biases in the patients.

The nature of errors made by the patients in this study is, therefore, consistent with the notion of spatial bias having a general impact on the patient's ability to scan across the page. Both LH and RH groups showed a significant correlation with the egocentric or page-based neglect measures, but only the RH group showed a significant correlation with the allocentric or word-based neglect measures. Interestingly, some differences in the relations between spatial reading errors and more general spatial biases emerged for LH and RH patients. Notably, for RH there were relations between tactile extinction and Sentence reading but this did not hold for LH patients. Chechlacz et al. (2010) have shown that damage to the right temporo-parietal junction (TPJ) is associated with tactile extinction and is also associated with spatial impairments in other modalities (visual extinction, also neglect—Chechlacz et al., 2010). This is consistent with the right TPJ playing a critical supramodal role in allocating spatial attention to stimuli. Here, it can be suggested that such supramodal processes would impact on reading too, so that patients fare less well when words are presented on the left (contralesional) side of the page.

Part 3: Recovery of reading skills: a 9-month follow-up

In part 3, the recovery of reading when patients were re-tested after 9 months was evaluated. Early research using PET-scans of adults with post-stroke aphasia after LH stroke have demonstrated right-sided activation of language processing (Weiller et al., 1995) indicating the presence of some form of plasticity of language function (Holland et al., 1996). On the other hand, other researchers argue that recovery operates through the re-enervation of regions of the LH in the penumbra of the stroke (see also Fink et al., 1997; Price & Crinion, 2005). The natural profile of recovery of reading following stroke has not been evaluated hitherto. For example, is there an improvement in aspects of lexical reading (affecting Exception words) or phonological aspects (e.g., affecting non-words)? How do improvements in reading relate to either the type of words, to the initial cognitive profile of the patient, or to the changes in other cognitive processes (e.g., overall language recovery)? To assess these issues, the reading data for these patients nine months post-lesion were compared with their cognitive profile derived from their initial screening.

Participants

All the patients who had participated in part 1 and had agreed to be contacted for a follow-up testing were contacted by letter or telephone nine months after their brain lesion. Six hundred and thirty-four patients were contacted. More than a quarter (26.5%) of these patients could not be reached (moved out of area, not responding to the research team's letter/calls, changed address/telephone number), 6.9% had passed away, 14.4% declined a follow-up screen and 3.1% were too ill to participate or were hospitalized at the time of re-screen. Three hundred and sixteen patients completed the follow-up testing (133 females; mean age = 71.6 and 183 males; mean age = 67.7). Ninety-seven patients had confirmed LH lesion, 128 patients had RH lesion, 40 had bilateral lesions and 51 patients had no CT or MRI results to confirm the location of their lesion. The mean days passed since the initial testing was 311 days, meaning that the mean actual time passed since the initial testing was in effect around 10 months.

For the analyses, only data from patients with confirmed unilateral LH ($n = 80$) or RH ($n = 120$) lesions were used to evaluate the effects of the laterality of the lesion. Less than one-sixth of these patients had received speech and language therapy intervention.

Results

Sentence reading accuracy

A repeated measures ANOVA with the factors test occasion (initial-follow up) and lesion site on Sentence reading scores revealed significant main effects of testing occasion [$F(1, 197) = 32.52$, $p < .001$, $\eta_p^2 = .142$], showing an average of 6.29% improvement in reading accuracy for all groups after nine months; and lesion site [$F(1, 197) = 4.97$, $p < .03$, $\eta_p^2 = .025$], showing a relative overall advantage in performance of 5.3% for the LH group. The interaction between these factors was not significant ($p > .05$). Figure 2A depicts

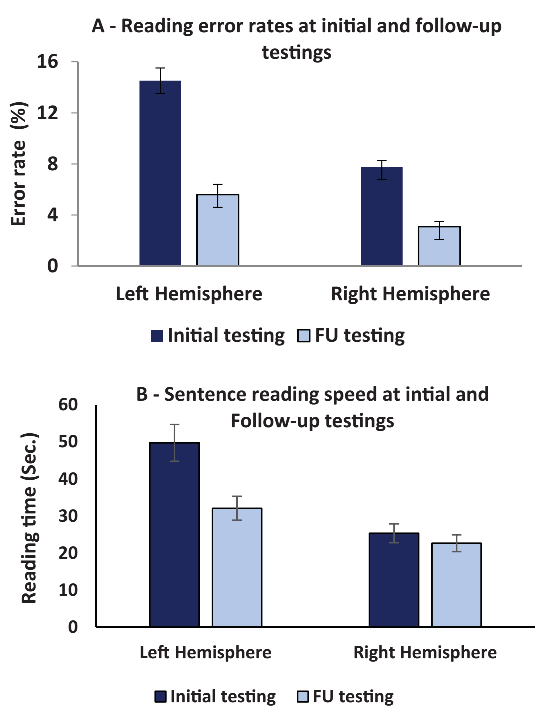

Figure 2. (A) Sentence reading error data at the initial and at follow-up testing (9 months post-stroke); (B) Reading speed data at the initial and after 9 months, illustrated separately for LH and RH group.

the error distribution data for the Sentence reading task for both testing occasions.

Sentence reading speed

The ANOVA on Sentence reading speed showed a significant main effect of testing occasion [$F(1, 197) = 10.48$, $p < .002$, $\eta_p^2 = .049$], showing an average of 10.1 s speedier reading at the follow-up occasion compared with the initial testing across both groups of patients. This equals 27% improvement after nine months across groups. There was a significant effect of lesion site [$F(1, 197) = 9.8$, $p < .002$, $\eta_p^2 = .048$], showing an average of 16.9 s in favor of the RH group, which is 41% speedier reading by the RH patients after nine months, compared with LH patients. interaction between test occasion and lesion site was also significant [$F(1, 197) = 5.32$, $p < .01$, $\eta_p^2 = .026$]. Further, paired sample *t*-tests investigated the nature of the improvement across test occasions. At the initial testing occasions, both patient groups showed significant impairment in Sentence reading speed. The gap in reading speed between the groups at the initial testing occasion was 23.7 s ($p < .002$), but this gap shrunk to 9.4 s ($p < .016$) at the follow-up testing. Compared to their individual initial performance, the LH group showed a significant speed gain across occasions (17.1 s, $p < .001$), while the RH group showed a non-significant speed gain of 2.67 s, $p > .05$). Figure 2B depicts the reading speed for both testing occasions.

Word-based reading improvement after 9 months

The accuracy of reading for each word type across the two testing occasions were compared. A repeated measure ANOVA with the factors testing occasion, word type, and lesion site showed significant main effects of testing occasion [$F(1, 196) = 30.3$, $p < .001$, $\eta_p^2 = .133$], showing an overall average in improvement of 6.64% across testing occasions; and of lesion site [$F(1, 196) = 9.75$, $p < .002$, $\eta_p^2 = .047$], showing a 6.95% advantage in improvement for the LH group compared with the RH group; and of word type [$F(2, 392) = 28.22$, $p < .001$, $\eta_p^2 = .125$], showing an average improvement across occasions of 7.3% for the Function words, 4.16% for Exception words and 6.29% for Regular words. There were significant two-way interactions between test occasion and lesion [$F(1, 196) = 5.49$, $p < .02$, $\eta_p^2 = .027$]; between test occasion and word type [$F(2, 392) = 5.4$, $p < .006$, $\eta_p^2 = .027$]; and between word type and lesion [$F(2, 392) = 16.64$, $p < .001$, $\eta_p^2 = .078$]. A three-way interaction was also observed between occasion, word type, and lesion; $F(2, 392) = 1.7$, but this interaction failed to reach the significance level ($p = .18$). Figure 3A depicts the rate of improvement in accuracy for each word type after nine months. The LH group shows stronger improvement than the RH group improvement in reading all three word-types. The RH group shows improvement only in Function and Regular words but not in Exception words. Two separate ANOVAs on the data from each hemisphere group, with the factors test occasion and word type, showed that for the LH group, there were significant main effects of test occasion [$F(1, 79) = 13.98$, $p < .001$, $\eta_p^2 = .150$] and word type [$F(2, 158) = 28.57$, $p < .001$, $\eta_p^2 = .266$]. The interaction between these two factors was not reliable ($F < 1.0$). For the RH group, there were reliable main effects of test occasion [$F(1, 119) = 14.04$, $p < .001$, $\eta_p^2 = .106$] and word type [$F(2, 238) = 4.69$, $p < .01$, $\eta_p^2 = .038$], and a reliable interaction between the two [$F(2, 238) = 10.86$, $p < .001$, $\eta_p^2 = .084$]. This interaction was decomposed by conducting pairwise *t*-tests on the improvement data for each word type which showed that the RH group made no reliable improvement in reading of Exception words after 9 months; $t(125) = 1.36$, $p = 0.17$. However, there was also some improvement in reading of Function words; $t(125) = 4.9$, $p < .001$ and Regular words; $t(125) = 4.0$, $p < 001$ for this group.

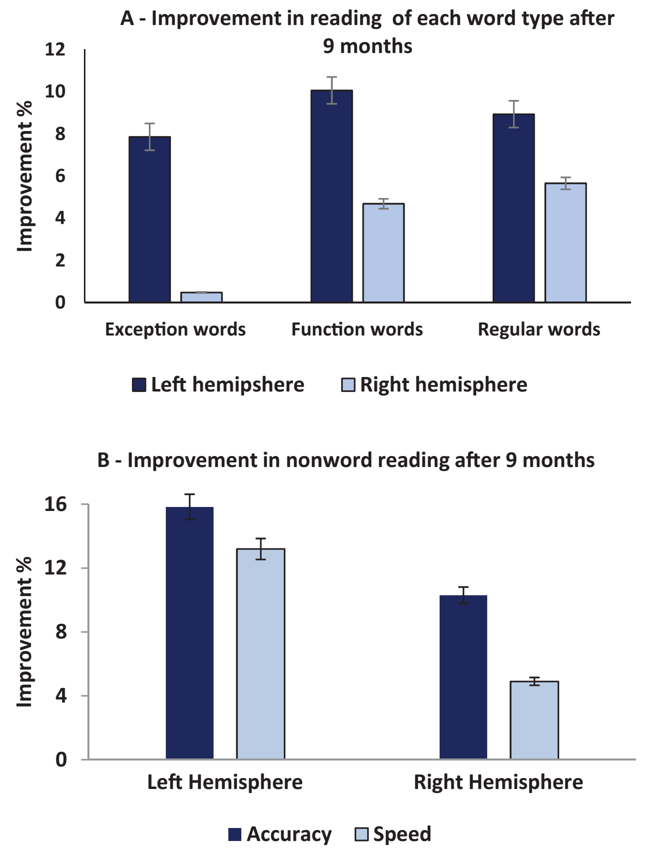

Figure 3. (A) Rate of improvement in accuracy for different word types after 9 months reported for each patient group; (B) Rate of Improvement (%) in accuracy and speed of non-word reading after 9 months reported separately for each lesion group.

Non-word reading accuracy

The reading accuracy for non-words across the two testing occasions were compared. The ANOVA with the factors test occasion and lesion site revealed a significant main effect of testing occasion [$F(1, 191) = 13.92$, $p = .001$, $\eta_p^2 = .068$] showing an overall improvement in non-word reading accuracy of 8% for all groups across testing occasions; and a significant main effect of lesion site [$F(1, 191) = 17.72$,

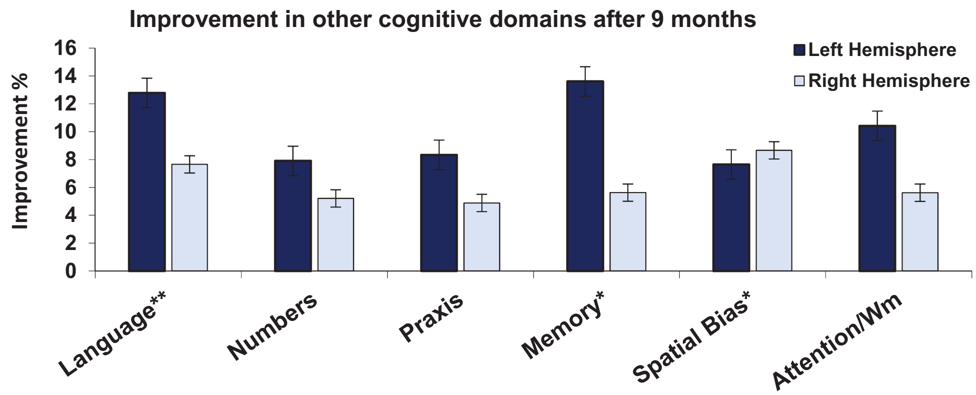

Figure 4. Standardized rates of improvement in other cognitive domains 9 months post-stroke for LH and RH patients when compared with their own baseline scores (** = .001, and * = .05 show the *p*-values for the difference between LH and RH group).

Table 4. Correlations between different cognitive domains and improvement in reading of sentences and non-words for LH and RH patients.

	Left hemisphere			Right hemisphere		
	Improvement %	Sentence reading	Non-word reading	Improvement %	Sentence reading	Non-word reading
Language (excl. reading)	10.93	**.364****	**.659****	5.16	**.294****	**.533****
Numbers	7.90	**.287****	**.318****	5.21	**.219***	**.253****
Praxis	8.33	0.25	−.162	4.88	.161	.067
Memory	13.61	**.256****	.220*	5.62	**0.226***	.026
Spatial bias	7.65	**.257***	0.12	8.66	−0.10	.168
Controlled Attention	10.42	**.291****	0.16	5.62	0.08	0.084
Average	9.8	–	–	5.87	–	–

* = .01; ** = .001 (two-tailed). All correlations are Bonferroni adjusted.

$p < .001$, $\eta_p^2 = .085$]. The RH group showed 13.5% advantage in overall performance, across occasions, over the LH group. However, this performance advantage could be attributed to the stronger baseline measurement for the RH group. There was no significant interaction between test occasion and task type ($p > .05$).

Non-word reading speed

The ANOVA on non-word reading speed showed no significant main effects of testing occasion ($p > .05$) but a significant main effect of lesion site [$F(1, 191) = 10.1$, $p < .002$, $\eta_p^2 = .051$]. The RH group needed shorter reading time than the LH group (12.7 *vs.* 18.9 s). Once again, this advantage seemed to be due to the LH group's poorer baseline performance at the initial testing. The interaction between these factors was not significant ($p > .05$). Figure 3B, shows the rates of improvement in accuracy and speed of Non-word reading in patients after nine months.

Improvement in language compared with improvement in other domains

The rates of overall improvement in different cognitive domains measured through the BCoS battery (Language, Memory, Praxis, Number processing, Spatial bias, and Controlled Attention) were calculated based on the number of sub-domain tests in which the patients showed improvement (i.e., receiving one score point when the performance in each domain goes from impaired at the initial testing to non-impaired at the follow-up testing and vice versa). Hence, the improvement was standardized for each domain. Figure 4 shows the data. In general, patients with LH lesions showed higher improvement rates in all domains bar in Spatial bias. This group showed also higher improvement scores in the domains Language and Memory compared with RH patients.

The correlations between the improvements in the cognitive domains and their improvements in Sentence reading and Non-word reading were calculated (see Table 4). For both LH and RH patients, there were significant positive correlations between the Sentence reading task and Language domain (not including Sentence reading and Non-word reading). Here, the improvement in Sentence reading was fully accounted for by the improvement in Language. For both patient groups, any improvement in sentence and Non-word reading was also fully accounted for by the improvement in the Number processing.

For LH patients, the Memory domain correlated with Sentence reading, but not Non-word reading. For the RH group, improvement in Spatial bias domain positively correlated with Non-word reading. Although all these domains showed improvement nine months post-stroke compared with the initial testing (especially for patients with LH lesion), the improvements in Sentence reading and Non-word reading were not fully accounted for by any improvement in the other domains—i.e., Praxis, and Controlled attention. Improvement in reading performance was partially accounted for by the improvement in the Memory domain (i.e., Sentence reading in LH patients) and Spatial bias (decrease in bias, at least for Non-word reading task in RH patients).

Discussion

Previous research suggests that most of language recovery seems to occur in the weeks following stroke, but residual recovery may occur over the duration of a patient's life, but prediction of level of recovery in an individual patient is rather difficult (Gerstenecker & Lazar, 2019). A multitude of factors can affect the accuracy of predicting the recovery outcome, which can create an inconsistency across patients (Price et al., 2010) that makes the prediction of recovery outcome highly individual and hard to accurately predict.

Jarso et al. (2013) argue that there are distinct mechanisms of recovery from aphasia after stroke with different time courses; and for brain reorganization (other brain areas compensating for the loss of function). Successful recovery depends not only on the time post-onset but also on the language task being used (and the level of performance of that language task).

Part 3 of this study showed that both the LH and RH patients improved their reading nine months after their lesion. The LH patients showed a greater rate of improvement in reading accuracy and speed when compared with the RH patients, but this also reflected the LH patients starting from a lower baseline. These improvement rates were most pronounced for Function words and Regular words compared with Exception words and especially pronounced for LH patients. A similar trend was discovered with regard to the improvement in Non-word reading in the LH group whose Non-word reading accuracy improved but not as strongly as for the Sentence reading. Reading speed improved for the LH group only.

The improvements in Sentence reading correlated with the improvements in certain cognitive domains (e.g., other Language tasks, Memory, Number processing for both groups, and Spatial bias for LH group only), but the gains in Non-word reading only correlated with Language domain and Number processing.

Alongside the improvement in reading specific types of word, there were also reduction in spatial errors in reading at nine months post-stroke. These reductions in spatial errors were fully accounted for by improvements in spatial attention in the patients, consistent with spatial attention being critical in generating the spatial reading errors.

It was reported here that at a follow-up testing the patients showed more improvement in the reading speed than in the accuracy of reading. Why is there a difference in recovery rate? The following two possibilities can be suggested.

i. Specificity of language skills measurements: It can be argued that measuring reading speed reflects an assessment of general efficiency in cognitive functions and in the sensorimotor system, while measuring accuracy rather reflects a more fine-grained assessment of specific reading skills. In view of that, it can be postulated that these patients showed more recovery in speed at the time of follow-up due to gained improvement in general efficiency systems, even in the absence of targeted rehabilitation. However, these patients did not improve equally well in specific language skills (e.g., reading skill), hence these patients were still making some reading errors at the follow-up measurement despite better reading speed.
ii. Speed–Accuracy tradeoff: this happens when the person spends more time on the task at hand in order to increase response accuracy (Wickelgren, 1977). Evans et al. (2019) examined the use of maladaptive speed–accuracy tradeoffs in people with aphasia during lexical decision. People with aphasia, for example, may act conservatively in their lexical decisions, leading to poorer performance that is below their achievement potential (i.e., longer RT, with no additional gain in accuracy). They can also act less conservatively and gain some speed but at the cost of diminished accuracy. It can be suggested that at the initial testing, which took place during the acute stage of the stroke (i.e., while in hospital settings and in a poorer general health and well-being; therefore, feeling more vulnerable) these patients may have acted less confidently and hence more conservatively in their responses. Conversely, at the follow-up measurement nine months post-stroke, all patients were tested at non-clinical settings (e.g., their homes or at the university offices), and many probably experienced some improvement in their general well-being; feeling less dependent and vulnerable, therefore, they may have responded less conservatively, leading to gain in response time without any higher accuracy rates.

One factor that should be considered carefully is that when a person is tested twice with the same test, there might be some risk of practice effect. However, this risk was deemed to be minimal in the follow-up testings because (i) the reading material comprised of a rather mundane piece of text (containing 42 words) and the patient read it only once—while in hospital during their acute stage of their stroke—and the retesting was conducted in a different environment (home or university office); (ii) Patients' reading errors were not corrected by the examiner, and they were not given any feedback on their overall reading performance afterwards; and (iii) the patients were not given a copy of the test material to keep.

General discussion

The current study used the Sentence and Non-word reading subtests from the BCoS battery to evaluate the nature and magnitude of the different subclasses of reading impairment in a large group of patients with left or right brain injuries. The three different parts aimed at (i) comparing the differences in error patterns between lesion groups in terms of the frequency and type of errors; (ii) comparing the results of the reading tests with performance in other language (reading excluded); and (iii) examining the recovery rate nine months post-lesion and the relation between recovery in reading compared with recovery in other cognitive domains.

In the first part, distinctive error profiles in reading different subclasses of words were examined indicating that most stroke survivors experience some deterioration in reading of words and non-words (both in speed and accuracy). The LH lesion group fared worse (68%) than those with RH lesion (54.5%) in reading sentences, but no sex differences in error patterns were observed. Both groups read more slowly and made more errors than their age-matched control group, however, the nature of this degradation differed for different hemisphere groups.

In addition to examining the accuracy and speed of reading sentences, the accuracy for reading different word types; Regular, Exception, Function words, and Non-words (pseudo-words) were analyzed in detail. Differential impairment in reading the three word-types offers valuable information about the nature of the impairment and about its possible anatomical cause. Significant differences emerged between lesion groups with regard to the frequency of reading errors for different word types and in reading non-words. Both groups had difficulties in lexical reading (reading words that defy pronunciation rules; Exception words), however, the error profiles for the hemisphere groups were slightly different. While the LH group committed more errors in reading Exception words than in the Regular words (lexicality effect), which in turn had more errors than in Function words (Exception > Regular > Function), the RH group had more errors in reading Regular words than Function and Exception words. The latter two word-types showed very similar error rates (errors in Regular > Exception = Function). These patterns of errors indicate that the LH group had varying degrees of difficulties with all the three word-types and, in particular, with low-frequency words and words low in imageability.

Low imageability denotes that the word cannot easily be translated into a concrete image (Day, 1979) which in turn diminishes the accuracy of recognition and reading of the word in patients. The LH group's error patterns support previous research by Sabsevitz et al. (2005) who maintained that processing of abstract concepts makes greater demands on left hemisphere, especially perisylvian phonological and lexical retrieval systems. Further evidence for separate verbal- and image-based semantic systems was proposed by Swaab et al. (2002) who suggested that low and high imageability words activate separate neural regions, which also concurs with Paivio's (1971, 1986) dual coding theory, which posits that abstract concepts are encoded and stored in memory in the form of symbolic or verbal representations, whereas concrete concepts are dually encoded into memory as both verbal representations and image codes grounded in perceptual experience (Sabsevitz et al., 2005, p. 189). The findings by Sabsevitz et al. (2005) were also compatible with the dual coding theory. However, using a lexical decision task, Binder et al. (2005) found that highly imageable words activated a bilateral network in the brain, and non-imageable words activated mainly a left hemisphere network.

Comparing the performance at group-level of different lesion groups on Non-word reading uncovered some differences in favor of the LH patients whose non-word reading was more accurate and faster than for the RH patients. For non-word reading, the individual needs to utilize the correct phonological qualities, and any deficit in this ability is a useful indicator of the types of dyslexia and possibly the location of the brain damage. Reading non-words is particularly challenging as it entails the involvement of three simultaneous components: grapheme parsing (the parsing of a letter string into its constituent graphemes), phoneme assignment, and phoneme blending (Coltheart & Ulicheva, 2018). Impaired non-word reading, when weighed up against other language functions, can therefore be a useful marker of the type of brain damage. For example, in deep dyslexia, the person cannot read aloud non-words at all (Coltheart, 2000) and it is suggested that lesion in the right hemisphere is involved in this type of impairment (Weekes et al., 1997). In some patients non-word reading is, in relative terms, impaired while word reading is intact (word > non-word) which can indicate phonological dyslexia (Coltheart, 1996; Coltheart & Ulicheva, 2018; Dérouesné & Beauvois, 1979). In other patients, word reading is impaired while non-word reading is intact (non-word > word); indicating surface dyslexia (see Marshall & Newcombe, 1973; Patterson et al., 1985). The LH group, in general, performed better on reading words than non-words (word > non-word profile), who overall fared worse than the RH group, albeit RH group fared worse than LH group in non-word reading. These findings correspond to previous findings by Lambon Ralph and Graham (2000) who reported that phonological and deep dyslexia to be associated with damage to the LH (temporal and inferior frontal regions).

Reading and speech both rely on numerous linguistic abilities. Among them are (i) the ability to correctly recognize letters, words and to articulate them, and (ii) to comprehend the content in relation to the context (presented either in written or spoken form). Reading comprehension refers to the ability to access semantic meaning from print and requires that reader builds a mental representation of the content of the text message (Perfetti et al., 2005) and involves a syntactic and semantic analysis of the text and its intended meaning. Both production and comprehension are therefore reliant on several cognitive and linguistic components; for example, long term memory, working memory, attention, prior general knowledge, context-related knowledge, inference-making ability, adequate vocabulary, and lexical access, understanding of the structure and coherence of the text, monitoring own understanding, just to name a few (e.g., see Oslund et al., 2018; Perfetti et al., 2005). In addition, reading aloud involves the involvement of not only the visual perceptual system, but also the motor output system (for eye-movement, and movement of the muscles involved in articulation of the sound of letters) and the attentional system (to keep track of the content). Disturbance in any of these systems or deficit in any of the brain networks that are involved in reading aloud will inadvertently lead to impaired reading performance. Hence, showing a lesion in the LH or RH, alone, would not necessarily impair reading.

One limitation of part 1 of this study was that patients' comprehension of the written sentences that they just had read was not explicitly measured through an independent subtest. However, language comprehension was indeed assessed indirectly through other subtests that required reasonable understanding of instructions and commands. In addition, patient's comprehension of the test instructions was assessed by the examiner at the end of the testing. An objective measure of patients' reading comprehension is recommended in future studies.

Part two of the study investigated the relation between reading and other cognitive domains and found strong associations between the scores from the reading task and not only other language components, but also BCoS with measures of Memory, Number processing, Praxis, Spatial bias, and Controlled attention. Patients who did poorly in the reading task tended to fare poorly on all other cognitive tasks as well.

Effect of spatial bias

Flawless reading (of both words and non-words) is, among other cognitive functions, heavily reliant on intact visual processing of stimuli (words), and intact spatial attention. Existence of visual spatial bias negatively affects reading performance. Following brain injury, many survivors show visual spatial bias that affects not only their visual processing of object, but it also affects other cognitive functions. Bickerton et al. (2011) associated the presence of neglect with a range of impairments in other cognitive tasks (see also Suhr & Grace, 1999). Corroborating these findings, the current study observed that some errors made in reading words were indeed related to the presence of visual spatial biases in patients, measured through other sub-tests that examined visual neglect and extinction. These reading errors were consistent with spatial bias having a general impact on the patient's ability to scan across the page (Riddoch et al., 1990; Vallar, 2001; Vallar et al., 2010). Both LH and RH groups showed a significant correlation with page-based neglect measures, but only the RH group showed a significant correlation with the neglect measure. Interestingly, some differences in the relations between spatial reading errors and more general spatial biases emerged between LH and RH patients.

Neglect dyslexia is a type of reading deficit caused by deficit in spatial attention (i.e., spatial neglect) which is manifested in errors made when the initial part of a word is omitted/misread ("clock" is read "lock"), or when the beginning or terminal part of a word or sentence is omitted/misread ("party" is read "part") because these words fall on the contralesional visual field of the person (Vallar, 2001; Vallar et al., 2010). According to Siéroff (2017), neglect dyslexia is caused by difficulty in orienting attention to the left side of verbal stimuli. Spatial dyslexia is also frequent in patients with left posterior lesions. Right neglect dyslexia is more common, but right unilateral spatial neglect is rare (Siéroff, 2017, p. 15). Using eye-tracking recordings, Primativo et al. (2013) showed that patients with neglect dyslexia are unable to correctly land their gaze in the appropriate area at the beginning or end of the word/sentence when it falls in their contralesional site (p. 273).

In this study, it was observed that the reading performance—in both lesion groups—correlated with their scores on the measures of egocentric or page-based neglect. However, only the RH group showed a significant correlation on the allocentric or word-based neglect. Moreover, the RH group showed an association between their Sentence reading performance and their scores on the tactile extinction measures. This finding supported previous fMRI evidence presented by Chechlacz et al. (2010) showing that the right Temporo-Parietal Junction (TPJ) is involved in, not only, tactile extinction, but also it is associated with spatial impairments in other modalities. This could indicate that right TPJ plays a critical supramodal role in allocating spatial attention to visual stimuli (i.e., words). The findings of the current study suggest that such supramodal processes would impact on Sentence reading, so that RH patients especially, performed poorly when the words were presented on the left (contralesional) side of the page.

Recovery in reading and other functions

The final section of this paper presented the results of the follow-up re-testing of all available patients around nine months after their stroke. Overall, both lesion groups showed varying degrees of improvement between the two testing occasions. After nine months, the LH group showed twice as much overall improvement in reading accuracy and speed across all word types, compared with the RH group (8.9% for LH *vs.* 4.6% for RH). Note that the LH group started with a lower baseline performance. However, reading the Exception words and non-words, specifically, seemed to be unresponsive to recovery. Both groups showed their lowest improvement rate in reading Exception and Non-words. Such resistance to improvement in non-word reading has been previously reported by Wilson (1994). Compared to the LH group's improvement in reading Exception words, the improvement rate for the RH group was vanishingly small. Furthermore, the LH group showed higher improvement rate in reading Function words than Regular words, and Exception words showed the least improvement (Function > Regular > Exception), while the RH group showed higher improvement in Regular than in Function and Exception words (Regular > Function > Exception).

The analysis of patients' improvement in reading non-words as a measure of phonological reading ability showed that even though the RH group overall had somewhat better non-word reading accuracy and faster reading speed, the LH group showed a higher improvement rate across testing sessions nine months post-stroke. However, some of this advantage in recovery can be attributed to the LH group's much poorer baseline performance at their initial testing. The importance of this finding is that although most language impairments are attributed to lesion in left regions of the brain, these findings signify the crucial role of right regions of brain in recovery from an acquired reading impairment, and this takes place not only in the reading skills but also across a variety of other cognitive functions, especially in Language, Memory and Controlled attention. A superior recovery in the LH group's reading skills, compared with the RH group, corroborates previous findings reporting that the LH patients show some degree of plasticity in language function (Holland et al., 1996; Weiller et al., 1995) which is in line with previous research by Weiller et al. (1995) who demonstrated that aphasia patients gain some recovery by greater activation of undamaged areas of the left hemisphere, such as frontal areas in and around Broca's area, extending to the prefrontal cortex.

Given that reading is reliant on many other cognitive functions than language, the rate of improvement in reading performance was weighed up against improvement in other cognitive functions including other language tasks than reading words and non-words. Reliable associations were found between proficient Sentence reading and other cognitive domains, such as Memory, Number processing/arithmetic, Spatial bias, and Language (excluding reading words and non-words). However, reading non-words only correlated with Language and Number processing.

To read a new or unfamiliar word, the reader must convert letters into sounds that eventually form a whole word. Most dyslexias involve impaired phonological processing of letters, hence reading novel or uncommon words can become difficult. Although the central dyslexias are less clearly linked to specific lesions; it was found that LH patients more often showed signs of phonological dyslexia/alexia. They also showed a reading profile that indicated the existence of surface dyslexia/alexia; performed better on common words than on irregular words. RH patients, on the other hand, had more difficulty in reading common words and non-words than reading uncommon words and Function words. In addition, there was little improvement in performance after 9 months in these skills.

Overall, both hemisphere groups performed better on words than non-words, nevertheless, the difference in accuracy of reading between word and non-word reading was much higher for the LH group (21% worse on non-words than Regular words) while RH group's performance on non-words was only 7% worse than on reading common words. This magnitude of difference lies within the performance range for healthy controls.

A word of caution in relation to the reporting of the follow-up testing is that at the time of the follow-up measurements, almost half the patients were not available for retesting for a variety of reasons: ∼10% were not able to take part in the follow-up study due to poor health or had deceased and 40% were not either able (for other reasons than poor health), or willing to participate or were unapproachable. Of importance for the interpretation of the improvement rates after nine months would that minority group of 10% who were too ill to participate or deceased. There is a hypothetical likelihood that this might have affected the findings.

Language is a complex cognitive function that requires involvement of several different brain areas (Price et al., 2010) and the interaction between a variety of cognitive and perceptual and motor systems. Language disorders can appear in different forms, such as speech production and comprehension, reading and text comprehension, writing, naming objects, understanding gestures, and producing gestures.

Evidence from functional neuroimaging and lesion studies has shown that many brain regions support both language comprehension and language production (Awad et al., 2007; Scarborough, 1990). This evidence indicates that some functions are underpinned by a specific area in the brain (e.g., Broca) whose involvement in language production (e.g., speech and reading) is essential and other (Wernicke's area) that is crucial for language comprehension. Nevertheless, some language functions share some anatomical and cognitive correlates, e.g., the role of grammar in both reading and writing (production and comprehension of written language).

Considering that different components of the language network are highly interwoven; this will entail that impairment as well as recovery in one component can have an impact on other parts of the network. Specific language functions are therefore the result of the integration of several neural activities. A close association was observed between reading performance and performance in other linguistic skills in stroke patients. Nevertheless, this is not always the case. A person might show poor performance in reading but not in speech. For example, Bishop et al. (2009) found that poor language in children does not automatically affect their proficiency in reading words and sentences. Although, these children's reading comprehension was affected by the language impairment.

The findings of the study substantiate that distinct and fine-grained differences could be identified between LH and RH patients. Also, distinctive error profiles in reading different word types were observed that can be used to discriminate between different subtypes of alexia/dyslexia, though at a group-level.

To sum up, acquired language impairments can encompass disturbances in the comprehension, production of both oral and written language. Using the reading tasks of the BCoS, the nature and type of the speech and reading impairment in survivors of brain injury were examined. Nine months re-testing of some the patients showed that both lesion groups made some recovery, but the LH patients had made greater recovery in reading than the RH patients when weighed against their initial baseline reading performance.

It should be emphasized that the findings from this large-scale study reflect their performance as groups (LH or RH), and therefore any dyslexia/alexia subtypes cannot be inferred, based only on group-level findings.

Based on the study, future investigations should endeavor to (i) register word-length effect and time measurement, (ii) maximize the accuracy of scoring, patients' reading should be voice-recorded for later assessment by two external examiners. This will enable the researcher to analyze each patient's performance on word-level (e.g., word length effect), and to detect any allocentric attentional bias, and word substitutions, letter migration, and (iii) to relate specific reading impairments (e.g., word types) to specific lesion types, and finally (iv) to test patients' comprehension of the material they read immediately after reading.

Concluding remarks

In general, recovery after a brain injury acts on both physical and cognitive levels. Specific linguistic functions are fulfilled through the integration of neural activity in many regions subserving several functions (Price, 2012). Past research shows that post-stroke language recovery, especially, is possible and can happen both through brain reorganization and compensatory recruitment of alternative intact neural structures (Turkeltaub et al., 2011) but early rehabilitative intervention is crucial for successful recovery. The most apparent areas of recovery appear to be improvement in the processing speed, verbal memory, and visuoconstrictive skills (Millis et al., 2001).

Post-injury recovery in language functions is dependent on numerous non-linguistic factors, such as age, sex, handedness, type and severity of the lesion, co-existence of multiple neurological and functional impairments, concurrent decline in cognitive functions necessary for language processing (e.g. memory, attention, sensorimotor system), availability of rehabilitative program (speech and language therapy), time-lapse since onset, pre-morbid intellectual status, pre-morbid intelligence, occupational, cultural and educational history and social milieu, to name a few (e.g. see Ali et al., 2021; Gerstenecker & Lazar, 2019; Lawal, 2021—though see Lazar et al., 2008; and Pedersen et al., 2004 for alternative views). Even physical comorbidity can affect recovery e.g., diabetes mellitus (Nys et al., 2005). Moreover, there is inter-patient variability in how a stroke damages the brain and, more critically, how the same lesion can have inconsistent effects on cognitive abilities (including speech) in two different patients (Seghier & Price, 2016), which makes prediction of the outcome of recovery on an induvial level less accurate.

The multifunctional interconnective nature of the language network may have implications in the planning of rehabilitative interventions, hence employing a holistic approach, that takes into account impairments in other functions and domains that influence reading performance (e.g., perceptual, cognitive) can be beneficial to an efficient language rehabilitation.

This study provided some valuable insight in the nature and rate of prevalence of various reading impairments and set these in relation to the prospect of recovery and how co-morbid cognitive decline in other domains can play a role in recovery. The findings can especially inform clinical practice, therapy and rehabilitation planning following traumatic brain injury.

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Appendix A: Domain-structure of the BCoS battery.