Reading Ability and Neural Configurations for Verbal and Nonverbal Information Processing

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7 November 2019

Abstract

Evolutionary theory suggests that lateralisation sees the execution of verbal and nonverbal information processing in opposite hemispheres to optimise performance (Rogers et al., 2004). More recently, a spectrum of laterality has been characterised by the following neural configurations: (1) a typical configuration where opposite sides of the brain process either type of information (i.e., left for language and right for perception, or the reverse), (2) a mixed configuration where both hemispheres process one type of information and a single hemisphere processes the other, (3) a bilateral configuration where both hemispheres process both types of information, or (4) a crowded configuration where both types of information are processed in a single hemisphere (Lust, Geuze, Groothuis, & Bouma, 2011). Neural configurations of verbal and nonverbal information processing have been underexplored in terms of behavioural impact on tasks which require the concurrent use of these processes, such as reading. With a prevalence of atypical configurations in poor readers already demonstrated (Illingworth & Bishop, 2009), it was predicted that atypical configurations would be most disadvantageous to possess due to a competition for resources within or across hemispheres. The behavioural impact of neural configuration was tested using functional transcranial Doppler ultrasound. Existing Word Generation and Landmark paradigms were used to measure the lateralisation of verbal and nonverbal processing in a large sample (N = 116). A battery of literacy tests measuring phonological skill and retrieval, oral expression, oral reading fluency, spelling, and handwriting was administered. The lateralisation of verbal information processing and oral reading fluency were significantly related; stronger right lateralisation was associated with faster reading. Average readers possessed typical and crowded configurations, while those with bilateral and mixed configurations displayed above-average reading. While this result was unexpected, it provides support for the view that both hemispheres of the brain play a role in the optimal performance of verbal information processing, potentially via the communication enabled by the corpus callosum (Hirnstein et al., 2008).

Statement of Originality

This work is submitted for completion of the degree of Bachelor of Philosophy combined with a Master of Research (Cognitive Science). This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by any other person except where due reference is made in the thesis itself.

Nicola Filardi | 7 November 2019

Acknowledgements

To my family, for being there always. To Nic Badcock, for four years of mentorship and friendship. For your patience, understanding and encouragement to keep learning. For placing your trust in me on numerous projects and for always being there to challenge me. To Greg Savage, for providing your time, a fresh pair of eyes, and critical thought. To Saskia Kohnen, for showing interest in my research throughout the year and dedicating your time to provide insight on the result. To Rauno Parrila, for your helpful provision of information regarding your Reading History Questionnaire and its scoring. To Erin Banales on behalf of the Macquarie University Reading Clinic, for the coordination and provision of test kits and manuals to borrow. To Peter Humburg and Serje Robidoux, for lending your knowledge of methods in statistical analysis. To Ayeh and Ioanna for endless snacks, support and friendship throughout the year. To Lesley McKnight for the 'desk with the view' and your help on the sidelines over the years.

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Introduction

Laterality

Humans process a complex number of stimuli in day-to-day life. Anatomically, the human brain consists of two hemispheres which are responsible for processing such stimuli. The idea of a specialised hemisphere for processing a single type of information is termed ‘laterality’, and can be linked to evolutionary pressure (Corballis, 2017). Different cognitive functions, such as verbal and nonverbal information processing, could be specialised to either side of the brain for efficiency. A single hemisphere may be unable to handle both verbal and nonverbal information processing without some cost to performance (Helmstaedter et al., 2004). Strength of laterality is determined by assessing the level to which a single hemisphere is activated and specialised for a process in comparison to the other hemisphere. Animal studies have displayed the advantageous phenomenon of specialisation, with better dual-task performance in individuals with more highly-lateralised brains (Güntürkün et al., 2000; Rogers et al., 2004; Vallortigara & Rogers, 2005). The extent and behavioural relevance of lateralisation in humans remains uncertain and debated (Bach et al., 2010; Chiarello et al., 2009; Lust, Geuze, Groothuis, & Bouma, 2011; van Ettinger-Veenstra et al., 2010). This could be due to variability within neural configurations of verbal and nonverbal information processing that we are yet to understand.

The development of configurations of neural information processing occur in one of two ways (O'Regan & Serrien, 2018). Causal complementarity states that specialised areas of the brain are required for the development of two different functions such as (1) the verbal process of language, and (2) the nonverbal process of perception (Cai et al., 2013). This is to ensure that subsystems of these two different processes are able to freely develop (Kosslyn, 1987). Thus, the development of one process in one hemisphere must cause the development of the different process in the other. This ultimately means that the two types of information can be processed in parallel and cannot be processed in the same hemisphere.

The statistical hypothesis differs from causal complementarity in its assertion that the configuration of two different neural processes within the brain occurs independently. Thus, different information systems can be processed either in parallel, across both hemispheres, or within a single hemisphere (Illingworth & Bishop, 2009). Each process is specialised between hemispheres by chance, without impact from the other hemisphere. We therefore see the possibility of four neural configurations: (1) a typical configuration where opposite sides of the brain preferentially process different types of information (i.e., left for language and right for perception, or less commonly, the reverse), (2) a bilateral configuration where both hemispheres process both types of information, (3) a mixed configuration where both hemispheres process one type of information and a single hemisphere preferentially processes the other, or (4) a crowded configuration where both types of information are preferentially processed within a single hemisphere (Lust, Geuze, Groothuis, & Bouma, 2011). If we place these four configurations on a spectrum of competition for resources (1) would be highly lateralised—no competition for resources—with configurations (2) and (3) showing a graded introduction of a competition for resources, until the least lateralised configuration of (4) is reached with maximal competition for resources.

The statistical hypothesis would be best to explain the behavioural relevance of laterality in tasks requiring two different functions. Task performance would be on a spectrum, with those possessing typical neural configurations being the highest performers and those with crowded configurations being the lowest performers due to a competition of resources within a single hemisphere. If this were to hold true, the idea could be realised in a task such as reading, where acquisition and performance require both verbal and nonverbal information processing. Two common paradigms to assess verbal and nonverbal processes are the language task of Word Generation and the visuospatial Landmark task.

Word Generation task

The Word Generation task is a commonly-used paradigm that assesses verbal lateralisation using neural imaging (Brown et al., 2005). Since its introduction (Knecht et al., 1996), the task has proven to be reliable against other measures of verbal lateralisation (Knecht et al., 1998). To activate language information processing within the brain, participants are presented with a letter of the alphabet and asked to think of words beginning with that letter. They then report these words out loud. The reproduction of words aloud ensures task compliance and enables the measurement of verbal fluency (Lust, Geuze, Groothuis, van der Zwan, et al., 2011).

A limitation of this task is that individuals with poor literacy skills could have a decreased ability to generate as many words as an individual with average or above average literacy skills. This could recruit fewer neural resources, introducing a systematic laterality difference between poor and good readers related to methodology rather than physiology. This limitation is overcome by ensuring no correlation between performance on the task and laterality (Illingworth & Bishop, 2009), which makes continued use of this measure reasonable.

The Landmark task

A gold standard task for the measurement of nonverbal laterality has not yet been agreed upon (Whitehouse et al., 2009). Despite this, the Landmark task is frequently used to activate visuospatial information processing within the brain (Fink et al., 2000; Flöel et al., 2005; Harvey et al., 1995; Jansen et al., 2004; Lust, Geuze, Groothuis, & Bouma, 2011; O'Regan & Serrien, 2018; Rosch et al., 2012). This task typically reveals predominantly right lateralised activity (Badzakova-Trajkov et al., 2010; Volz & Gazzaniga, 2017). For the Landmark Task, participants are asked to make judgements about the placement of a vertical line on a horizontal line, judging whether the vertical line is centred on the horizontal line (Fink et al., 2000; Flöel et al., 2002). Visuospatial processing tasks generally show nonverbal processing as right lateralized, however they sometimes show a degree of bilateral activation (Clements et al., 2006). Increasing task difficulty is considered to provide the most representative and strong neural activity for measurement of the lateralisation of nonverbal processing (Cai et al., 2013).

Lateralisation: An unclear advantage

A large majority of individuals with typical neural configurations show the function of language in their left hemisphere and the function of visuospatial (or other nonverbal) processing in their right hemisphere (Nielsen et al., 2013; Shulman et al., 2010). Some display the reverse of this configuration, where the right hemisphere is responsible for language processing in approximately 10% of individuals (Knecht et al., 2001; Seghier et al., 2011), and the left hemisphere is responsible for visuospatial processing. Researchers have repeatedly found that the specialised hemisphere in this configuration is best for performance (Bach et al., 2010; Chiarello et al., 2009.) For example, those with less specialised neural configurations performed worse on verbal and nonverbal tasks (Mellet et al., 2014). The concurrent performance of two functions in an underspecialised hemisphere may crowd that hemisphere at a behavioural cost. Still, the benefit of possessing a typical or a reversed neural configuration has not been consistently replicated among humans.

The work of Lust, Geuze, Groothuis, and Bouma (2011) saw limited advantage to having single-hemisphere specialisation. Initially, individuals (N=26) completed a Word Generation task, followed by a Landmark task. The individuals then performed the task in tandem. Neural imaging revealed that having two functions predominantly subserved by opposite, single hemispheres showed an increase in dual-task performance. The strength of lateralisation made no difference to single-task performance. However, a less lateralised brain was associated with poorer performance for both verbal and nonverbal tasks. This finding was not replicated in later work (N=71); while there was still no advantage for a typical neural configuration, there was no detriment for a less lateralised brain (Lust, Geuze, Groothuis, van der Zwan, et al., 2011). Sample selection is a possible limitation here, as the first study assessed only a small number of right handers while the second assessed more than two times the number of individuals, whose handedness profiles varied. Further, there was no active recruitment for a spectrum of neural configuration, with bilateral groups being identified post data collection. Failure to replicate results across a more representative sample highlights that the behavioural relevance of laterality is yet to be resolved.

The initial paper Lust paper may not have been sufficiently powered to associate bilaterality with poorer task performance. Over time researchers have suggested that there may be no performance cost for having a single hemisphere process verbal and nonverbal information, or both hemispheres processing either type of information (Flöel et al., 2005). Indeed, patterns of activation for each function may be intra-hemispheric, rather than interhemispheric (Ocklenburg et al., 2016; Ringo et al., 1994). This could result in the ability of an underspecialised hemisphere to perform different tasks in tandem with no real competition for resources within the hemisphere. So, perhaps strong lateralisation possesses no real advantage at all. There is a requirement for sufficiently powered studies with consideration of neural configurations and varied samples in order to clarify inconsistencies within the literature.

The complex nature of reading

Fluent reading is a complex process which requires multiple skills for performance. The phases in which children are theorised to learn to read highlight the number of skills required (Ehri, 2005; Frith, 1986). The logographic phase occurs prior to formal education and involves the identification of words through recognisable graphic features. As demands of vocabulary volume increase, it becomes much harder to discriminate salient features of words using this skill. The phase of phonic knowledge then develops, assisting in word identification, allowing words to be sounded out if they have not been seen before. Young learners are able to begin to match up spoken words with written words. The orthographic phase further allows for the child to read words as whole units, without needing to sound them out. This phase is memory based and individuals become able to recognise letters sequentially without visual or cue-based reading as before.

The Dual-Route Model of skilled reading utilises two key processes which are embedded in the aforementioned phases (Coltheart, 2006; Coltheart et al., 1993). The model begins with letter recognition. The model then splits into the two processes. Firstly, the non-lexical route represents the rule-based system of sequentially translating letters into sounds and recognising the relationship between these letter sounds to form words. Secondly, the lexical route uses stored memory to access learned words which are memorised across three systems: (1) their orthography, pertaining to the spelling of words, (2) their phonics, pertaining to the pronunciation of words, and (3) their semantics, pertaining to the meaning of words.

A fluent reader would likely find strength in both of the model routes. However, an impairment of any stage of these routes should serve as a reminder that poor readers or dyslexics may not fail at reading in the same way (Castles, 2006). It is the type and level of impairment which defines their poor reading ability. It therefore makes sense that the assessment of reading fluency should be multi-faceted and exploratory in order to define poor reading type or stage of impairment. Individuals should be tested on multiple reading and language skills in order to draw conclusions about their overall reading ability.

Atypical neural configurations and reading

Moving away from typical configurations, atypical hemispheric specialisation (i.e., reversed, bilateral, mixed and crowded configurations) is associated with language impairments (Badcock, Bishop, et al., 2012; Bishop, 2013), including those with poor reading (Illingworth & Bishop, 2009; Xu et al., 2015). Indeed, Orton argued that reduced cerebral dominance was an explanatory factor in dyslexia from an early time (Orton, 1925). However, review of this notion throughout the changing landscape of psychological research in the 1960s to present times has shown that this is not necessarily correct (Hiscock & Kinsbourne, 1982; Willows et al., 2012). While two functions crowding a single hemisphere may not consistently equate to poor performance, based on the literature, reading may be a more specific ability that can best highlight the behavioural relevance of neural configurations.

Here, the umbrella term of poor reading covers those individuals with phonological, surface, mixed, and letter position dyslexia (Castles & Coltheart, 1993; Kohnen, Nickels, et al., 2012; McArthur et al., 2013). Poor readers are considered to be those who are performing one or more standard deviations below the mean on standardised reading assessments (McArthur et al., 2016). Poor reading is known to affect approximately 15% of Australian adolescents and adults aged 15-74 who struggle to read the written materials which are necessary for functioning in day-to-day life (Department of Education, Employment and Workplace Relations, 2011). This number is concerning due to the negative mental health outcomes associated with poor reading. Most significant is the toll of anxiety, which drives the development of internalising problems (Francis et al., 2019). Without a known cause for poor reading, possibly due to the heterogeneity of the impairment, the literature has reported conflicting theories and implementation of interventions which are unsuccessful (Vellutino et al., 2004).

Researchers have spent decades looking for an underlying neural mechanism to explain poor reading. Attempts to locate and explain the mechanism have been related to auditory or visual information processing, and suggested deficits in attention or memory (Badcock & Kidd, 2015; Birch & Belmont, 1965; Hari & Renvall, 2001; Isaki & Plante, 1997; Tallal, 1980). A novel account of poor reading may be apparent if the role of neural configurations is explored. A wider variation of reading ability is seen in those with atypical configurations of language than those with typical configurations (Illingworth & Bishop, 2009; Xu et al., 2015). The negative relationship between atypical configurations and reading is problematic for the achievement of skilled reading, as skilled reading has been significantly linked to language information processing in the typically configured left hemisphere (Richlan, 2012; Rumsey et al., 1997; Salmelin et al., 1996; Turkeltaub et al., 2003).

It is agreed that phonological awareness is a key skill in the acquisition of reading (Tallal, 1980). Phonological awareness requires perceptual processing in order to recognize units of speech sounds (Bogliotti et al., 2008). Fluent reading requires increased single-hemisphere activation of language processing in order to conceptualise and project these units of sound onto orthographic information (Ziegler et al., 2014; Ziegler & Goswami, 2005). Impairment of these skills may result in an underspecialised reading system which stunts reading development (Pugh, 2006; Vandermosten et al., 2011). These results lead to the view that poor readers are processing written stimuli differently to typical readers (Brunswick et al., 1999). This idea is supported by the statistical hypothesis.

The activation of less left-hemispheric resources in poor readers has been displayed across multiple brain imaging techniques (i.e, functional magnetic resonance imaging, positron emission tomography, functional transcranial Doppler ultrasound), displaying both structural and functional differences (Habib, 2000; Illingworth & Bishop, 2009; McCrory, Mechelli, Frith, & Price, 2005; Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010; Shaywitz, Mody, & Shaywitz, 2006). The left parieto-temporal and occipito-temporal brain areas are thought to be linked to fluent reading ability, and poor readers show less neural activity in these areas during reading (Richlan, 2012; Shaywitz & Shaywitz, 2005). In what may be compensation to rectify phonological-processing deficits, poor readers have also shown the activation of the right hemisphere throughout development. The left hemisphere is thought to have neural specialisation in terms of high-frequency analysis making it more suitable for verbal information processing (Gummadavelli et al., 2013). The use of the suboptimal right-hemisphere to process reading information could potentially explain how poor reading ability can improve with age but still remain somewhat lagged (Hoeft et al., 2011; Turkeltaub et al., 2003). The idea that poor readers develop a reversed, bilateral, mixed or crowded configuration of language processing in attempt to achieve fluent reading should be further explored. Whether we develop atypical neural configurations for reading as a result of phonological processing difficulties, or whether poor reading ability is a result of predetermined neural configurations is yet to be established. Consistent evidence of a relationship between poor reading and atypical neural configurations would expand our knowledge on the cause of reading difficulties and help to create targeted intervention. This would be achieved by an understanding of how poor reading develops.

Is there a bilateral or mixed advantage?

What if specialised hemispheres working in parallel is not the answer to better cognitive performance at all? While the brain comprises two anatomical components, it is the development of the corpus callosum with the evolution of human brains that allows for the rapid communication between hemispheres. Corpus callosal size is a mediator of hemispheric cross-talk in human brains (Josse et al., 2008). This exchange of information may be more advanced than that previously displayed in other species, with the resources of two hemispheres uniting to form a single efficient system in order to improve cognitive performance (Gazzaniga, 2000; Làdavas & Umiltà, 1983). Higher performance on verbal and nonverbal tasks, or higher intellectual abilities as assessed by IQ scores in mixed or bilateral individuals are interpreted as an advantage of simultaneous access to resources in both hemispheres (Fine et al., 2007; Hirnstein et al., 2008; Hulshoff Pol et al., 2006).

Upon learning to read at a young age, it has been suggested that bilateral activation occurs, but progression onto fluent reading requires moderation of right hemisphere activation (Turkeltaub et al., 2003; Waldie, Haigh, Badzakova-Trajkov, Buckley, & Kirk, 2013; Waldie & Mosley, 2000). Indeed, the right hemisphere has been seen to play an important role in processing language information during development, highlighted by the positive relationship between age and cortical thickness (Brown et al., 2012; Vigneau et al., 2011). Thus, strong lateralisation for language may be a characteristic of a developed brain (Scheppele et al., 2019). However, this does not mean that a typical configuration must be synonymous with optimal cognitive performance. More average to above average readers having this configuration in the population could be due to what may have been an initial evolutionary process of decreasing right hemispheric activation across development.

Research suggests that inhibition of the right hemisphere during development sees a decrease in information flow from the left to right hemisphere (Seghier et al., 2011). This could be a disadvantage if the role of the corpus collosum is to benefit less lateralised brains to co-operate together. Indeed, no cost to language performance after early left-hemispheric damage highlights the potential benefit of coordinated left and the right hemisphere use (Tivarus et al., 2012). The failure of research to consider a bilateral advantage until recent decades could be the cause of a stalemate in the literature regarding the behavioural relevance of verbal and nonverbal laterality. Animals may have an underdeveloped corpus callosum. This may explain the link between strong lateralisation and better performance that is true of animals, which is difficult to replicate in the present-day human brain (Bisazza et al., 1998; Vallortigara et al., 1999). Perhaps individuals with typical neural configurations are not taking full advantage of the possible relatively recent evolutionary bridge between the hemispheres. This could explain why there is inconsistent evidence in replicating the advantage of possessing a typical neural configuration in humans.

Laterality measurement techniques

Learning about lateralisation from patients with brain damage after brain injury or death was the initial way to explore the neural location of information processing. Broca's seminal work on language laterality from this type of sample concluded that *'we speak with the left hemisphere*' (Broca, 1865). Later, the introduction of the Wada technique for pre-operative exploration saw the administration of anaesthesia to shut-down a single hemisphere while a live patient performed a task. Eventually this process was repeated on the other hemisphere when the patient was medically able (Kekhia et al., 2011). This technique allowed the measurement of the lateralistion of information processing to inform upcoming brain surgery. There are significant health risks associated with the Wada procedure, therefore it is only performed when medically necessary. And so, the introduction of functional neuroimaging has been warmly welcomed to the study of lateralisation. Over the years neuroimaging has provided the invaluable benefit of learning from not only functioning brains, but healthy brains. From the years of research following the development and administration of these techniques, we now know that the neural representation of language is far more complex than previously proposed (Vigneau et al., 2006). This warrants the study of verbal lateralisation and its relationship with nonverbal lateralisation in the current study, which could be a stepping stone to clarify parts of what we currently know about language.

Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) scans are examples of modern imaging techniques that allow for non-invasive assessment of lateralisation. Similar patterns of verbal and nonverbal activation have been found using these scans, despite small differences in tasks and technology (Fiez & Petersen, 1998). While this is the case, these scans are expensive (in the range of hundreds of dollars) and can have the participant feeling quite uncomfortable, being subjected to confined spaces, loud noises and restriction in movement.

Functional transcranial Doppler (fTCD) ultrasound is an emerging tool used to assess lateralisation. The technique assesses neural activity by measuring blood-flow velocity in either hemisphere through the middle cerebral arteries. It is relatively inexpensive in comparison to fMRI and PET and quick to set up, with the individual being free to make small movements without affecting signal quality. The participant wears a headmount with two small ultrasound probes placed on the scalp overlaying the temporal-bone windows on either side of the head, with a small amount of gel to ensure conduction of the signal (see diagram in Figure 1). FTCD has been valididated against fMRI for assessing lateralisation (Chilosi et al., 2019; Knecht et al., 1998; Somers et al., 2011). Due to the low cost, this technique affords the opportunity to test a significantly larger sample than more expensive techniques. Moreover, where participants have performed a Word Generation paradigm in both a fTCD and a fMRI simulation environment, the measurement of lateralisation has been shown to be less affected in the fTCD environment (Rapaport, 2017). FTCD is therefore an optimal tool for studying lateralisation.

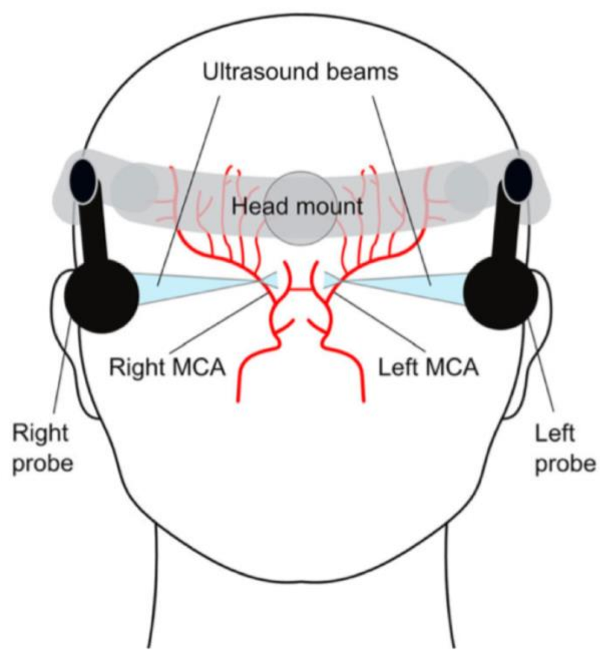

Figure 1. Diagram of Doppler setup (Badcock & Groen, 2017).

The role of handedness in predicting cerebral specialisation

The origin of human language is debated. Some suggest the possibility of language developing as a consequence of manual gestures (Kendon, 2017). This is one basis for the belief that language lateralistaion can be predicted by hand preference. Over the years, research has shown a connection between handedness and language lateralisation; however, it is now considered a weak association. While approximately 95% of right-handers are left lateralised for language, so are approximately 70-80% of left-handers (Corballis, 2012). Despite this, left-handers have increased variability in their neural configurations, having more chance of possessing reversed, mixed or bilateral hemispheric specialisation for language (Somers et al., 2015). This is interesting in terms of what there is to learn about reading ability and neural configurations, as evidence exists displaying poorer cognitive ability in left and mixed handed individuals (Annett, 1992; Johnston et al., 2009; Nicholls et al., 2010). One issue with the relationship between handedness and lateralisation involves the ways in which handedness is classified, and the report of findings only when a significant relationship has been found (Bishop, 1990; Bishop et al., 1996). In exploring neural configurations and their effects on behaviour, researchers can either be too selective with their sample, choosing left-handed participants only (Cai et al., 2013), or too random with their sample, resulting in oversaturation of right handers (Gutierrez-Sigut et al., 2015; Mellet et al., 2014). If used in a balanced way, the inclusion of handedness as a recruitment tool may be useful in achieving a sample of individuals with varied neural configurations of verbal information processing.

Assessment of lateralisation and reading

To the best of our knowledge, only some studies have explored the potential relationship between lateralisation and the behaviour of reading. Illingworth and Bishop (2009) highlighted that poorer readers are more weakly left lateralised for language. More recently, Waldie, Wilson, Roberts, and Moreau (2017) sought to uncover whether reading performance was indeed related to left-hemisphere activation. The authors used a rhyming task, and lower reading performance by a dyslexic group was not explained by fMRI data, which showed that both dyslexics and controls activated a left-lateralised network for reading in the same fashion. Further, higher activity in both sides of the brain was associated with reading accuracy. The conclusions of this study may be hindered by its limitations. The authors formed their dyslexic group by self-report of past and current reading difficulty, along with typical tests of intelligence, and poor performance on phonologically-related tests of both literacy and mathematics. The final sample included 11 dyslexics, 11 dyscalculics (who struggle to comprehend numbers and mathematics), 13 comorbid individuals, and 12 individuals of typical ability. Concerningly, dyscalculics were combined with the individuals of typical ability to form the control group, while those who were comorbid were joined with the dyslexia group. This disrupts the idea of pure typical and atypical reading groups; while issues with mathematics are not synonymous with reading difficulties, the basis of these impairments rest with phonological deficits (Landerl, Fussenegger, Moll & Willburger, 2009). Further, the reading battery used for assessment could have been wider in scope to tackle other errors such as irregular-word reading (McArthur et al., 2013) and letter migrations (Kohnen, Nickels, et al., 2012). Thus, with adjustment for these limitations, this study provides a firm building block upon which to base the current study.

Currently, the literature taps into only a small amount of what we should know about the lateralisation of language and reading performance, as well as lateralisation more generally.

A search for clarification

The current study sought to explore the relationship between verbal and nonverbal lateralisation and its relationship with behaviour – more specifically, reading performance. To do so, a large and more representative sample of the broader range of lateralisation diversity was sought; a unique sample in the literature. This was achieved by recruiting for variation of both handedness and reading abilities. The study was conducted in two phases. The first phase explored whether there was an association between verbal lateralisation and reading behaviour. Points of interest to complete this exploration were (1) whether any association between verbal lateralisation and reading was influenced by nonverbal lateralisation, and (2) whether verbal lateralisation was associated with any particular reading subskills. Phase two examined whether there was an association between the four neural configurations and reading ability. Points of interest for this phase were (1) whether the incidence of poor reading would be related to neural configurations of verbal and nonverbal lateralisation, and (2) whether a crowded configuration was related to poorer reading.

It was expected that (1) the left and right hemispheres would operate relatively independently in processing either verbal or nonverbal information respectively, (2) that a competition for resources within the hemispheres would be present on a spectrum, where typical configurations would have no competition for resources, and crowded configurations would have a high level of competition for resources, and (3) this competition for resources in crowded configurations would be associated with poor reading. These predictions were based on the statistical hypothesis and the idea that a single hemisphere lacks the capacity to perform differing cognitive processes without a competition for resources resulting in poor performance.

Methods

This study was approved by the Macquarie University Ethics Committee (Clearance: 5201835496718).

Sample

Size and Power

A power analysis using G*power was performed. A sample size of 112 participants were required to achieve a power of 0.8 with a medium effect size when conducting a penalised regression with 30 predictor variables. We therefore sought a sample size of 132 participants to allow for a 15% attrition rate due to poor fTCD ultrasound quality while still meeting the desired power and effect size. This increased sample size power ensures reduced chance of making a Type 2 error; claiming no effect when an effect exists.

Recruitment

We recruited participants using two strategies. We administered a screener to first year psychology students at Macquarie University. The screener included the short version of the Adult-Reading History Questionnaire – Revised (Kirby et al., 2008) to assess if students had a history of reading difficulties. Participants were also asked to identify their hand preference from the options: (1) left-handed, (2) ambidextrous, (3) right-handed. A standardised test of handedness such as the Flinders Handedness Survey (Nicholls et al., 2013) was not administered at this stage of recruitment due to the limited number of items allowed to be included in the university screener. As a result of this recruitment strategy, students who displayed a history of poor reading, or who self-reported being left-handed or ambidextrous were invited to take part in our study.

The next recruitment strategy made use of the SONA and iLearn systems at Macquarie University to access an unselected sample of undergraduate students. These students were enrolled in a Bachelor of Arts or Science - Psychology, or a Bachelor of Speech, Language and Hearing Sciences. The resulting recruitment pool therefore included first-, second-, and third-year university students, providing possible variation in reading skill. These students either received course credit, payment or an equivalent combination as renumeration for their time.

Final sample

A sample of 120 individuals was recruited. Three individuals were removed due to failure to achieve an fTCD signal of quality. One individual was removed due to falsely reporting a native-English background until after the testing session. Therefore, the final sample consisted of 116 native-English speakers, exceeding the 112 participants required as per the initial power analysis. Eighty-five of these participants belonged to the unselected sample, 21 had responded from the poor reading invitation and 10 had responded to the left-handed invitation.

The sample included 42 males and 74 females. Gender imbalance reflects the recruitment pool formed by undergraduate courses at Macquarie University that are over-represented by females. Participants were aged from 18-47 years (M = 21.41, SD = 4.76, Median = 20, min = 18, max = 47). There were 77 right-handed individuals, 31 left-handed individuals, and 8 ambidextrous/mixed-handed individuals. Therefore, left- and mixed-handed individuals made up approximately one third of the sample. This final handedness count was based on a FLANDERS assessment and not the initial self-report.

Laterality measures

Equipment

This study utilised a Delica EMS-9U fTCD system and associated software by Delica Medical Equipment Co. in Shenzen, China. Participants wore a flexible headmount to which 2-MHz ultrasound transducer probes were attached to rest over the temporal window of the left and right sides of the head, as shown in Figure 1. The temporal window is the thinnest part of the skull located between the temple and the ear, enabling best access to either middle cerebral artery. A conductive ultrasound gel was placed on the probes prior to contact with the head, allowing for an acceptable ultrasound signal which took the trained-researcher between five to 15 minutes to achieve.

The fTCD paradigms described below were presented on a Dell Precision Tower 3620 running Windows 7, with an AOC FREESYNC 144Hz 24-inch desktop monitor (1920 x 1080 pixels). Paradigms were coded using MATLAB_2017b 64-bit (MathWorks Inc., 2017) and run by associated Psychophysics Toolbox 3.0.13 functions (Kleiner et al., 2007). The background display was always coloured grey (RGB 160 160 160) and text was presented in white (RGB 255 255 255) Arial 20-point font.

Word Generation task

The Word Generation task comprised 20 trials, excluding the letters k, q, u, x and z as infrequently used letters. Participants received written instructions for this task (see Appendix 1). Each trial lasted 50 s and included the presentation of: a blank screen (20 s), an auditory tone (500 ms) and the words ‘Clear mind’ (5 s), a letter (2.5 s), a blank screen (7.5 s), an auditory tone (500 ms) and the word ‘Stop’ (1 s), and the word ‘Relax’

(15 s). Participants were instructed to say out loud words beginning with the presented letter as soon as it appeared on screen, stopping at the ‘Stop’ auditory and visual cues, and thinking of nothing for the remainder of the ‘Relax’ period. Figure 2 depicts a schematic diagram of a single Word Generation task trial. The task differed from the traditional paradigm by replacing the silent generation period to overt generation, which has delivered equivalent results (Gutierrez-Sigut et al., 2015). This change reduced the risk of task non-compliance by having the participant speak out loud for the generation.

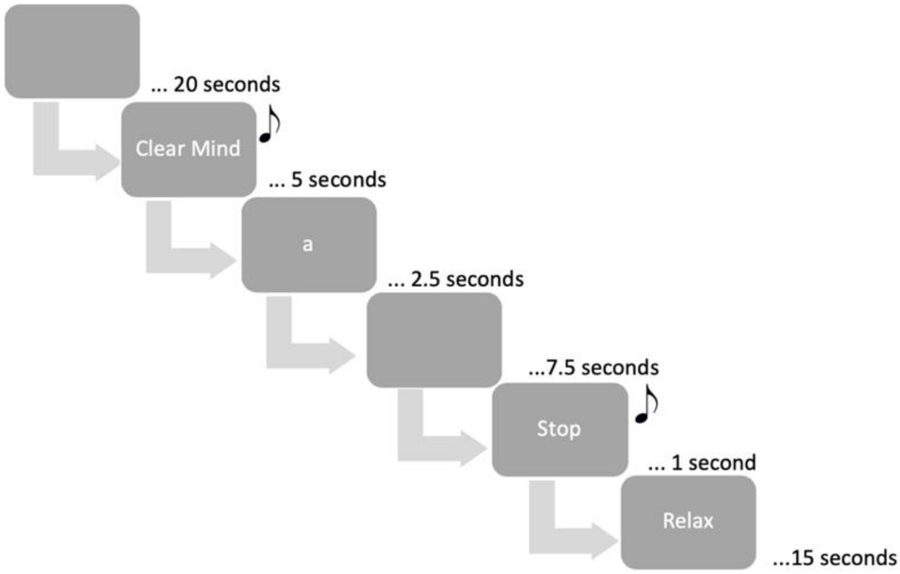

Figure 2. Schematic diagram of the current Word Generation trial.

Landmark task

The Landmark task involved 20 trials to match the number of Word Generation trials. Participants received written instructions for this task (see Appendix 2). A trial lasted 54.4 s and included the presentation of: a blank screen (20 s), an auditory cue (500 ms) and the words ‘Clear Mind’ (5 s), presentation of stimuli (14.4 s), and the word ‘Relax’ (15 s). Figure 3 depicts a schematic diagram of a single Landmark task trial. The presentation of stimuli included eight judgements to be made by key press, as to whether the vertical lines were in the centre or were off-centre on a horizontal line. Each vertical line was presented for 160 ms, along with an interstimulus mask of 20 ms. Within a trial, four vertical stimuli were placed at the centre of the horizontal line, two vertical stimuli were placed to the left and two were placed to the right of centre. The offset of the line from centre always had a visual angle of 1°. The order of the location of the vertical stimuli was randomised within each trial. Participant performance was measured by accuracy of their judgement across all trials.

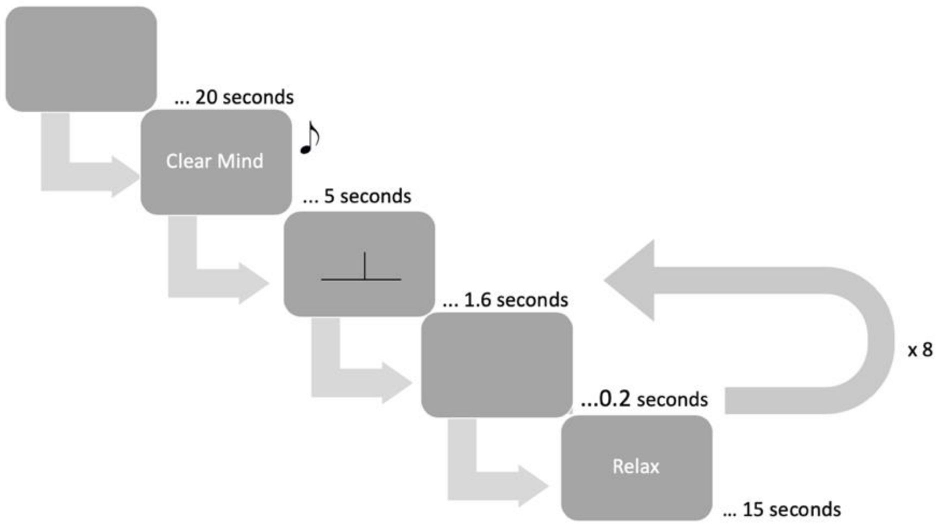

Figure 3. Schematic diagram of the current Landmark trial.

Behavioural measures

Reading History

Adult Reading History Questionnaire – Revised (ARHQ-R)

This survey assessed histories of reading difficulty (Kirby et al., 2008). Respondents reported their past and present: (1) reading and spelling abilities, (2) attitudes toward their education, (3) level of effort and assistance required to academically succeed, and (4) amount of reading texts for academic and recreational purposes. There is a 20-item version and a 56-item version of this test. The 20-item version was administered for recruitment purposes and the 56-item version was administered during the testing session. The reliabilities of these forms and their subcategories for our sample are reported in Table 1.

Participants responded via a 5-point Likert scale (responses 0-4). The individual received a score for each section in addition to a total score. Section and total scores were calculated by dividing the total score by the maximum score available (i.e., score divided by 56 items x 4 as the highest possible responses). This resulted in a score between 0 and 1. A score of 0.4 or more indicated a history of reading difficulty.

Table 1. Reliability of ARHQ-R surveys

Form	N	Subcategory	Cronbach's α	Number of items
Screener	1141	Total	.839	20
		Primary	.878	8
		Current	.698	12
Whole	113	Total	.921	56
		Primary	.874	15
		Secondary	.815	19
		Current	.798	22

Handedness

Flinders Handedness survey (FLANDERS)

This survey assessed hand preference to perform 10 skills (Nicholls et al., 2013). Responses ranged from -1 for left hand preference, 0 for mixed hand preference, or 1 for right hand preference. Handedness was assessed by the sum of all items. A score between -10 to -5 indicated left handedness, a score between -4 to 4 indicated mixed-handedness and a score of 5 or above indicated right handedness. The split-half reliability of this measure is high (r = .96).

Quantification of Hand Preference Task (QHP)

This task measured handedness on a continuum (Bishop et al., 1996). Seven numbered piles of three cards were placed at 30-degree angles in a semi-circle formation (see Figure 4). The administrator called a pile number in an interleaved order at speed, and the participant picked up a card from the instructed pile. Hand preference was calculated by subtracting 0.50 from the division of the number of right-hand pick-ups by the total number of pick-ups (21). Scores ranged between -0.5 and 0.5, with -0.5 representing absolute reliance on the left hand and 0.5 indicating absolute reliance on the right hand.

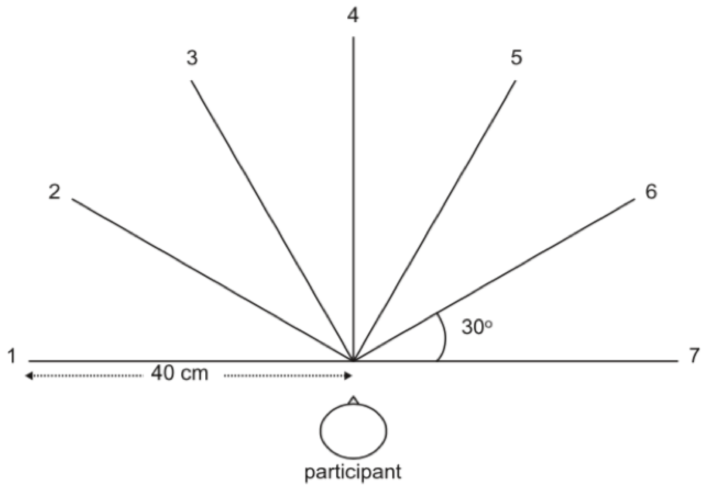

Figure 4. Bird's eye view of Quantification of Hand Preference setup

Final details

A total of 113 individuals completed the entire survey of the ARHQ-R. A history of reading difficulty highlighting risk of poor reading was found for 41 individuals. Seventy-two individuals performed at an average or above average range. While the majority of our sample were right-handed, the measurement of handedness by the QHP as demonstrated in Table 2 suggests a far higher range of variability in hand preference.

Table 2. Frequency of handedness traits

							Frequencies (%)		
	N	M	SD	Median	Min	Max	Left	Mixed	Right
FLANDERS	116	4.07	8.44	10	-10	10	31	7	78
QHP	114	0.63	0.36	0.64	-0.05	0.05	21	51	42

Reading measures

As discussed in the introduction, reading is a complex ability which requires the mastery of many skills. A wide and thorough battery of reading ability is necessary to explore a variety of variables indicative of poor reading and types of dyslexia. The following measures were included after consultation with reading clinicians in order to cover reading abilites including: phonological decoding, whole word recognition, fluency, accuracy, spelling and vocabulary.

Castles and Coltheart, 2nd ed. for Adults

The Castles and Coltheart test (CC2A; Castles et al., 2009) assesses key processes of single word reading: phonological decoding and whole-word reading. The test consists of three lists of 55 items containing nonwords (e.g., ‘gop’), irregular words (e.g., ‘yacht’), or regular words (e.g., ‘bed’). Nonwords can only be read via grapheme-to-phoneme correspondences (i.e., sounding out). Irregular words can only be read by whole-word recognition. Regular words can be read using either process.

Each test item is presented individually in black text on a white flash card. Word lists are interleaved upon presentation. The examiner presents one card at a time, with items increasing in difficulty as the test continues.

Correct and incorrect responses are scored zero and one respectively. A word list is discontinued upon five consecutive errors made within that list. The test is administered until all three lists are discontinued, or until the participant reaches the last item on the test. The sum of each list is converted to a standard score using normative data from a sample of undergraduate Macquarie University students in 2013 (results remain unpublished). The Cronbach’s α from the current study for each subtest of this measure are as follows: (1) real words α = .69, (2) irregular words α = .84, and (3) nonwords α = .93.

Clinical Evaluation of Language Fundamentals Australia and New Zealand 5th ed.

The Clinical Evaluation of Language Fundamental Australia and New Zealand 5th ed. (CELF-5; Semel, Wiig, & Secord, 2013) assesses various language abilities.

Recalling sentences

This subtest measures the process and recall of verbal information, and the ability to reproduce sentence structures of increasing difficulty. The subtest consists of 26 items which are to be administered as per the manual. The items are scored using a four-point scale (0-3). The following constitute a single error: (1) any word that is changed, added substituted or omitted, and (2) transpositions which do not change the meaning of the item. A transposition changing the meaning of a sentence constitutes two errors (e.g. ‘Was the van followed by the ambulance?’ repeated as ‘Was the ambulance followed by the van?’). The test continues until either all items have been administered or an individual receives four consecutive scores of zero. The CELF-5 is noted in its manual to have high test-retest reliability (r = .90) for this subtest.

Comprehensive Test of Phonological Processing 2nd ed.

The Comprehensive Test of Phonological Processing 2nd ed. (CTOPP-2; Wagner, Torgesen, & Rashotte, 2013) assesses phonological processing, an ability which contributes to reading development. The Rapid Symbolic Naming subtests assess the retrieval of phonological information from long-term memory; a skill which enables an individual to execute a sequence of language operations quickly and repeatedly.

Rapid Colour and Object Naming.

The test consists of 36 items shown as coloured squares which are randomly arranged in a nine-by-four layout on a white A4 page. Each square is coloured either blue, red, green, yellow, black or brown. Colours of the squares are randomly interleaved in order. Participants label the colours out loud as fast as they can from left to right, row by row, until they reach the final item. The participant is timed and the overall time in seconds is the participant’s raw score. The Rapid Object Naming subtest is administered in the same fashion, except each item is an object instead of a square. Objects include a pencil, star, fish, chair, boat and key which are also interleaved in the same nine-by-four layout. The total time taken in seconds to label all items is the participant’s raw score. The test manual states that each subtest has high test-retest reliability; colours (r = .92) and objects (r =.86).

Friedmann, Castles and Kohnen

This unpublished assessment measures whole word reading, migration errors and phonological decoding (FriCasKoh; Friedmann, Castles, & Kohnen, 2011).

Single word reading

Students are instructed to read 140 words out loud as fast and as accurately as they can. The words are presented in black font in a single column which spans over five white A4 pages with 28 words to a page. The participant turns the pages to continue reading. There is no discontinue rule for this subtest. An accuracy score is calculated by scoring items one if read correctly or zero if read incorrectly. A score of fluency consists of the time taken in seconds to read the entire word list. A higher number of words read correctly in a shorter amount of time indicates better reading fluency. The reliability of this subtest in the current study was α = .69.

Word pair reading

Ability to prevent letter migration between words is measured (e.g. ‘cried, tries’ becoming ‘cries, tried’). The participant reads 35 pairs of migratable words out loud as fast as they can. Pairs are printed in two columns in black font over two white A4 pages. Participants read row by row until they read the final pair. Three raw scores were created: time taken in seconds to read all pairs, number of pairs read correctly (two words correct), and number of 70 words read correctly. A higher number of pairs read correctly in a shorter amount of time indicates higher ability to distinguish letter positions. The reliability of this subtest in the current study was $\alpha = .99$.

Nonword reading

This subtest measures the ability to phonologically decode 30 nonwords without error. Nonwords are printed in black font in a central column on a white A4 page. The participant must read the nonwords as fast and as accurately as they can. Two raw scores were created: time taken in seconds to read the nonword list, as well as the number of nonwords read correctly. A higher number of nonwords read accurately in a shorter amount of time indicates superior phonological decoding ability. The reliability of this subtest in the current study was $\alpha = .65$.

Letter Position Test

This test assesses the ability to position letters in migratable words, indicating whether an individual has letter position dyslexia (LetPos; Kohnen, Marinus, et al., 2012). Characteristics of letter position dyslexia include migration errors, difficulty in distinguishing similar words, difficulty determining whether a word is real, and difficulty defining a written word.

Sixty words with migratable letters (e.g., pirates and parties) are written in black font on two A4 white pages. Each page contains 30 words, listed in two columns of 15 words each. The participant reads down the left column and down the right column before turning the page to do the same. Participants receive two scores: time in seconds taken to read all 60 items, and number of items read correctly. The reliability of this test in the current study was $\alpha = .62$.

Tests of Word Reading Efficiency 2nd ed.

This assessment consists of two subtests which measure phonological decoding and sight word reading ability, revealing performance for both reading fluency and accuracy (TOWRE-2: Torgesen, Rashotte, & Wagner, 2012). Participants are required to read as many of 108 sight words as they can in 45 seconds. They are then required to read as many of 63 nonwords as they can in 45 seconds. A correct response is scored as one and an incorrect response is scored as zero. Otherwise, if the participant reads an entire list in less than 45 seconds their time taken to read the list in seconds becomes their score. The participant receives two final scores, one for either test. The TOWRE-2 test manual highlights the assessment's high validity (α = .90). The reliability of the sight word subtest in the current study was α = .95. The reliability of the phonemic decoding subtest in the current study was α = .92.

Weschler Individual Achievement Test 3rd ed.

This assessment provides insight into oral-language, reading and written language abilities (WIAT-III; The Psychological Corporation, 2016). The following subtests were used in the current study.

Oral Expression

Expressive vocabulary. Word retrieval and spoken vocabulary abilities are measured. The individual says a word that best corresponds to a picture and description upon instruction (e.g., "Tell me the word that means… a brush for cleaning teeth" with a picture of a toothbrush shown to the participant). This component of the subtest includes 17 items: correct responses are scored one and incorrect responses are scored zero. The test is administered until the individual finishes all items or is awarded four consecutive scores of zero. The reliability of this subtest in the current study was α = .66.

Oral word fluency. An individual's word retrieval ability and flexibility in thought processing is measured. The individual must name as many items as they can out loud which belong to a category. First, they must name as any animals as they can in 60 seconds. Second, they must name as many colours as they can in 60 seconds. The individual receives a score of one for each item that they name within the time limit as per acceptable responses listed in Appendix C of the WIAT-III manual. The Oral Expression subtest is noted to have high test-retest reliability in the test manual (r = .93).

Listening comprehension

Receptive vocabulary. This subtest consists of 19 items. For each item the participant is shown four pictures in a two by two grid. The examiner says a word out loud and the participant is required to pick the image that best corresponds to the word they heard or alert the administrator that they do not know the answer. Correct items receive a score of one, and incorrect items receive a score of zero. The test is completed upon administration of the last item or until the participant is awarded four consecutive scores of zero. The reliability of this subtest in the current study was α = .50.

Oral reading fluency

This subtest is administered per the WIAT-III manual. This resulted in all the participants in the current study reading two passages out loud. The participant had to read the passage within the maximum time outlined in the manual. Timing begins when the individual reads the first word and ends when they finish the last word. A passage related comprehension question is administered at the end of the passage to ensure the individual was reading for meaning, however the correctness of the comprehension question makes no difference to the overall scores.

For each passage, completion time in seconds, addition errors, other errors and word count are summed respectively. The scores for each passage are summed in these subcategories. This resulted in four final raw scores. Oral reading fluency was calculated by subtracting total other errors from the total words read and dividing this by the total time required to read the passages. This number is then multiplied by 60. Oral reading accuracy was calculated by subtracting the sum of total addition errors and total other errors from the total words read in the administered passages. Oral reading rate consisted of the total time taken to read all administered passages.

The components of this subtest are noted by the test manual to have high test-retest reliability (all exceeding r = .82).

Woodcock Johnson – Tests of Achievement 3rd ed.

This measure assesses cognitive development and academic achievement (WJ-III: Woodcock, McGrew, & Mather, 2001).

Spelling (Test 7)

This subtest measures the ability to produce written words in response to oral prompts. The results can shed light on phonetically accurate and inaccurate spellers. Words are read out loud to the participant, followed by the use of the word in a sentence. Individuals complete 32 items, scoring one for correct responses and zero for incorrect responses. Poor performance may indicate poor grapheme/phoneme correspondence or failure to memorise visual features of words.

The subtest is noted in the test manual to have high test-retest reliability (r =.90). The reliability of this subtest in the current study was α = .84.

Spelling of Sounds (Test 20)

This subtest measures phonological and orthographic coding as a result of auditory processing. Poor performance may indicate poor phoneme/grapheme knowledge, poor phonological processing or poor auditory attention. Twenty-three nonsense words are read out loud to participants who write down how they think these nonwords would be spelt should they have been real words. The items are scored as per the manual, with a maximum score being 45.

This subtest is noted to have high test-retest reliability in the test manual (r = .76). The reliability of this subtest in the current study was α = .69.

York Adult Assessment Battery – Revised

This assessment battery assesses reading, spelling, writing and phonological skills in adults (YAA-R: Warmington, Stothard, & Snowling, 2013).

Handwriting speed

Participants are instructed to copy the sentence ‘Erosion is a gravity driven process that moves solids in the environment’ as many times as they can in 120 seconds. The score for this subtest is the number of words written in the time allocation divided by two. A poorer score suggests difficulty in writing as a part of literacy skill.

Design and Procedure

The session was conducted in a quiet laboratory and took between one-and-a-half and two hours to complete. The researcher disclosed details regarding the session to the participant, who then read an information form confirming the details that had been explained to them. All participants were informed that they were free to leave the session at any time with no detriment to their course credit or payment. Written consent to take part in the study was then provided by the participant.

The procedure was divided into two parts: (1) setup for the measurement of lateralisation and administration of the laterality measures, lasting for approximately one hour, and (2) administration of the behavioural and reading measures, lasting for approximately 45 minutes. The fTCD setup and laterality tasks were always completed prior to the administration of the behavioural and reading measures.

For part one, participants sat at a desk viewing a desktop computer display screen. A keyboard was placed in front of the participant. Written instructions for the Landmark task were displayed on the computer screen. Participants completed a three-trial demonstration of the Landmark task using the key board as instructed. The researcher monitored participant performance during the demonstration to ensure understanding of the task.

Participants then completed the full Landmark task. Upon completion of the Landmark task, participants were encouraged to take a short break prior to commencing the Word Generation task. The keyboard was removed, and a microphone was placed in front of the participant in its place. Participants then read the instructions for the Word Generation task on the screen. Once they completed this task, the headset was removed, and participants were offered another short break.

For part two of the study, participants moved to a separate table in the same room, sitting directly opposite the examiner. Participants completed the FLANDERS, the full version of the ARHQ-R, and then the QHP task. Reading measures were administered as per the order in Table 5 in the Results section.

Procedure of analysis

Processing laterality data

In order for the analysis of continuous fTCD data, data were divided into epochs with upper and lower values consisting of baseline and period of interest timings in relation to an event marker. Epochs were defined surrounding these event markers from -15 seconds to 30 seconds. The Baseline period occurred from -15 seconds to -5 seconds. The Word Generation and Landmark tasks were coded with event markers to time-lock task related activity via a parallel port. These markers were set to occur at the presentation of the target letter in the Word Generation task, and auditory and visual 'Clear mind' cue in the Landmark task. The period of interest for the Word Generation task was set as 4 to 14 seconds after the event marker (Gutierrez-Sigut et al., 2015). The period of interest for the Landmark task was set as 14 to 24 seconds, deemed as most appropriate for the performance of this sample.

Taking these predetermined conditions into account, DOPOSCCI (version 3) was used in conjunction with MATLAB in order to assess cerebral specialisation of verbal and nonverbal information (Badcock et al., 2018). This is a software which allows researchers to summarise fTCD data while being able to visualise and interpret results (Badcock, Holt, et al., 2012). It is based upon previous data processing methods within the literature (Deppe, Knecht, Henningsen, & Ringelstein, 1997; Deppe, Ringelstein, & Knecht, 2004; Knecht et al., 2001). The software removed extraneous leading and trailing data before the first and after the last epoch in a recording. Then, cardiac cycles were averaged in a linear fashion to remove influence on blood flow (Badcock et al., 2018; Deppe et al., 1997).

In attempt to retain fTCD data where possible, activation correction was performed. Blood flow velocity values below -3 SD and above 4 SD from the mean, which affected less than 5% of the data, were adjusted to the median value of each epoch. Data were normalised on an epoch by epoch basis to a mean of 100 within each epoch in order to correct for left-right probe-angle differences (Deppe, Knecht, Lohmann, & Ringelstein, 2004). Increases and decreases in blood flow activity were measured relative to baseline. Thus, the average value of the baseline period in an epoch was subtracted from all values within that epoch in order to create a reference point for blood flow fluctuation.

Epochs with extreme values were rejected from analysis based on two criteria: (1) epochs including values exceeding a 50% increase or decrease in value from the mean of the epoch values, or (2) epochs including values where left-minus-right activation separation was greater than 8 times the individual's interquartile range of blood flow variability, which affected more than 1% of the data in the epoch (Badcock, Nye, et al., 2012).

Phase One

Calculation of Laterality Indices and their categorisation

At the individual level, the left and right cerebral blood flow values from all acceptable epochs were averaged. The Laterality Index was calculated as the average left-minus-right signal within the period of interest for each individual. Negative values reflect right-hemisphere specialisation and positive values reflect left-hemisphere specialisation. Strength of lateralisation can be interpreted by considering whether the laterality value is very high or very low compared to those calculated for other individuals. Lateralisation categorisation was based on whether the 95% confidence interval (CI) overlapped with zero. Lateralisation was considered to be left if the lower CI was greater than zero, right if the upper CI was less than zero, or bilateral if the CI included zero (Whitehouse & Bishop, 2009). Split-half reliability was calculated by correlating the laterality indices for the odd and even epochs for the group (Bishop et al., 2009). The reliabilities for the Word Generation and Landmark tasks were high; α = .71, CI [.60,.79], and α = .78, CI [.70,.84] respectively.

Behavioural data processing

All behavioural data were scored by hand in session. All reading measures were audio recorded for double scoring. Where discrepancy of scores occurred, the audio was revisited and the result of this third check was used. Raw scores were converted to standard scores where normative data were available. Histograms of each subtest and descriptive statistics were created in GraphPad Prism (Version 8.1.12). The histograms were inspected for normality. Finally, the Word Generation audio files for each participant were transcribed for descriptive analysis of the number of items generated. Landmark accuracy scores for each trial were written to file as a part of our Landmark task MATLAB script.

Penalised regression

The study aimed to assess the existence of a relationship between verbal lateralisation and reading behaviour. To do so, a penalised regression technique was needed. Penalised regression is most suited to research where the measured variables are high in number and are likely associated, as in the current study where there were 30 variables and multiple related reading subskills were measured. The use of this regression controls for the Type 1 error rate risk innate in the number of variables measured. Penalised regression allows for a balance between overfitting the data and achieving a parsimonious model. The application of penalties introduces a bias to the current sample which reduces the variability of the specified model when applied to different samples. As a result, the models are more accurate and informative than those produced by traditional regression methods. The downfall of traditional regression is the successive addition and removal of variables while using an estimation of least squares only on the resulting reduced set of predictors. Traditional regression provides low bias at the cost of poorer accuracy; i.e., less generalisation between different samples. The cost of introducing bias in a penalised regression is therefore small, as the bias ultimately assists with the production of more replicable models in psychological research (Helwig, 2017). When the dataset is made of many variables, a small difference between samples can result in drastically different models (Tibshirani, 1996). The penalised regression minimises this risk.

There are three types of penalised regression models: lasso, ridge, and the elastic-net. A lasso model eliminates variables considered uninformative to the outcome by setting coefficient alphas directly to zero when a parameter is nonsignificant or 'irrelevant' in comparison to others (Ranstam & Cook, 2018). For variables that are related, this model is thought to be too automatic as it selects only a single variable from that group to be included in the model and rejects the other (Yang & Wen, 2018). Due to the large number of variables assessed in the current study which were often tapping into the measurement of common reading skills, this model would therefore have been too rigid to use. This is due to the lack of control over which variables remain included in the model.

Ridge regression is appropriate for use when it is believed that all of the measured variables play some role in predicting an outcome. This is because no variables are removed while this regression is performed. Instead, ridge regression groups correlated variables together and attempts to reduce insignificant groups to zero (Schreiber-Gregory & Henry M Jackson Foundation, 2018). The use of ridge regression assumes all of the measured variables are associated with the outcome being predicted. With this assumption, the use of ridge regression in the current study would make the results susceptible to a Type 1 error. The aim of the current study was to explore the potential relationship between reading measures and verbal laterality; at no point was it certain that any relationship between the assessed reading measure and verbal lateralitt would exist. Thus, a ridge regression was inappropriate for analysis in the current study due to its failure to be selective with variables. Therefore, a balance of selection criteria needed to be achieved.

Elastic-net Regression

The hybrid of the lasso and ridge models of penalised regression is the elastic-net regression and it is best suited to the current data set. The model starts with the sum of the squared residuals and adds the lasso regression penalty as well as the ridge regression penalty. These penalties are known as lambda (λ). The elastic-net model uses a cross validation of λ lasso and λ ridge penalties in order to find the best values for variable coefficients (Zou & Hastie, 2005). This type of penalised regression is thought to be best at dealing with intercorrelated predictor variables: it both groups and shrinks the coefficients of associated variables and then leaves them in the model or removes them all at once.

The current study has a large number of variables which were likely to measure similar outcomes but were unlikely to all be relevant, and so the grouping and removal offered by an elastic-net approach was deemed to be suitable for analysis. An elastic-net regression was therefore conducted using the Glmnet package for use in R Studio (Friedman et al., 2010; RStudio Team, 2018). This package combines the lasso and ridge λs in order to create a single penalty. In order to find the best elastic-net model of outcomes a cross-validation method is typically used. This method when applied to the current study's data produced an improbable result. Following statistical advice from the Macquarie University Faculty of Human Science's statistician, decrease in λ was plotted against change in difference from the null model (R^2) for model selection. A point of visual inflection was used to determine an elastic-net model where maximum variance was gained. This point corresponds to the largest gain in variance explained before there is a diminishing return of adding more variables. In order to confirm the suitability of this model, an Akaike information criteria analysis was performed on surrounding models of this inflection. A linear regression was run on the elastic-net outcome model in order to estimate the explained variance.

Phase Two

The incidence of poor reading

To diagnose dyslexia, we used the phonological decoding and sight words subtests of the TOWRE 2, as well as the Letter Position test. We categorised the following types of dyslexia: (1) phonological dyslexia, (2) surface dyslexia, (3) mixed dyslexia (phonological and surface dyslexia), and (4) letter position dyslexia. The following cut-offs were used in order to diagnose individuals: less than -1.3 standard deviations below the mean on one test and greater than 1 standard deviation above the mean on another (McArthur et al., 2013). As there were no standard scores for the Letter Position test, and higher scores relate to more errors, Z scores were calculated and then reversed for classification purposes.

Phonological dyslexia was defined as having a TOWRE Phonemic Decoding score below -1.3 SD from the mean and a TOWRE Sight Word score above -1 SD from the mean. Surface dyslexia was defined as having a TOWRE Sight Words score below -1.3 SD from the mean and a TOWRE Phonemic Decoding score above -1 SD from the mean. Letter position dyslexia was defined as having a Letter Position test score less than -1.3 SD from the mean and TOWRE Phonemic Decoding and Sight Words scores greater than -1 SD from the mean. The Letter Position test approach has its limitations as it does not have normative data. However, we created norms based on the randomly recruited participants for the current study only (*n* = 85). Mixed dyslexics were defined as having both phonological and surface dyslexia. They had TOWRE Phonemic Decoding and Sight Words scores less than -1.3 SD from the mean. Below average readers were defined as having a score on the TOWRE Phonemic Decoding, Sight Words or Letter Position test below -1.3 SD from the mean. The number of individuals identified as aforementioned poor readers are displayed in Table 3.

Table 3. Incidences of poor reading subtypes

Poor reading subtype	N
Phonological dyslexia	1
Surface dyslexia	1
Mixed dyslexia	0
Letter position dyslexia	13
Below average reader	6

Neural configuration group comparisons

In order to ascertain whether there were patterns of behaviour associated with neural configurations, the individuals with crowded neural configurations were matched to a typical, a mixed, and a bilateral individual. Matches were randomly generated using R Studio by minimising the difference between each crowded case (n = 11) on age, sex, and FLANDERS handedness. There were only 8 bilateral cases, therefore all of these individuals were used.

One-way ANOVAs and Gabriel tests

Group means for each neural configuration were calculated on all fluency variables highlighted by the final linear regression model from Phase 1 of the analysis. These groups were compared, with the use of a Gabriel test which is a post-hoc test for unplanned contrasts of uneven group sizes (e.g., n = 11 versus n = 8).

Relationship between poor reading and neural configurations

A chi-squared test was conducted to reveal any relationship between poor reading and neural configurations of verbal and nonverbal information processing. To confirm any null effects, Bayesian statistics were included. R Studio and the default settings of the BayesFactor package (version 0.9.12-4.2) were used to conduct the analyses (R Core Team, 2019; RStudio Team, 2015). A Bayes factor contingency analysis was performed in order to determine whether the outcome was conclusive. Finally, one-way ANOVAs for words generated, Landmark accuracy, and overall neural activation would be run on the verbal and nonverbal tasks to ensure no one configuration was effortfully overexerting another.

Results

Phase One

Verbal and nonverbal laterality

Group-averaged change in blood flow velocity for the Word Generation and Landmark tasks are displayed in Figure 5. The verbal lateralisation task showed significantly higher left-hemisphere activation, with a positive difference from zero; $t(116) = 4.16$, $p < .001$, $d = 0.38$; and the nonverbal lateralisation task showed significantly higher right-hemisphere activation, with a negative difference from zero; $t(115) = -13.28$, $p < .001$, $d = -1.23$. These results are consistent with previous uses of the Word Generation and Landmark tasks as measures of verbal and nonverbal laterality. Verbal laterality displayed no significant correlatation with nonverbal laterality (see Figure 6, $r = 0.11$, $p = .24$). The results were therefore in line with statistical theory.

Neural configurations

Individuals received a Laterality Index per task performed, defining their overall neural configuration. Evidence was found for all neural configurations noted in the literature. Figure 6 displays scatterplots of individual laterality indices with error bars of 95% confidence intervals and their categorisation as a result of their respective values. Table 4 details the prevalence of each configuration in the current sample

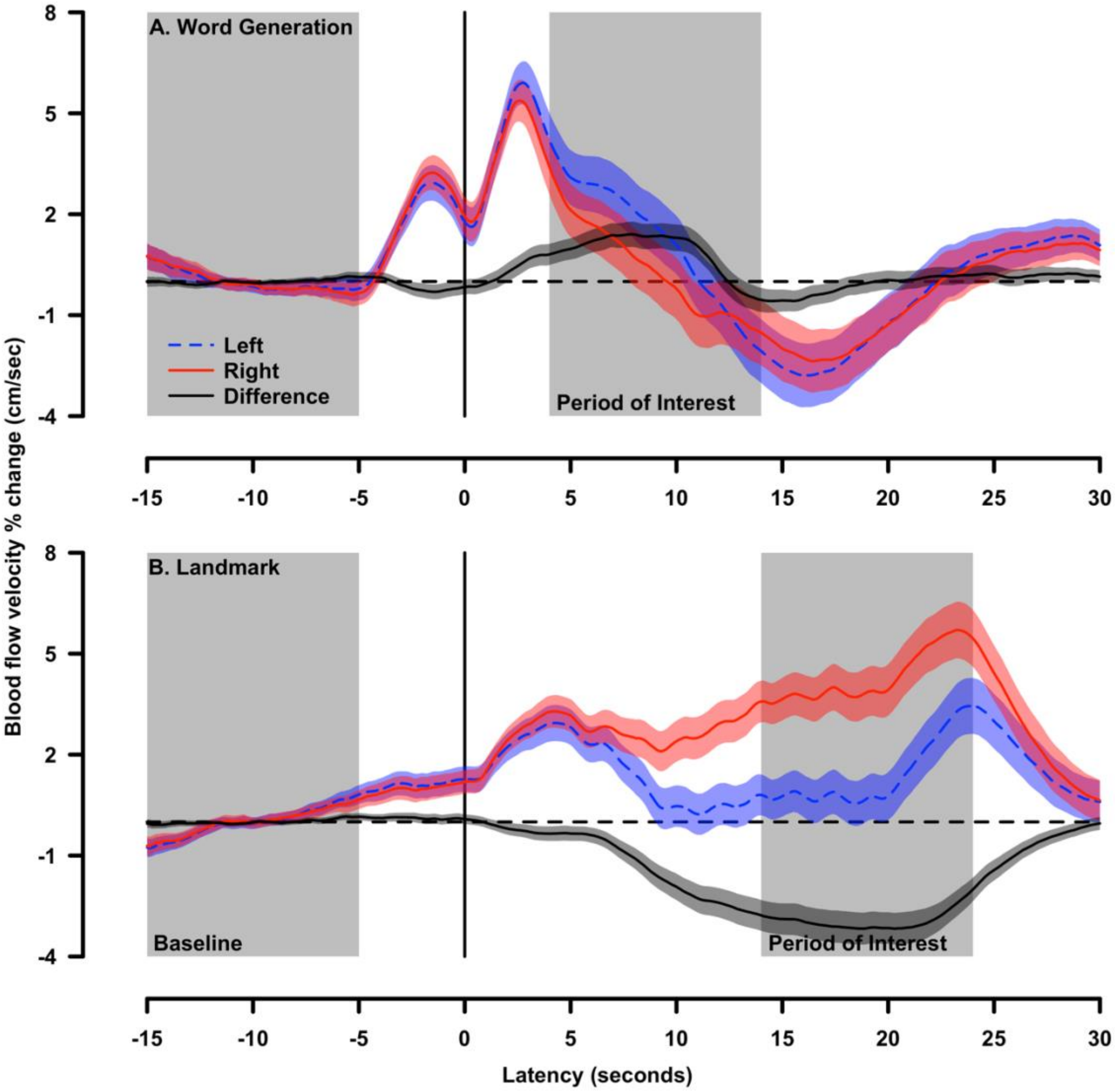

Figure 5. Group averaged change in blood flow velocity for the verbal and nonverbal tasks for the left and right hemispheres, and left-minus-right difference, as a function of task latency.

Notes. Error regions reflect the 95% confidence intervals.

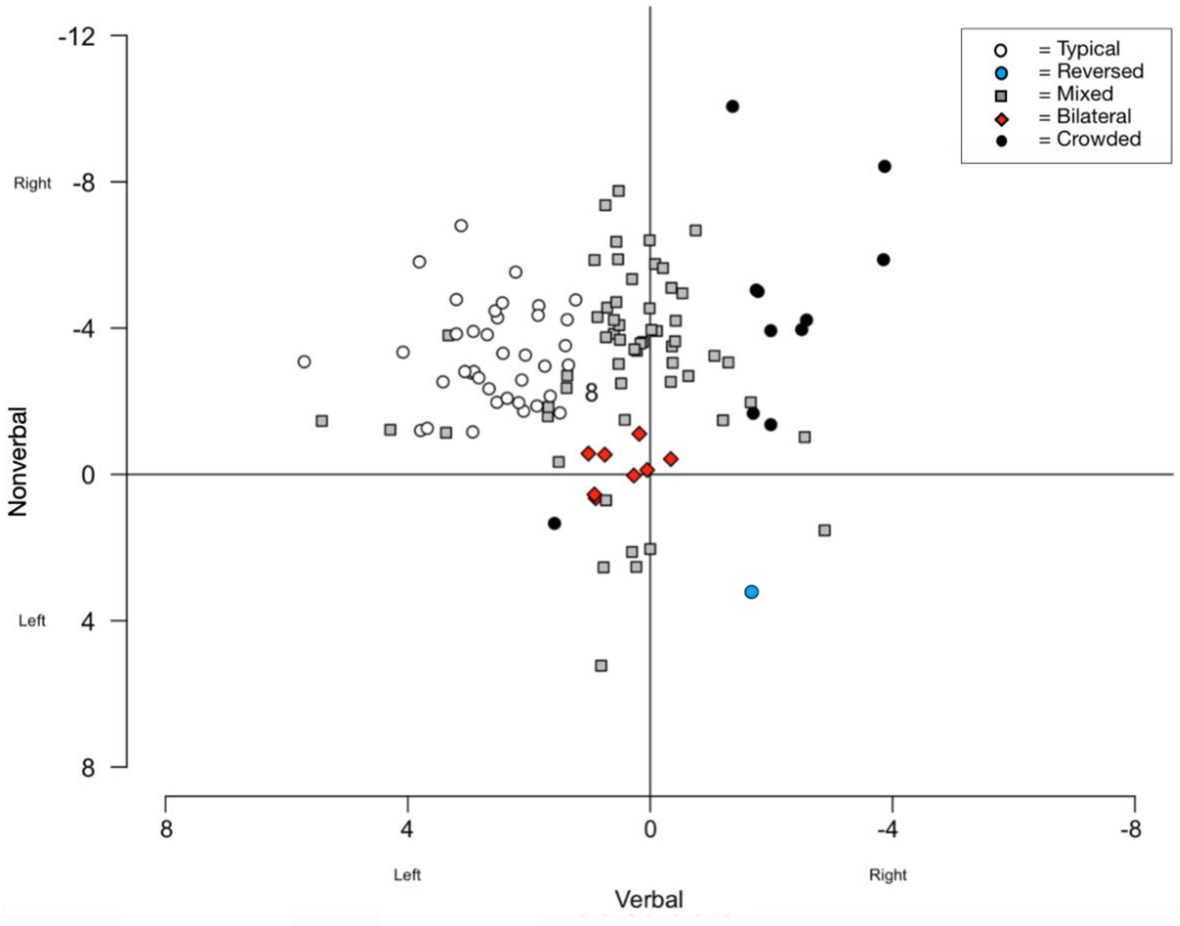

Figure 6. Scatterplot of laterality indices for both verbal and nonverbal tasks after consideration of 95% confidence intervals.

Table 4. Prevalence of neural configurations in the sample

Neural Configuration	Configuration Style	N
Typical	Left hemisphere for language, right hemisphere for perception	37
Reversed	Right hemisphere for language, left hemisphere for perception	1
Mixed	Both hemispheres for language, right hemisphere for perception	47
	Both hemispheres for language, left hemisphere for perception	6
	Left hemisphere for language, both hemispheres for perception	4
	Right hemisphere for language, both hemispheres for perception	2
Bilateral	Both hemispheres for language, both hemispheres for perception	8
Crowded	Left hemisphere for both language and perception	1
	Right hemisphere for both language and perception	10

Reading outcomes

The group reading outcomes are presented in Table 5. The distributions for all of the measures were normal.

Table 5. Descriptive statistics of behavioural performance for the entire sample.

Measures	M	SD	Median	Range
TOWRE-2				
Sight Word Efficiency	104.74	12.32	104	80 - 130
Phonemic Decoding Efficiency	107.33	12.30	108	80 - 130
CC2-A				
Real Word Reading	51.40	31.58	50	0 - 100
Irregular Word Reading	46.20	32.73	42	1 - 100
Pseudoword Reading	38.54	30.96	32	1 -1 00
WIAT-III				
Oral Expression				
Expressive Vocabulary	99.84	12.88	97	65 - 130
Oral Word Fluency				
Animals	71.81	9.67	71	49 - 96
Colours	61.64	7.76	61	47 - 82
Sentence Repetition	101.47	13.75	100	75 - 140
WIAT-III				
Oral Reading Fluency				
Oral Reading Accuracy	101.86	13.27	99	74 - 119
Oral Reading Fluency	108.66	8.88	109	90 - 134
Oral Reading Rate	40.00	0.00	40	40
Listening Comprehension				
Receptive Vocabulary	106.46	16.39	110	18 - 135
FriCasKoh				
Single Word Reading				
Total Words Read	135.84	2.95	137	127 - 140
Total Seconds Taken	82.34	15.32	79	38 - 129
Word Pairs				
Total Words Read	68.45	1.75	69	62 - 70
Total Pairs Read	33.47	1.69	34	27 - 35
Total Seconds Taken	41.80	7.54	42	19 - 67
Non-Word Reading				
Total Words Read	27.36	2.44	28	19 - 30
Total Seconds Taken	27.36	8.38	25	14 - 62
WJ-III				
Spelling (Test 7)	15.55	2.89	16	6.7 - 18
Spelling of Sounds (Test 20)	12.84	4.06	13	2.8 - 18

Measures	M	SD	Median	Range
YAA-R				
Writing Speed	30.61	4.23	30	21.5 - 42
CTOPP-2				
RAN				
Colours	20.95	3.96	21	14 - 36
Objects	23.11	3.92	22	15 - 35
The Letter Position Test				
Total Words Read	37.35	8.98	36	24 - 72
Total Seconds Taken	57.29	2.98	58	43 - 60
Word Generation Task				
Total words spoken per session	92.99	19.72	91	53 - 147
Words generated per trial	4.7	1	4.6	2.7 - 7.4
Landmark Task				
Accuracy	0.75	0.13	1	0.31 - 0.96

Result of elastic-net regression

Figure 7 displays the plot of a decrease in λ against change in difference to R^2. The point of visual inflection where maximum variance is gained is denoted by the vertical dashed line. This sweet-spot of λ strength was between steps 12-14 of λ application. An AIC was run on the output of each of these levels of λ. The highest quality model was at λs 13 and 14 (AIC = 450.69) The point where maximum variance was gained was decided to be the model produced at λ step 13.

Relationship between reading fluency and verbal laterality

A linear regression was then performed on the nine variables in the elastic-net model, tabulated in Table 6. The significant variables and others in the model reflected fluent speeded oral reading and retrieval of vocabulary. The RAN Colours displayed a significant positive relationship between right lateralisation and reading fluency, the opposite of the expected left lateralised behavioural advantage. The difference in relationship direction between the FriCasKoh Single Word and Word Pair subtests may be due to task difference (i.e., list reading versus prevention of word/letter migration) and task length (i.e., 140 items versus 35 items). Perhaps the Word Pair subtest calls upon a type of information processing best to be predominantly performed in the left hemisphere.

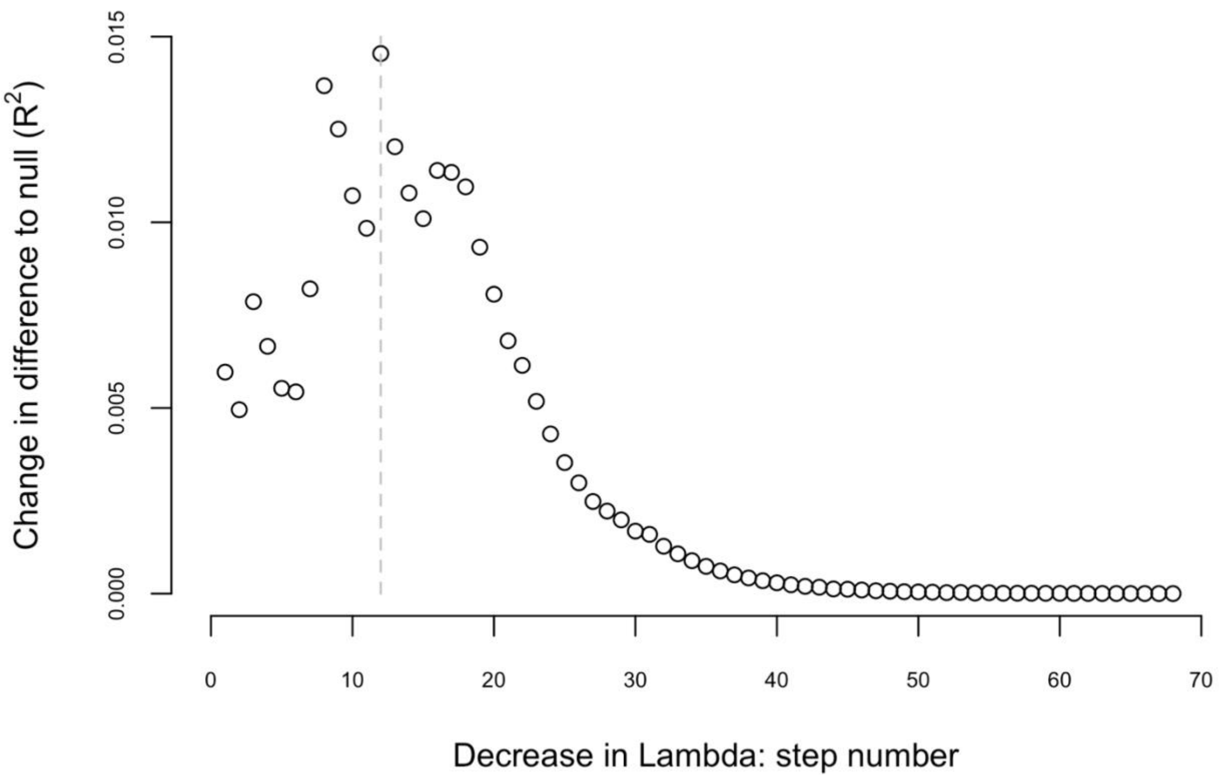

Figure 7. Difference from R^2 as a function of decreasing λ regularisation.

Table 6. Linear regression of elastic-net regression outcomes.

	Estimate	Std. Error	t value
Intercept	-5.133	4.113	1.248
WIAT-III			
Oral Expression			
Expressive Vocabulary	-0.028	0.015	1.897
Oral Word Fluency			
Animals	0.037	0.019	1.918
Oral Reading Fluency			
Oral Reading Fluency	0.020	0.025	0.793
Oral Reading Accuracy	0.014	0.015	0.927
FriCasKoh			
Single Word Reading			
Total Seconds Taken	0.036	0.016	2.208*
Word Pairs			
Total Seconds Taken	-0.076	0.035	2.192*
CTOPP-2			
RAN			
Colours	0.134	0.049	2.740**
FLANDERS	0.032	0.021	1.548
Landmark Task	0.061	0.072	0.846

Notes. ** < .001, * < .01
Residual standard error: 2.839 on 101 degrees of freedom | Multiple R-squared: 0.096
F (11,101) = 2.089, p = .028

Neural configuration group comparisons

Results from one-way ANOVAs comparing group means for variables revealed in the linear model and used to diagnose dyslexia (TOWRE-2) are presented in Table 7. Post-hoc Gabriel test analyses are found in Appendix 3. The following analyses are explored by looking at the Crowded group differences initially, which should display significantly poor performance on reading measures in comparison to other groups based on competition for resources. The Typical group is explored thereafter, which should display significantly higher performance on reading measures in comparison to the other groups based on no competition for resources.

Crowded comparisons

The significance found for TOWRE-2 Phonemic Decoding was driven by a difference between the Crowded and Bilateral groups, where the crowded individuals performed worse than their bilateral peers. The significance of the WIAT-III Oral Reading Fluency variable was driven by a difference between the Crowded group and both the Bilateral and Mixed groups, where the crowded individuals performed worse than their bilateral and mixed peers. The WIAT-3 Oral Expression - Animals significance was driven by a difference between the Crowded group, and the Mixed and Bilateral groups, with the crowded group again being outperformed by their mixed and bilateral peers. Finally, the significance of the FriCasKoh Word Pairs variable was driven by a difference between the Crowded and Bilateral groups where the crowded individuals performed worse than their bilateral peers.

Typical comparisons

The significance found for the CTOPP-2 RAN Colours was driven by the difference between the Typical and Mixed groups, where the typical individuals performed worse than their mixed peers. The significance of the WIAT-III Expressive Vocabulary variable was driven by a difference between the Typical and Bilateral groups, where the typical individuals were outperformed by their bilateral peers. The significance of WIAT-3 Oral Reading Accuracy was driven by a difference between the Typical and Mixed groups, where the mixed individuals outperformed their typical peers. While no groups performed below average, it is clear that the Bilateral and Mixed groups possessed an advantage over their crowded and typical peers.

Unexpected achievers: Bilateral and Mixed groups

To curtail the possibility that Mixed and Bilaterally configured individuals may be outperforming their peers due to an increase in effort, one-way ANOVAs were performed to compare average performance of configurations on accuracy in the Landmark task and the number of words generated in the Word Generation task, as well as overall fTCD activation values for each task. Words generated, $F(3, 36) = 1.18$, $p = 0.331$, $n_2 = 0.09$, and Landmark accuracy, $F(3, 37) = 0.96$, $p = 0.42$, $n_2 = 0.07$, between groups did not differ significantly. Activation for the Word Generation, $F(3, 37) = 0.41$, $p = 0.745$, $n_2 = 0.03$, and the Landmark task, $F(3,37) = 0.65$, $p = 0.591$, $n_2 = 0.05$, did not differ significantly. These results suggest some inherent benefit to possessing Bilateral and Mixed configurations.

Relationship between poor reading and neural configurations

Poor reading was not related to neural configuration, χ_2 (3, $N = 116$) = 7.26, $p = .06$. Due to the closeness of this *p*- value to significance, a Bayes Factor Contingency analysis was conducted. The resulting Bayes factor was 1.01, suggesting that the finding in the current study is inconclusive based on this sample size.

Table 7. Results from one-way ANOVAs comparing group means for variables.

Variable		Group: M (SD)								F	η2
		Crowded		Typical		Mixed		Bilateral			
CTOPP-2	RAN (Colours)	21.64	(3.11)	22.00	(4.40)	*19.73*	*(5.12)*	19.63	(3.07)	3.5*	0.22
TOWRE-2	Phonemic Decoding	103.45	(9.08)	102.36	(12.82)	110.36	(11.33)	**118.13**	**(11.28)**	3.85*	0.24
	Sight Words	100.73	(13.48)	102.82	(10.66)	113.18	(13.30)	111.75	(13.70)	2.54	0.17
Letter Position Test	Seconds Taken	41.36	(8.21)	39.55	(10.53)	33.36	(4.54)	32.38	(5.80)	2.12	0.15
WIAT-III	Expressive Vocabulary	100.73	(13.14)	97.18	(12.99)	107.09	(11.53)	*113.00*	*(10.27)*	3.11*	0.2
	Oral Reading Fluency	103.00	(7.81)	106.55	(9.61)	**114.45**	**(4.11)**	**115.88**	**(9.09)**	6.25*	0.34
	Oral Reading Accuracy	97.00	(92.13)	92.82	(4.64)	*110.18*	*(12.58)*	104.88	(15.56)	4.88*	0.28
	Oral Expression (Animals)	65.00	(8.29)	73.45	(8.76)	**77.64**	**(7.34)**	**79.88**	**(10.70)**	5.78*	0.32
FRICASKO	Word Pairs	45.45	(6.52)	42.27	(9.19)	38.91	(4.85)	**35.75**	**(7.65)**	3.24*	0.21
	Single Words	84.91	(15.81)	84.64	(17.85)	73.36	(9.72)	81.50	(15.38)	1.43	0.1
Verbal Laterality	Words Generated	89.55	(20.26)	91.27	(20.82)	94.00	(25.60)	92.36	(35.14)	1.18	0.09
	Activation	4.96	(6.61)	3.84	(7.87)	0.65	6.94	3.70	(6.94)	0.41	0.03
Nonverbal Laterality	Landmark Accuracy	0.73	(0.14)	0.78	(0.10)	0.69	(0.17)	0.75	(0.14)	0.65	0.05
	Activation	5.18	(5.52)	4.30	(6.54)	6.94	(5.77)	7.17	(2.10)	0.96	0.07

Notes. '*' denotes significance (p = < 0.05). Bold: score significantly better than crowded score. Italic: score significantly better than typical score. Activation = Period Average Blood Flow Velocity Value

Discussion

The current study sought to explore whether there was any association between verbal lateralisation and reading behaviour, and whether neural configurations of lateralisation would be associated with behavioural disadvantage. In the current sample, verbal and nonverbal information processing lateralised independently. Most interestingly, verbal laterality was related to reading behaviour; specifically to measures which were all indicative of reading fluency. Advanced reading skill is said to require a combination of phonological awareness and a fluency factor (Wolf & Bowers, 2000). So, the current study suggests that the behavioural relevance of laterality may lie in the relationship of verbal information processing and reading. The CTOPP-2 RAN is known to predict oral reading fluency to a great extent (Papadopoulos et al., 2016), and this variable held the most significant relationship with verbal laterality. Other significant relationships between reading and verbal laterality highlighted oral reading ability, including oral expression and oral reading accuracy.

The low-level processes called upon by the RAN include graphemic and phonological knowledge, oculomotor behaviour and the sequencing of stimuli (Jones et al., 2009). The subtest's assessment of these processes reflect the role of perception in reading that neural configurations may impact. While nonverbal information processing was not significantly relevant to verbal information processing, the relationship was still present in the model from the elastic-net regression. What is known of the RAN task is that perceptual attention must rapidly disengage from current stimuli in order to engage with the next (Altani et al., 2017). This is reflected in the process of mapping speech units onto orthographies, with failure to efficiently process letters of words negatively impacting reading fluency. The exploration of laterality and reading in the current study has revealed preliminary support for the idea that the behavioural relevance of verbal laterality may be in regard to reading fluency.

Hemispheres working together

Hemispheres working together may be the answer to understanding better cognitive performance. The current study revealed that 32% of the sample possessed a typical neural configuration. Interestingly, 41% of the sample possessed a mixed configuration where verbal processing was bilateral in nature and nonverbal processing remained in the right hemisphere. This provides some understanding as to why the current sample showed an overall strong relationship between reading fluency and right-sided verbal lateralisation, while the opposite was originally expected. Approximately half of the current sample had a level of verbal processing occurring in their right hemisphere along with nonverbal processing. Further, the group comparison displayed that while typically configured individuals on average performed reading tasks with no difficulty, mixed and bilateral individuals performed better than their typical peers on reading tasks. Thus, there appears to be an advantage to having a less lateralised configuration for verbal processing on reading fluency. So, while reduction in hemispheric cross-talk for reading fluency may occur as an evolutionary and ‘typical’ process of the brain (Waldie et al., 2013), perhaps failure to specialise during development is just as common, and even beneficial. The question of how this advantage has arisen may be answered by a review of the corpus collosum.

The potential role of the corpus collosum

The corpus collosum is a fibre tract, enhancing the communication of information across the cerebral hemispheres (Gazzaniga, 2000). It is debated whether the purpose of the corpus collosum is to excite both hemispheres to process information, supporting a more bilateral view of language information processing, or to inhibit the activation of two hemispheres for the performance of one function, supporting the development of a typical neural configuration (Bloom & Hynd, 2005). And so, who is able to be benefit, and when are they able to benefit, from having a corpus collosum?

While some hypotheses exist suggesting that each hemisphere possesses different time and frequency processing abilties which may play a role in the specialisation of verbal and nonverbal functions (Washington & Tillinghast, 2015), differences in corpus callosal size could also be a mediator of hemispheric specialisation and cognitive performance during development (Westerhausen et al., 2018). The larger the corpus callosum, the more it is thought to hinder the capacity of the soon-to-be underspecialised hemisphere to complete verbal information processing (Hinkley et al., 2016; Josse et al., 2008). A typical neural configuration therefore does not use the full extent of the resources available in the brain to process verbal information. Rather, this configuration predominantly uses only half of the available resources in the brain and strengthens this use for adequate efficiency. While this may not be detrimental to reading performance, a large corpus callosum could therefore be an impediment to an individual in unlocking advanced reading achievement.

In contrast, decreased corpus callosal size could be what assists those with mixed and bilateral configurations of verbal information processing in achieving above average reading performance. No resources in either hemisphere are hindered when corpus callosal size is decreased. It is the activation of all available resources in the brain and the opportunity for maximized cross-talk between hemispheres which would benefit mixed and bilateral neural configurations (Hirnstein et al., 2008). Thus, for the behaviour of reading fluency at least, it appears that the team work of both hemispheres is better than a single hemisphere specialising in a cognitive process alone.

Cognitive performance and sex differences

It has been posited that stronger lateralisation predicts higher nonverbal processing performance and lower verbal processing performance for males (Hirnstein et al., 2019). Bilateral or mixed neural configurations of verbal processing in females is thought to be indicative of their superior verbal ability (Dorion et al., 2000; Levy & Reid, 1978). As highlighted in the Methods section, the current sample was over-represented by females. So, finding an advantage of these neural configurations within our own study may flag the possibility of inflation due to sex. However, other studies have suggested that sex is not a significant factor in regard to laterality and performance and may only be present for certain verbal tasks (e.g., present for phonological but not semantic tasks; (Shaywitz et al., 1995; Sommer, Aleman, Bouma, & Kahn, 2004)). Despite this, the discrepancy calls for future studies to seek a more sex-balanced sample during recruitment, including sex as a factor in the analyses with adequate power in order to be rid of this limitation.

Reading and the Crowded Neural Configuration

The search for an underlying neural mechanism for poor reading has been prominent. An aim of this study was to explore the potential of the crowded neural configuration to be a risk factor for poor reading. The current study could not conclude that neural configurations are correlated with poor reading. In fact, a crowded configuration appears to be on par with a typical configuration. The following points will explore the limitations of the current study which may have been relevant to the inconclusive result.

The need for a more generalised reading sample

Our understanding of crowding and reading could perhaps be better informed if a sample of both university students and those from the general population were recruited. University level students may have been exposed to developmental environments which impact their attitude toward reading, allowing for heightened reading experience, altering their ability (Verboord & van Reese, 2003). While we recruited for reading variability, low reading performance of an individual at university level may not be comparable to low reading performance of those in the wider population. Future research should keep focused on accessing variable populations by the recruitment strategies in the current study, however the ARHQ-R should also be administered to members of the wider population in order to access a more general sample of poor readers of varied ability.

Unlocking the role of age in a crowded configuration

The current study did not have the capacity to assess the literature regarding hemispheric deactivation for reading fluency over the course of development. A study testing children has highlighted no effect of possessing a crowded configuration, with no significant difference in cognitive performance between typical or crowded individuals being found (Groen et al., 2012). Other child samples have also displayed that bilateral or reversed configurations of language are linked positively to verbal language performance (Everts et al., 2010). In contrast, adults have evidenced lower levels of verbal and nonverbal task performance being found in those with a crowded configuration in comparison to their typical peers (Powell et al., 2012). Yet, the current study provided no evidence of a relationship between possession of a crowded configuration and being a poor adult reader.

A possible explanation for the inconsistency of results across age groups could be explained by sample demography in the current study and the potential negative effect of less hemispheric interaction during reading development (Yu et al., 2014). Child samples which do not display a detriment of crowding unlike in adult samples could be suggestive of negative crowding effects developing with age. With three of the current study's eldest participants (age > 30) possessing crowded configurations, and two of these individuals being poor readers, this notion is worth further exploration. While the finding may be spurious, future studies should include a group of middle-aged and older adults in their samples to establish any rate of change in neural configuration toward a crowded configuration with ageing.

Future directions

Further work should be completed among both children, adolescent, middle-aged and older adults in order to examine the impact of neural configurations on cognitive performance throughout development. Preferably, this research would be longitudinal in nature to enable cognitive abilities and neural configurations to be tracked over time at an individual level. However, cross-sectional studies of varying age categories could also provide substantial opportunity to explore and compare group differences. For example, cross-sectional studies across a key transition period, such as before and after receiving reading training at school, would contribute to our understanding of the causality or consequence of neural configuration on development and the role of the corpus callosum. As a starting point, assessment of corpus callosal size and function is required. To do this, research plans would need to budget the use of MRI for structural and functional imaging, or EEG for behavioural assessment looking at the rate of transfer between the hemispheres while performing reading tasks. FTCD may be appropriate for screening of neural configurations prior to participants being assessed by more expensive techniques. Studies in these fashions would allow the assessment of laterality for verbal and nonverbal processes over an even more varied population in the developing brain.

Conclusion

The significance of this work was its finding that the lateralisation of verbal information processesing was related to the behaviour of reading fluency. The lateralisation of both verbal and nonverbal information processing were independent from one another. Reading fluency was significantly related to predominantly right sided lateralisation of verbal processing, which was the opposite finding of that expected from literature, but could perhaps be explained by the large number of mixed configured individuals who were bilateral for verbal processing in the current sample.

The current study provided inconclusive evidence as to whether there was an association between the four neural configurations and poor reading ability. Most interestingly, the available data shows that while a typical neural configuration of verbal and nonverbal information processing does not surmount to cognitive advantage, neither did a crowded neural configuration. Both groups performed at an average level of reading fluency. The way in which the neural configurations were believed to be on a spectrum in terms of competition for resources while performing different tasks concurrently was therefore not evidenced.

The mixed and bilateral configurations unexpectedly offered cognitive advantage, with above-average performance for reading fluency displayed in this sample. It appears that hemispheres working together do better than those hemispheres solely performing a specialised function, or performing two functions at the same time. Further research as outlined above should be pursued in order to continue the expansion of our knowledge of reading fluency and neural configurations of verbal and nonverbal information processing.

Appendix 1.

Instructions for the Word Generation task

This session can be broken down into trials.

Each trial begins with a rest period. It is important to relax and not speak during this period.

You will then be instructed to "Clear Mind". Let your mind go blank.

You will then see a letter appear on the screen.

Say as many words as you can that begin with that letter.

When you see the word "Stop", stop saying words.

Then follow the instruction to "Relax" until the next trial.

If you have any questions, please ask them now. Otherwise, say that you are ready to begin

Appendix 2.

Instructions for the Landmark task

Let your mind go blank.

After a rest period, you will be instructed to ’Clear Mind'.

When you see a long horizontal and a short vertical line on the screen,

choose whether the vertical line is at the centre or not.

Press the 'B' key for centre and the ‘?/" key for left or right of centre.

When you see the word 'Relax' let your mind go blank.

It is important that you do not talk during the rest period.

If you have any questions, please ask them now. If not, press spacebar to start.

Appendix 3.

Gabriel post-hoc tests

Variable		Neural Configuration		Mean Difference	95% CI	Cohen's d
CTOPP-2	RAN (Colours)	Crowded	Typical	0.05	[-0.91, 1.00]	0.03
			Mixed	-0.92	[-1.87, 0.03]	-0.57
			Bilateral	-0.51	[-1.54, 0.53]	-0.29
		Typical	Mixed	-0.97*	[-1.92, -0.01]	-0.6
TOWRE-2	Phonemic Decoding	Crowded	Typical	1.64	[-11.83, 15.11]	0.07
			Mixed	-6.46	[-19.93, 7.02]	-0.28
			Bilateral	-14.67*	[-29.3, -0.04]	-0.59
		Typical	Bilateral	-16.307*	[-30.94, -1.67]	-0.66
	Sight Words	Crowded	Typical	-1.64	[-16.7, 13.42]	-0.06
			Mixed	-12.27	[-27.33, 2.79]	-0.48
			Bilateral	-11.02	[-27.38, 5.34]	-0.4
Letter Position Test	Seconds Taken	Crowded	Typical	0.47	[-0.57, 1.5.00]	0.27
			Mixed	-0.27	[-1.31, 0.76]	-0.16
			Bilateral	-0.46	[-1.58, 0.66]	-0.24
WIAT-III	Expressive Vocabulary	Crowded	Typical	0.27	[-0.83, 1.38]	0.15
			Mixed	-0.49	[-1.6, 0.62]	-0.26
			Bilateral	-0.95	[-2.15, 0.26]	-0.46
		Typical	Bilateral	-1.21784*	[-2.42, -0.02]	-0.6

Notes. * denotes significant difference between groups. Table continued on next page.

	Variable	Neural Configuration		Mean Difference	95% CI	Cohen's d
WIAT-III	Oral Reading Fluency	Crowded	Typical	-0.39	[-1.42, 0.63]	-0.23
			Mixed	-1.27*	[-2.29, -0.24]	-0.73
			Bilateral	-1.42*	[-2.54, -0.31]	-0.75
	Oral Reading Accuracy	Crowded	Typical	0.32	[-0.71, 1.34]	0.18
			Mixed	-0.99	[-2.02, 0.04]	-0.57
			Bilateral	-0.59	[-1.71, 0.52]	-0.31
		Typical	Mixed	-1.31*	[-2.34, -0.28]	-0.75
	Oral Expression (Animals)	Crowded	Typical	-0.88	[-1.94, 0.19]	-0.49
			Mixed	-1.31*	[-2.37, -0.25]	-0.73
			Bilateral	-1.54*	[-2.7, -0.39]	-0.79
FRICASKO	Word Pairs	Crowded	Typical	-0.42	[-1.55, 0.71]	-0.22
			Mixed	-0.87	[-1.99, 0.26]	-0.45
			Bilateral	-1.28*	[-2.51, -0.06]	-0.62
	Single Words	Crowded	Typical	-0.02	[-1.18, 1.14]	-0.01
			Mixed	-0.76	[-1.92, 0.4.00]	-0.39
			Bilateral	-0.22	[-1.48, 1.04]	-0.1

Notes. * denotes significant difference between groups.

Appendix 4.

Ethics clearance

Human Sciences Subcommittee
Macquarie University, North Ryde
NSW 2109, Australia

MACQUARIE University

18/12/2018

Dear Dr Badcock,

Reference No: 5201835496718
Project ID: 3549
Title: The Neural Location of Language Processing and Its Effect on Reading

Thank you for submitting the above application for ethical review. The Human Sciences Subcommittee has considered your application.

I am pleased to advise that ethical approval has been granted for this project to be conducted by Dr Nicholas Badcock, and other personnel: Nicola Filardi, Professor Gregory Savage.

This research meets the requirements set out in the National Statement on Ethical Conduct in Human Research 2007, (updated July 2018).

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the National Statement, available from the following website: https://nhmrc.gov.au/about-us/publications/national-statement-ethical-conduct-human-research-2007-updated-2018.

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol. You will be sent an automatic reminder email one week from the due date to remind you of your reporting responsibilities.

3. All adverse events, including unforeseen events, which might affect the continued ethical acceptability of the project, must be reported to the subcommittee within 72 hours.

4. All proposed changes to the project and associated documents must be submitted to the subcommittee for review and approval before implementation. Changes can be made via the Human Research Ethics Management System.

The HREC Terms of Reference and Standard Operating Procedures are available from the Research Services website: https://www.mq.edu.au/research/ethics-integrity-and-policies/ethics/human-ethics.

It is the responsibility of the Chief Investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Faculty Ethics Officer.

The Human Sciences Subcommittee wishes you every success in your research.

Yours sincerely,

Dr Naomi Sweller

Chair, Human Sciences Subcommittee

The Faculty Ethics Subcommittees at Macquarie University operate in accordance with the National Statement on Ethical Conduct in Human Research 2007, (updated July 2018), [Section 5.2.22].

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