

Developing a unified framework of reading and attention through attentional-oculomotor exercise and cognitive neuroscience examinations of frontal-eye-field structure and function

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ABSTRACT

Reading is a cognitive skill that involves integrating multiple processes. One of these processes is attention, but the theoretical models of reading and attention are typically considered separately. Given the role of attention in successful reading, and research that suggests attention is affected in dyslexia, this thesis proposes a unified framework of reading + attention to better understand how these cognitive processes work together, with a focus on the attentional process of oculomotor activity.

Experiment 1 developed a novel approach to isolate orthographic lexical decision processing and a gaming-style health bar task to manipulate attentional-oculomotor exercise. Through manipulation of stimulus location, Experiment 1 suggested peripheral attentional-oculomotor exercise was more beneficial to reading performance than central attentional-oculomotor exercise, supporting recent theories of oculomotor activity in reading. Experiments 2 and 3 further developed this paradigm, and observed benefits of both peripheral and central attentional-oculomotor exercise on reading suggesting fine-grained oculomotor processes may also play a role in the reading + attention relationship. All three of these studies observed word frequency of lexical targets was associated with improved performance in the lexical decision task while bigram frequency of sublexical foils was associated with worse performance, which will be a useful measure for future studies that are attempting to isolate these processes.

Experiment 4 used data from a hybrid reading and attention fMRI experiment to localize the interaction between reading and attention in the frontal-eye-field – a region involved in oculomotor activity. An interaction in fMRI activation was observed in the frontal-eye-field, supporting theories of the region's involvement in reading and attention. The frontal-eye-field region of interest identified in Experiment 4 was used in Experiment 5 to identify the connectivity profile of the frontal-eye-field with other reading + attention regions. Connections with the basal ganglia, cerebellum, and superior parietal lobule were highlighted, which are implicated across a number of components in the reading and attention networks.

Using these findings as a framework, a combined model of reading + attention was proposed to serve as a foundation for future research on reading + attention. The findings will have implications in both the research fields of reading and attention, as well as applications in the development of reading interventions for dyslexia, which can benefit from attentional-oculomotor exercise.

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LIST OF ABBREVIATIONS

A-O	attentional-oculomotor
A6vl	ventrolateral Brodmann's area 6
BOLD	blood oxygen level-dependent
dIPu	dorsolateral putamen
DTI	diffusion tensor imaging
EPI	echo-planar imaging
EW	exception word
FEAT	FMRI Expert Analysis Tool
FEF	frontal-eye-field
fMRI	functional magnetic resonance imaging
FSL	FMRIB Software Library
GLM	general linear model
GP	globus pallidus
HAL	Hyperspace Analogue to Language
HBDT	health bar decision task
HCP	Human Connectome Project
LDT	lexical decision task
MNI	Montreal Neurological Institute
MPRAGE	magnetization prepared rapid acquisition gradient echo
MRI	magnetic resonance imaging
MSE	mean square error
OLDT	orthographic lexical decision task
PH	pseudohomophone
TE	echo time
TR	repetition time

CHAPTER 1: Introduction

This chapter is adapted from the content of the following manuscripts:

Kress, S., Caron, S., Neudorf, J., Borowsky, B., & Borowsky, R. (submitted). Practice in the periphery: Effects of central vs peripheral attentional-oculomotor exercise on reading and graphical tasks. Submitted to: *Quarterly Journal of Experimental Psychology*.

Kress, S., Neudorf, J., Ekstrand, C., & Borowsky, R. (submitted). Bridging reading and attention through connectivity with the frontal-eye-field. Submitted to: *Brain Structure and Function*.

The acquisition of literacy is one of the most important epigenetic achievements of *Homo Sapiens*.
(Wolf, 2018, p. 1)

Reading is a complex marriage of multiple cognitive skills, including visual processing, attention, language processing, and – if reading aloud – motor speech output. These different components must work together efficiently for successful reading, and understanding the interplay between these components is an active area of research.

In order to read successfully, one must systematically move their eyes across a page of text. Models of reading typically outline the route from visual input to phonological output (e.g., Owen & Borowsky, 2003), and visual attentional models exist to outline how shifts in attention are made (e.g., Corbetta & Shulman, 2002). But, to date, there has been minimal work unifying these models to describe visual attention processes in the context of reading. This is a critical unification and by understanding the interplay between visual attention and reading, the field will better understand the mechanisms behind reading successfully and reading deficits.

The goal of this thesis is to begin working towards a unified framework of reading and attention. Through a combination of cognitive behavioural and neuroimaging studies, these experiments will help elucidate the role visual attention plays in successful reading, with the hope that this knowledge can be applied to the development of reading interventions.

1.1 Current models of reading and reading difficulties

For most of us, reading is like breathing. We do both without thinking (or so it seems), and both activities are life sustaining. Anyone who loves books cannot imagine a life devoid of reading.

(Arrowsmith-Young, 2014, p. 122)

1.1.1 Dual-route model of reading

One well-established model of reading processes is the dual-route model of reading (see Figure 1.1). According to this model, there are two routes (one sublexical, the other lexical) that are involved in reading processes.

Both routes begin similarly in the occipital lobe for general visual processing and encoding of letters (orthographic encoding) at which point they diverge. The sublexical route is used for the grapheme-to-phoneme conversion of print symbols to sounds, and then through the phonological lexical system is able to access the meaning of words in the semantic system and/or output the word as speech (Borowsky et al., 2006; Ekstrand, Neudorf, Gould, et al., 2019; Kress et al., 2023; Wingerak et al., 2017). This route takes a dorsal path, proceeding from the occipital lobe up through the middle and superior temporal gyri, angular gyrus, and superior parietal lobule to the frontal operculum, insula, and inferior frontal gyrus (Borowsky et al., 2006, 2007; Ekstrand, Neudorf, Gould, et al., 2019). The sublexical route is particularly well suited for the decoding of pseudohomophones, which are non-words that when phonetically decoded through grapheme-to-phoneme conversion, sound like real words (e.g. *nynth* is a pseudohomophone for *ninth*), and as such are useful for forcing phonetic decoding during experimental reading tasks.

The lexical route uses whole-word sight reading to recognize the patterns of highly familiar words in the orthographic lexical system. This gives access to the semantic system and phonological lexical system to access the meaning and sound of the word, respectively. This route takes the ventral stream, proceeding from the occipital lobe through the inferior temporal lobe, the temporal pole, and the inferior frontal gyrus (Borowsky et al., 2006, 2007; Cummine et al., 2015; Ekstrand, Neudorf, Gould, et al., 2019). Along with processing highly familiar words, the lexical route is crucial for identifying exception words, which are words that do not follow the typical spelling-sound correspondences of a language (e.g. *ninth* is an exception word that would likely use a short-*i* sound in the pronunciation if phonetically decoded). Generally, reading processes in both routes are considered more left-hemisphere lateralized, but there is

individual variability in the degree of language lateralization observed (Neudorf, Kress, et al., 2020).

Not all models of reading employ a dual-route structure. As Owen and Borowsky (2003) describe, single route models exist which employ only one non-semantic route from visual text input to phonological representation. This is achieved by grouping the orthographic encoding and orthographic lexicon components under a single orthographic representation set, and likewise grouping the grapheme-to-phoneme conversion and phonological lexicon components under a single phonological representation set, with only a single non-semantic connection between these two generalized components. The connectionist models proposed by Seidenberg and colleagues (e.g., Harm & Seidenberg, 1999) are an example of this single route model conceptualization. The Naïve Discriminative Reading Aloud model (Hendrix et al., 2019) is from a different single route family, which employs lexeme units as an intermediary between orthographic and phonological units.

The route or routes described by these models bring together the language processes involved in successful reading, but in some individuals, reading difficulties may arise.

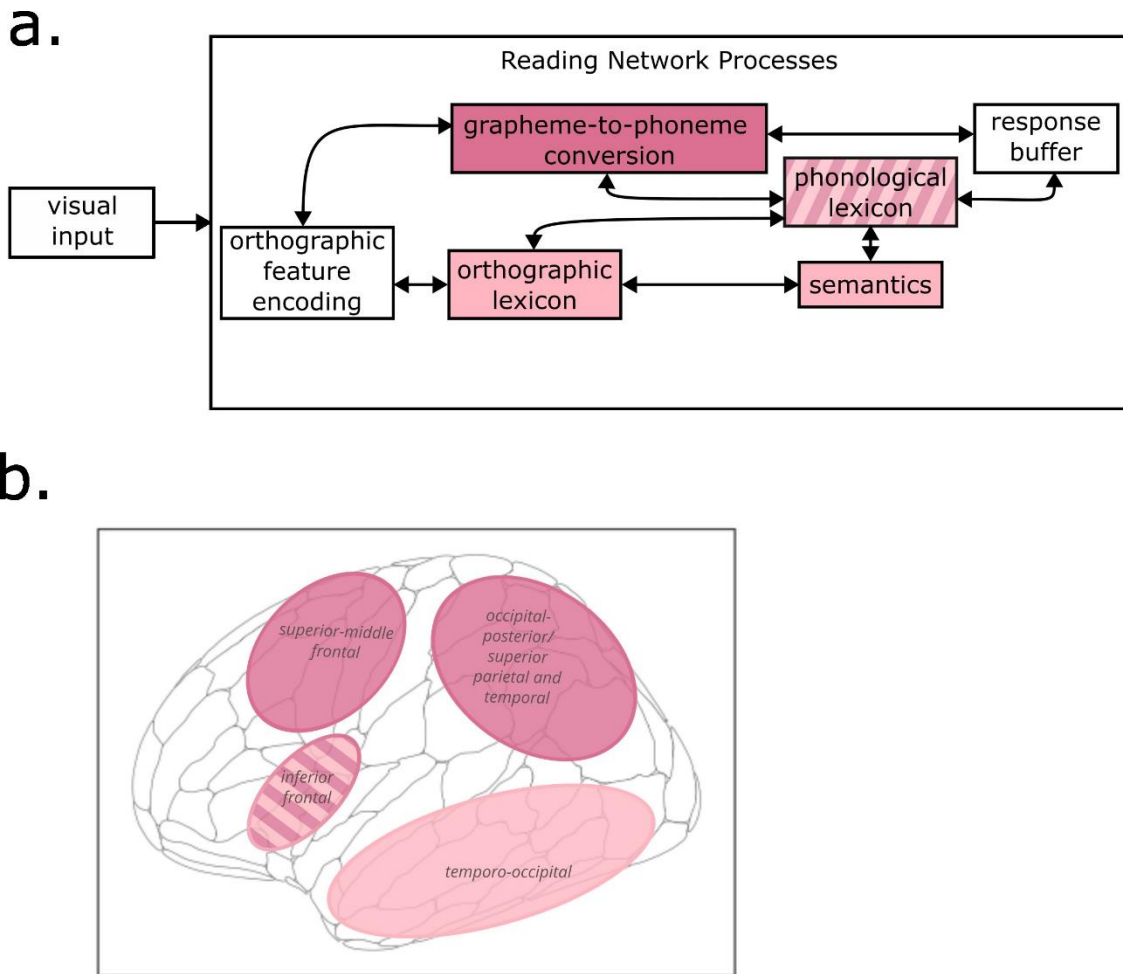


Figure 1.1. Dual route model of reading in box-and-arrow form (a) and mapped broadly onto brain regions (b)

Examples of dual route models on which this figure is based include Owen and Borowsky (2003) and Coltheart et al. (2001). Sublexical reading regions are depicted in dark pink while lexical reading regions are depicted in light pink. Generally, reading processes are considered more left-hemisphere lateralized, but note this is not necessarily the case for all individuals (Neudorf, Kress, et al., 2020).

1.1.2 Disorders in reading

Dyslexia is the term used to describe difficulties in reading, whether these difficulties are acquired through brain injury or arise during childhood. Developmental dyslexia is a reading difficulty that is not due to brain injury and rather involves childhood reading acquisition difficulties which may persist to become adult reading difficulties (Castles & Coltheart, 1993).

The theories underlying dyslexia have evolved over the years. One theory that has been considered is the phonological deficit hypothesis, which argues that the reading difficulties experienced by individuals with dyslexia are driven by deficits in phonological processing (Shaywitz, 1996) – the sublexical route in the dual-route models. However, this account overlooks the existence of deficits in lexical, whole-word processing. Addressing this gap, other researchers describe subtype-based models of dyslexia, typically classifying individuals into those with sublexical processing deficits (phonological dyslexia), lexical processing deficits (surface dyslexia) or both types of deficits (Castles & Coltheart, 1993; McDougall et al., 2005; Partanen et al., 2019b). In cases of dyslexia, differences in the activation and connectivity of regions along the dorsal-sublexical route are often identified, particularly the arcuate fasciculus and temporal-parietal regions (Partanen et al., 2019a, 2021; Vanderauwera et al., 2017). Along the ventral-lexical route, individuals with reading difficulties can exhibit lower activation in fusiform and inferior frontal regions (Partanen et al., 2019a).

1.1.3 Reading needs interventions

Improving literacy is a global issue; the international median rate of students at or below the low reading benchmark is 16% (Brochu et al., 2018). Both children and adults can struggle with literacy. The Council of Ministers of Education Canada and Statistics Canada (2013) reported 17% of adult Canadians are at the lowest levels for literacy. Given the vital role that reading plays in everyday activities, and the currently existing gaps in many individuals' reading ability, reading interventions can help individuals improve their reading skills. Extracurricular reading is perhaps the broadest option for improving reading skills, and higher levels of reading engagement are associated with better reading comprehension and vocabulary (Pfof et al., 2013), but this natural form of reading practice is partially reliant on the individual's baseline ability and interest in reading. If individuals with dyslexia have negative associations with the reading experience, any anxiety or frustration that accompanies the activity could discourage them from extracurricular reading (Stanovich, 1986).

Rather than relying on organic reading, which could contribute to existing equity gaps in reading ability, educational organizations could instead use interventions that specifically target reading (reading-focused interventions). Reading-focused interventions could include activities such as phonetic decoding (Foorman et al., 2018), text reading, orthographic rule instruction, multisensory instruction (Hall et al., 2022), and individually tailored reading interventions (Partanen et al., 2019a, 2019b, 2021). These exercises are often administered over multiple sessions, and under the guidance of an educator or specialist, which can help ensure the individual is making regular progress in their reading improvement. However, the extended timeframes and personnel required in most reading interventions may pose barriers for children from impoverished communities, and for adults juggling multiple responsibilities.

In the previously described models of dyslexia, the focus is on the nature of the reading deficits experienced by the individual, and under those perspectives, reading-focused interventions are a reasonable intervention to pursue. Alternatively, interventions could target important cognitive processes that make reading easier (cognitive exercise interventions). Cognitive exercise interventions that target the attentional system may be well-suited to improve reading, as we will see in the upcoming sections and chapters. Other theories of dyslexia go beyond reading processes to consider the visual attention factors that contribute to successful and disordered reading, and it is here where we can begin to link reading and attention processes. Given the multi-modal system of reading, this approach opens numerous avenues for activities to indirectly improve reading, particularly through visual attention, which is a key component in reading processes (e.g., Ekstrand et al., 2016; Ekstrand, Neudorf, Gould, et al., 2019; Ekstrand, Neudorf, Kress, et al., 2019; Gabrieli & Norton, 2012).

1.2 Models of visual attention

All reading begins with attention – in fact, several kinds of attention.
(Wolf, 2010, p. 145)

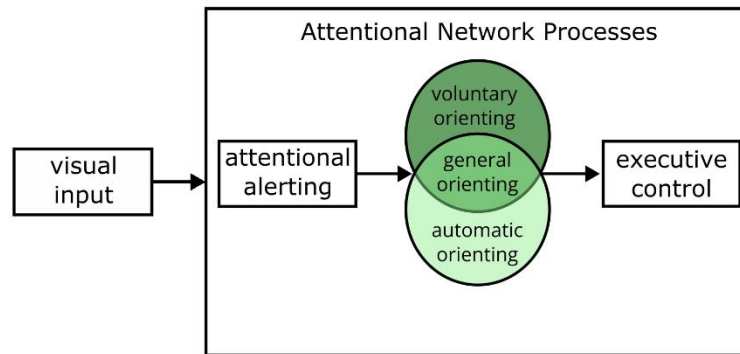
Before we can explore the theories of dyslexia that link to visual attention, it is important to first consider models of visual attention in isolation.

At the higher level of visual attention, there are two relevant models to discuss. The first is the attentional networks model (see Figure 1.2), which is derived from the processes isolated by the attention network test (J. Fan et al., 2002). In the attention network test, three attentional processes are isolated. The first is the alerting network, which involves right hemisphere parietal-

frontal regions and notifies the participant to expect a salient event. The second is the orienting network, which generally involves parietal-frontal regions and connections and is associated with the successful disengagement and reengagement of the attentional system to a new target location or stimulus of interest. The third and final network is the executive control network, which involves frontal lobe regions and plays a role in conflict processing.

The second model is Corbetta and Shulman's model of attentional orienting (Corbetta & Shulman, 2002). Rather than being an opposing model, Corbetta and Shulman's model of attentional orienting is arguably a complement to the attentional networks model, describing the mechanisms of the attentional orienting network (and some aspects of the alerting network) in detail. Similarly to the dual-route model of reading, Corbetta and Shulman promote a dual-route model of attention involving ventral and dorsal networks. The ventral attention network is typically considered to be right lateralized. This network is thought to be involved in automatic attentional orienting processes which are primarily stimulus-driven, rather than goal-directed. In Corbetta and Shulman's (2002) model, two key regions in the ventral attention network are the temporoparietal junction (at the intersection of the inferior parietal lobule and superior temporal gyrus) and the ventral frontal cortex (consisting of portions of the inferior and middle frontal gyri). The temporoparietal junction is considered by Corbetta and Shulman (2002) to be involved in the ventral attention system as a circuit breaker which interrupts goal-driven voluntary processing in the dorsal attention system in favour of a new salient stimulus. In contrast, Geng and Vossel (2013) argue that the temporoparietal junction's role in the attention network is one of contextual updating, rather than circuit breaking. In this view, the temporoparietal junction informs, but not necessarily interrupts, the voluntary attention system of task-relevant stimuli. The dorsal attention network is more bilaterally organized. This network is thought to be involved in voluntary attentional orienting processes, which are primarily top-down and goal-directed (Corbetta & Shulman, 2002). In this network, Corbetta and Shulman highlight the intraparietal sulcus, superior parietal lobule, and frontal-eye-field.

a.



b.

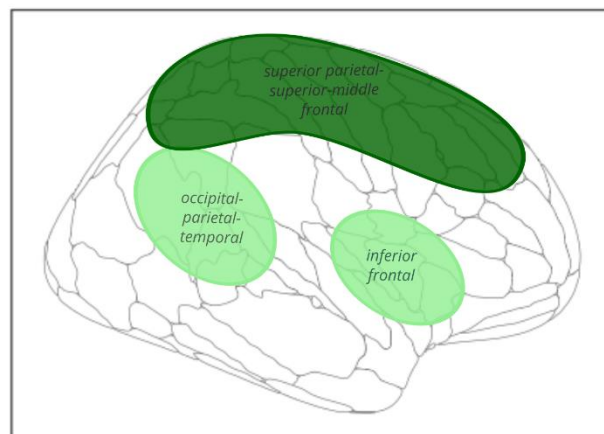


Figure 1.2. Attentional network model in box-and-arrow form (a) and broadly mapped onto brain regions (b)

Dorsal voluntary attentional orienting regions are depicted in dark green while ventral automatic attentional orienting regions are depicted in light green. Generally, attentional processes are considered more right-hemisphere lateralized, and that is how the regions are depicted here, but note this is not necessarily the case for all sub-processes or individuals (Corbetta & Shulman, 2002).

1.3 Unifying models of reading and attention

With this background on models of reading and visual attention in isolation, we can explore how these processes come together. The magnocellular theory of dyslexia provides good context for this unification.

1.3.1 Attentional processes for reading: the magnocellular theory

In order to read successfully, one must engage processes to encode visual input, maintain fixation, orient attention, and move the eyes. All of these – in particular control over fixation, visual orienting, and eye movements – are components of oculomotor processing (Boden & Giaschi, 2007; Morrison, 1984) and also visual attention network processes as described in the previous section. Stein (2001, 2014) describes how deficits in these components of visual attention and oculomotor control may contribute to reading deficits. Termed the magnocellular deficit theory, this theory about visual processing in dyslexia ties back to our traditional understanding of the subsystems within the visual cortex (see also Boden & Giaschi, 2007 for a review).

In their influential review of the visual processing of form, colour, and movement, Livingstone and Hubel (1988) describe a subdivided visual pathway arising from cellular differences in the lateral geniculate nucleus (the differentiation begins with cellular differences in the retina, which feed these two pathways). The first visual pathway employs small parvo-cells, and the layers with these cells are slow to respond and sensitive to colour and high resolution (Schiller et al., 1990). The second visual pathway – which is of interest in our discussion on the magnocellular deficit theory – employs large magno-cells, and the layers with these cells are quick to respond, and sensitive to contrast and motion, but insensitive to colour. Moving beyond the lateral geniculate nucleus, the two pathways remain relatively differentiated through the subdivisions of the primary visual cortex (Livingstone & Hubel, 1988; Hubel & Wiesel, 1959; Schiller et al., 1990; Atkinson, 1992), but note that the two streams do become integrated in regions such as V4 and MT (Ferrera et al., 1992; Maunsell et al., 1990) and thus should not be considered completely distinct at all levels.

Researchers in the field of dyslexia observed that individuals with reading deficits could also experience difficulties with visual and attentional tasks, such as orienting (Facoetti et al., 2000), motion processing (Eden et al., 1996), attentional processing (Taran et al., 2022), and visuo-spatial processing (Franceschini et al., 2022). These findings provide the foundation for

the magnocellular deficit theory, which argues that dysfunction in regions and connections in the motion-sensitive magnocellular pathway contributes to the reading deficits observed in dyslexia (Boden & Giaschi, 2007; Stein, 2001). Not all researchers support the directionality proposed by the magnocellular deficit theory, instead arguing that deficits in language processing regions are the cause of the general magnocellular stream deficits, rather than the other way around (Olulade et al., 2013). Reading interventions can benefit visual processing ability (Olulade et al., 2013) and attentionally demanding interventions through video game play can benefit reading ability (Bertoni et al., 2021; Pasqualotto et al., 2022), which does not help determine causality in the reading + attention relationship. Regardless of direction, the research on both sides supports a link between the motion-sensitive magnocellular system and reading processes.

1.3.2 Reading and attention overlap

Previous research from our lab found that greater experience with peripheral demands in video games was associated with faster reading speeds, which may indicate that peripheral visual demands exercise oculomotor activity (Kress et al., 2023). This same study observed greater experience with central demands in video games was associated with slower reading speeds, demonstrating that visual-spatial demand location exhibits a double dissociation with reading speed. This double dissociation suggests that visual-spatial demands employ oculomotor processes differently depending on location, with peripheral demands exercising oculomotor processes more than central demands. Based on our previous work, in this thesis we propose attentional-oculomotor (A-O) exercise as a form of cognitive exercise which may benefit reading performance through improved oculomotor processing.

When neuroimaging research on skilled readers is considered, there is further support for the links between reading and attention that are argued for in the magnocellular deficit theory of dyslexia. In our lab's previous research, we observed overlap between lexical reading and attentional orienting in the temporoparietal junction (Ekstrand, Neudorf, Gould, et al., 2019; Ekstrand, Neudorf, Kress, et al., 2019). Non-invasive stimulation of the posterior parietal cortex (in which the temporoparietal junction is situated) improves word reading performance (Bertoni et al., 2022), supporting the previously described overlap between lexical reading and attention in the temporoparietal junction. In pre-reading children, regions that become functionally sensitive to words have stronger connectivity with visual attention regions such as the precentral gyrus and inferior parietal cortex (Saygin et al., 2016).

Recent connectivity work has demonstrated the reading sensitive regions of the fusiform gyrus (sometimes deemed the visual word form area) have significant structural and functional connections with attentional network regions such as the intraparietal sulcus and frontal-eye-field (Chen et al., 2019). The arcuate fasciculus – a white matter tract associated with language processing and implicated in dyslexia (Cross et al., 2023; Partanen et al., 2021; Vanderauwera et al., 2017) – closely overlaps with the activation observed in attentional processing tasks and connects the temporoparietal junction with other regions in the ventral attention network (Bernard et al., 2020).

In contrast to the growing body of research highlighting the overlap between the ventral attention network's temporoparietal junction and reading processes, there is a gap in the knowledge on the role of the dorsal attention network's frontal-eye-field in reading. The FEF is particularly important for its role in oculomotor control. Models of oculomotor control describe the system underlying our eye movements, which involves deciding when and to where eye shifts should take place (Tatler et al., 2017). This control over eye movements is critical in reading, where the reader must systematically shift their eyes across a page. In particular, we see the dyslexia literature frequently discussing proposed links between attentional network dysfunction and the reading deficits that are the hallmark of the disorder (Boden & Giaschi, 2007; Boros et al., 2016; Facoetti et al., 2000; Vidyasagar & Pammer, 2010; Ward & Kapoula, 2021).

Oculomotor control difficulties would contribute to difficulties with attentional orienting processes, such as maintaining fixation or moving eyes accurately (Boden & Giaschi, 2007; Morrison, 1984). In the reading network, these attentional orienting difficulties would be most likely to translate to difficulties with visual letter processing (orthographic feature encoding) or phonetic decoding (grapheme-to-phoneme conversion), as these processes are more associated with voluntary attention and oculomotor control than whole-word processing via the orthographic lexicon (Ekstrand, Neudorf, Kress, et al., 2019), and both orthographic and phonological processes are important to successful reading (Acha et al., 2024). Given the importance of the frontal-eye-field in oculomotor control (Bedini & Baldauf, 2021; Schall et al., 2017), the frontal-eye-field as a region of interest (ROI) presents a clear avenue for further investigation in this thesis.

1.4 The Current Research

This thesis weaves together two branches of research to achieve the primary objective of linking reading and attention processes. The first branch is the cognitive-behavioral branch (Chapter 2). Using cognitive behavioural experiments, online and in the lab, the studies described in this chapter will examine the role of attentional-oculomotor exercise in reading, and test whether the benefits of attentional-oculomotor exercise can be realized in short-term, experimental settings. Specifically, Experiment 2 tests the causal effects of peripheral and central visual demands on performance in both general visual and specific lexical processing tasks and introduces a novel visual processing task using stimuli inspired by video games. Experiments 2 and 3 refine our attentional-oculomotor exercise paradigm to focus on reading improvements. All of these experiments additionally test the ability of the reading task to isolate lexical vs sublexical processes by analysing the effects of word and bigram frequency on performance.

The second branch is the neuroimaging branch (Chapters 3 and 4). Using functional magnetic resonance imaging (fMRI) data collected from our lab's previous work (Ekstrand, Neudorf, Kress, et al., 2019), and fMRI data from a large openly available dataset (Van Essen et al., 2013), these later experiments will employ analyses of brain structure and function. In Experiment 4, based on the knowledge of reading and attention from past research, we take an ROI-based approach to further analyse the open data from our previous study (Ekstrand, Neudorf, Kress, et al., 2019), focusing specifically on the frontal-eye-field. With the frontal-eye-field localized in Experiment 4 we then apply this ROI to the large open Human Connectome Project (HCP) dataset (Van Essen et al., 2013) for analyses of structural connectivity. These structural connectivity analyses will help us better understand the network connectivity of the frontal-eye-field to other important reading + attention regions.

The final chapter (Chapter 5) will bring together these two branches of research to discuss the implications on basic reading and attention models and propose a framework of combined reading and attention.

CHAPTER 2: Practice in the periphery – Effects of central vs peripheral attentional-oculomotor exercise on reading and graphical tasks

This chapter is adapted from the content of the following manuscript:

Kress, S., Caron, S., Neudorf, J., Borowsky, B., & Borowsky, R. (submitted). Practice in the periphery: Effects of central vs peripheral attentional-oculomotor exercise on reading and graphical tasks. Submitted to: *Quarterly Journal of Experimental Psychology*.

2.1 Introduction

When an athlete wants to improve at activities like weightlifting, or running, they will prepare a training regimen of exercises targeted to strengthen their muscles or their endurance. Non-athletes also engage in physical exercise to maintain their form and health, and just as lifting weights or practicing for a marathon improves your physical fitness, one can also engage in cognitive exercise to maintain or improve mental skills such as memory (Holmes et al., 2019) or arithmetic (Sella et al., 2016). There is also commercial interest in cognitive exercise, with mobile applications and games purporting to improve cognitive skills. Nintendo's game, *BrainAge*, is one example of a commercial game which aims to improve cognitive skills through a variety of mini-games (Nouchi et al., 2012). In the case of *BrainAge*, researchers observed improvements in executive function and processing speed relative to the control group, thus demonstrating the potential for commercial video games to improve cognitive skills.

Reading is an incredibly valuable cognitive skill and uniquely human experience. Printed text is a common occurrence on signage, medication labels, employment contracts, or bank documents, which all need to be read and comprehended to act on appropriately. Difficulties with reading therefore lead to difficulties in carrying out many day-to-day tasks required for success and well-being. The goal of our present research is to test whether reading can be improved through cognitive exercise, namely attentional-oculomotor (A-O) exercise.

2.1.1 Attentional-oculomotor exercise for reading

The form of cognitive exercise that we are interested in for the purposes of our research is A-O exercise, which we will define as activities that encourage processing in the visual-attentional system and promote oculomotor processes. The visual attention system integrates a number of visual and attentional processes, including low level visual processing, attentional alerting and orienting mechanisms, and higher-level executive control (Corbetta & Shulman, 2002; J. Fan et al., 2002). The visual attentional system is traditionally conceptualized as a two-network system (Corbetta & Shulman, 2002). The ventral attention network handles bottom-up control processes, which are those stimulus-driven responses that capture attention automatically (e.g., looking automatically to the source of a sudden sound or movement), and include the inferior frontal and middle frontal gyri. The temporoparietal junction also plays a role in this network and is thought to act as a switching mechanism (interrupting top-down attention, engaging bottom-up attention) when a salient stimulus arrives in an unattended location. The dorsal attention network handles top-down attentional control processes, which are those goal-driven responses that are capturing attention through voluntary effort (e.g., instructions to attend to a certain stimulus). Regions such as the frontal-eye-field (FEF) and intraparietal sulcus/superior parietal lobule are noteworthy regions of the dorsal attention network.

2.1.2 Video game play as attentional-oculomotor exercise

Based on the literature, video game play may be one activity that promotes A-O exercise. Video games expose players to an assortment of visual stimuli both in central and peripheral areas of the screen. The visual stimuli presented in video games can be thought of as attentional cues with near 100% validity – if a stimulus appears on-screen, it is almost always important and should be attended to. The high frequency, high relevance visual stimuli presented peripherally would encourage substantial use of oculomotor processes, thus contributing to A-O exercise. Training studies have observed oculomotor system changes in structure and performance following video game play in older adults (Diarra et al., 2019; West et al., 2013). In a structural brain connectivity study, Kowalczyk et al. (2018) found that the connectivity in visual-spatial regions was greater in real-time strategy players compared to people who do not play games regularly, and behavioural studies have suggested that action video game play may improve reading ability in children (e.g., Bertoni et al., 2021; Franceschini et al., 2017; Pasqualotto et al., 2022).

The research on the relationship between game-based A-O exercise and reading ability has focussed on long timeframes. In training studies, participants receive multiple hours of training over the course of several days or weeks (e.g., Bertoni et al., 2021; Diarra et al., 2019; Franceschini et al., 2017), while cross-sectional studies typically include variables that reflect months or years of accumulated video game experience (e.g., Kress et al., 2023). The current study seeks to determine whether the benefits of A-O exercise on reading performance can be realized in a brief and efficient timeframe.

2.1.3 Measures of lexicality and sublexicality

Word frequency has been used in past reading research as a measure to help predict how reliant a stimulus might be on either the lexical or sublexical route (Borowsky et al., 2013). Word frequency is a measure of how likely a word is to appear in the given corpus. Generally, researchers find that higher word frequency is associated with faster response times (Borowsky et al., 2013; Borowsky & Besner, 1993; Brysbaert & New, 2009), and greater activation in ventral brain regions (Borowsky et al., 2013), and is thus thought to reflect the level of involvement of the lexical route.

Bigram frequency is another corpus-based word characteristic and is a measure of how frequently a pair of letters appears in the corpus (Balota et al., 2007). There are multiple ways to combine the frequencies of each bigram to calculate a single measure for the word. One option is the sum bigram frequency, where the frequencies of each bigram are simply added together. Another option is the mean bigram frequency, where the sum bigram frequency is divided by the number of bigrams in the word. Bigram frequency is less well studied compared to word frequency, but higher bigram frequency is associated with faster reading response times and greater activation in dorsal brain regions (Borowsky et al., 2013), and thus may reflect the level of involvement of the sublexical route.

In the context of the lexical decision task (LDT), most designs focus on word stimuli with nonword foils (Borowsky & Besner, 1993; Masson & Borowsky, 1998). In this task, the participant must decide whether the stimulus is a word or not. These designs may not be ideal for isolating lexical and sublexical processing, as the word and nonword stimuli are not matched on their non-orthographic lexical features (Kress et al., 2021). For example, using non-specific word targets (e.g. *gave*) and pronounceable but meaningless nonword foils (e.g. *bave*), a participant could rely on any combination of orthographic (spelling), phonological (sound), and semantic

(meaning) representations to inform the correct response. An improved LDT design uses exception word targets (e.g. *yacht*) and pseudohomophone foils which are matched on the semantic and phonological features of the word (e.g. *yawt* is a pseudohomophone for the real word *yacht*). This specialized LDT forces one to rely on orthographic lexical representations because the sublexical and/or semantic representations can no longer be used to successfully determine whether the stimulus spells a real word or not (Ekstrand et al., 2016; Neudorf, Ekstrand, Kress, & Borowsky, 2019; Neudorf, Ekstrand, Kress, Neufeldt, et al., 2019). For this unique quality of isolating orthographic lexical route processing, we call it an orthographic lexical decision task (OLDT). However, word and bigram frequency effects have not been studied in the context of the specialized OLDLT, leaving a gap in the literature regarding whether this lexical decision variant can reflect orthographic lexical processing more clearly than tasks using the non-specific word stimuli and unmatched nonword foils.

2.1.4 The current study

The goal of the current study is to investigate whether A-O exercise can have an immediate impact on visual processing and reading, such as during a single experiment session. Inspired by the use of video games to improve reading ability, we developed a new type of visual stimulus and task design for use in A-O exercise – a novel health bar decision task (HBDT) which uses stimuli resembling the health bars found in video games in a decision task similar to the OLDLT. In the HBDT, the participant indicates whether the health bar matches the number presented. This task will not utilize reading processes as heavily as the OLDLT, so it reflects general visual processing and can be used for A-O exercise, and because it uses stimuli resembling those found in video games, it may better reflect the benefits of video game play on reading in a more controlled environment than what is found in commercial games. The location of the stimuli presented in our two tasks can be manipulated to induce A-O exercise through peripheral or central visual demands.

If standard task practice effects are present (which we refer to as the task learning hypothesis), participants will experience performance benefits between a first block and second block, regardless of whether peripheral or central visual demands are presented first. If exposure to peripheral visual demands is beneficial and exposure to central visual demands is detrimental, as our previous reading aloud research suggests (Kress et al., 2023), then participants who are exposed to peripheral before central conditions should show improved performance, compared to

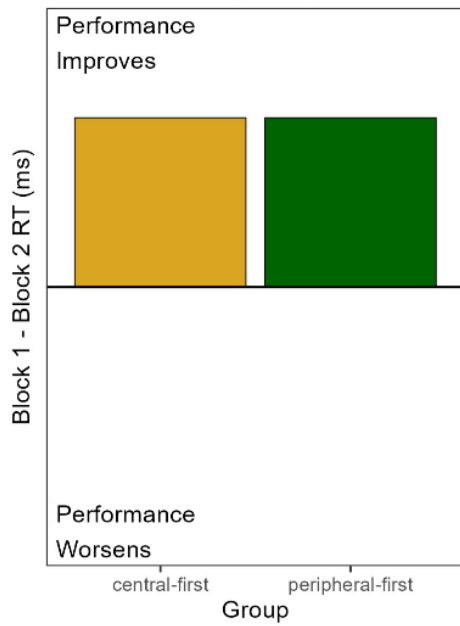
participants who are exposed to central before peripheral conditions (which we refer to as the A-O exercise hypothesis).

Thus, there are three hypothesized patterns of results we may expect to see in our single session paradigm:

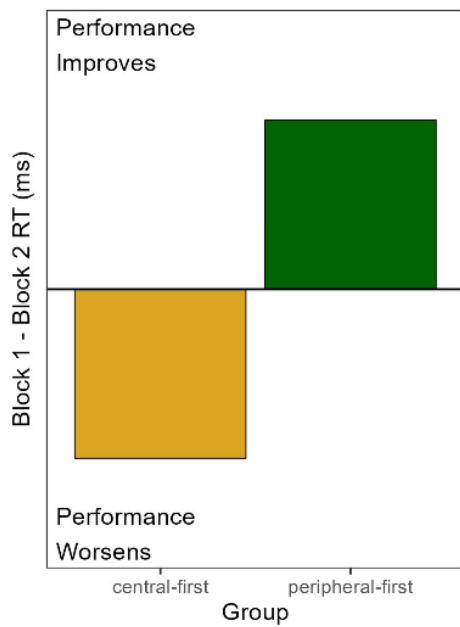
1. The task learning hypothesis: If participants' performance is based on general experience with the task, we will expect to see typical task-learning effects, whereby performance in the second block is better than in the first block (see Figure 2.1a)
2. The A-O exercise hypothesis: If our paradigm promotes A-O exercise in the same manner as previous studies on visual demands in video games, we expect to see a similar dissociation in performance between central and peripheral blocks, as was observed by Kress et al. (2023). In this case, there should be a beneficial effect when peripheral blocks are presented first, and a detrimental effect when the central blocks are presented first (see Figure 2.1b).
3. A blend of task learning and A-O exercise: Both patterns could be present and result in a blended response pattern in our data (see Figure 2.1c).

Additionally, in our OLDT, we will test correlations of performance with the lexical measure of word frequency and sublexical measure of bigram frequency to confirm that targets in our OLDT are successfully isolating lexical processes, as we expect. In tasks that isolate lexical processing, researchers typically observe a word frequency effect in which performance is better for items with higher word frequency (Borowsky et al., 2013). We expect to replicate this typically observed word frequency effect in our study. Bigram frequency is less well studied, but has been shown to be associated with sublexical processes (Borowsky et al., 2013). Our inclusion of word and bigram frequency analyses will help researchers better understand the role of the lexical and sublexical processes in the OLDT.

a. Task-Learning Hypothesis



b. Attentional Exercise Hypothesis



c. Attentional Exercise + Task Learning

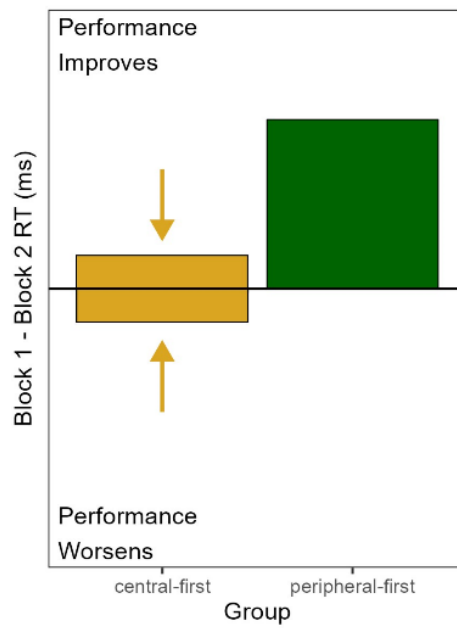


Figure 2.1. Task learning (a), A-O exercise (b), and A-O exercise + task learning (c) hypotheses with difference scores

2.2 Experiment 1: Attentional-oculomotor exercise online

2.2.1 Method

2.2.1.1 Participants

This study was approved by the University of Saskatchewan Behavioural Research Ethics Board (see Appendix B). We recruited 61 participants¹ (28 cisgender men, 29 cisgender women, 4 non-binary or transgender participants; $M = 37.97$ years, $SD = 12.90$ years) through the UK-based Prolific recruitment platform (<https://prolific.co>) who were covertly pre-screened using Prolific’s pre-screening filter options. Participants were pre-screened for country of residence (Canada or the United States), first language (English), language-related disorders (none), vision (normal or corrected-to-normal), and handedness (right). Participants were recruited between November and December 2022. As compensation for participating, participants received £6.75. Participants provided informed consent by registering for the study on Prolific after reading the description (which contained the full written consent form). Informed consent was confirmed by repeating a brief version of the consent form in the PsychoPy experiment, which participants had to agree to with a keypress before the experiment would proceed.

Table 2.1 Demographic characteristics as a function of group assignment

		Central-first	Peripheral-first	
		Group	Group	
Mean age in years (<i>SD</i>)		37.63 (13.58)	38.34 (12.34)	$p = .830$
Gender	Cisgender Man	15	13	$\chi^2 = 0.14$
	Cisgender Woman	16	13	$\chi^2 = 0.31$
	Non-binary/Transgender	1	3	$\chi^2 = 1$

¹ Online studies are known for issues with data quality (Douglas et al., 2023; Thomas & Clifford, 2017). We originally recruited 80 participants, and exclusions were made as follows to ensure high data quality:

- Completed portions of the study twice, compromising their data (2 participants)
- Demographics discrepant with our pre-screening criteria (2 participants)
- Reported issues with viewing the instructions properly (1 participant)
- Stratified reaction times, where the reaction time values presented as discrete bands rather than a continuous value, suggesting issues with the keyboard polling rate, or missing response in over half the trials of at least one block, suggesting hardware issues with the keyboard-press detection or participants failing to pay attention (4 participants)
- Unusual error rate or reaction time performance, where error rates were exceedingly high or reaction times exceedingly slow or fast, suggesting participants attempting to exploit the experiment (e.g., always pressing the same button) or failing to follow directions (10 participants)

2.2.1.2 Apparatus and Stimuli

The experiment was designed in PsychoPy Version 2022.2.4 (Peirce et al., 2019; *PsychoPy*, 2022) and hosted online through Pavlovia (<https://pavlovia.org/>). Participants were requested to use a computer with a screen size of 14 inches or larger so that the stimuli and instructions would appear on-screen correctly. Additionally, participants used standardized credit card dimensions to calibrate their screen size at the start of the experiment (code adapted from Morys-Carter, 2020) and were instructed to sit approximately 70 cm from their computer monitor to maximize the consistency in the size and visual angle of stimuli between participants.

Peripheral and Central Presentation. The two tasks in this study were both presented in two different versions that differed in target location. In both versions, a star-shaped visual-spatial cue appeared onscreen for 150 ms in the target location before the stimulus appeared. In the centrally presented conditions, the target location was always the centre of the screen. In the peripherally presented conditions, the target location was randomly selected from one of four locations (top, bottom, left, or right) which were 6.1 cm (4.98 degrees of visual angle using a sitting distance of 70 cm) from the centre of the screen.

Orthographic Lexical Decision Task. The OLD T is a reading task that focuses on orthographic lexical processes through its use of exception word targets and pseudohomophone foils. The OLD T blocks consisted of 120 exception words (target stimuli; e.g., *ninth*) which require orthographic lexical processing in order to be decoded and 120 corresponding pseudohomophones (foil stimuli; e.g., *nynt*) which do not use orthographic lexical processing, but still can activate phonological and semantic processing via phonetic decoding processes. The exception word and pseudohomophone stimuli are listed in Appendix A, Tables A.1 and A.2. The OLD T stimuli were presented in white text (Open Sans font) on a black background, with a maximum word height of 1.1 cm and maximum word length of 3.5 cm, and flanked by two pairs of white letter x's (i.e., XX), one above and one below the letter string (making the overall dimensions of these stimuli, including the flankers, 3.8 cm tall by 3.5 cm wide).

Health Bar Decision Task. The HBD T is a novel task designed to reflect aspects of video game play by using stimuli found in video games. The HBD T blocks of the experiment consisted of a set of images depicting a red and white bar (meant to resemble the health bar in a typical video game) which was 1cm tall by 3.4 cm long and flanked with a two-digit number above and below the bar (overall dimensions of the stimuli, including the flankers, were 3.8cm

tall by 3.4 cm wide). The proportion of the bar that was red ranged from 10% to 90%, in increments of 10%. The flanker number ranged from 20 less than the red proportion of the bar to 20 greater than the red proportion of the bar, in increments of 10. The flanking number was restricted such that it could not be lower than 10 or greater than 90, so all flanking numbers were two digits. With these parameters, the set of health bar images totalled 39 unique images, five images each for the health bar values 30 to 70, four images each for the health bar values 20 and 80, and three images each for the health bar values 10 and 90 (see Appendix A, Table A.3).

2.2.1.3 Procedure

After being recruited through Prolific, participants were directed to Pavlovia to complete the online study. The order of the task location blocks was counterbalanced such that half the participants received the centrally presented tasks first. The order of the HBDT and OLDT for each participant was the same in both location (central vs peripheral) blocks and counterbalanced such that half the participants received the HBDT first:

- 1. Central-HBDT, 2. Central-OLDT, 3. Peripheral-HBDT, 4. Peripheral-OLDT
 - 17 participants
- 1. Central-OLDT, 2. Central- HBDT, 3. Peripheral-OLDT, 4. Peripheral-HBDT
 - 15 participants
- 1. Peripheral-HBDT, 2. Peripheral-OLDT, 3. Central-HBDT, 4. Central-OLDT
 - 15 participants
- 1. Peripheral-OLDT, 2. Peripheral-HBDT, 3. Central-OLDT, 4. Central-HBDT
 - 14 participants

In the HBDT, participants were instructed to press the left arrow key on the keyboard if the proportion of the health bar that was filled red and the number flanking the health bar matched and press the right arrow key if these did not match (240 trials). In the OLDT, participants were instructed to press the left arrow key if the stimulus spelled a real word and press the right arrow key if the stimulus did not spell a real word (240 trials). Figure 2.2 outlines the counterbalancing and trial process for both tasks. The two tasks would then repeat for the other location block (240 trials \times 4 blocks = 960 trials total in the experiment). There was a set of eight practice trials before each block. As part of the instructions, participants were asked to use their index finger to press the left arrow key and their middle finger to press the right arrow key

(see Figure 2.3). The instructed hand position on the keyboard was intended to match the hand position of a similar study where participants responded with mouse clicks (this study is not reported here). After completing the study, participants were redirected to SurveyMonkey (<https://www.surveymonkey.com>) to complete the post-experiment demographics questions.

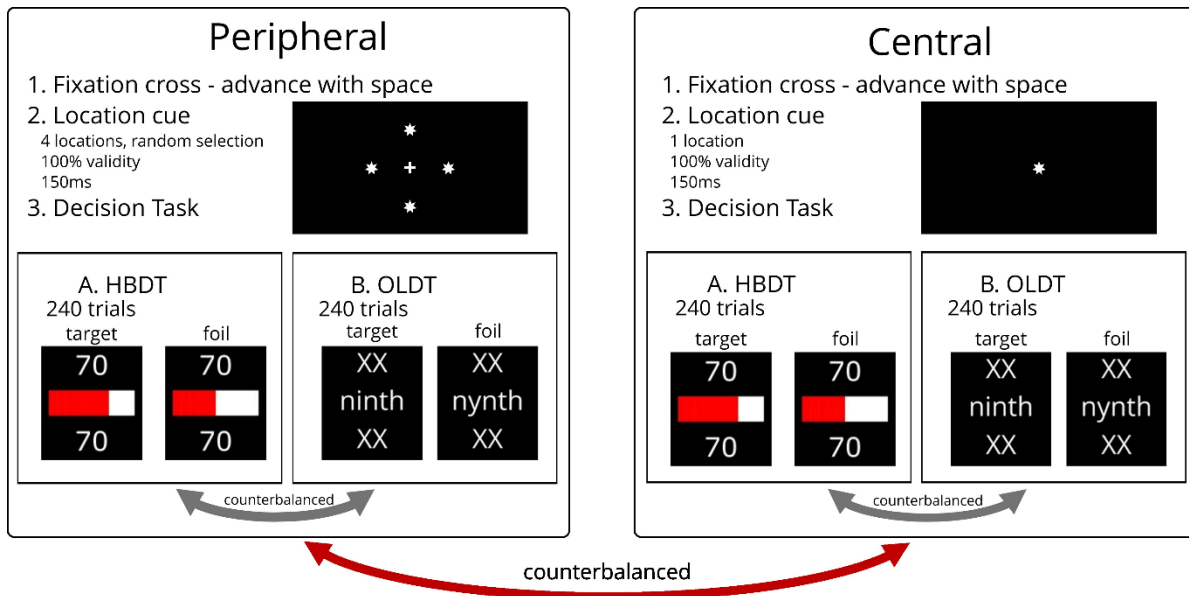


Figure 2.2. Block counterbalancing and trial procedure for Experiment 1

The health bar and orthographic lexical decision tasks are counterbalanced such that the same task is presented first in both the peripheral and central block for a given participant.

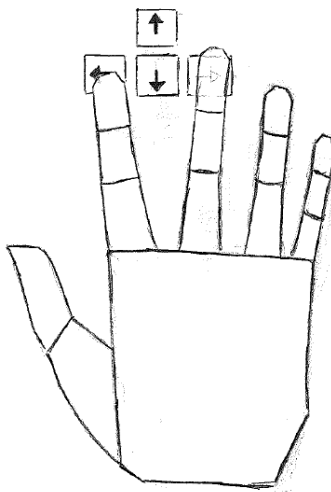


Figure 2.3. Instructed hand position on arrow keys for Experiment 1

Participants received written instructions on this hand position.

2.2.2 Results

For our analyses we examined by-subjects and by-items median reaction time (which is more robust against outlier responses than mean reaction time) of correct responses to exception word targets and pseudohomophone foils. The values reported in text are the mean of these median response times. We also examined by-subjects and by-items mean error rates. Trials with missing responses, and OLD T item pairs with outlier error rates (error rates which exceeded 3 SD outside the mean error rate; 4 OLD T item pairs (*climb/clime*, *dost/dawst*, *sieve/siv*, and *soot/suht*) were removed prior to the analysis. The participants were collapsed into two groups, central-first vs peripheral-first, and the counterbalancing of task order was not examined in this study.

2.2.2.1 By-subjects results

Reaction time and error rate block 1 – block 2 difference scores were computed based on the correct responses to target or foil stimuli (see Tables 2.2 and 2.3). With this calculation, positive values indicate performance benefits, while negative values indicate performance detriments.

Table 2.2. Experiment 1 reaction time, error rates, and difference score computations (by-subjects, on targets)

Order	Task	Block (Location)	Mean Reaction Time		Mean Error Rate	
			ms	(SD)	%	(SD)
Central- first	HBDT	1 (Central)	737.71	(126.81)	24.65	(15.38)
		2 (Peripheral)	748.93	(87.13)	16.54	(8.44)
		Difference Score	- 11.22	(112.12)	8.11	(12.87)
	OLDT	1 (Central)	609.21	(70.12)	8.11	(4.49)
		2 (Peripheral)	635.66	(84.05)	10.80	(4.84)
		Difference Score	- 26.45	(38.41)	- 2.69	(3.74)
Peripheral- first	HBDT	1 (Peripheral)	760.94	(98.90)	23.48	(15.82)
		2 (Central)	707.45	(96.77)	15.68	(10.29)
		Difference Score	53.49	(66.56)	7.80	(9.83)
	OLDT	1 (Peripheral)	652.89	(101.76)	8.92	(3.45)
		2 (Central)	573.77	(76.39)	6.00	(3.56)
		Difference Score	79.12	(41.47)	2.92	(3.42)

A set of General Linear Models (GLMs) were used to assess the difference scores in 2 (Task: HBDT vs OLDT, within-subjects) \times 2 (Order: central-first vs peripheral-first, between-subjects) mixed-measures designs. For targets, the main effect of Task (HBDT: $M = 19.55$ ms, $SD = 98.10$; OLDT: $M = 23.74$ ms, $SD = 66.26$), $F(1,59) = 0.20$, $MSE = 4213.69$, $p = 0.660$, and Task \times Order interaction, $F(1,59) = 3.01$, $MSE = 4213.69$, $p = .088$, were not significant. There was a main effect of Order on target stimuli, $F(1, 59) = 36.25$, $MSE = 6085.05$, $p < .001$, whereby peripheral-first participants ($M = 66.31$ ms, $SD = 56.46$) had greater improvements in block 2 than central-first participants ($M = -18.83$ ms, $SD = 83.49$). We also observed a significant double dissociation of visual demands on OLDT target performance in terms of the 95% confidence intervals, whereby the OLDT target difference score were greater than zero for peripheral-first participants, and less than zero for central-first participants (Masson & Loftus, 2003 see Figure 2.4).

The same GLM analysis was also conducted on the block 1 – block 2 target difference scores for target error rate. There was a significant main effect of Task on targets, $F(1,59) = 27.16$, $MSE = 68.85$, $p < .001$, whereby the HBDT exhibited larger error rate improvements ($M = 7.96$ %, $SD = 11.43$) than the OLDT ($M = -0.02$ %, $SD = 4.54$). The main effect of Order (central-first: $M = 2.71$ %, $SD = 10.86$; peripheral-first: $M = 5.36$ %, $SD = 7.70$) and Task \times Order interaction were not significant on target stimuli, $F(1, 59) = 2.77$, $MSE = 76.87$, $p = .101$ and $F(1, 59) = 3.86$, $MSE = 68.85$, $p = .054$, respectively.

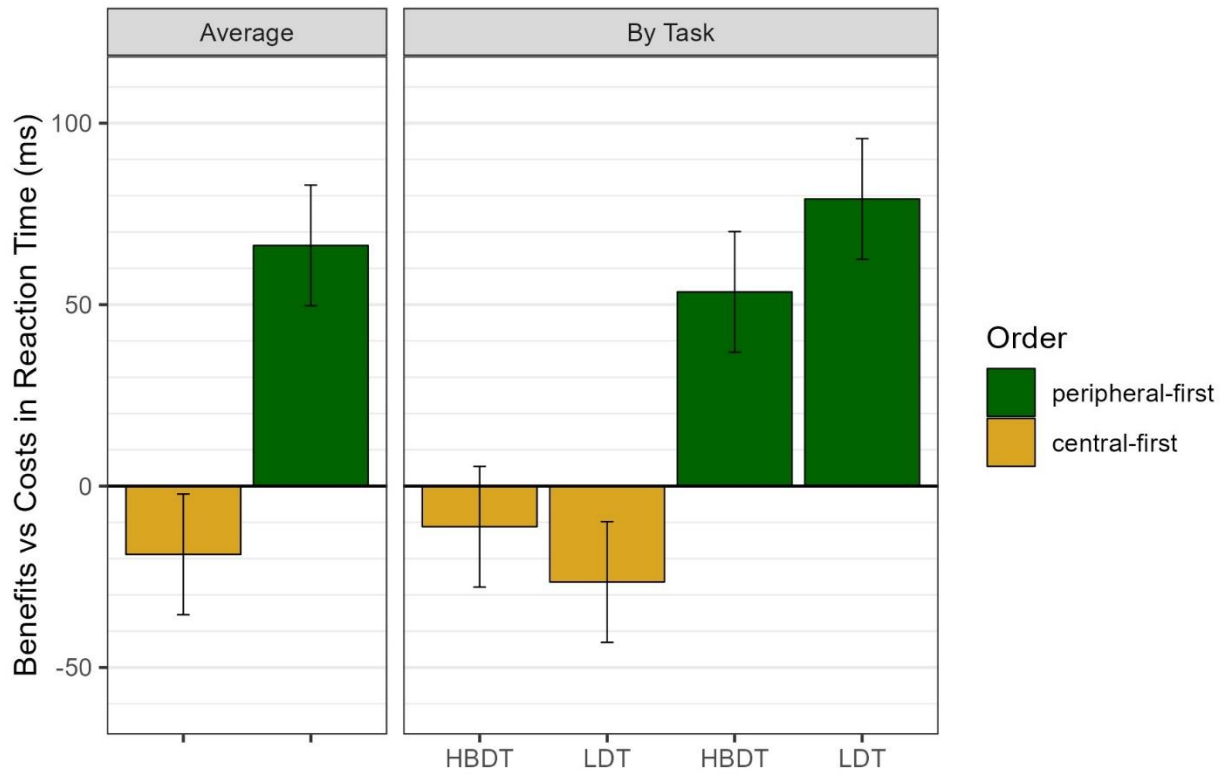


Figure 2.4. Experiment 1 benefits vs costs in reaction time as a function of Task and Order (by-subjects, on targets)

Error bars are 95% confidence intervals based on the calculation methods recommended by Masson & Loftus (2003). Positive values indicate performance improved in Block 2.

The same analyses were conducted on the foil stimuli, given our interest in how the stimuli were processed differently in this specialized OLD T. Reaction time and error rate block 1 – block 2 difference scores were computed for foil stimuli (see Table 2.3) in the same manner as for target stimuli. We used two 2 (Task: HBD T vs OLD T, within-subjects) \times 2 (Order: central-first vs peripheral-first, between-subjects) mixed-measures GLMs to assess the difference scores. On reaction time, there was a main effect of Order, $F(1, 59) = 33.64$, $MSE = 7762.25$, $p < .001$, whereby peripheral-first participants exhibited larger improvements towards foils ($M = 72.71\text{ms}$, $SD = 70.39$), than central-first participants ($M = -19.93\text{ms}$, $SD = 99.81$). The main effect of Task (HBD T: $M = 13.56\text{ms}$, $SD = 119.96$; LDT: $M = 34.67\text{ms}$, $SD = 70.03$) and Order \times Task interaction were not significant on foil stimuli, all F 's < 2.05 , all p 's $> .157$ ($MSE = 7232.79$). On foil error rate, there was a main effect of Order, $F(1, 59) = 5.21$, $MSE = 42.84$, $p = .026$, whereby peripheral-first participants exhibited larger improvements towards foils ($M = 3.57\%$, $SD = 6.25$) than central-first participants ($M = 0.86\%$, $SD = 7.11$). There was also a main effect of Task, $F(1, 59) = 22.73$, $MSE = 35.21$, $p < .001$, whereby there were larger improvements in the HBD T ($M = 4.71\%$, $SD = 7.75$) than the OLD T ($M = -0.42\%$, $SD = 4.51$). The Order \times Task interaction was not significant, $F(1, 59) = .01$, $MSE = 35.21$, $p = .905$.

Table 2.3 Experiment 1 reaction time, error rates, and difference score computations (by-subjects, on foils)

Order	Task	Block (Location)	Mean Reaction Time		Mean Error Rate	
			ms (SD)		% (SD)	
Central- first	HBDT	1 (Central)	766.40	(138.22)	29.90	(12.48)
		2 (Peripheral)	787.50	(104.69)	26.55	(13.40)
		Difference Score	- 21.09	(48.96)	0.94	(3.68)
	OLDT	1 (Central)	646.60	(73.70)	10.30	(7.45)
		2 (Peripheral)	665.36	(90.76)	11.94	(8.38)
		Difference Score	-18.77	(33.59)	-1.64	(4.89)
Peripheral- first	HBDT	1 (Peripheral)	782.01	(132.96)	27.60	(14.85)
		2 (Central)	730.22	(121.20)	21.40	(15.44)
		Difference Score	51.79	(82.37)	6.19	(7.18)
	OLDT	1 (Peripheral)	689.24	(124.63)	7.87	(5.15)
		2 (Central)	595.60	(87.24)	6.93	(4.17)
		Difference Score	93.63	(48.96)	0.94	(3.68)

2.2.2.2 By-Items Results

With the current design, the perceived benefit of peripheral-first presentation may be due to the peripheral tasks being more difficult than the central tasks, so participants simply perform better in the easier central tasks, regardless of order.

Analysing the data from a by-items perspective allows us to address this issue, as all items were presented in all conditions. With this perspective, a Peripheral Attentional Exercise Score is calculated as peripheral-first participants' central block (Central Block 2) minus central-first participants' central block (Central Block 1). The difference score between these two blocks can be considered a view of the peripheral attentional exercise effect, with any effects of difficulty accounted for (because we are comparing the same location). Similarly, a Central Attentional Exercise Score is calculated as central-first participants' peripheral block (Peripheral Block 2) minus peripheral-first participants' peripheral block (Peripheral Block 1).

Reaction time block 1 – block 2 difference scores were computed based on the correct responses to target or foil stimuli (see Tables 2.4 and 2.5, for reaction times and error rates).

A one-way GLM analysis was conducted on the block 1 – block 2 difference scores for target item reaction time. There was a significant main effect of Exercise Type, $F(1,115) = 12.98$, $MSE = 1462.69$, $p < .001$, whereby peripheral exercise was associated with greater target reaction time improvements ($M = 35.45$ ms, $SD = 37.89$) than central exercise ($M = 17.36$ ms, $SD = 38.54$). Exercise Type was also significant for error rate on targets, $F(1,115) = 23.18$, $MSE = 37.48$, $p < .001$, with peripheral exercise exhibiting larger target error rate improvements ($M = 2.13$ %, $SD = 5.80$) than central exercise ($M = -1.74$ %, $SD = 6.40$)

Table 2.4. Experiment 1 reaction time, error rates, and difference score computations (by-items, on targets)

Exercise Type	Task	Block (Participant Group's Location)	Mean Reaction Time		Mean Error Rate	
			ms (SD)		% (SD)	
Central	OLDT	1 (Peripheral-first's peripheral – pre-training)	654.56	(45.47)	8.93	(9.96)
		2 (Central-first's peripheral – after central training)	637.20	(38.14)	10.67	(10.58)
		Difference Score	17.36	(38.55)	-1.74	(6.40)
Peripheral	OLDT	1 (Central-first's central – pre-training)	614.29	(49.23)	8.13	(10.52)
		2 (Peripheral-first's central – after peripheral training)	578.84	(32.90)	6.00	(9.11)
		Difference Score	35.45	(37.89)	2.13	(5.80)

As in the previous analyses, reaction time and error rate block 1 – block 2 difference scores were computed based on the correct responses to foil stimuli (see Table 2.5). We used two one-way (Exercise Type: central vs peripheral) repeated-measures GLMs to assess the difference scores. On foil reaction time, there was a main effect of Exercise Type, $F(1, 114) = 56.21$, $MSE = 1646.49$, $p < .001$, whereby peripheral exercise exhibits greater improvements on foil reaction time ($M = 53.16\text{ms}$, $SD = 34.95$) than central exercise ($M = 13.24\text{ms}$, $SD = 43.91$). On foil error rate, there was also a main effect of Exercise Type, $F(1, 114) = 65.94$, $MSE = 52.30$, $p < .001$, whereby peripheral exercise exhibits greater improvements on foil error rate ($M = 3.34\%$, $SD = 5.27$) than central exercise ($M = -4.12\%$, $SD = 7.96$).

Table 2.5. Experiment 1 reaction time, error rates, and difference score computations (by-items, on foils)

Exercise Type	Task	Block (Participant Group's Location)	Mean Reaction Time		Mean Error Rate	
			ms	(SD)	%	(SD)
Central	OLDT	1 (Peripheral-first's peripheral – pre-training)	681.78	(53.85)	7.87	(9.41)
		2 (Central-first's peripheral – after central training)	668.56	(42.83)	11.99	(11.32)
		Difference Score	17.36	(38.55)	-1.74	(6.40)
Peripheral	OLDT	1 (Central-first's central – pre-training)	651.76	(49.63)	10.27	(11.57)
		2 (Peripheral-first's central block – after central training)	598.60	(45.35)	6.93	(9.21)
		Difference Score	35.35	(37.89)	2.13	(5.80)

2.2.2.3 Word Frequency and Bigram Frequency

To test whether our OLDT is successfully isolating lexical processes, we used simple correlations to analyse the relationship between word frequency, bigram frequency and our two dependent variables (reaction time and error rate). We used \log_e -transformed HAL word frequency as our word frequency measure and mean bigram frequency as our bigram frequency measure (see Appendix A). In a previous reading aloud study (Borowsky et al., 2013), these word and bigram frequency measures were used to reflect ventral-lexical and dorsal-sublexical processing, respectively. \log_e -transformed HAL word frequency and mean bigram frequency were derived from the complete English Lexicon Project database (Balota et al., 2007). Pseudohomophones, being non-words, do not have a word frequency measure associated with them, and as such, we used the base word frequency for these stimuli instead (i.e., the word frequency of the real word from which the pseudohomophone is derived).

We ran our simple correlations separately for each central and peripheral exercise block, resulting in four correlations for a given dependent variable – frequency combination. Consistently across blocks, we observed significant correlations between word frequency and exception word performance, such that higher word frequencies were associated with faster reaction times and lower error rates (see Table 2.6). In exception words, there were no significant correlations with bigram frequency and performance. In contrast, we observed consistent significant correlations between bigram frequency and pseudohomophone performance, such that higher bigram frequencies were associated with slower reaction times and higher error rates (see Table 2.6). There were no significant correlations with base word frequency and performance for the pseudohomophones.

Table 2.6. Simple correlations between reaction time or error rate and word/bigram frequency for Experiment 1 (targets and foils)

EWs: yacht		Aggregate	Central	Central	Peripheral	Peripheral
			Exercise 1	Exercise 2	Exercise 1	Exercise 2
Reaction Time	WF	- 0.64 ***	- 0.59 ***	- 0.41 ***	- 0.59 ***	- 0.58 ***
	BF	0.02	0.05	0.04	- 0.02	- 0.01
Error Rate	WF	- 0.54 ***	- 0.49 ***	- 0.50 ***	- 0.53 ***	- 0.49 ***
	BF	0.02	0.06	-0.01	0.00	0.00
PHs: yawt						
Reaction Time	WF	- 0.04	- 0.05	0.02	- 0.07	- 0.02
	BF	0.37 ***	0.31 **	0.29 **	0.41 ***	0.27 *
Error Rate	WF	- 0.12	- 0.08	- 0.11	- 0.13	- 0.09
	BF	0.40 ***	0.29 **	0.40 ***	0.39 ***	0.38 ***

Note. WF: log_e-transformed HAL word frequency, BF = mean bigram frequency

Degrees of Freedom for all correlations = 115.

Significance levels for the aggregate correlations: * < .05, ** < .01, *** < .001.

The block-based correlations have *p*-values which are Bonferroni-corrected for multiple comparisons (* < .0125, ** < .0025, *** < .00025).

2.2.3 Interim discussion

The results of Experiment 1 show that short-term attentional-oculomotor exercise in the form of exposure to peripheral visual demands may benefit visual processing tasks, and the consistent trends in the reaction times and error rates (both in terms of block values and difference scores) suggest there are no speed-accuracy trade-offs. The pattern of results appears to support the blended attentional exercise + task learning hypothesis, as we see improvements after peripheral blocks, while there is minimal change after central blocks.

The results of Experiment 1 demonstrate a clear double dissociation between the higher word frequency and improved performance for exception words, and higher bigram frequency and worse performance for pseudohomophones. For pseudohomophones to exhibit worse performance as a function of increased bigram frequency, it suggests that – due to increased sublexical activation – those high frequency bigrams may be making the pseudohomophones appear more word-like. This evidence supports our argument that our OLDT with exception word targets and pseudohomophone foils is well designed to isolate lexical processing, where strong word frequency effects support the idea that exception word targets optimally activate orthographic lexical route representations, and bigram frequency may be a useful measure to assess the involvement of the sublexical route for pseudohomophone foil processing in this task. This novel finding is an exciting contribution to the field of lexical decision but should be replicated in additional OLDT studies.

It is important to note that the counterbalance of our design was intended to examine whether reading performance (via the OLDT), general visual processing performance (via the HBDT), both, or neither could be impacted by manipulations of stimuli location. Given our interest in reading processes, our follow-up should refine the paradigm to target reading processes specifically. These refinements can also modify the manipulation of stimulus location in specific test blocks to control the attentional difficulty of the test task. To address concerns regarding increased task difficulty in the peripheral block contributing to the observed results, we developed a refined A-O exercise paradigm that controls the location of the pre- and post-exercise tasks. Additionally, we used a similar OLDT to the current study, so that we can test the replicability of the word and bigram frequency double dissociation on performance.

2.3 Experiment 2: Attentional-oculomotor exercise in the lab

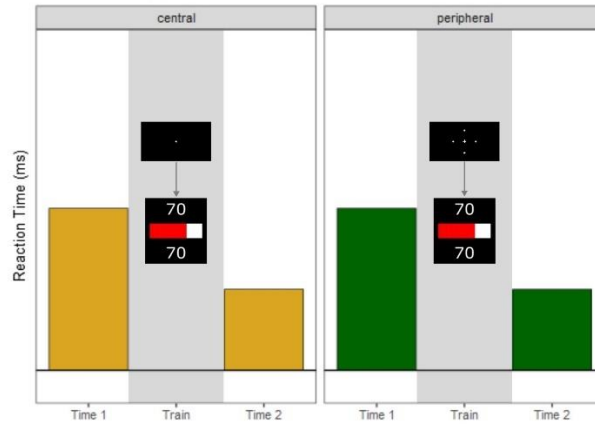
In Experiment 1, we were interested in the presence of any effect of attentional exercise, as this would support our theory that short-term attentional exercise may be able to benefit reading performance. For Experiments 2 and 3, we refined our attentional-oculomotor exercise paradigm to focus exclusively on the OLD T as our target task of interest, with the HBD T as a training task. These new designs will address Experiment 1's issues regarding task difficulty as the pre- and post- training task are matched on location. Additionally, our use of the same OLD T from Experiment 1 gives us the opportunity to replicate the double dissociation between the word frequency and bigram frequency effects on exception word target and pseudohomophone foil performance, respectively.

2.3.1 Hypotheses

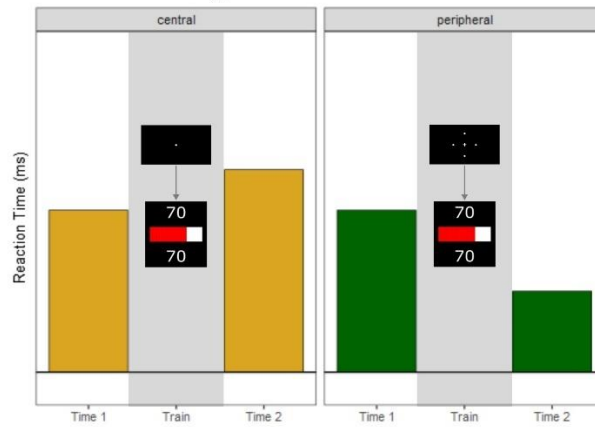
In this design, we expected to see an interaction between Training Group and Time, where participants who take part in peripheral A-O exercise should exhibit larger performance improvements than the participants who take part in central A-O exercise (see Figure 2.5).

Additionally, we expected to see a replication of the double dissociation between the word and bigram frequency effects on exception word and pseudohomophone performance, respectively, which would further support the OLD T as a task to isolate orthographic processing.

a. Task-Learning Hypothesis



b. Attentional Exercise Hypothesis



c. Attentional Exercise + Task Learning

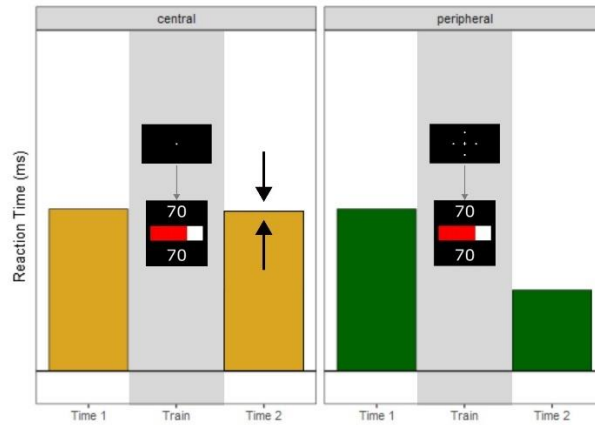


Figure 2.5. Task learning (a), A-O exercise (b), and A-O exercise + task learning (c) hypotheses for reaction times

2.3.2 Method

2.3.2.1 Participants

We recruited 40 participants (9 cisgender men, 31 cisgender women; $M = 19.85$ years, $SD = 3.54$) through the University of Saskatchewan SONA participant pool during the Fall 2023 term. As compensation for participating, participants received two bonus course credits. The first language of all participants was English. Additionally, although two participants were left-handed, all participants reported using the mouse with their right hand. This study was approved by the University of Saskatchewan Research Ethics Board (see Appendix B) and all participants provided informed consent before participating.

Participants were randomly assigned to the training groups such that half the participants received the central HBDT as their training task and the other half received the peripheral HBDT as their training task. There were no significant differences between the training groups in terms of age or gender (see Table 2.7).

Table 2.7. Demographic characteristics as a function of group assignment

	Central Group	Peripheral Group	
Mean age in years (<i>SD</i>)	20.65 (4.40)	19.05 (2.26)	$p = .159$
Gender			
Cisgender Man	4	5	$\chi^2 = 0.11$
Cisgender Woman	16	15	$\chi^2 = 0.03$

Note. All participants reported using the mouse with their right hand.

2.3.2.2 Apparatus and Stimuli

The experiment was designed in PsychoPy Version 2023.1.3 (Peirce et al., 2019; *PsychoPy*, 2023) and run in a dimly lit, quiet experiment room. The experiment computer was a Lenovo ThinkCentre M70q computer running Windows 10. An HP E243 23.8-inch monitor displayed the experiment stimuli. Responses were recorded with a standard keyboard and mouse. The OLDT and HBDT stimuli were the same as Experiment 1. The OLDT stimuli were split into two half-blocks (see Appendix A). These half-blocks were counterbalanced such that half the participants in each training group received Half-Block A as the pre-training task and the other participants received Half-Block B as the pre-training task.

2.3.2.3 Procedure

An experimenter was present for the duration of the experiment and there was a set of eight practice trials before each of the three tasks. After providing informed consent, participants began the experiment with the pre-training reading task, which was a 120 trial OLDT (half the length of the OLDT in Experiment 1). In the half-OLDT, a fixation cross would appear, and participants would press the spacebar to begin the trial. After a 150ms interstimulus interval where no fixation cross, stimulus, or cue were on-screen, a letter-string stimulus would appear. Participants were instructed to left-click if the letter-string spelled a real word, and right-click if the letter-string did not spell a real word. Then participants received one block (240 trials) of either the central or peripheral HBDT as their training task, depending on the group to which they were assigned. The HBDT followed the same procedure as in Experiment 1 with one exception. Instead of using the keyboard, participants were instructed to use the mouse to left-click for target responses and right-click for foil responses. After the training task, participants completed a post-training reading task, which was a half-OLDT following the procedure of the pre-training task but using the other set of 120 trials. Finally, participants completed their demographics form and were debriefed on the purpose of the study. Figure 2.6 depicts the design and trial procedure of this experiment.

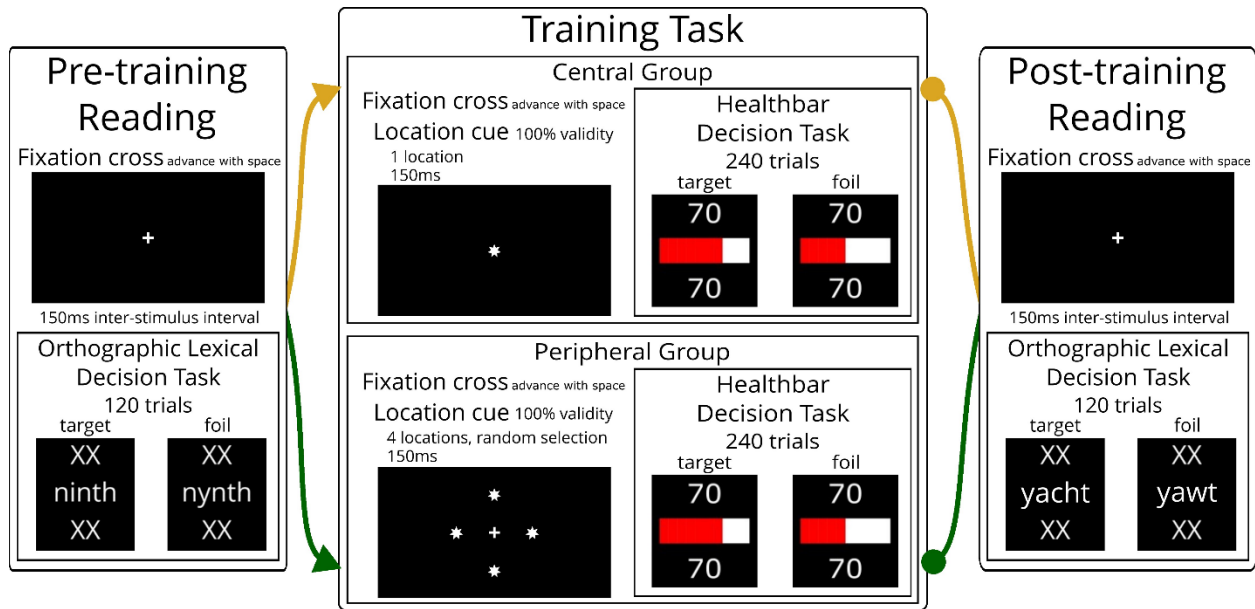


Figure 2.6. Training group assignment and trial procedure for Experiment 2

2.3.3 Results

As in Experiment 1, we examined participant or item median reaction time and mean error rate to correct responses on both exception word targets and pseudohomophone foils. The reaction times reported in text are the mean of these median response times. OLDT item pairs with outlier error rates (error rates which exceeded 3 SD outside the mean error rate) were removed prior to the analysis (6 item pairs: *brooch/broatch*, *dost/dawst*, *sieve/siv*, *soot/suht*, *suave/swawv*, *suede/swaid*).

2.3.3.1 By-subjects results

A 2(Training Group: central vs peripheral; between subjects) \times 2(Time: pre-training vs post-training) mixed measures GLM was conducted on median reaction times to target stimuli to test the effect of A-O exercise (through the HBDT) on OLDT performance. There was a main effect of Time, $F(1, 38) = 20.92$, $MSE = 1878.54$, $p < .001$, whereby participants responded more quickly to targets post-training ($M = 581.06\text{ms}$, $SD = 69.05$) than pre-training ($M = 625.38\text{ms}$, $SD = 85.16$). There was no effect of Training Group (peripheral: $M = 605.84\text{ms}$, $SD = 87.04$; central: $M = 600.59\text{ms}$, $SD = 73.75$), $F(1, 38) = 0.05$, $MSE = 10444.53$, $p = .820$, nor was there a Training Group \times Time interaction, $F(1,38) = 0.003$, $MSE = 1878.54$, $p = .958$ (see Figure 2.7). The same GLM was conducted on mean error rates to targets. There was a main effect of Training Group on targets, $F(1, 38) = 6.29$, $MSE = 38.74$, $p = .017$, whereby participants in the peripheral training group had worse error rates ($M = 9.77\%$, $SD = 6.68$) than participants in the central training group ($M = 6.28\%$, $SD = 3.71$). The main effect of Time (pre-training: $M = 7.57\%$, $SD = 5.34$; post-training: $M = 8.48\%$, $SD = 5.97$) and Training Group \times Time interaction were not significant, both $F(1, 38) = 0.82$, $MSE = 20.31$, $p = .372$.

The same 2(Training Group: central vs peripheral; between subjects) \times 2(Time: pre-training vs post-training) mixed measures GLM was conducted on median reaction times to foil stimuli. There was a main effect of Time on foils, $F(1, 38) = 38.38$, $MSE = 3751.48$, $p < .001$, whereby participants responded more quickly after training ($M = 650.57\text{ms}$, $SD = 75.89$) than before training ($M = 735.41\text{ms}$, $SD = 119.42$). There was no effect of Training Group (central: $M = 698.66\text{ms}$, $SD = 108.39$; peripheral: $M = 687.32\text{ms}$, $SD = 109.08$), $F(1, 38) = 0.16$, $MSE = 16594.04$, $p = .696$, nor was there a Training Group \times Time interaction, $F(1, 38) = 1.37$, $MSE = 3751.48$, $p = .250$. On mean error rate for foils, there were no significant effects or interactions, all F 's < 1.01 , all p 's $> .323$ (Time-pre-training: $M = 13.23\%$, $SD = 8.93$; Time-post-training: M

= 13.57%, $SD = 9.04$; Training Group-central: $M = 13.19\%$, $SD = 10.23$; Training Group-peripheral: $M = 13.61\%$, $SD = 7.55$).

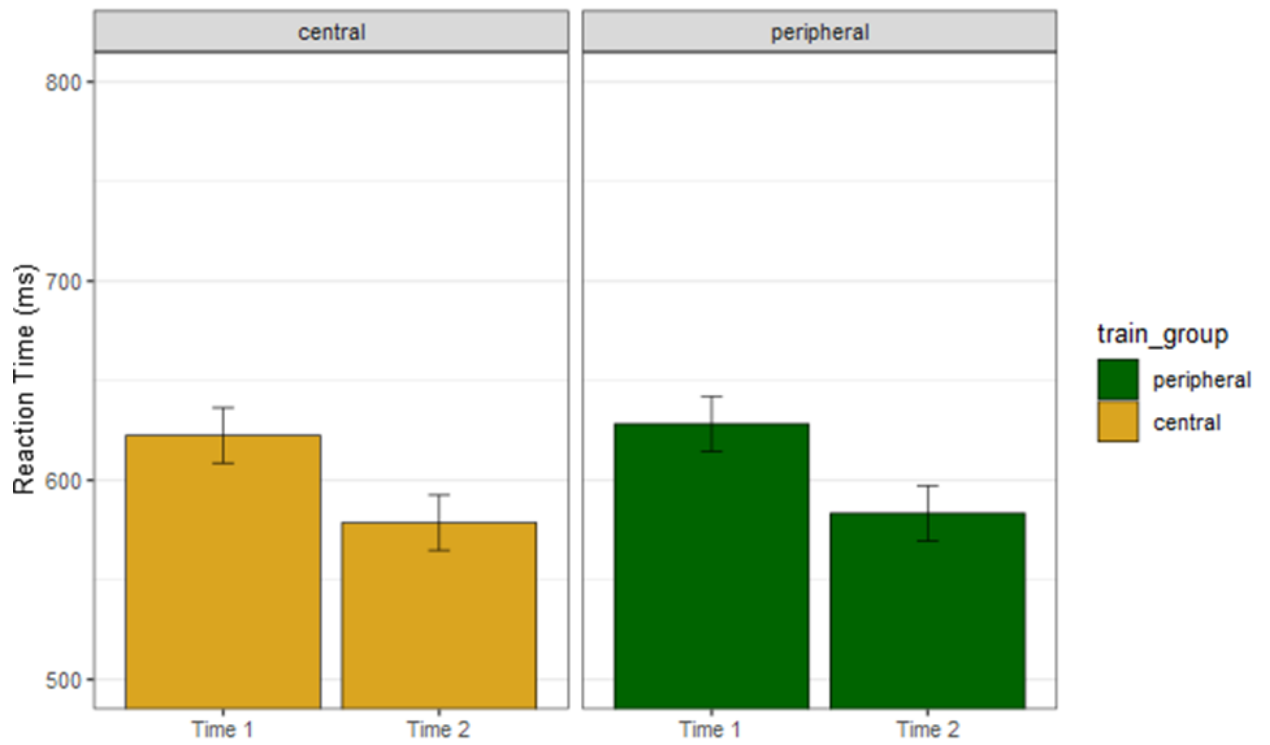


Figure 2.7. Experiment 2 reaction time as a function of Time and Training Group (by-subjects, on targets)

Error bars are 95% confidence intervals based on the calculation methods recommended by Masson & Loftus (2003).

2.3.3.2 By-items results

On target stimuli, a by-items $2(\text{Training Group: central vs peripheral}) \times 2(\text{Time: pre-training vs post-training})$ repeated measures GLM was conducted on median reaction time to test the effect of attentional exercise (through the HBDT) on OLDT performance. There was a main effect of Time, $F(1, 113) = 75.33$, $MSE = 3305.54$, $p < .001$, whereby targets received quicker responses post-training ($M = 594.87\text{ms}$, $SD = 74.70$) than pre-training ($M = 641.61\text{ms}$, $SD = 85.64$). There was no effect of Training Group (central: $M = 616.30\text{ms}$, $SD = 82.64$; peripheral: $M = 620.18$, $SD = 84.71$), $F(1, 113) = .70$, $MSE = 2443.64$, $p = .403$, nor was there a Training Group \times Time interaction, $F(1,113) = .61$, $MSE = 2000.89$, $p = .436$. The same GLM was conducted on mean error rates. There was a main effect of Training Group, $F(1, 113) = 24.23$, $MSE = 57.93$, $p < .001$; targets received higher error rates from participants in the peripheral training group ($M = 9.82\%$, $SD = 14.23$) than participants in the central training group ($M = 6.32\%$, $SD = 12.51$). There was no effect of Time (pre-training: $M = 7.59\%$, $SD = 13.04$; post-training: $M = 8.55\%$, $SD = 13.96$), $F(1,113) = 1.33$, $MSE = 80.03$, $p = .252$, nor was there a Training Group \times Time interaction, $F(1, 113) = 1.34$, $MSE = 79.15$, $p = .249$.

We ran $2(\text{Training Group: central vs peripheral}) \times 2(\text{Time: pre-training vs post-training})$ repeated measures GLMs on median reaction time and mean error rate for foil stimuli. In terms of reaction time, there was a main effect of Time, $F(1, 113) = 144.14$, $MSE = 3681.23$, $p < .001$, whereby foils were responded to more quickly after training ($M = 664.96\text{ms}$, $SD = 87.24$) than before training ($M = 733.19\text{ms}$, $SD = 100.55$). There was also a main effect of Training Group, $F(1,113) = 12.02$, $MSE = 3425.37$, $p < .001$, where foils were responded to more quickly by participants in the peripherally trained group ($M = 689.57\text{ms}$, $SD = 100.29$) than participants in the centrally trained group ($M = 708.58\text{ms}$, $SD = 99.09$). There was no Training Group \times Time interaction, $F(1,113) = 0.11$, $MSE = 4294.18$, $p = .741$. There were no significant effects on foil error rates, all F 's < 2.38 , all p 's $> .126$ (Time-pre-training: $M = 13.33\%$, $SD = 15.23$; Time-post-training: $M = 13.60\%$, $SD = 15.91$; Training Group-central: $M = 13.20\%$, $SD = 15.56$; Training Group-peripheral: $M = 13.73\%$, $SD = 15.58$).

2.3.3.3 Word frequency and bigram frequency

As in Experiment 1, we used simple correlations to analyse the relationship between word frequency, bigram frequency and our two dependent variables (reaction time and error rate). We used the same word and bigram frequency measures as in Experiment 1.

Similarly to Experiment 1, we ran our simple correlations separately for each training group and pre- vs post-training block, resulting in four correlations for a given dependent variable – frequency combination, and thirty-two correlations in total. Word frequency was significantly correlated with exception word performance, such that higher word frequencies were associated with faster reaction times and lower error rates (see Table 3.2). Bigram frequency was significantly correlated with pseudohomophone performance, such that higher bigram frequencies were associated with slower reaction times and higher error rates (see Table 3.2). There were no significant correlations with bigram frequency and exception word performance nor with base word frequency and pseudohomophone performance.

Table 2.8 Simple correlations between reaction time or error rate and word/bigram frequency for Experiment 2 (targets and foils)

EWs: yacht		Central Training			Peripheral Training	
		Aggregate	Time 1	Time 2	Time 1	Time 2
Reaction Time	WF	- 0.64 ***	- 0.56 ***	- 0.54 ***	- 0.50 ***	- 0.55 ***
	BF	0.04	- 0.01	0.04	0.06	0.05
Error Rate	WF	- 0.54 ***	- 0.48 ***	- 0.39 ***	- 0.46 ***	- 0.48 ***
	BF	0.07	0.05	0.12	0.01	0.05
PHs: yawt						
Reaction Time	WF	- 0.06	- 0.05	- 0.04	- 0.02	- 0.08
	BF	0.33 ***	0.21	0.33 **	0.26 *	0.28 **
Error Rate	WF	- 0.12	- 0.09	- 0.12	- 0.12	- 0.08
	BF	0.40 ***	0.36 ***	0.24 *	0.27 *	0.46 ***

Note. WF: log_e-transformed HAL word frequency, BF = mean bigram frequency.

Degrees of Freedom for all correlations = 114.

Significance levels for the aggregate correlations: * < .05, ** < .01, *** < .001.

The block-based correlations have *p*-values which are Bonferroni-corrected for multiple comparisons (* < .0125, ** < .0025, *** < .00025).

2.3.4 Interim Discussion

With Experiment 2, we were able to replicate the double dissociation of a word frequency effect on exception word performance, a bigram frequency effect on pseudohomophone performance, and the absence of these effects with their counterparts. However, we did not observe a difference between the peripheral and central A-O exercise groups in this refined paradigm. It may be the case that in the new paradigm, the single block of A-O exercise was not enough to induce the additional benefit expected of peripheral A-O exercise. To address this, we extended the exercise duration in Experiment 3 in order to boost the paradigm's sensitivity for detecting differences in these exercise groups.

2.4 Experiment 3: Extended attentional-oculomotor exercise

2.4.1 Method

2.4.1.1 Participants

We recruited thirty-nine participants who were included in the analysis² (12 cisgender men, 25 cisgender women, 1 non-binary or transgender participants, 1 preferred not to respond; $M = 22.77$ years, $SD = 6.64$) through the University of Saskatchewan SONA participant pool during the Winter and Spring 2024 terms. As compensation for participating, participants received two bonus course credits. As in Experiment 2, the first language of all participants was English and all participants reported using the mouse with their right hand (although four participants were otherwise left-handed). This study was approved by the University of Saskatchewan Research Ethics Board (see Appendix B) and all participants provided informed consent before participating.

Participants were randomly assigned to the training groups such that half the participants received the central HBDT as their training task and the other half received the peripheral HBDT as their training task. There were no significant differences between the training groups in terms of age or gender, although the peripheral training group was marginally older than the central training group (see Table 2.9).

Table 2.9 Demographic characteristics as a function of group assignment

		Central Group	Peripheral Group	
Mean age in years (<i>SD</i>)		21.75 (5.79)	23.84 (7.44)	$p = .332$
Gender	Cisgender Man	3	9	$\chi^2 = 3.00$
	Cisgender Woman	15	10	$\chi^2 = 1.00$
	Non-binary/Transgender	1	0	
	Prefer not to respond	1	0	

Note. All participants reported using the mouse with their right hand.

² Forty English-first-language participants took part in the study, but one was excluded during the data quality check prior to analysis for outlier error rates during the OLDT.

2.4.1.2 Apparatus and stimuli

The apparatus and stimuli in Experiment 3 were the same as those used in Experiment 2.

2.4.1.3 Changes in procedure

The experiment design and procedure were nearly the same as Experiment 2, with two major exceptions. The first change was in the training HBDT length. The training HBDT was doubled (i.e. two HBDT blocks instead of one), with a brief participant-controlled break of 10-30s to reduce eye-fatigue during training. The second change was in the OLDT design. The OLDT blocks for Experiment 2 were peripherally presented to increase the difficulty of the task. This also made the design more similar to our earlier experiment where we first observed the double dissociation between central and peripheral visual demands on reading performance (Kress et al., 2023). The peripherally presented OLDT was not cued, to keep the stimulus presentation consistent between Experiments 2 and 3, and followed the same timing procedure. The participant would see the fixation cross and press the spacebar to begin the trial. Then, after a 150ms interstimulus interval where no fixation cross, stimulus, or cue were on-screen, the letter-string stimulus would appear randomly in one of the four target locations, and the participant would make their response (see Figure 2.8). The four target locations were the same as those used in the HBDT.

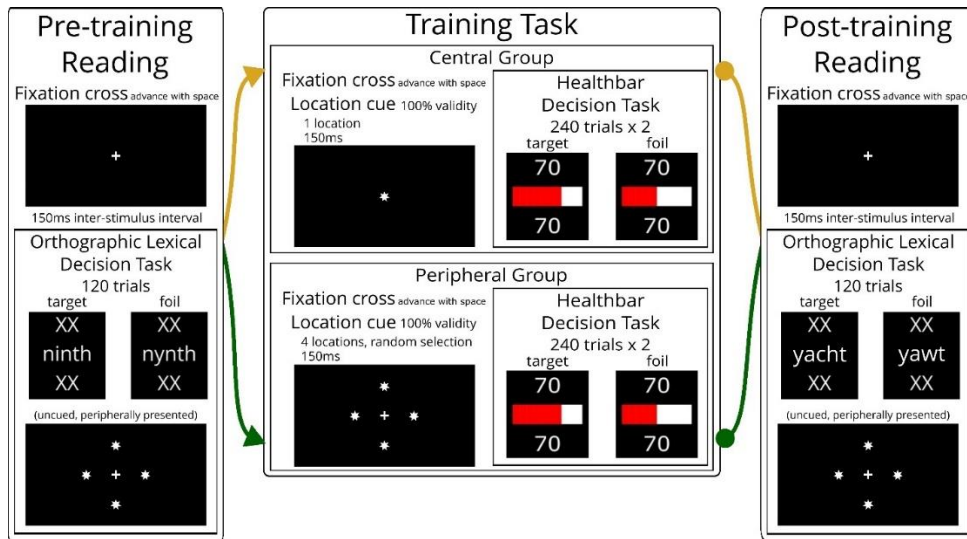


Figure 2.8. Training group assignment and trial procedure for Experiment 3

2.4.2 Results

The analysis for Experiment 3 followed the same steps as the previous experiment. We examined participant or item median reaction time and mean error rate to correct responses and the values reported in text are the mean of these median response times. Trials with missing responses and OLDT item pairs with outlier error rates (error rates which exceeded 3 SD outside the mean error rate) were removed prior to the analysis (7 item pairs: *dost/dawst*, *leapt/lept*, *mauve/moav*, *sieve/siv*, *soot/suht*, *suave/swawv*, *suede/swaid*).

2.4.2.1 By-subjects results

As in the previous experiment, a 2(Training Group: central vs peripheral; between subjects) \times 2(Time: pre-training vs post-training) mixed measures GLM was conducted on median reaction times to target stimuli to test the effect of attentional exercise (through the HBDT) on OLDT performance. There was a main effect of Time, $F(1, 37) = 29.91$, $MSE = 1123.67$, $p < .001$, whereby participants responded more quickly post-training ($M = 699.34\text{ms}$, $SD = 69.83$) than pre-training ($M = 740.93\text{ms}$, $SD = 71.48$). There was also a marginal effect of Training group (central: $M = 700.36\text{ms}$, $SD = 68.13$; peripheral: $M = 740.95\text{ms}$, $SD = 73.52$), $F(1,37) = 3.89$, $MSE = 8261.10$, $p = .056$. There was no significant Time \times Training Group interaction, $F(1, 37) = 0.06$, $MSE = 1123.67$, $p = .801$. Figure 2.9 depicts the main effect of Time in both groups. When the same GLM was conducted on error rates, there was a significant effect of Training Group, $F(1, 37) = 7.48$, $MSE = 49.69$, $p < .001$, with participants in the central group ($M = 6.28\%$, $SD = 4.69$) responding with less errors than participants in the peripheral group ($M = 10.65\%$, $SD = 6.50$). The main effect of Time (pre-training: $M = 7.69\%$, $SD = 6.02$; post-training: $M = 9.12\%$, $SD = 6.02$) and the Time \times Training Group interaction were not significant, $F(1, 37) = 2.73$, $p = .107$ and $F(1,37) = 0.21$, $p = .900$, respectively ($MSE = 14.74$ for both).

We also ran the 2(Training Group: central vs peripheral; between subjects) \times 2(Time: pre-training vs post-training) mixed measures GLM on median reaction times to foil stimuli. There was a main effect of Time, $F(1, 37) = 48.22$, $MSE = 2101.40$, $p < .001$, whereby participants responded more quickly to foils after training ($M = 765.78\text{ms}$, $SD = 86.37$) than before training ($M = 837.94\text{ms}$, $SD = 112.80$). There was no effect of Training Group (central: $M = 798.16\text{ms}$, $SD = 103.23$; peripheral: $M = 805.75\text{ms}$, $SD = 110.51$), $F(1, 37) = 0.06$, $MSE = 18596.49$, $p = .807$, and there was no Training Group \times Time interaction, $F(1, 37) = 0.03$, $MSE = 2101.40$, $p = .873$. On error rate for foils, there was a main effect of Time, $F(1, 37) = 5.32$, $MSE =$

= 22.41, $p = .027$, whereby participants responded with more errors after training ($M = 14.50\%$, $SD = 9.20$) than before training ($M = 12.03$, $SD = 9.41$). The effect of Training Group (central: $M = 14.56\%$, $SD = 8.54$; peripheral: $M = 11.90\%$, $SD = 10.03$). and Training Group \times Time interaction were not significant, all F 's < 0.91 , all p 's $> .347$.

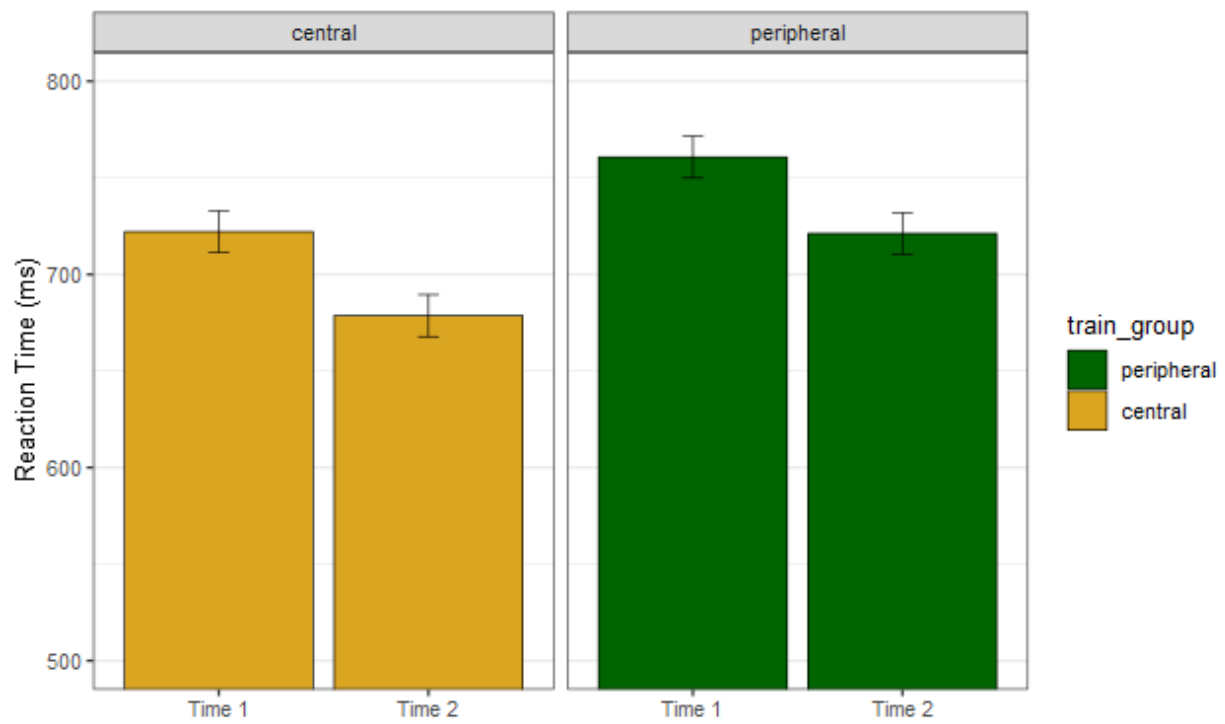


Figure 2.9. Experiment 3 reaction time as a function of Time and Training Group (by-subjects, on targets)

Error bars are 95% confidence intervals based on the calculation methods recommended by Masson & Loftus (2003).

2.4.2.2 By-items results

A set of by-items 2(Training Group: central vs peripheral) \times 2(Time: pre-training vs post-training) repeated measures GLMs was conducted on median reaction time and mean error rate to test the effect of attentional exercise (through the HBDT) on OLD T performance.

On target reaction time, there was a main effect of Time, $F(1,112) = 79.74$, $MSE = 3574.53$, $p < .001$, whereby targets were responded to more quickly post-training ($M = 711.03\text{ms}$, $SD = 71.97$) than pre-training ($M = 761.25\text{ms}$, $SD = 90.41$). There was also a main effect of Training Group, $F(1,112) = 82.45$, $MSE = 2962.74$, $p < .001$, whereby targets were responded to more quickly by participants in the central group ($M = 712.89\text{ms}$, $SD = 80.77$) than in the peripheral group ($M = 759.39\text{ms}$, $SD = 83.73$). There was no significant Time \times Training Group interaction, $F(1,112) = 0.45$, $MSE = 3605.77$, $p = .505$. On error rates, there was a significant effect of Training Group, $F(1,112) = 37.19$, $MSE = 59.52$, $p < .001$, whereby targets were responded to with less errors by participants in the central group ($M = 6.30\%$, $SD = 10.83$) than in the peripheral group ($M = 10.73\%$, $SD = 14.19$). There was a significant effect of Time on targets (pre-training: $M = 7.78\%$, $SD = 11.56$; post-training: $M = 9.25\%$, $SD = 13.92$), $F(1,112) = 3.94$, $MSE = 62.33$, $p = .050$. There was no Time \times Training Group interaction, $F(1,112) = 0.006$, $MSE = 61.13$, $p = .938$.

On foil reaction time, there was a main effect of Time, $F(1, 112) = 154.02$, $MSE = 3411.58$, $p < .001$. This main effect of Time was driven by faster responses to foils after training ($M = 776.06\text{ms}$, $SD = 89.99$) than before training ($M = 844.25\text{ms}$, $SD = 91.53$). There was no effect Training Group (central: $M = 808.79\text{ms}$, $SD = 94.67$; peripheral: $M = 811.51\text{ms}$, $SD = 99.22$), $F(1,112) = 0.23$, $MSE = 3595.79$, $p = .631$, nor was there a Time \times Training Group interaction, $F(1,112) = 0.69$, $MSE = 4442.25$, $p = .407$. On error rate, there was a main effect of Time, $F(1, 112) = 6.09$, $MSE = 99.95$, $p = .015$, in which participants responded with more errors to foils after training ($M = 14.51\%$, $SD = 17.26$), than before training ($M = 12.19\%$, $SD = 14.24$). There was also main effect of Training Group, $F(1,112) = 6.25$, $MSE = 116.31$, $p = .014$, in which foils were responded to with lower error rates by participants in the peripheral training group ($M = 12.08\%$, $SD = 14.29$) than the central training group ($M = 14.61\%$, $SD = 17.20$). The Time \times Training Group interaction was not significant, $F(1,112) = 0.004$, $MSE = 95.19$, $p = .945$.

2.4.2.3 Word frequency and bigram frequency

As in the previous experiments, we used simple correlations to analyse the relationship between word frequency, bigram frequency, and our two dependent variables (reaction time and error rate). We used the same word and bigram frequency measures as the previous experiments, and followed the same procedure. Replicating the results of the previous experiments, we observed a significant correlation between word frequency and exception word performance, such that higher word frequencies were associated with faster reaction times and lower error rates, and a significant correlation between bigram frequency and pseudohomophone performance, such that higher bigram frequencies were associated with slower reaction times and worse error rates (see Table 2.10). As in the previous experiments, bigram frequency was not correlated with exception word performance and base word frequency was not correlated with pseudohomophone performance. With these consistent results, the double dissociation appears to be robust.

Table 2.10. Simple correlations between reaction time or error rate and word/bigram frequency for Experiment 3 (on targets and foils)

EWs: yacht		Central Training			Peripheral Training	
		Aggregate	Time 1	Time 2	Time 1	Time 2
Reaction Time	WF	-0.65 ***	- 0.45 ***	- 0.50 ***	- 0.55 ***	- 0.49 ***
	BF	0.06	0.09	0.06	0.02	0.01
Error Rate	WF	-0.52 ***	- 0.42 ***	- 0.33 **	- 0.58 ***	- 0.44 ***
	BF	0.02	- 0.08	0.05	0.03	0.04
PHs: yawt		Aggregate				
Reaction Time	WF	- 0.03	- 0.13	0.00	- 0.04	0.05
	BF	0.42 ***	0.43 ***	0.33 ***	0.33 ***	0.29 **
Error Rate	WF	- 0.13	- 0.11	0.00	- 0.18	- 0.17
	BF	0.45 ***	0.37 ***	0.31 **	0.44 ***	0.41 ***

Note. WF: log_e-transformed HAL word frequency, BF = mean bigram frequency.

Degrees of Freedom for all correlations = 113.

Significance levels for the aggregate correlations: * < .05, ** < .01, *** < .001.

The block-based correlations have *p*-values which are Bonferroni-corrected for multiple comparisons (* < .0125, ** < .0025, *** < .00025).

2.5 Discussion

Bringing together the research fields of reading and attention, the goal of this set of studies was to test whether short-term attentional exercise could benefit reading performance. Our hypothesis that attentional exercise may benefit reading ability drew from the past literature on cognitive exercise (e.g., Nouchi et al., 2012), past links between reading and attention (Boden & Giaschi, 2007; Ekstrand, Neudorf, Kress, et al., 2019), and recent work on the relationship between video games and both reading and attention (Bertoni et al., 2021; Kress et al., 2023).

2.5.1 *Potential attentional-oculomotor exercise effects*

In both the by-subjects and by-items analyses of Experiment 1, we observed an effect of Order, whereby the peripheral A-O exercise demonstrated improved performance over time, while central A-O exercise demonstrated either minimal change or worsened performance over time. These reaction time benefits did not come at the cost to accuracy, meaning participants were not experiencing speed-accuracy trade-offs with this improved reaction time performance. However, although this was replicated by-subjects and by-items, there was some concern that these effects may be attributable to task difficulty, particularly in the by-subjects analysis.

The designs of Experiments 2 and 3 were intended to address this concern by controlling the location of the pre- and post- training reading task. In this case, we observed a significant effect of Time on reaction times, whereby participants responded more quickly after training than before training, however, there was no interaction that would suggest peripheral A-O exercise was more effective than central A-O exercise at inducing reading improvements in the OLDIT. These improvements in reaction time were accompanied with no significant changes in error rates for Experiment 2, and higher error rates after training in some conditions for Experiment 3. With the results of Experiment 2 and 3 in mind, it may have been the case that Experiment 1's effects were driven by task difficulty, although note that the interleaved design of the blocks in Experiment 1 meant that there was the potential for a longer period for differences to emerge relative to Experiment 2. Further, the significant by-items effect of Task in the Experiment 1 analyses suggests that the effect cannot be fully accounted for by task difficulty alone. The next section will unpack the attentional processes present in our A-O exercise paradigm as we consider explanations for the results of Experiments 2 and 3 and options to further refine the design of the A-O exercise.

2.5.2 Which attentional processes benefit from attentional-oculomotor exercise?

Our goal was to test whether short-term A-O exercise had the potential to provide any amount of reading performance benefit and we can bring past findings together with the current study to make some predictions regarding the relevant systems. Our A-O exercise consisted of briefly flashing a star at the target location, which one could argue would activate both the alerting (when will the target appear) and orienting (where will the target appear) mechanisms of the attentional network (Dye et al., 2009; J. Fan et al., 2002; see Figure 1.2). In the dyslexia research field, the dysfunction in the orienting system is most frequently discussed when exploring the overlapping reading + attention deficits in dyslexia (Boden & Giaschi, 2007; Gori et al., 2014, 2016; Taran et al., 2022). Oculomotor processing and attentional orienting are also more frequently discussed over the alerting system when testing action video games as a cognitive exercise tool (Diarra et al., 2019; Dye et al., 2009; Pasqualotto et al., 2022; West et al., 2013). For these reasons, we suspect that attentional orienting, rather than attentional alerting, is the more relevant process when designing an A-O exercise task to benefit reading. These attentional orienting processes could involve large oculomotor shifts, such as those required to shift from the centre of the screen to the peripheral of the screen during a video game, or from the end of one line to the start of the next line while reading a book. Attentional orienting processes could also involve small oculomotor shifts, such as those required to precisely target the enemy you are looking at in a video game, or those required to shift between, or within, nearby words in a sentence.

When one considers attentional orienting processes, this can be subcategorized into the voluntary and reflexive orienting processes discussed by Corbetta and Shulman (2002). The star cue could be considered a reflexive orienting cue, albeit one with 100% validity. In the peripheral A-O exercise this reflexive orienting cue required large oculomotor shifts to move from the central fixation cross to the target location for the HBDT. The reflexive orienting cue for the central A-O exercise condition would not require this same large oculomotor shift. It would be reasonable to expect the exercise of this reflexive orienting process to benefit reading, as we originally hypothesised, given that past research has suggested action video games (which emphasize peripheral processing) benefit reading processes (Bertoni et al., 2021; Franceschini et al., 2017; Pasqualotto et al., 2022).

Our designs, which varied the degree of large reflexive orienting movements, did not lead to differences in the reading performance between the central and peripheral A-O exercise groups. This could be because our training period was too short, which still is a valuable contribution to the field as we have made progress on identifying where the lower threshold is on training time to observe A-O exercise effects but not distinguish between peripheral and central A-O exercise differences. Alternatively, it could instead mean we need to target a different attentional process for A-O exercise. We will explore this second explanation in more detail.

Voluntary orienting processes, and in particular fine-grained voluntary oculomotor processes, would be good A-O exercise to consider in future designs. The HBDT involves small voluntary oculomotor movements from the health bar in the centre of the screen, up or down to the flanker number, and then potentially back to the health bar to evaluate its size. These small oculomotor movements are present in both the central and peripheral versions of the task. Reading also involves small systematic oculomotor movements between word segments or whole words, and large oculomotor movements generally only need to take place when the reader reaches the end of the line or the end of the page. With this in mind, it could be the case that both peripheral and central versions of the HBDT were sufficient to induce the type of A-O exercise that could most benefit reading (i.e. small oculomotor movements).

2.5.3 Isolating orthographic processing

The reading task we used in this set of experiments was an OLDIT, where participants indicated whether the presented letter-string spelled a real word or not. In this case, the foils were pseudohomophones, which are non-words that sound like a real word if they are phonetically decoded (Cummine et al., 2015; Neudorf, Ekstrand, Kress, Neufeldt, et al., 2019; Wingerak et al., 2017). The use of exception word targets and pseudohomophone foils should force orthographic lexical processing in tasks such as the OLDIT, as an incorrect response will be generated if participants focus on phonological and/or semantic instead of orthographic lexical representations.

Our theory is supported by the results in our word and bigram frequency analyses which show that performance is better for exception words that have high word frequency, while performance is worse for pseudohomophones that have high bigram frequency. Our word frequency effect aligns with past research that has attributed the effect to enhanced orthographic processing (Borowsky et al., 2013; Borowsky & Besner, 1993; McCann et al., 1988). The

research on bigram frequency effects is far more limited, but bigram frequency has been attributed to phonological processing in past research (Borowsky et al., 2013). Given this attribution to phonological processing, we argue that the worse performance for high bigram frequency pseudohomophones represents a form of phonological interference (due to activation of the phonological lexicon via the sublexical grapheme-to-phoneme conversion route).

It is likely the case that both routes are running in parallel (Paap & Noel, 1991), so successful performance in the OLDT simply requires monitoring the orthographic lexicon, which exception words will activate strongly and quickly by utilising word frequency sensitive connections (Borowsky et al., 2013; Borowsky & Besner, 1993; McCann et al., 1988). The pseudohomophones will not activate the orthographic lexicon as strongly, nor as quickly, so the activation from the bigram frequency sensitive grapheme-to-phoneme conversion path in the sublexical route will have more opportunity to (incorrectly) intervene. Single route models will have a difficult time accounting for this double dissociation because they can only make use of one non-semantic path from orthographic to phonological representations to handle the opposing effects.

Given this double dissociation, our results suggest that both lexical and sublexical processing benefited from attentional exercise in our studies. This is an exciting extension to the past research on attentional training during reading, as most previous studies have focused on the benefits of attentional training (through video game play) on sublexical processes specifically (Bertoni et al., 2024; Franceschini & Bertoni, 2019). Future studies could use reading tasks that isolate phonetic decoding, such as reading exception words and pseudohomophones aloud (e.g., Kress et al., 2023) or a phonological LDT with pseudohomophone targets and nonword foils (e.g., McCann et al., 1988) to further contrast the impact of short-term attentional exercise on the two reading systems.

In light of the current results, we should also consider the results of Kress et al. (2023), where we observed experience with peripheral visual demands was beneficial while experience with central visual demands was detrimental to reading aloud performance. These results are somewhat different from those observed in our current experiments. Experiment 1 was consistent with the Kress et al. (2023) results, while Experiment 2 and 3 replicated the peripheral but not central A-O exercise effects. One common difference that exists in Kress et al. (2023) and Experiment 1, where the double dissociation between peripheral and central A-O exercise exists,

relative to Experiments 2 and 3, is the mixing of peripheral and central visual demands. The A-O exercise in Kress et al. (2023) is provided by the participants' video game experience, and video games include a mix of peripheral and central visual demands. Although the location of stimulus presentation was blocked, Experiment 1 included a combination of peripheral and central A-O blocks to serve as both training and testing measures, so its design is more mixed than Experiments 2 or 3, where only one type of A-O exercise was presented. It could be the case that mixed A-O exercise captures the shared benefits of both types of visual demands, allowing peripheral-exclusive A-O exercise benefits to be observed.

2.5.4. Limitations and future directions

In Experiment 3, targets and foils exhibited some degree of speed-accuracy trade-offs. The increase in exception word target errors could indicate that the sublexical route has become more efficient following exercise, resulting in interference with lexical processing (e.g., with A-O exercise, *ninth* more quickly leads to the incorrect /*ninth*/ - note the short *i*-sound). For pseudohomophone foils, the increase error rates could similarly reflect an increase in sublexical processing, but in this case resulting in more efficient phonological lexical activation (e.g., with A-O exercise, *nynth* quickly activates the lexical representation for *ninth*, and the participant incorrectly responds that the stimulus was a word).

Paradigm refinements should include manipulations of the exercise duration, such as by comparing single session designs to multi-session designs. Manipulating the exercise duration will determine where the optimal window is to maximize the benefits of attentional exercise while minimizing the temporal costs for the individual. In comparisons of single session vs multi-session designs, researchers may also be able to bring participants back for delayed post-tests, to evaluate the persistency of the benefits gained through large or small A-O exercise (e.g., Pasqualotto et al., 2022).

With our new idea of exercising small, rather than large, oculomotor movements, future refinements of the A-O exercise paradigm should include a modified version of the HBDT to reduce small oculomotor movements in one of the training groups. This could be done by overlaying the number with the health bar or by briefly presenting the number at the target location, followed by the health bar in the same location (see Figure 2.10). Either of these designs would minimize the involvement of small oculomotor movements in the given group, and help determine what type of attentional process is most important for A-O exercise to

improve reading. Ideally, a future study would include three conditions, one each for large movements, small movements, and no movements to compare the effectiveness of all three options against the others. Additionally, eye-tracking could be employed to verify the magnitude of the oculomotor movements that are occurring in each condition.

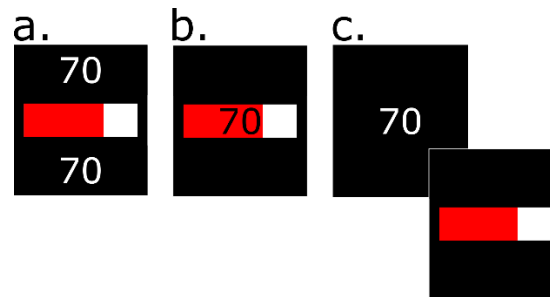


Figure 2.10. Examples of the original health bar stimulus (a) vs an alternate health bars with the value overlaid (b) and with the value and image in sequence (c)

2.5.5. Interim conclusion

Our set of experiments manipulated the location of stimuli to test whether A-O exercise may support reading processes. Although Experiment 1 offered some support of our A-O exercise hypothesis, Experiments 2 and 3 raised questions about whether large or small oculomotor shifts matter most in visual attention processes when trying to improve reading ability.

If future studies successfully narrow down an A-O exercise effect, programmes could be developed to specifically target particular reading processes. This will benefit individuals with dyslexia, as they can focus on the exercise that is most relevant to their individual reading deficit. For example, someone with surface dyslexia can focus on the exercise that targets orthographic processing, while someone with phonological dyslexia can focus on the exercise associated with phonological processing (Castles & Coltheart, 1993; Franceschini & Bertoni, 2019; McDougall et al., 2005; A. Sotiropoulos & Hanley, 2017).

Short A-O exercise activities such as a “game-like” version of the task in these studies could provide a boost in reading performance that is worthy of future research. With further study, the A-O exercise demonstrated in our experiments can be refined to be a quick and engaging activity to add to the toolkits of educators who support individuals with reading difficulties.

CHAPTER 3: The frontal-eye-field in hybrid reading and attention processes

This chapter is adapted from the content of the following manuscript:

Kress, S., Neudorf, J., Ekstrand, C., & Borowsky, R. (submitted). Bridging reading and attention through connectivity with the frontal-eye-field. Submitted to: *Brain Structure and Function*.

Data from this chapter is from our previously published study:

Ekstrand, C., Neudorf, J., Kress, S., & Borowsky, R. (2019). How words and space collide: Lexical and sublexical reading are reliant on separable reflexive and voluntary attention regions in hybrid tasks. *Cortex*, 121, 104–116.
<https://doi.org/10.1016/j.cortex.2019.08.006>

3.1 Introduction

In reading research, there is often an emphasis on ventral-occipital visual processing regions such as the visual word form area (Chen et al., 2019; Neudorf, Gould, et al., 2022; Saygin et al., 2016), temporal lobe for semantics (Neudorf, Ekstrand, Kress, & Borowsky, 2019), and inferior frontal regions for speech output (Price, 2012). These regions alone do not tell the full story of reading in the brain; as can be seen in the thorough review on written and spoken language processing by Price (2012), reading is a highly networked process that utilizes regions from cerebellum to frontal pole.

From our previous OLDT experiments, it would appear that A-O exercise, involving either small or large oculomotor shifts, can result in improved reading performance. One region that is thought to be involved in oculomotor activity, but is not always well-considered in the reading literature, is the frontal-eye-field (FEF). The goal of this chapter is to situate the role of the FEF in reading processes through what we know about the attention network, and equipped with this background knowledge, localize the FEF activation in a hybrid reading + attention task.

3.1.1 Anatomy of the frontal-eye-field

The FEF was first examined in primates before research on function and structure moved to identifying the human homologue (see Schall et al., 2017 for a review). The research on the

FEF stretches back to the 1800s (although the term ‘frontal-eye-field’ did not see use until the 1920s and 1930s) and covered a number of non-human primate species before the human FEF was explored as well. Although the precise location varies, the FEF is typically localized to the arcuate sulcus in non-human primates (the human homologue to this sulcus is the precentral sulcus). Often, the region labelled as FEF will be located lateral to the supplementary motor area in the primates.

In humans, the FEF is typically located at the posterior middle frontal gyrus, with the posterior boundary being the precentral gyrus, and is captured in Brodmann’s area 6 although sometimes Brodmann’s area 8 is also acknowledged (Bedini & Baldauf, 2021; Schall et al., 2017; see Figure 3.1). In terms of white matter connectivity with other regions, reviews of the FEF note that the superior longitudinal fasciculi I and II have terminations in the region (Bedini & Baldauf, 2021) and other studies on frontal lobe structural connectivity have identified superior longitudinal fasciculus and arcuate fasciculus terminations in Brodmann’s area 6 and/or the functionally localized FEF (Rojkova et al., 2016; Umarova et al., 2010).

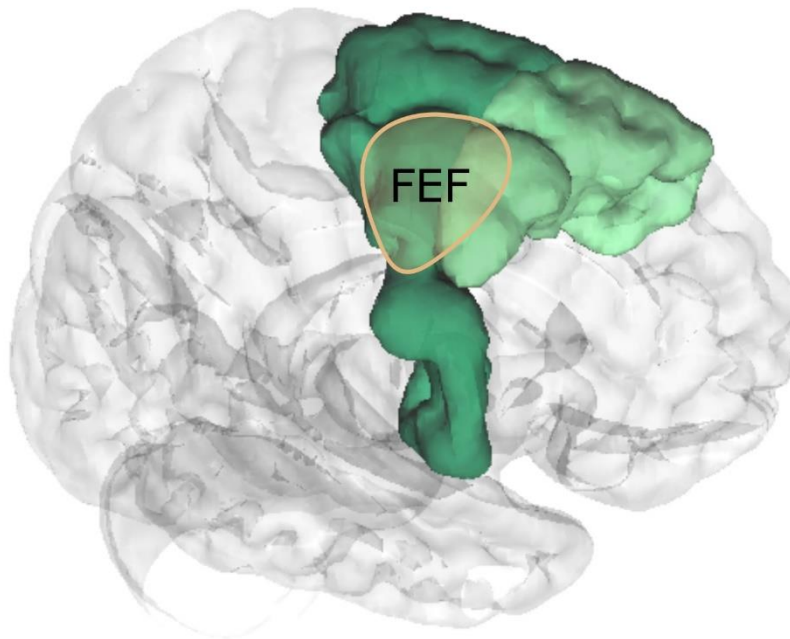


Figure 3.1. Typical FEF location on a glass human brain based on past literature

Typically, the FEF (tan) is localized in the posterior middle frontal gyrus, in Brodmann's area 6 (dark green) and Brodmann's area 8 (light green). Image visualization was done in DSI Studio and the circle for the FEF was added outside the program.

3.1.2 Frontal-eye-field in attention

Numerous visual attention roles have been attributed to the FEF throughout the literature. In an early positron emission tomography study on the human FEF, the main focus was on FEF activation during saccades (Paus, 1996). In the modern literature, the FEF is involved in dorsal attention processes such as oculomotor control, saccades, and orienting (Corbetta et al., 2008; Corbetta & Shulman, 2002; Schall et al., 2017). Other large scale studies on functional connectivity have similarly situated the FEF in the network of dorsal attention regions (Yeo et al., 2011). More recent reviews have expanded the FEF's role to encompass the processing of spatial information more generally (Bedini & Baldauf, 2021).

As a region in the dorsal attention network, the FEF is often implicated in the voluntary aspects of oculomotor control, for example making goal-directed eye movements, or suppressing a reflexive eye movement to shift the eyes in the opposite direction (the anti-saccade task; see Diarra et al., 2019). In a video game training study (Diarra et al., 2019), increases in FEF grey matter volume post-training were related to improved oculomotor control through increased anti-saccade task accuracy. Given the theoretical importance of oculomotor control in reading (see Chapter 1), it is therefore reasonable to expect that the FEF – as a key region in oculomotor processes – should be important in reading processes as well.

3.1.3 Frontal-eye-field in reading

There is surprisingly little research on the FEF in reading processes, given the importance of oculomotor control to successful reading as described by the magnocellular deficit theory. Often, the research that has examined overlap between reading and attention ends up focusing on other regions, middle occipital gyrus (Ekstrand, Neudorf, Kress, et al., 2019), or, quite frequently, the temporoparietal junction (Bertoni et al., 2022; Ekstrand, Neudorf, Gould, et al., 2019; Ekstrand, Neudorf, Kress, et al., 2019).

There has been some reading research that has supported the notion that the FEF is important to consider in understanding the links between reading and attention/oculomotor processes. One recent connectivity study found there were significant functional connectivity associations between the visual word form area of the fusiform gyrus and the FEF, which suggests the FEF may be relevant to reading processes (Chen et al., 2019). However, the same study noted that structural connectivity between the fusiform gyrus and attention network regions (including the FEF) was predictive of attentional but not reading task performance. In one of our

recent structure-to-function prediction studies (Ekstrand et al., 2020), we found that our connectivity-based model was able to predict reading-related activation in the FEF, lending further support to the involvement of the FEF in reading processes.

3.1.4 Past work in hybrid reading + attention tasks

Our lab previously published a novel study in which participants completed a hybrid reading + attention task during fMRI (Ekstrand, Neudorf, Kress, et al., 2019). The hybrid reading + attention paradigm was designed to provide insight on how the two cognitive processes work together, rather than interpreting the functional overlap based on separate tasks. Our original study employed the dual route models of both reading and attention as the theoretical framework on which the hypotheses were generated.

We observed the lexical reading + attention tasks (utilizing exception words) had greater activation than the sublexical reading + attention tasks (utilizing pseudohomophones) in the right temporoparietal junction – a well-established ventral attention region – supporting past findings which have demonstrated lexical reading + attention overlap in the temporoparietal junction (Ekstrand, Neudorf, Gould, et al., 2019). Other findings included greater activation during the sublexical reading + attention tasks in traditionally dorsal voluntary attention regions such as the inferior frontal gyrus and superior parietal lobule, and particularly low activation in the middle occipital gyrus (which has been identified as a spatial attention region in an early neuroimaging study; Mangun et al., 1998) during the lexical reading + reflexive attention task.

The results supported theories of reading and attention overlap and demonstrated the viability of hybrid reading + attention tasks for examining the interplay between these processes. However, the original study took a whole brain, voxel-based analysis approach, and did not focus on examining activity patterns specifically in the FEF. In light of our theories regarding the role of oculomotor activity in successful reading, the goal of the current chapter is to revisit the data from our previous publication (Ekstrand, Neudorf, Kress, et al., 2019), but specifically focus on identifying any interaction between reading + attention on fMRI activation in the FEF.

3.1.5 The current study

Our hybrid reading + attention dataset provides an excellent opportunity to examine the role of the FEF in shared reading and attention processes. Given the role of the FEF in oculomotor processes (Bedini & Baldauf, 2021; Corbetta et al., 2008; Diarra et al., 2019; Schall et al., 2017), the FEF should have significant activation in both automatic and voluntary cueing

conditions. Specifically, given the overlap in reading and attention processes, and our theorized role of oculomotor activity in successful reading, we expect there to be an Attention \times Reading interaction in the FEF's blood oxygen level dependent (BOLD) signal.

3.2 Experiment 4: Frontal-eye-field and hybrid reading + attention

3.2.1 Method

3.2.1.1 Participants

Thirty English-first-language participants with normal or corrected-to-normal vision completed our hybrid reading attention task. We obtained ethics approval through the University of Saskatchewan Biomedical Research Ethics Board (see Appendix C). Participants provided informed consent to participate in the neuroimaging study.

3.2.1.2 Neuroimaging protocol

Participants wore MRI compatible goggles (for presentation of stimuli during fMRI) and headphones (to reduce noise from the scanner and facilitate participant-researcher communication) during the study. EPrime software running on a Windows computer controlled the presentation of stimuli during fMRI. All neuroimaging data were collected on a 3-Tesla Siemens Skyra scanner.

An anatomical whole-brain T1-weighted image was collected for each participant. This image was collected with an MPRAGE sequence (TR = 1900ms, TE = 2.08ms). The four functional tasks used a T2*-weighted protocol for image acquisition, and were collected as four counterbalanced runs (approximately 3m2s per run) in a single session. Each run utilized a 55-volume sequence with 4mm slice thickness and a 1mm gap between each slice (TR = 3300ms, TE = 30ms, flip angle = 90°). There was a gap during fMRI image acquisition to allow participants to respond to the word stimuli. With the TR of 3300ms, this gap paradigm meant that in any given trial there was 1650ms of image acquisition, followed by a 1650ms gap for participants to name the target letter string (Borowsky et al., 2007; Ekstrand, Neudorf, Kress, et al., 2019).

3.2.1.3 Hybrid reading + attention task design and procedure

The experiment had four different hybrid reading + attention task runs, in which the attentional cueing could be either voluntary or reflexive, and the reading task could involve either exception words or pseudohomophones. There were twenty-five exception words and twenty-five pseudohomophones used in this experiment, and these stimuli were primarily a

subset of the stimuli used in the previous experiments, but were not all matched pairs¹. The order of the four task runs was counterbalanced, and the order of reading + attention trials within the block was randomized. Each task run began with five relaxation trials (3300ms each) where a black fixation cross (0.6° of visual angle tall) was displayed at the centre of the screen. Then the task proceeded with five sets of five reading + attention trials followed by five relaxation trials (i.e., 5 relax + (5 task + 5 relax) * 5 = 55 volumes and 25 task trials). For both types of attentional cueing, participants were instructed to shift their attention without moving their eyes, so all task runs involved covert orienting (i.e., shifting the focus of attention without moving the eyes; in contrast to overt orienting, which is a shift in attention that is accompanied with eye movement; Chica et al., 2014).

In the voluntary attention tasks, participants were instructed to covertly orient their attention depending on the colour of the fixation cross. A blue fixation cross meant to shift attention to the left, while a pink fixation cross meant to shift attention to the right. The procedure for the voluntary attention trials began with the black fixation cross presented for 1650ms (during fMRI acquisition) in the centre of the screen. Then, there was a 1650ms gap in fMRI acquisition where the trial took place. During this gap, the fixation cross would change colour to either blue (representing the left side) or pink (representing the right side) for 300ms. Both cues were used equally. Following cue presentation, the fixation cross would change back to black, and the letter-string stimulus would appear for 1000ms on either the left or right side of the fixation cross (with a cue validity of 75%). Then, the letter-string would disappear, and the screen would display only the black fixation cross for 350ms before the next trial began (see Figure 3.2a for an example of trial progression).

In the reflexive attention tasks, participants were instructed to covertly orient their attention to the location where an asterisk appeared. The procedure for the reflexive attention trials was similar to the voluntary orienting trials. As in the voluntary attention trials, the reflexive attention trials began with a black fixation cross presented for 1650ms (during fMRI acquisition) in the centre of the screen followed by a 1650ms gap in fMRI acquisition where the trial took place. During the gap, an asterisk would appear on either the left or right side for

¹ The following stimuli were present in Experiment 4 but not used in the experimental trials of Experiments 1-3: exception words *door*, *geese*, *glove*, *wasp*, and *wolf*, and pseudohomophones *blud*, *wull*, *brayn*, *coyn*, *flaim*, *gurl*, *hupe*, *krib*, *leef*, *mhug*, *mowth*, *poap*, *shedd*, *tohste*, *tuthe*.

150ms. Both cues were used equally. Following cue presentation, the asterisk disappeared and the letter-string stimulus appeared for 1000ms on either the left or right side of the fixation cross (with a cue validity of 50%). Then, the letter-string disappeared and the screen displayed only the fixation cross for 500ms before the next trial began (see Figure 3.2b for an example of trial progression).

During tasks with real words, participants were instructed to read the word aloud and during blocks with pseudohomophones, participants were instructed to sound out the letter-string as if it were a real word. In both cases, participants were instructed to respond as quickly and accurately as possible during the gap in acquisition (while the scanner was making no noise) and minimize mouth movements while responding.

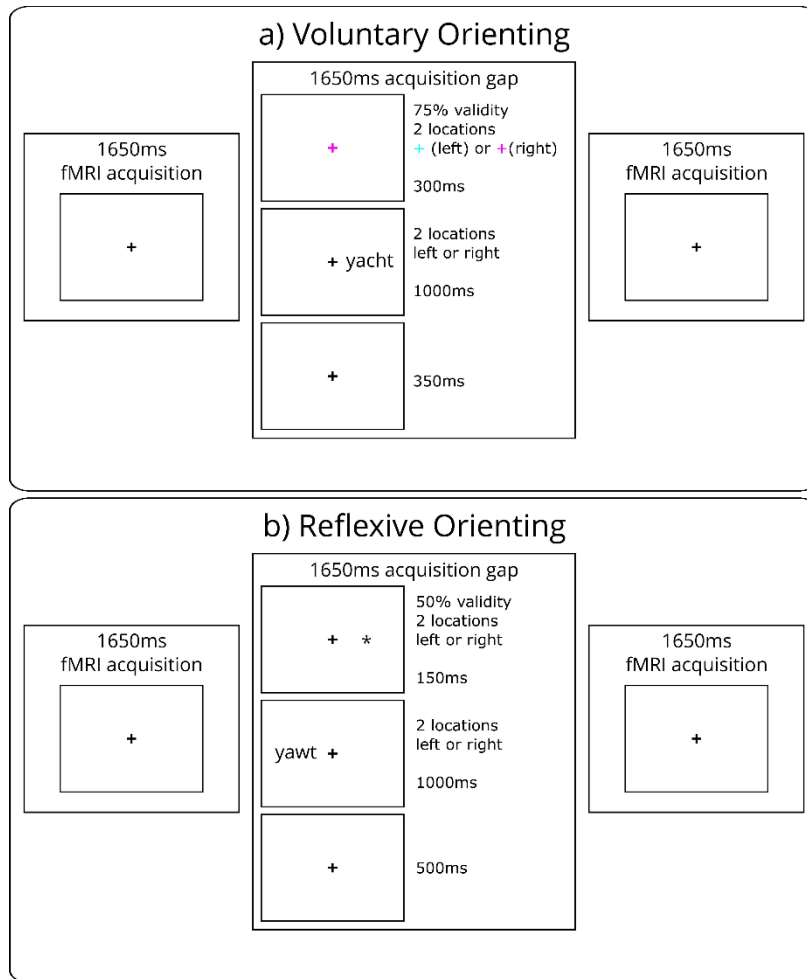


Figure 3.2 Example trial procedure for Experiment 4

There were four blocks in Experiment 4: a) voluntarily cued exception words, reflexively cued exception words (not shown), voluntarily cued pseudohomophones (not shown), and b) reflexively cued pseudohomophones. Trials could be left-cued or right-cued, and the cues could be valid or invalid.

3.2.2 Analysis

The output analysed here is openly available on the Open Science Framework (Ekstrand, 2019). The original analysis (see Ekstrand, Neudorf, Kress, et al., 2019 for the full description of the preprocessing and analysis steps) was conducted using FSL (Jenkinson et al., 2012), specifically the FEAT analysis pipeline which includes preprocessing parameters. Within FSL/FEAT, BET was used for brain extraction and MCFLIRT was used for timing and motion correction. Other preprocessing steps included 5mm spatial smoothing, high pass temporal filtering, and image registration (first registering participants' functional images to their anatomical image, followed by registration to the standard MNI template). The GLM analysis used FSL's FLAME1 tool to conduct a 2×2 repeated measures ANOVA. This was a higher-level analysis which was conducted after lower-level analyses of the task versus rest contrasts for each condition.

For our analysis we examined the z -stat image for the Attention \times Reading interaction. Using FSL, we created a binary mask of the combined superior frontal, middle frontal, and precentral gyri regions from FSL's built in Harvard-Oxford Cortical atlas. These regions were selected to create the mask because they fully encompass the FEF's location as described in the literature (Bedini & Baldauf, 2021; Schall et al., 2017). We then masked our original z -stat image with this binary mask and brought the masked image into MRICroGL for thresholding. In MRICroGL, we set our threshold intensity to $z = 3.1$ (corresponding to $p < .001$) and minimum cluster size to the default of 32.

3.2.3 Results

From the analysis above, we identified three significant clusters of activation within our mask. Two of these clusters fell within the white matter of the left superior longitudinal fasciculus III and will not be discussed further here. The other significant cluster was within the grey matter of the left hemisphere, around the expected anatomical location for the FEF. This cluster was 45 voxels large, with a peak activation of $z = 3.6$. The cluster of activation lay wholly within Brodmann's area 6; when overlaid with the Brainnetome atlas (L. Fan et al., 2016), the peak of the cluster was within the region A6vl (also called MFG_7_6 by some atlas versions, see Figure 3.3) and all voxels within the cluster were in either region A6vl (44 voxels) or A6cdl (1 voxel).

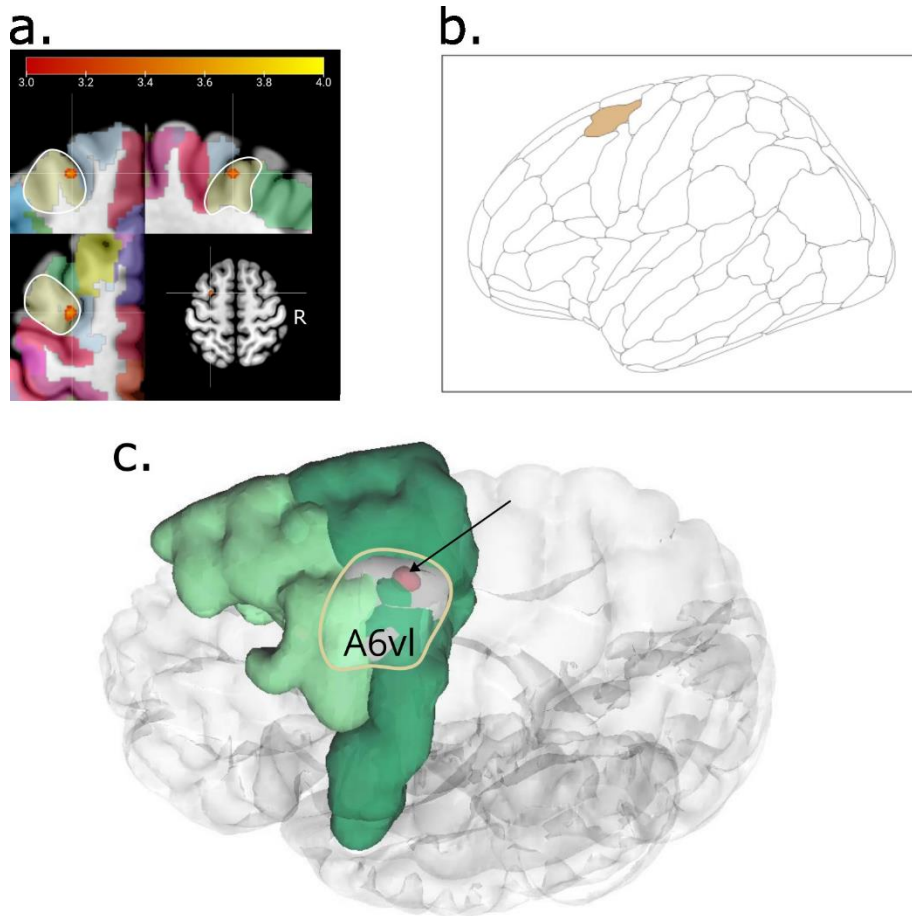


Figure 3.3 The FEF (Brainnetome A6vl) in various viewing contexts

The FEF (Brainnetome A6vl) is depicted in the context of our observed activation in multiple 2D planes (a), without activation on an inflated brain surface (b), and our observed activation on a glass brain (c). In the first image, the crosshairs are placed on the FEF cluster of activation at MNI coordinates (-27, 2, 58). The A6vl is yellow and surrounded by a white border. In the third image, an arrow points to the FEF cluster of activation and the A6vl is surrounded by a tan border. Visualization was conducted in MRICroGL, using the *ggseg* library in *R*, and in DSI Studio (the borders and arrow added outside the visualization programs).

3.3 Discussion

The goal of this chapter was to determine whether the FEF shows an interaction of reading and attention processes, given what we know about the FEF's involvement in the oculomotor system and our theories regarding oculomotor processes in reading.

3.3.1 Summary of findings

As expected, based on our hypotheses driven by the literature on oculomotor processes in reading, we observed an interaction in BOLD activation for Reading (exception word vs pseudohomophone) \times Attention (reflexive vs voluntary) at the intersection of the middle and precentral gyri. Specifically, we observed this interaction in activation in the Brainnetome atlas left hemisphere A6vl – the ventrolateral portion of Brodmann's area 6, which is considered part of the dorsal attention network (Yeo et al., 2011). This region of activation lines up well with the description of the FEF's location in the literature as being primarily within Brodmann's area 6 (Bedini & Baldauf, 2021; Schall et al., 2017).

3.3.2 Limitations and future directions

One limitation in this study comes from the original experimental design. As noted in the methods, participants in this task were instructed to covertly orient their attention, which would minimize eye movements if instructions were followed correctly. It could be possible that the FEF did not activate fully during the covert attention tasks, although an early fMRI study suggests the FEF activates equally in covert and overt tasks (Fairhall et al., 2009), so this may not be a concern. Regardless, an overt hybrid reading + attention task would allow us to compare covert vs overt reading + attention processes, and target the oculomotor aspects of attention, while in-scanner eye-tracking would help confirm whether instructions regarding eye movements are being appropriately followed.

3.3.3 Interim conclusion

Overall, these results are a promising step in understanding the role of the FEF in shared reading + attention processes. With our identification of the Brainnetome atlas' A6vl as a region of reading + attention task interaction, we have localized an atlas-based representation of the FEF which future studies can use as an ROI for examinations of both structure and function for reading, attention, and reading + attention overlap.

CHAPTER 4: Bridging reading and attention through connectivity with the frontal-eye-field

This chapter is adapted from the content of the following manuscript:

Kress, S., Neudorf, J., Ekstrand, C., & Borowsky, R. (submitted). Bridging reading and attention through connectivity with the frontal-eye-field. Submitted to: *Brain Structure and Function*.

4.1 Introduction

The interaction between reading and attention in the FEF from Chapter 4 helps support our theory regarding the involvement of the FEF and oculomotor activity in reading. However, the connectivity profile of the FEF in the context of our reading + attention model is unclear. Connectivity analyses are a valuable complement to our functional and behavioural studies on reading, attention, and oculomotor processes. By examining the strength of connections between regions, we can better predict how certain regions work together in a cohesive network.

4.1.1 Connectivity in the reading + attention networks

One recent study has taken a connectivity-based approach to examining the relationship between the reading and attention networks. Chen et al.'s (2019) study focused on the visual word form area as a region of interest (ROI). The visual word form area is a reading-specialized portion of the fusiform gyrus, and is typically considered part of the ventral lexical reading route (Price, 2012). Structural and functional connectivity analyses supported the involvement of the visual word form area in the reading network, with strong white matter connections between the visual word form area and the ventral route's inferior temporal sulcus, as well as strong correlations in functional activation (Chen et al., 2019).

As one of the few reading studies to include the FEF as an ROI (in this case making the traditional assumption that the FEF is specifically part of the attention network), it is interesting to highlight Chen et al.'s (2019) finding that the visual word form area had significant structural connectivity with the FEF, suggesting a link between reading and FEF's oculomotor processes. In the end, this study argued that although the fusiform gyrus' visual word form area was

connected with the reading network and the attention network, these two networks are distinct from each other due to differences in the ability for each network to predict behavioural performance. Nevertheless, in the field of reading literature where the FEF is scarcely represented, this study serves as the first connectivity-based evidence for the FEF's role in reading.

4.1.2 Graph theory techniques for brain connectivity analysis

There are multiple approaches a researcher can take for conducting connectivity-based analyses of brain structure and function. Chen et al. (2019) demonstrated two typical techniques for these analyses. Functional connectivity analyses use the correlation between the functional activation in two regions to determine the strength of the relationship between the two regions. Because the two regions do not need to be physically connected to each other to activate together, this form of functional connectivity analysis is considered an indirect measure of connectivity (Fornito et al., 2016). Structural connectivity analyses examine the strength and nature of the connections between regions in the brain, using diffusion tensor imaging (DTI) data as the basis of the analysis. In Chen et al.'s (2019) case, the structural connectivity measure was based on the probability that two regions were connected. This type of structural connectivity analysis is a measure of direct connectivity, because the two regions are physically connected to each other via the white matter (Fornito et al., 2016).

An alternate approach is to use graph theory measures to examine the strength of connections between regions in the brain. Graph theory techniques represent the brain as a system of nodes (i.e. regions) connected by edges (see Figure 4.1) which often represent a traditional measure of connectivity (e.g. white matter streamlines, functional correlations). Graph theory allows researchers to use techniques to calculate the strength of the relationship between two regions, while preserving the aspects of the brain's structure that can be lost in other analysis strategies (Fornito et al., 2016; Neudorf, Kress, et al., 2022).

One measure derived from graph theory, which will be relevant for our approach in this chapter, is communicability. Communicability is a diffusion-based measure of information transfer, that takes into account all the possible paths a signal could take between point A and point B, rather than only the shortest path (Estrada & Hatano, 2008; Fornito et al., 2016; Neudorf et al., 2023; see Figure 4.2). This approach provides a balanced measure that reflects both the

strength of the parallel paths between the two points, and length of the paths (with longer paths weighted more weakly than shorter paths).

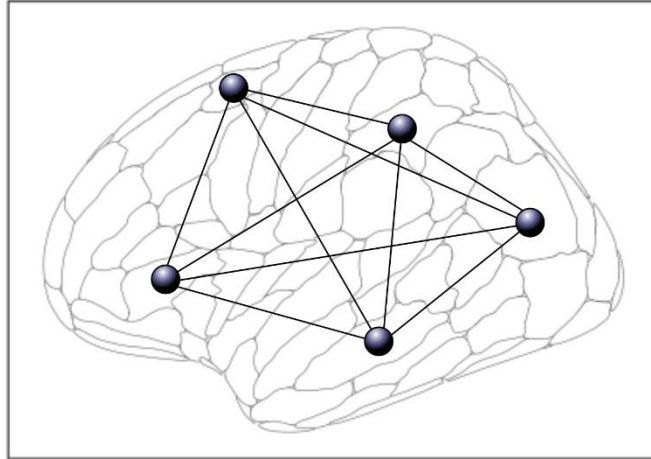


Figure 4.1 A graph theory representation of the brain.

Each node (black spheres) represents a single region in the atlas-based representation of the brain. The nodes are connected by edges (black lines), which can be weighted to represent the strength of different measures. A complete representation of the brain would have a node for every region and an edge for every non-zero connection.

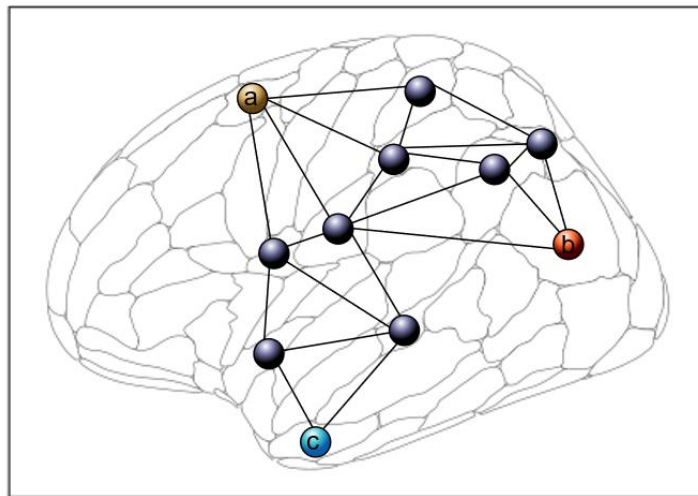


Figure 4.2 An example of communicability.

In this graph representation of the brain, the tan region (a) has high communicability with the red region (b) because there are many parallel connections between the two regions, but low communicability with the blue region (c) because there are fewer parallel connections.

4.1.3 The current study

Given what we have learned about the FEF's involvement in reading from Chapter 3, and inspired by the connectivity based approach of Chen et al. (2019), we approach the current chapter with research questions on the connectivity profile of the FEF in the context of the reading and attention networks, but using graph theory techniques.

To test the strength of the FEF's connections with other regions, we evaluated the connectivity profile of the large Human Connectome Project (HCP) dataset (Van Essen et al., 2013) against a null model. This approach gives insight into where the structural brain connectivity of our dataset is significantly greater (or less) than the randomly connected null brain. In our study, our null model brain was constructed with Rubinov and Sporns' rewiring algorithm (Fornito et al., 2016; Rubinov & Sporns, 2011), using the same implementation as our previous work (Neudorf et al., 2023), which is a conservative approach to null model construction because it preserves the overall strength of each regions' connections with other regions in the rewiring process (Fornito et al., 2016). Based on the literature on the FEF's role in the attention network, and our own findings on FEF's involvement in hybrid reading + attention, we have two hypotheses:

1. Given the FEF's involvement in the attention network, typically in the context of the dorsal attention stream (Corbetta & Shulman, 2002), the FEF should exhibit connectivity with both dorsal and ventral attention regions, but the connections between the FEF and dorsal regions may be stronger. As discussed in Chapter 3, some research finds superior longitudinal and arcuate fasciculi have terminations in the FEF (Bedini & Baldauf, 2021; Rojkova et al., 2016; Umarova et al., 2010), so other regions along these tracts may exhibit particularly strong connections through high communicability scores.
2. Given the shared processes between the reading and attention networks, and the relevance of oculomotor activity in reading, the FEF should exhibit significant connectivity with reading regions and networks in the form of high communicability.

4.2 Experiment 5: Frontal-eye-field connectivity in the Human Connectome

4.2.1 Method

4.2.1.1 Dataset

The DTI data of 696 participants from the Human Connectome Project - Young Adult dataset (HCP-YA; Van Essen et al., 2013) were used in this study. These participants were selected because they had both rs-fMRI and DTI available (although note that only the DTI data were used for the analysis reported in this thesis), and no errors arose while calculating the connectivity measures. In brief, the HCP-YA diffusion data collection consisted of a six-run session (9m50s per run) and utilized a multiband (3-factor) echo planar imaging sequence (TR = 5520ms, TE = 89.5ms) to acquire high-resolution (1.25mm) images and was minimally preprocessed (S. N. Sotiropoulos et al., 2013; WU-Minn Human Connectome Project Consortium, 2018). Participants in the complete HCP-YA dataset ranged in age from 22 to 35 years (Van Essen et al., 2013).

4.2.1.2 Connectivity Measures

Our connectivity measure for this analysis was communicability. As a diffusion measure of information transfer, communicability was a good choice for our analyses, because diffusion measures are thought to represent how signals move through the brain better than other graph theory measures which require assumptions about whole network knowledge (Neudorf et al., 2023).

4.2.1.3 Analysis Protocol

Using the Brainnetome atlas parcellations (L. Fan et al., 2016), the whole-brain streamline count and communicability matrices were calculated using the same methods as our previous work (Neudorf et al., 2023). Streamline count was calculated in DSI Studio (<https://dsi-studio.labsolver.org/>; Yeh, n.d.) with fibre count set to 1000000, step size set to one voxel, angular threshold set to 75°, minimum fibre length set to 20mm and maximum fibre length set to 500mm. Then, whole-brain communicability was calculated based on the streamline count matrix with the following equation which we implemented in Python:

$$Com_{ij} = [e^{S^{-1/2}WS^{-1/2}}]_{ij} \dots\dots\dots (4.1)$$

In this equation, W represents the connectivity matrix (in this study, the matrix of streamline counts), and $S^{-1/2}$ represents the inverted square root of the matrix S , which contains the strengths of the regions (the sum of that region's connection weights) along its diagonal (Crofts et al., 2011; Estrada & Hatano, 2008; Neudorf et al., 2023).

Using the Rubinov and Sporns' rewiring algorithm on the whole-brain connectivity matrix of mean streamline count (Fornito et al., 2016; Rubinov & Sporns, 2011) we constructed 500 null models and calculated the communicability of the null models. We then used the *scipy.stats* function *rankdata* to rank the communicability between our mean brain's FEF and each region relative to the null model's distribution. Dividing this rank by 500 (the number of null models) provides a permutation p -value for the proportion of regions which the FEF has significantly stronger or weaker communicability with (see Figure 4.3). We thresholded the communicability matrix with a two-tailed permutation p -value of .05, so regions with a permutation p -value of .025 were considered to have significantly lower communicability than the null distribution and regions with a permutation p -value of .975 were considered to have significantly higher communicability than the null distribution.

We selected one ROI from the Brainnetome atlas to represent the FEF in our connectivity analyses. The Brainnetome atlas region was the bilateral A6vl (the ventral-lateral portion of Brodmann's area 6). We took a theory-driven approach to this region selection. In Chapter 3, while analysing a previously published hybrid reading + attention dataset (Ekstrand, Neudorf, Kress, et al., 2019), we observed a cluster of prefrontal functional activation in what appeared to be an FEF or near-FEF region. A visual inspection relative to the Brainnetome atlas revealed the cluster was situated within the A6vl atlas region. Given our interest in shared reading + attention processes, the A6vl (also called MFG_7_6 by some atlas versions) was therefore a good candidate to represent the FEF in our analyses.

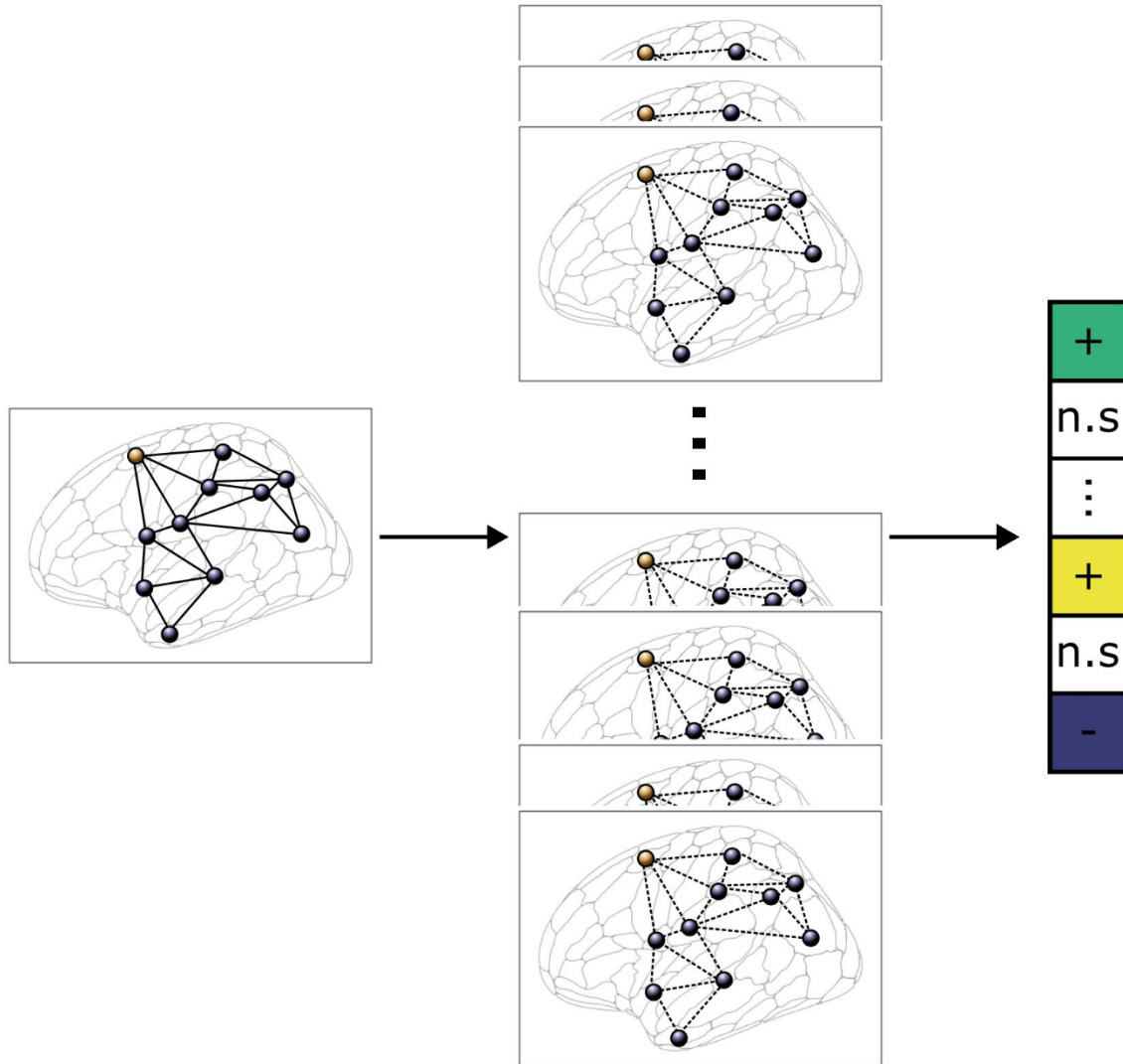


Figure 4.3 Schematic of analysis and comparison to null model.

From our mean representation of connectivity between each region (left), we constructed null models (middle, dashed lines represent the rewiring of connections between regions) and ranked the mean brain's communicability relative to the distribution of null models to calculate a matrix of values representing which FEF connections had significantly higher or lower communicability relative to the null model (right).

4.2.2 Results

Three values are considered in the results. The first value is communicability, as calculated in the methods above. The second value is the null-centred communicability, which is the difference between the communicability value and the mean communicability value of that connection in the null distribution. The null-centred value provides a perspective on the strength of the communicability between the two regions relative to the null model, with negative values meaning the communicability was lower than the average null model and positive values meaning the communicability was higher than the average null model. Finally, the permutation p -value is included as a measure of whether the mean brain significantly differed from the null model distribution. A permutation p -value $< .025$ means that connection had lower communicability than 97.5% of the null models in the distribution. A permutation p -value $> .975$ means that connection had higher communicability than 97.5% of the null models in the distribution. These were the permutation p -values used for thresholding the communicability matrix.

4.2.2.1 Brainnetome connectivity

Both left and right hemisphere FEF had significantly higher communicability than the null model in a cluster of regions neighbouring the FEF while regions that were distant from the FEF had communicability that was significantly lower than the null model (see Figure 4.4). These clusters of high and low communicability likely reflect the proximity of these regions to the FEF, as regions with fewer steps between them tend to have higher communicability (Fornito et al., 2016).

Interestingly, the right hemisphere FEF had two additional regions of high communicability. Both were right hemisphere subcortical regions (see Figure 4.4b). The first was the Brainnetome's right hemisphere GP, which corresponds to the globus pallidus (communicability = 0.039, null-centred communicability = 0.032, permutation $p = 0.976$), and the second was the Brainnetome's right hemisphere dIPu, which corresponds to the right hemisphere dorsolateral putamen (communicability = 0.029, null-centred communicability = 0.023, permutation $p = 0.978$).

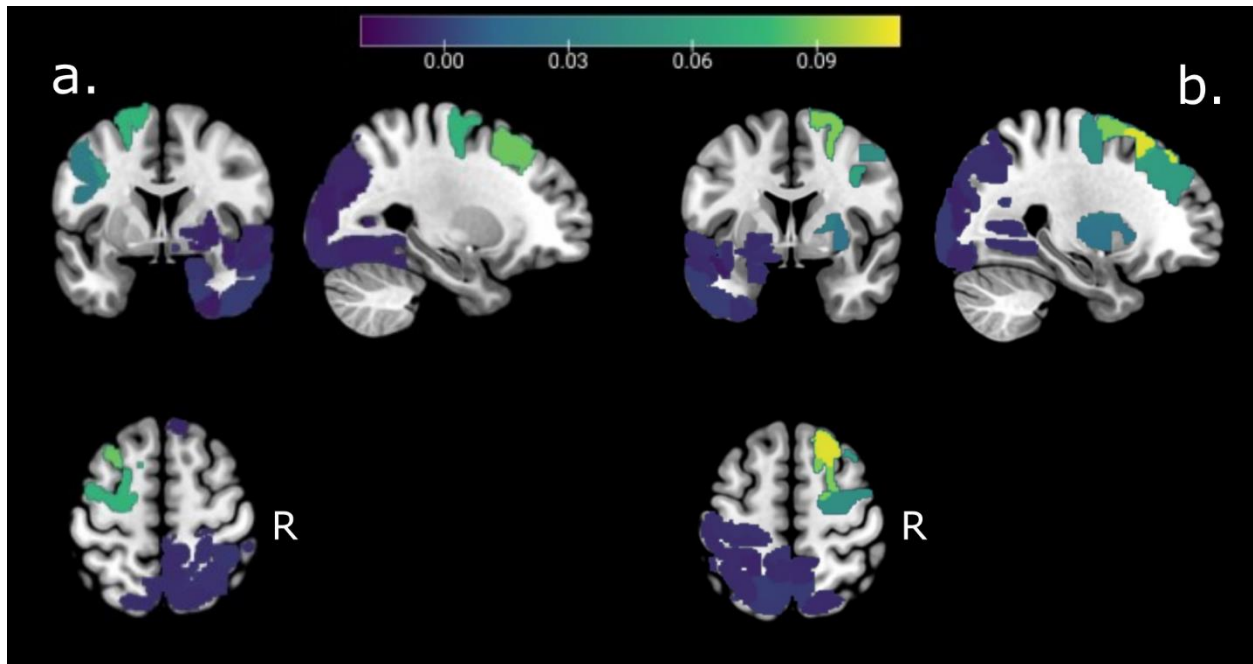


Figure 4.4 Null-centred communicability with the left FEF (a) and the right FEF (b).

These figures depict the null-centred communicability between each hemisphere's FEF and the other regions in the Brainnetome atlas. The left hemisphere is depicted on the left side of the images. In both images you can see the horse-shoe shaped cluster of high communicability around the respective FEF, and the widespread low communicability in more distant regions (contralateral and temporal/occipital). The right hemisphere FEF (b) displays high communicability with the ipsilateral basal ganglia (specifically the globus pallidus and dorsolateral putamen regions). Visualization was done in MRICroGL.

4.2.2.2 Frontal-eye-field to basal ganglia tractography

To further evaluate the connection between the FEF and subcortical regions, we explored the tractography of the template brain provided by DSI Studio (Yeh, 2022, 2024). DSI Studio's template brain is a 1065 participant subset of the HCP-YA dataset which has been averaged and registered to MNI space. Our FEF region (labeled as MFG_7_6 in DSI Studio's Brainnectome atlas) was selected as the seed, and our two subcortical regions selected as ROI (dlPu: BG_R_6_6; GP: BG_R_6_2; both from DSI Studio's Brainnectome atlas) in two separate deterministic tracking runs. For both runs, we set the seed count to 1000000, angular threshold to 75°, minimum fibre length to 20mm and maximum fibre length to 500mm.

When the right dorsolateral putamen was the ROI, one tract cluster was identified, which proceeded from the FEF through the right dorsolateral putamen to fan out in terminations across the right parietal lobe (see Figure 4.5a). These terminations were primarily in the right superior parietal lobule. When the right globus pallidus was the ROI, the same right FEF to right superior parietal lobule cluster was observed. In addition, another tract cluster was highlighted, which crossed hemispheres to terminate in the left brainstem and cerebellum (around Crus I/II; see Figure 5.5b). This tract cluster resembled the corticopontine tract (Rojkova et al., 2016). In both cases, some fibres also terminated in the subcortical regions without proceeding further to the parietal lobe or cerebellum.

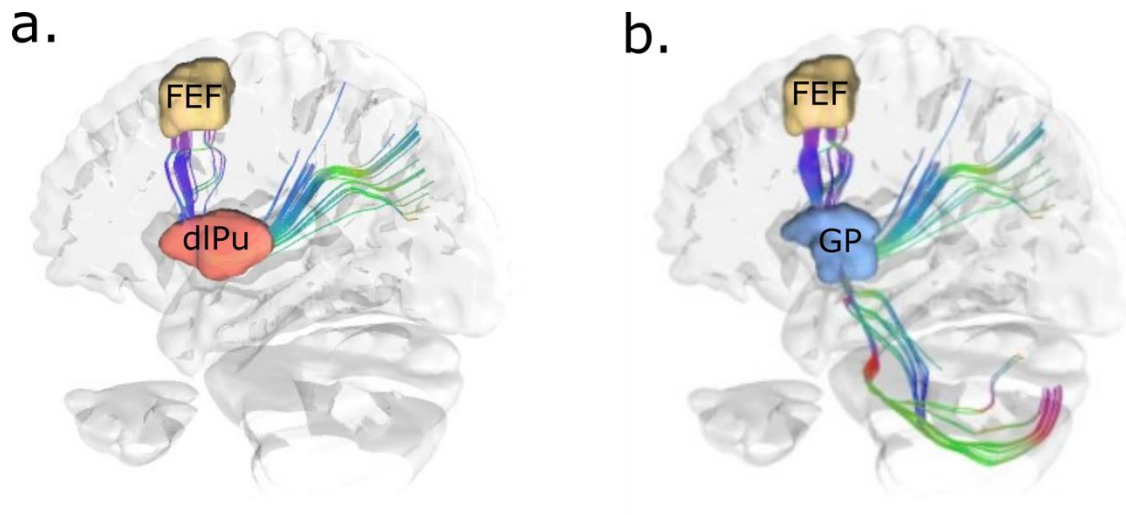


Figure 4.5 Tracts between the FEF and dorsolateral putamen (a) or globus pallidus (b)
 The right FEF (Brainnetome's A6vl/MFG_7_6) is portrayed in tan. The dorsolateral putamen (dIPu/BG_R_6_6) is portrayed in red. The globus pallidus (GP/BG_R_6_2) is portrayed in blue. Image visualization was done in DSI Studio.

4.3 Discussion

4.3.1 Summary of results

This analysis of the HCP dataset built off of our FEF ROI which we localized in Chapter 4 to examine the structural connectivity profile of the FEF. We observed greater communicability relative to the null model from the right FEF to the right dorsolateral putamen and globus pallidus, suggesting strong parallel connections between these regions. With tractography analysis of DSI Studio's mean brain, we found the white matter seeded in the FEF passed through the dorsolateral putamen or globus pallidus to reach the parietal lobe, and passed through the globus pallidus to reach the brain stem and left hemisphere Crus I/II in the cerebellum. Although these regions and connections are not what we initially expected to identify with this analysis, a literature review in light of these results reveals how the basal ganglia may be relevant to future reading + attention investigations.

4.3.2 The superior parietal lobule in attention and reading

White matter connections from the FEF to the superior parietal lobule support past findings that have situated the superior parietal lobule within the reading and attention networks. In reading, the superior parietal lobule is typically attributed to the dorsal sublexical stream (Borowsky et al., 2006), but superior parietal lobule activation has been observed in both lexical and sublexical reading tasks (Mickleborough et al., 2015). In attention, the superior parietal lobule is a dorsal attention region involved in voluntary attentional orienting processes (Corbetta & Shulman, 2002; Mickleborough et al., 2015). At the intersection of reading and attention, voluntary attention and pseudohomophone reading tasks have been found to share overlapping activation in the superior parietal lobule (Ekstrand, Neudorf, Gould, et al., 2019). The tract clusters we observed from FEF to superior parietal lobule thus may support the transfer of information between these well-known dorsal reading and attention routes.

4.3.3 The basal ganglia in attention and reading

The basal ganglia regions have been observed to be involved in reading and attention studies across a variety of contexts. Lesions in the putamen are associated with symptoms of human spatial neglect, which is a deficit in spatial attention processing (Corbetta & Shulman, 2002; Karnath et al., 2002). In a recent review on the subcortical network in Parkinson's Disease, Esposito et al. (2021) review the presence of voluntary attentional processing deficits in

individuals with Parkinson's Disease, and attribute these deficits to the dysfunction of the basal ganglia, particularly the putamen, that is present in the disorder.

Past research has also suggested subcortical regions play a role in reading related processes. The putamen has been associated with rhythm (Gould et al., 2017, 2018) and motor timing (Price, 2012). Both rhythm and motor timing are subcomponents in reading and language processes. The processing of rhythm is an important subprocess in reading successfully, as rhythm helps with syllabic stress and timing. In terms of reading, rhythm and motor timing can benefit the dorsal sublexical stream, as phonetic decoding will involve parsing the syllabic stress patterns and imagining the speech sounds (Gould et al., 2017).

4.3.4 The corticopontine tract and cerebellum in attention and reading

The FEF to globus pallidus white matter cluster includes terminations in the brainstem, which resembles the corticopontine tract (Rojkova et al., 2016). FEF to brainstem terminations are supported by the literature, both in human (Doron et al., 2010) and non-human (Stanton et al., 1988). Doron et al. (2010) argue that connections from the intersection of the middle, frontal, and precentral gyri (i.e. FEF) and to the cerebellum via the corticopontine tract support eye movement functions. This argument is supported by Stanton et al. (1988), as the macaque's corticopontine projections from the FEF have terminations in Vermis VI and VII which are cerebellar regions associated with eye movement control.

Human studies of cerebellar function further support the role of the cerebellum in attention. Functional connectivity research has suggested the Crus I is associated with the dorsal attention network and there was a positive correlation between Crus I activation and the researcher's FEF ROI (Rohr et al., 2019). This same study found that FEF to Crus I functional connectivity was associated with the executive control traits of attention switching and inattention (higher connectivity was correlated with higher attention switching and higher inattentive traits).

In reading, the right cerebellum Crus I and II have been associated with semantic processing (Nakatani et al., 2022), so there is prior evidence for the Crus' involvement in reading (although note that Nakatani's functional study observed this in the right Crus I/II, whereas our structural connectivity results involve the left Crus I/II). In our own past research (Neudorf, Ekstrand, Kress, & Borowsky, 2019) we observed functional activation of the left cerebellum's

lobule VI, which neighbours Crus I, and attributed the activation to semantic processing in that study.

Thus, the cerebellum, particularly the Crus I/II regions, has been implicated in both reading (through semantics) and attention (through executive control), which supports the role of the FEF through basal ganglia to brain stem/cerebellum tract in this reading + attention network.

4.3.5 Limitations

Our null model approach used Rubinov and Sporns' (2011) rewiring technique, which preserves many features of the original network. In our study, we observed many regions where connectivity was either significantly less than, or did not differ from, our null model. It may be the case that the rewiring approach we took was too conservative to detect the other connections with the FEF. Alternative null-model generation techniques that are less conservative (for example, lattice-based null models) could help highlight other regions associated with the FEF (Fornito et al., 2016). For the analysis reported here, we focused on the measure of communicability, however, it is important to recall that communicability's diffusion-based approach is designed to weight more distance connections as weaker. This could punish more distant occipital-parietal connections to the FEF. Although less biologically plausible, other measures such as shortest-path length could provide another perspective on the connections the FEF has with other regions, and examining characteristics such as the centrality of the FEF could provide insight into how crucial the FEF is to the reading or attention network as a whole (Neudorf, Ekstrand, et al., 2020).

4.3.6 Future directions

Although beyond the scope of this thesis, which focuses on oculomotor activity in reading, another region that would benefit from similar connectivity analyses is the temporal parietal junction. The temporoparietal junction is traditionally considered part of the ventral attention network (Corbetta & Shulman, 2002), but also overlaps with regions in the reading network (Ekstrand, Neudorf, Gould, et al., 2019; Ekstrand, Neudorf, Kress, et al., 2019). A recent transcranial random noise stimulation study (Bertoni et al., 2022) found that stimulation to the temporoparietal junction improved reading performance. A connectivity study could help clarify the role that the temporoparietal junction plays in each of the reading and attention networks, and complement the work on oculomotor activity in reading that is presented here.

The HCP dataset also contains data from behavioural tasks such as oral reading recognition, picture vocabulary and the Variable Short Penn Line Orientation Test (a test of spatial orientation). Although the dataset does not include neuroimaging data for these tasks, analysis techniques such as partial least squares regression (McIntosh & Lobaugh, 2004) could be used to predict task performance based on the connectivity profile of the FEF. Given our theories on the role of oculomotor activity in reading, we may expect individuals with strong connectivity between the FEF and reading regions should have better reading task performance. The globus pallidus and putamen were highlighted in our analysis here, and may be two such regions whose connections with the FEF will predict reading success.

4.3.7 Interim conclusion

This study has identified subcortical and cerebellar connections with the FEF as a network of white matter that may contribute to shared reading + attention processes. With further research on the structure and function of these regions, the field will be able to test whether reading and attention performance can be predicted by the connectivity in these regions. The identification of this subcortical and cerebellar FEF network is an important step in developing a unified framework of reading + attention in the brain.

CHAPTER 5: General Discussion

This chapter is adapted from the content of the following manuscripts:

Kress, S., Caron, S., Neudorf, J., Borowsky, B., & Borowsky, R. (submitted). Practice in the periphery: Effects of central vs peripheral attentional-oculomotor exercise on reading and graphical tasks. Submitted to: *Quarterly Journal of Experimental Psychology*.

Kress, S., Neudorf, J., Ekstrand, C., & Borowsky, R. (submitted). Bridging reading and attention through connectivity with the frontal-eye-field. Submitted to: *Brain Structure and Function*.

And so to completely analyze what we do when we read would almost be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all of its history.

(Huey, 1908/1968, p. 6)

The goal of this thesis was to begin developing a framework of combined reading + attention processes through the hypothesized link of oculomotor activity. As discussed in Chapter 1, models of reading (Owen & Borowsky, 2003) and attention processes (Corbetta & Shulman, 2002) have been well developed over the years in their respective cognitive neuroscience fields. However, these models have developed primarily in isolation, which does not align with current theories of overlapping reading and attention processes, and the attentional processing link observed in dyslexia, as described by the magnocellular deficit theory (Boden & Giaschi, 2007; Stein, 2001). Bringing reading and attention processes together in a unified framework of reading + attention would help researchers better account for the full myriad of processes required during successful reading, and the improved understanding of the reading system could inform reading interventions to help individuals with dyslexia who wish to improve their reading ability.

Experiments 1, 2, and 3 took a cognitive-behavioural approach to examining the reading + attention link. These experiments systematically iterated upon a mixed design of the orthographic lexical decision task (OLDT) to measure orthographic lexical processes, combined

with the novel health bar decision task (HBDT) to measure general visual processing and act as a form of A-O exercise. Experiment 2 and 3 demonstrated that both central and peripheral A-O exercise may contribute to improved reading performance. These experiments will help the field identify the minimum training time needed for effective A-O exercise. Although we originally intended and expected the central A-O exercise condition to not provide any benefit to reading performance, the small oculomotor movements inherent in the condition may have been sufficient to yield a beneficial A-O exercise effect in the OLDT. From this finding, we have identified small eye movements, rather than large eye movements, as a promising next avenue to explore in future studies.

Importantly in these three experiments, we observed a clear double dissociation between word frequency on exception word performance and bigram frequency on pseudohomophone performance, along with their absence in the opposing stimulus type. This supports the argument that the OLDT, using exception word targets and pseudohomophone foils, isolates orthographic processing. Given that most LDT studies simply use non-specific word targets and nonword foils, it was previously impossible to isolate the influence of the orthographic, semantic, and phonological systems, so the ability to isolate orthographic lexical target processing is a valuable contribution to the field of word reading research. Furthermore, because the OLDT design is able to isolate between lexical and sublexical route processes (as demonstrated by the double dissociation between word and bigram frequency and exception word targets and pseudohomophone foils), we are able to observe how both lexical and sublexical processing benefits from A-O exercise.

Experiment 4 analysed a novel hybrid reading + attention task (Ekstrand, Neudorf, Kress, et al., 2019), driven by the theories of oculomotor involvement in reading and attention processing. In this analysis, we observed a previously unreported interaction in reading + attention BOLD activation in the Brainnetome's A6v1 (also called MFG_7_6) which corresponds to the location of the FEF as described in the literature.

Experiment 5 was able to use the FEF ROI identified in Experiment 4 to conduct a connectivity analysis on a subset of the large HCP dataset (Van Essen et al., 2013). With the graph theory measure of communicability as our focus, we observed strong parallel connections between our right hemisphere FEF and right hemisphere putamen and globus pallidus in the basal ganglia. Tractography analyses on a standard brain template revealed this high

communicability with the basal ganglia may be supporting connections to the brainstem, cerebellum, and superior parietal lobule, which all play known roles in reading and attention. When the results of these studies are considered together, there are a few implications of our work for reading models as well as for a framework for unifying reading and attention models.

5.1 Models of reading

The double dissociation between word frequency on exception word performance and bigram frequency on pseudohomophone performance (with no effects on the opposing counterparts) is an important contribution to the word reading literature. Word frequency was associated with improved exception word performance in the OLDT, which supports well-replicated previous findings of word frequency as a measure of lexical processing involvement. Bigram frequency was associated with worse pseudohomophone performance in the OLDT, which supports the understudied theory that bigram frequency is a measure of sublexical processing involvement (Borowsky et al., 2013). As we develop this programme of research further, it will be important to successfully isolate lexical processes and sublexical processes so that we can understand which components of the attention network are interfacing with which stages of the reading networks. By demonstrating that word frequency represents lexical processing and bigram frequency represents sublexical processing, we have established the viability of these two measures as tools to verify which reading processes are involved in a given task.

The double dissociation would be a challenge for single-route models to account for because a single route model must reconcile why exception words are sensitive to word frequency in a manner that improves performance, pseudohomophones are sensitive to bigram frequency in a manner that worsens performance, and the effects are absent in the opposing counterparts. Accounting for the double dissociation would be difficult given that the major single route models are also limited to being single mechanism models. For example, the single route model by Plaut and Booth (2000) uses a sigmoid input-output activation function, which has been shown to not account for different directions of observed effects within the same range of reaction times (Borowsky & Besner, 2006).

Our ability to distinguish between the lexical and sublexical routes (through our use of exception words and pseudohomophones) during an A-O exercise paradigm is an important contribution to the literature on attentional training for reading. The past studies on attentional

training during reading have primarily focused on sublexical benefits as a function of attentional training via video games (Bertoni et al., 2021, 2024; Franceschini et al., 2015) and we have replicated that finding here by observing a benefit of A-O exercise on pseudohomophone foil performance. Excitingly, our exception word targets also exhibited a benefit of A-O exercise, extending the benefits of attentional training for reading beyond the sublexical route to include lexical processing as well. These observations would not have been possible without our use of exception word targets and pseudohomophone foils, and will help push the field of attentional training for reading beyond the historical sublexical route focus.

5.2 A framework to unify models of reading + attention

The results of all the experiments can be brought together to begin building a unified framework of reading and attention. Figure 5.1 depicts the proposed framework of reading + attention that we are beginning to develop, and the changes in this figure reflect the findings of the previous chapters. Experiments 1-3 have shown that attentional-oculomotor exercise may benefit reading task performance, which demonstrates the importance of attention in reading. This is represented by including the reading and attention models as a single figure (5.1a), with visual input feeding into the reading and attention networks simultaneously to be processed by occipital lobe regions.

Then, our framework diverges into ventral routes for lexical and reflexive attentional alerting/orienting processes, and dorsal routes for sublexical and voluntary attentional orienting processes. The anatomical models in Figure 5.1b are updated to reflect the findings of all the experiments. The cognitive experiments examined A-O exercise, the effects of which may be driven by oculomotor processing in the FEF, which is nested in the dorsal sublexical + voluntary attention regions. Experiment 4 further supported the role of the FEF, localizing a reading × attention interaction in the region. The connectivity analysis in Experiment 5 helped identify the connections between the FEF and other reading + attention network regions. From the basal ganglia, to the parietal lobe, pons, and cerebellum these connections represent a broad collection of reading and attention processes from rhythm (Gould et al., 2017, 2018), semantics (Nakatani et al., 2022; Neudorf, Ekstrand, Kress, & Borowsky, 2019) and phonological processing (Borowsky et al., 2006; Ekstrand, Neudorf, Gould, et al., 2019) to orienting (Mickleborough et al., 2015) and eye movement control (Doron et al., 2010; Stanton et al., 1988). We have overlaid these white matter tracts on the reading + attention figure to represent the structure underlying

the shared reading + attention processes. The overlap between the reading + attention systems is particularly highlighted in this framework by the inclusion of the superior parietal lobule, which is active for both reading and attention tasks (Mickleborough et al., 2015). As illustrated in this framework, the FEF is closely situated with dorsal sublexical + voluntary attentional regions, which would be used during phonetic decoding of pseudohomophones. This association with the sublexical regions may account for why pseudohomophones exhibited large exercise benefits in our three A-O exercise experiments. The ventral routes are also represented by the inclusion of the cerebellum, specifically Crus I/II, which is associated with semantic processing (Neudorf, Ekstrand, Kress, & Borowsky, 2019). This framework will serve as a foundation for unified reading + attention processes, which future studies will be able to develop further.

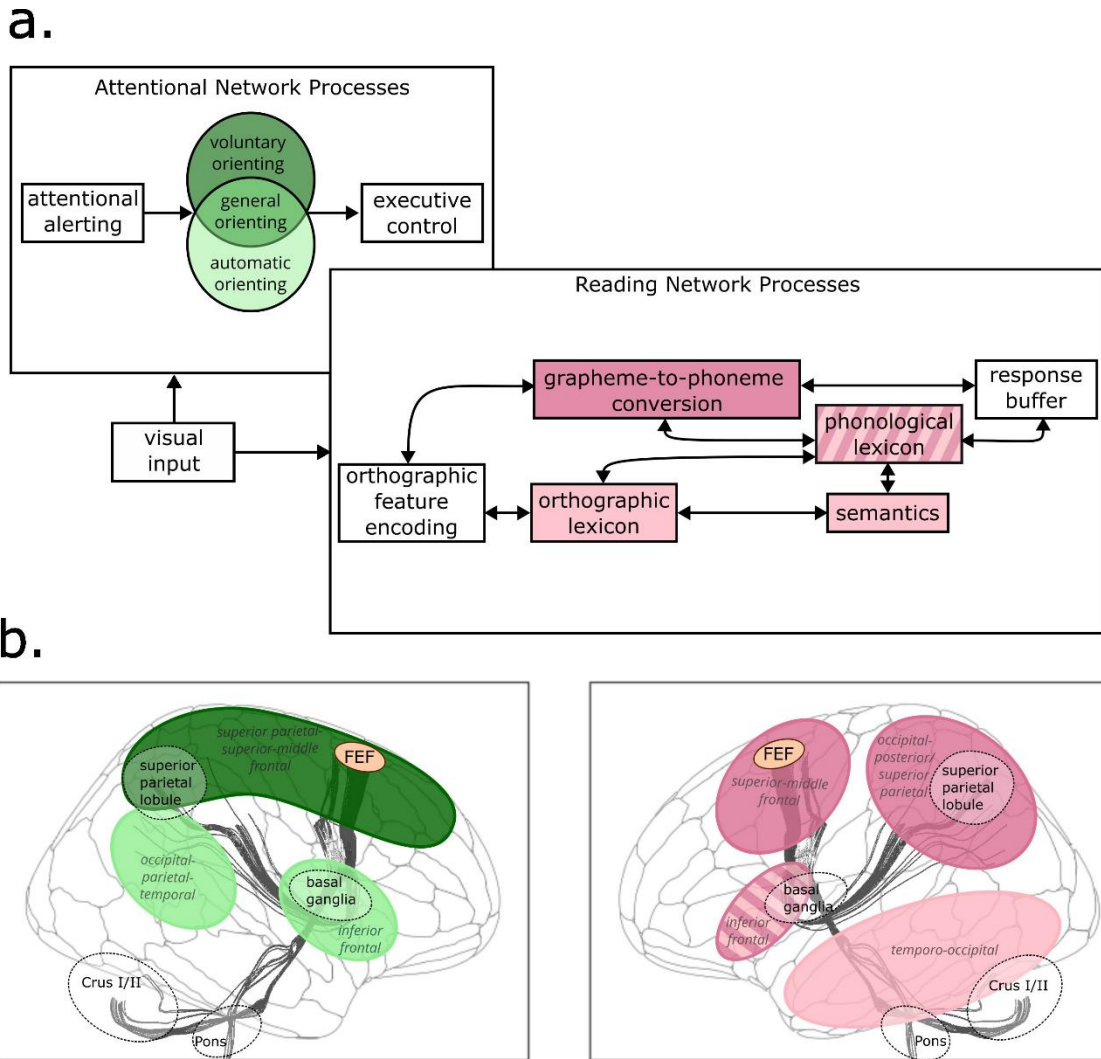


Figure 5.1. A proposed unified framework of reading and attention in box-and-arrow form (a) and mapped onto brain regions (b)

The FEF is highlighted in tan on the inflated brain (b) and white matter connections to the superior parietal lobule, Crus I/II, and pons via the basal ganglia are included, reflecting the findings of Experiments 4 and 5.

5.3 Limitations and future directions

With the results of the current experiments, we are able to argue for a unification of the reading and attention models, but more research needs to be done to map out how the networks work with each other. To develop our reading + attention framework further into a complete model, we will need to design more studies that will test the interactions of reading and attention, so that we can determine which components of the networks are independent, rather than reflections of the same processes. Based on the magnocellular deficit theory (Boden & Giaschi, 2007; Stein, 2001) and other studies linking reading and attention (Bertoni et al., 2021; Ekstrand, Neudorf, Kress, et al., 2019), we may expect sublexical processes such as grapheme-to-phoneme conversion and attentional orienting processes (particularly voluntary orienting) to integrate quite closely with each other. It would also be helpful in future research to include a no-exercise condition to see what degree of the effect, if any, can be attributable to test-retest effects.

The neuroimaging studies each had limitations reflecting the designs of their respective data collection circumstances. The design of Experiment 4 was tailored for our research questions regarding the reading \times attention interaction, but had less power than the large HCP-YA dataset. Experiment 5, on the other hand, employed high-quality DTI from the HCP-YA dataset, but lacked tailored reading + attention task to answer our other research questions. In this thesis, we were able to use the task-based data of Experiment 4 to inform the high-powered connectivity analysis in Experiment 5. Future neuroimaging studies can take the strengths of the two experiments together to develop a high-quality dataset of DTI and fMRI reading + attention tasks so that the results observed in Experiments 4 and 5 can be replicated and extended.

A clear next step in this research will be to bring our A-O exercise paradigm from Experiments 1-3 to fMRI. As we refine our A-O exercise paradigm further, fMRI will give us the opportunity to examine which regions are involved most in A-O exercise, and how activation during reading changes as a function of the exercise. The FEF we localized in Experiment 4 will be a region of interest in these analyses. If DTI is incorporated into the imaging protocol, we could examine the tracts highlighted by the connectivity analysis in Experiment 5 and test whether these tracts predict behavioural performance, task activation, and/or changes in these variables of interest. A subset of our participants in Experiment 4 have DTI so future analyses could examine how the structural connectivity of the FEF predicts the task-based activation we reported here. Our HCP-YA subset and a subset of our participants in Experiment 4, also have

resting-state fMRI data, so future analyses could also examine the differences in the FEF's task-based and resting-state functional connectivity profiles.

As the role of the FEF in reading becomes more well understood, future studies can turn their attention to the related supplementary and cingulate eye fields. These two regions have similar functional and structural profiles to the FEF (Herbet & Duffau, 2022), but are less well studied and could potentially be relevant to the reading network as well.

5.4 Conclusion

Within this thesis, we see support for the development of a unified reading + attention framework. Experiments 1-3 observed attentional-oculomotor exercise effects on reading, and demonstrated a double dissociation between word and bigram frequency on exception words and pseudohomophones that will be valuable in future reading research that strives to isolate lexical and sublexical processing. With these designs we have demonstrated that the A-O exercise in our paradigm is able to benefit both lexical and sublexical processing performance, a finding that has not been well-examined in earlier training research. Research and clinical practice on dyslexia will particularly benefit from these findings, as, with further study, word and bigram frequency effects could one day be included in the scoring of cognitive reading tests to help detect surface vs phonological dyslexia with greater precision than simple accuracy scores.

Experiment 4 further supported the role of attention in reading by identifying reading × attention activation in the FEF. Finally, Experiment 5 used the FEF as an ROI to examine the connectivity profile of this reading + attention region and identify other important regions in the shared network, including the basal ganglia, superior parietal lobule, and cerebellar Crus I/II.

Taken together, these studies have supported our theories of reading + attention as a shared network, which we have proposed a framework for in Figure 5.1. With future studies of structure, function, and behaviour during reading + attention in isolation or combined, researchers in the fields of reading and attention can come together to develop the model further and identify the mechanisms behind reading successfully. With further development, the reading + attention model will help inform the field of dyslexia, so that reading interventions can be developed which exercise the aspects of visual attention that are most important to reading. Thus, the reading + attention model, though still in its early framework stages here, has the potential to benefit both research – through a better understanding of these cognitive processes – and education – through the development of improved reading interventions.

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APPENDICES

Appendix A: Lists of stimuli

Table A.1. List of exception word and pseudohomophone stimuli (half-block A)

EW	PH	Length	WF	EW BF	PH BF	EW	PH	Length	WF	EW BF	PH BF
aunt	<i>ahnt</i>	4 4	7.95	3200.00	<i>1921.67</i>	one	<i>wun</i>	3 3	14.17	6718.50	<i>1601.50</i>
blood	<i>bludd</i>	5 5	10.86	2025.00	<i>1142.50</i>	pear	<i>payr</i>	4 4	6.88	4110.00	<i>1082.00</i>
bought	<i>bawt</i>	6 4	10.95	1505.20	<i>767.00</i>	plaid	<i>plad</i>	5 4	6.66	2241.00	<i>2551.33</i>
bread	<i>bredd</i>	5 5	9.11	3656.25	<i>4520.75</i>	post	<i>poast</i>	4 5	12.53	3874.33	<i>3382.50</i>
breast	<i>brest</i>	6 5	8.93	4638.80	<i>7433.50</i>	prove	<i>proov</i>	5 5	10.36	2815.00	<i>2425.75</i>
broad	<i>brawd</i>	5 5	9.44	2098.00	<i>1961.75</i>	push	<i>pusch</i>	4 5	9.87	2174.67	<i>2271.50</i>
bull	<i>bul</i>	4 3	9.03	2417.67	<i>1684.50</i>	realm	<i>relm</i>	5 4	8.89	4388.50	<i>4071.00</i>
climb	<i>clime</i>	5 5	8.72	2367.00	<i>2986.50</i>	said	<i>sed</i>	4 3	12.77	1635.00	<i>6043.50</i>
come	<i>cumm</i>	4 4	12.36	3447.67	<i>1163.67</i>	scarce	<i>skairce</i>	6 7	7.54	3067.00	<i>1292.83</i>
do	<i>doo</i>	2 3	14.12	1246.00	<i>1572.00</i>	sew	<i>soe</i>	3 3	7.18	2311.00	<i>981.50</i>
done	<i>dunn</i>	4 4	12.07	4894.33	<i>1599.67</i>	shove	<i>shuv</i>	5 4	7.72	2375.25	<i>1118.00</i>
dread	<i>dred</i>	5 4	7.82	3551.50	<i>5720.67</i>	some	<i>summ</i>	4 4	13.86	2408.33	<i>1241.00</i>
flood	<i>flud</i>	5 4	9.17	1729.25	<i>961.67</i>	soul	<i>soal</i>	4 4	10.38	2487.33	<i>2760.00</i>
four	<i>fohr</i>	4 4	11.35	2527.67	<i>583.00</i>	source	<i>sorce</i>	6 5	12.13	2325.20	<i>2583.25</i>
full	<i>phul</i>	4 4	11.96	2329.67	<i>1367.00</i>	spread	<i>spred</i>	6 5	10.03	3480.40	<i>5089.50</i>
ghoul	<i>gool</i>	5 4	8.82	2297.00	<i>1812.00</i>	steak	<i>staik</i>	5 5	7.32	4958.50	<i>3267.50</i>
gone	<i>gawn</i>	4 4	10.86	4747.67	<i>732.33</i>	suave	<i>swawv</i>	5 5	5.90	1660.25	<i>548.50</i>
gross	<i>groass</i>	5 6	9.03	2897.25	<i>2699.20</i>	suite	<i>swete</i>	5 5	10.87	3756.75	<i>3236.00</i>
have	<i>hav</i>	4 3	14.92	2269.67	<i>1677.00</i>	sweat	<i>swet</i>	5 4	8.53	3190.75	<i>1465.67</i>
heard	<i>hurd</i>	5 4	11.80	3508.50	<i>1587.00</i>	threat	<i>thret</i>	6 5	9.83	4525.20	<i>3565.00</i>
hearth	<i>herth</i>	6 5	6.04	3430.80	<i>5289.25</i>	ton	<i>tuhn</i>	3 4	9.37	5566.50	<i>558.67</i>
hood	<i>huhd</i>	4 4	8.93	1793.00	<i>228.33</i>	tough	<i>tuf</i>	5 3	9.76	2018.75	<i>865.00</i>
leapt	<i>lept</i>	5 4	6.57	3002.75	<i>2826.33</i>	tread	<i>tred</i>	5 4	8.13	4181.75	<i>6561.00</i>
lose	<i>loos</i>	4 4	10.55	2981.67	<i>2280.00</i>	truth	<i>trooth</i>	5 6	10.87	2265.75	<i>2790.00</i>
mauve	<i>moav</i>	5 4	5.66	2022.50	<i>1196.00</i>	vase	<i>vavs</i>	4 4	6.29	2686.00	<i>604.33</i>
monk	<i>munk</i>	4 4	8.24	3621.67	<i>1529.67</i>	where	<i>wehr</i>	5 4	13.03	6355.75	<i>587.67</i>
most	<i>moast</i>	4 5	13.11	3808.67	<i>3333.25</i>	womb	<i>woom</i>	4 4	7.82	1290.00	<i>1623.67</i>
mourn	<i>mohrn</i>	5 5	6.35	2335.25	<i>876.75</i>	wood	<i>wuhd</i>	4 4	10.09	1236.00	<i>30.00</i>
mow	<i>moh</i>	3 3	6.64	1639.50	<i>1040.00</i>	world	<i>werld</i>	5 5	12.60	1781.50	<i>3851.75</i>
none	<i>nunn</i>	4 4	11.41	5040.67	<i>1547.00</i>	yearn	<i>yern</i>	5 4	5.85	2617.50	<i>4824.33</i>








































Note. Word characteristics were generated from the complete English Lexicon Project (Balota et al., 2007). Pseudohomophone characteristics are noted in italics. WF = log_e-transformed HAL word frequency. BF = mean bigram frequency. Pseudohomophones use the base-word frequency of the corresponding exception word. Experiment 1 did not utilize the counterbalanced blocks and all stimuli were presented in all OLDT blocks. The counterbalanced blocks were used for Experiments 2 and 3.

Table A.2. List of exception word and pseudohomophone stimuli (half-block B)

EW	PH	Length		WF	BF	EW	PH	Length		WF	BF		
bear	<i>bair</i>	4	4	10.07	3690.67	1684.33	own	<i>oan</i>	3	3	12.56	813.50	4054.00
both	<i>boath</i>	4	5	12.60	2018.00	3307.75	pint	<i>pynt</i>	4	4	7.29	7274.00	1916.33
bowl	<i>bohl</i>	4	4	9.28	1063.33	686.333	poll	<i>poal</i>	4	4	8.98	2922.00	2951.33
break	<i>braik</i>	5	5	10.77	3320.75	2298.25	pour	<i>pohr</i>	4	4	9.34	2864.67	920.00
breath	<i>breth</i>	6	5	9.58	4672.00	3748.50	pull	<i>puhl</i>	4	4	10.25	2314.33	366.67
brooch	<i>broatch</i>	6	7	4.19	1162.00	3083.00	put	<i>puht</i>	3	4	12.32	1332.00	493.33
caste	<i>kast</i>	5	4	7.39	5745.75	3637.33	roll	<i>rohl</i>	4	4	9.99	3660.00	1579.33
comb	<i>coam</i>	4	4	7.39	2621.67	2490.33	says	<i>sez</i>	4	3	12.20	1009.00	2055.00
cough	<i>cawff</i>	5	5	7.70	2480.00	1329.00	seize	<i>seeze</i>	5	5	7.56	1837.75	1757.50
does	<i>duz</i>	4	3	13.17	4785.67	389.00	shoe	<i>shue</i>	4	4	8.56	1805.00	1379.00
dost	<i>dawst</i>	4	5	5.93	3573.00	2371.25	sieve	<i>siv</i>	5	3	6.20	2907.50	2352.00
earn	<i>ern</i>	4	3	9.39	3363.33	7046.50	soot	<i>suht</i>	4	4	5.65	1782.00	730.33
foot	<i>fuht</i>	4	4	10.10	1632.33	508.67	soup	<i>soop</i>	4	4	8.71	1989.00	1674.67
front	<i>frunt</i>	5	5	11.26	4687.00	2670.00	sponge	<i>spunge</i>	6	6	7.38	4601.20	3316.20
gauge	<i>gaige</i>	5	5	8.50	1359.75	1759.25	stead	<i>sted</i>	5	4	6.52	5294.00	8044.00
give	<i>gihv</i>	4	4	12.35	2117.67	458.00	stood	<i>stould</i>	5	6	9.58	3339.75	3379.60
great	<i>grait</i>	5	5	12.47	5271.50	3319.00	suede	<i>swaid</i>	5	5	6.50	3837.50	1247.00
grow	<i>groe</i>	4	4	10.12	2380.67	2063.67	swear	<i>sware</i>	5	5	8.52	2638.75	3994.00
head	<i>hed</i>	4	3	11.60	2895.00	5820.50	thread	<i>thred</i>	6	5	10.95	3280.00	4839.00
heart	<i>hawrt</i>	5	5	10.73	3661.25	1299.00	tomb	<i>toom</i>	4	4	8.73	2006.67	2340.33
height	<i>hite</i>	6	4	9.40	1493.00	5005.33	touch	<i>tuch</i>	5	4	10.46	2684.75	1899.33
hook	<i>huhk</i>	4	4	9.36	1582.00	222.00	tour	<i>toor</i>	4	4	10.06	3101.67	3303.33
learn	<i>luhrn</i>	5	5	11.18	4177.25	671.00	trough	<i>trawf</i>	6	5	6.90	2579.40	2475.50
love	<i>luv</i>	4	3	12.20	2477.00	649.50	two	<i>tu</i>	3	2	13.03	483.00	1450.00
meant	<i>ment</i>	5	4	10.51	4787.75	5308.33	wear	<i>wair</i>	4	4	10.35	3380.00	1521.33
month	<i>munth</i>	5	5	11.24	4521.25	2952.25	whose	<i>hoos</i>	5	4	10.61	2198.50	2084.00
mould	<i>mohld</i>	5	5	6.82	2122.25	747.25	won	<i>wunn</i>	3	4	10.22	4491.50	1369.00
move	<i>moov</i>	4	4	11.29	2138.00	1619.00	wool	<i>wul</i>	4	3	7.63	1780.33	1132.50
ninth	<i>nynth</i>	5	5	7.56	6421.50	2091.00	would	<i>wuhd</i>	5	4	14.06	1811.75	30.00
once	<i>wunce</i>	4	5	12.15	4491.00	2101.00	your	<i>yor</i>	4	3	14.35	2207.67	2665.00

Note. Word characteristics were generated from the complete English Lexicon Project (Balota et al., 2007). Pseudohomophone characteristics are noted in italics. WF = log_e-transformed HAL word frequency. BF = mean bigram frequency. Pseudohomophones use the base-word frequency of the corresponding exception word. Experiment 1 did not utilize the counterbalanced blocks and all stimuli were presented in all OLDT blocks. The counterbalanced blocks were used for Experiments 2 and 3.

Table A.3. Table of health bar stimuli

Health Bar Value	Flanker Number Value									Total Count
	10	20	30	40	50	60	60	80	90	
10	 10	 5	 5							20
20	 5	 15	 5	 5						30
30	 5	 5	 20	 5	 5					40
40		 5	 5	 20	 5	 5				40
50			 5	 5	 20	 5	 5			40
60				 5	 5	 20	 5	 5		40
70					 5	 5	 20	 5	 5	40
80						 5	 5	 15	 5	30
90							 5	 5	 10	20

Note. The number of times the stimulus was presented per block is indicated in italics beside the image.

Appendix B: Behavioural Research Ethics

These are copies of the most recent re-approval and amendment of the lab's behavioural ethics.

Ethics approval was maintained throughout my PhD (2021 – 2024).



UNIVERSITY OF
SASKATCHEWAN

Behavioural Research Ethics Board (Beh-REB) 26-Jan-2024

Certificate of Re-Approval

Ethics Number: 00-09

Principal Investigator: Ron Borowsky

Department: Department of Psychology and Health
Studies

Student(s): Alice Li
Josh Neudorf
Scott Caron
Shaylyn Kress

Funder(s): Natural Sciences and Engineering Research Council of Canada
Saskatchewan Health Research Foundation

Sponsor:

Title: Basic Reading Processes: Reliance on Sight Vocabulary (SV) and Phonetic Decoding
(PD) During Normal Reading Acquisition

Approval Effective Date: 24-Feb-2024

Expiry Date: 24-Feb-2025

Acknowledgment Of: N/A

Review Type: Delegated Review

* This study, inclusive of all previously approved documents, has been re-approved until the expiry date noted above

CERTIFICATION

The University of Saskatchewan Behavioural Research Ethics Board (Beh-REB) is constituted and operates in accordance with the current version of the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans - TCPS 2 (2022). The University of Saskatchewan Beh-REB has reviewed the above-named project. The proposal was found to be acceptable on ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this project, and for ensuring that the authorized project is carried out according to the conditions outlined in the current approved protocol. This Certificate of Approval is valid for the above time period provided there is no change in experimental protocol or consent process or documents.

ONGOING REVIEW REQUIREMENTS

Any significant changes to the proposed method, or consent and recruitment procedures must be reported to the Chair through submission of an amendment for Beh-REB consideration in advance of implementation.

To remain in compliance, a status report (renewal or closure form) must be submitted to the Beh-REB Chair for consideration within one month prior to the current expiry date each year the project remains open, and upon project completion. Please refer to the Research Ethics Office website for further instructions and current forms.

Digitally Approved on behalf of the Chair
Behavioural Research Ethics Board
University of Saskatchewan

Certificate of Approval Amendment

Ethics Number: 00-09

Principal Investigator: Ron Borowsky

Department: Department of Psychology and Health
Studies

Student(s): Braedyn Borowsky
Josh Neudorf
Scott Caron
Shaylyn Kress

Funder(s): Natural Sciences and Engineering Research Council of Canada

Sponsor:

Title: Basic Reading Processes: Reliance on Sight Vocabulary (SV) and Phonetic Decoding (PD) During Normal Reading Acquisition

Approved On: 21-May-2024

Expiry Date: 24-Feb-2025

Approval Of: Amendment to remove (Alice Li) and add (Braedyn Borowsky) student personnel and remove a funder.

Acknowledgment Of: TCPS2 CORE Tutorial Certificate: Braedyn Borowsky
experiment2_consent_debrief_May21_2024.docx

Review Type: Delegated Review

CERTIFICATION

The University of Saskatchewan Behavioural Research Ethics Board (Beh-REB) is constituted and operates in accordance with the current version of the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans - TCPS 2 (2018). The University of Saskatchewan Beh-REB has reviewed the above-named project. The proposal was found to be acceptable on ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this project, and for ensuring that the authorized project is carried out according to the conditions outlined in the current approved protocol. This Certificate of Approval is valid for the above time period provided there is no change in experimental protocol or consent process or documents.

ONGOING REVIEW REQUIREMENTS

Any significant changes to the proposed method, or consent and recruitment procedures must be reported to the Chair through submission of an amendment for Beh-REB consideration in advance of implementation.

To remain in compliance, a status report (renewal or closure form) must be submitted to the Beh-REB Chair for consideration within one month prior to the current expiry date each year the project remains open, and upon project completion. Please refer to the Research Ethics Office website for further instructions and current forms.

*Digitally Approved by Pammla Petrucka
Chair, Behavioural Research Ethics Board
University of Saskatchewan*

Appendix C: Biomedical Research Ethics

This is a copy of the most recent re-approval of the lab's biomedical ethics. Ethics approval was maintained throughout my PhD (2021 – 2024).



Biomedical Research Ethics Board (Bio-REB) 22-Dec-2023

Certificate of Re-Approval

Ethics Number: 01-125

Principal Investigator: Ron Borowsky

Department: Department of Psychology and Health Studies

Locations Where Research Activities are Conducted: Royal University Hospital, Saskatoon, Canada

Student(s): Alice Li
Chelsea Ekstrand
Josh Neudorf
Justin Andrushko
Shaylyn Kress

Funder(s): Natural Sciences and Engineering Research Council of Canada

Sponsor:

Title: Functional Magnetic Resonance Imaging (fMRI) and Electroencephalography (EEG)

Approval Effective Date: 15-Jan-2024

Expiry Date: 15-Jan-2025

Acknowledgment Of:

Review Type: Delegated Review

IRB Registration Number: Not Applicable

* This study, inclusive of all previously approved documents, has been re-approved until the expiry date noted above

Ethics Number: 01-125

Principal Investigator: Ron Borowsky

2 / 2

CERTIFICATION

The University of Saskatchewan Biomedical Research Ethics Board (Bio-REB) has reviewed the above-named project. The project was found to be acceptable on scientific and ethical grounds. The principal investigator is responsible for obtaining any other administrative or regulatory approvals that may pertain to this project, and for ensuring that the authorized project is carried out according to governing law. This approval is valid for the specified period, provided there is no change to the approved project.

FIRST TIME REVIEW AND CONTINUING APPROVAL

The University of Saskatchewan Research Ethics Boards review above minimal risk projects at full-board meetings. If a project is reviewed at a full-board meeting, any subsequent projects being added with the same protocol may be reviewed through the delegated review process. Research classified as minimal risk is reviewed through the delegated review process. The initial Certificate of Approval indicates the approval period the REB has assigned to a study.

To remain in compliance, the REB must receive a status report form (renewal or closure) prior to the assigned expiry date each year. Any specific requirements of the sponsoring organizations deemed necessary for continuing ethics review (e.g., requirement for full-board review and approval) should be indicated by the researcher to the REB. Any change to the approved project must be reported to the Chair of the Bio-REB for consideration in advance of its implementation through the amendment process.

REB ATTESTATION

In respect to clinical trials, the University of Saskatchewan Bio-REB complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Part C Division 5 of the Food and Drug Regulations, and carries out its functions in a manner consistent with Good Clinical Practices. The University of Saskatchewan is constituted and operates in accordance with the current version of the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans - TCPS 2 (2022). If a member of the REB is named as an investigator on a project under review, the member is absent from REB deliberations and decisions regarding the project. This approval and the views of the Bio-REB have been documented in writing.

*Digitally Approved by Dr. Ildiko Badea, Ph.D.
Chair, Biomedical Research Ethics Board
University of Saskatchewan*