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FACULTY OF SCIENCE AND TECHNOLOGY

School of Psychology

**Investigating oculomotor control during the learning and
scanning of character strings**

By

Mengsi Wang

B.S., Wuhan University, China, 2015

Submitted in partial fulfilment of the requirement for the degree of
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Contents

<i>STUDENT DECLARATION FORM</i>	<i>i</i>
<i>Acknowledgements</i>	<i>ii</i>
<i>Contents</i>	<i>iii</i>
<i>Abstract</i>	<i>vi</i>
<i>Table List</i>	<i>viii</i>
<i>Figure List</i>	<i>ix</i>
<i>Chapter 1: Introduction</i>	<i>1</i>
1.1 A brief history of eye movement research	4
1.2 Basic characteristics of eye movements	6
1.3 Measures of eye movements	10
1.4 Eye movement control in reading	12
1.4.1 The decisions of when and where to move the eyes	12
1.4.2 How much information can be extracted to the right of fixation in reading?	14
1.5 Eye movement models in reading of alphabetic languages	16
1.5.1 E-Z Reader	16
1.5.2 SWIFT	19
1.6 Spacing format effects on eye movements during reading	21
1.7 Special issues in Chinese reading	26
1.7.1 The psychological reality of words in Chinese reading	27
1.7.2 Word segmentation in the reading of unspaced Chinese texts	29
1.7.3 Saccade target selection in Chinese reading	32
1.8 Thesis outline	36
<i>Chapter 2: Eye movement control during learning and scanning of Landolt-C stimuli (Experiment 1)</i>	<i>39</i>
2.1 Introduction	39

2.2	Method	46
2.2.1	Participants	46
2.2.2	Apparatus	46
2.2.3	Materials	47
2.2.4	Experimental design	48
2.2.5	Procedure	49
2.3	Data analysis	51
2.4	Results	52
2.4.1	Learning session	52
	<i>Learning blocks</i>	52
2.4.2	Scanning session	57
	<i>Analysis of global measures</i>	58
	<i>Analysis of local measures</i>	63
2.5	Discussion	66
 Chapter 3: Eye movement control during learning and scanning of English		
	<i>Pseudoword strings in English native speakers (Experiment 2)</i>	75
3.1	Introduction	75
3.2	Method	79
3.2.1	Participants	79
3.2.2	Apparatus	80
3.2.3	Stimuli	80
3.2.4	Experimental design	82
3.2.5	Procedure	83
3.3	Results	84
3.3.1	Learning session	85
3.3.2	Scanning session	90
3.4	Discussion	100
 Chapter 4: Eye movement control during learning and scanning of English		
	<i>Pseudoword strings in Chinese native speakers (Experiment 3)</i>	110

4.1	Introduction	110
4.2	Method	121
4.2.1	Participants	121
4.2.2	Apparatus, Stimuli, Experimental design & Procedure	121
4.3	Results	123
4.3.1	Learning session	125
4.3.2	Scanning session	133
4.4	Discussion	143
Chapter 5: General Discussion		155
5.1	Learning block effects in the learning session	156
5.2	Exposure frequency effects in the learning session	158
5.3	The rate of learning effects	160
5.4	Exposure frequency effect in target detection during scanning	161
5.5	The roles of spacing and alternating shadings in string scanning	164
5.6	Saccadic targeting in the scanning of strings with or without boundary information	166
5.7	Overall conclusions and implications	167
5.8	Future Directions	170
Bibliography		172

Abstract

Word spacing plays an important role in both word identification and saccadic targeting in the reading of spaced languages (e.g., English), however, the spacing facilitation is not present when word spacing is added in normally unspaced Chinese text in Chinese native speakers (e.g., Grade-3 children, young adults, old adults). Frequency effects are well-documented in the reading of normal text. However, it remains controversial as to whether frequency effects would occur in non-reading tasks, such as searching for a target in normal text or text-like strings. Furthermore, it is unclear whether spacing would also play an important role in the guidance of eye movement control in text-like string scanning as it does in the reading of spaced languages.

In three experiments, the present thesis examined how exposure frequency effects are established during the learning of novel stimuli in a learning session (Landolt-C clusters in Experiment 1 vs. pseudowords in Experiments 2 & 3) and how the simulated exposure frequency would affect the scanning of longer strings with or without boundary demarcation cues (spaced vs. unspaced shaded vs. unspaced) in a scanning session. Importantly, the present thesis investigated whether learning and scanning of novel character strings would be qualified by the stimulus type (Landolt-C vs. English pseudoword) and the population (English native speakers vs. Chinese participants).

In Experiment 1, robust interactive effects between exposure frequency and learning blocks (e.g., learning rate effects) occurred during the learning of target stimuli. However, the exposure frequency effects did not carry over to the

scanning session. Robust spacing effects occurred. Spacing facilitated eye movements to a greater degree than the shading manipulation. In Experiments 2 & 3, again, robust learning rate effects occurred in learning target pseudowords. The exposure frequency was simulated successfully and effectively during learning, however, the exposure frequency showed no influence on eye movements in the scanning session. The meta-analysis across the three experiments demonstrated that learning was more effective using pseudoword stimuli relative to Landolt-C stimuli, and more effective in Chinese participants than English participants. Generally, the degree of shading facilitation was much smaller in the scanning of Landolt-C strings compared to pseudoword strings and it was smaller for English participants relative to Chinese participants. The constant occurrence of learning rate effects across experiments suggests the replicability and reliability of the current character learning paradigm. Spacing facilitation constantly occurred in scanning either Landolt-C strings or pseudoword strings, indicating that spacing plays an important role in non-reading string scanning tasks. The absence of exposure frequency effects in the scanning session across three experiments seems to suggest that exposure frequency effects might not occur in string scanning when the task is to search for a pre-learned target in the string. The differential pattern of shading and spacing facilitation between Chinese participants and English participants suggests an influence from the writing system of the native language on eye movements in the current string scanning.

Table List

Table 2-1 Mean first fixation duration (ms), total viewing time (ms) and fixation number on target clusters across the learning blocks.....	54
Table 2-2 Fixed effect estimates from the LMMs for first fixation duration, total viewing time and fixation number on target clusters across the learning blocks.....	54
Table 2-3 Mean hit rate, means of RT, FFD, TT and fixation number in learning assessment tasks	56
Table 2-4 Fixed effect estimates from GLMM on mean hit rate and LMMs on RT, FFD, TT, FN across targets in learning assessment blocks.	57
Table 2-5 Global measures from observations on all clusters and local measures from observations on target clusters during scanning.	60
Table 2-6 Fixed effect estimates from LMMs on global measures and local measures.	61
Table 3-1 Descriptive statistics in the learning session.....	86
Table 3-2 Descriptive statistics in the scanning session.....	92
Table 4-1 Means of first fixation duration, total reading time and fixation number on target pseudowords in learning and learning assessment. Hit rate and reaction time in the learning assessment were also included.....	127
Table 4-2 Means and Standard errors of independent variables examined in the scanning session.....	134

Figure List

Figure 1-1 Schematic diagram of the E-Z Reader 7 (Reichle et al., 2003). (See the text for detailed description of the model's assumptions.).....	19
Figure 1-2 A schematic diagram of the SWIFT model (Engbert et al., 2005).....	21
Figure 1-3 Framework of Chinese word segmentation and word recognition (Li et al. 2009). CR indicates character recognizer.....	32
Figure 2-1 An example of a Landolt-C cluster. The gap size of each Landolt-C ring is 6 pixels. Each Landolt-C ring occupise 30 pixels. There were 8 possible gap orientations each of which was equi-rotated through 360 deg. (e.g., 0 deg., 45deg., 90 deg., 135 deg., etc).....	47
Figure 2-2 Example Landolt-C strings presented in the three cluster demarcation forms. There might be a target cluster embedded in the string at the second to the eighth cluster position.	48
Figure 2-3 The left panel plots the interactive effect between exposure frequency and learning block on log transformed total viewing time during target learning. The right panel plots the same effect observed on log transformed total fixation number.	55
Figure 2-4 The distribution of initial landing positions on target clusters across all the conditions in the scanning session.....	65
Figure 3-1 Example pseudoword strings displayed under the three demarcation formats: spaced string, shaded string and unspaced strings. The target triplet in this example was in the third triplet position, 'ruz'.....	82
Figure 3-2 Mean total reading times during the learning of HF target and LF targets across the five learning blocks. The vertical lines represent error bars.....	88
Figure 3-3 Initial landing position distributions on the target triplet across all conditions in the scanning session.	100
Figure 4-1 An example from a Chinese textbook used by first-year primary school students.	118

Figure 4-2 Mean total reading times on HF targets and LF targets across blocks. The vertical lines represent standard errors. 129

Figure 4-3 Initial landing position distributions on the target triplet across all conditions in the scanning session. 143

Chapter 1: Introduction

Word frequency effects are widespread in reading, learning novel words during reading and lexical decision tasks. Such effects are prevalent in languages, irrespective of whether the language is printed with word spacing or without word spacing. Word frequency is considered as one of the most important linguistic characteristics of a word, as well as a temporal marker of lexical processing. However, little is known regarding how word frequency effects are established during the learning of novel words in isolation, which is an important means of word acquisition at early ages. Also it is not clear, how such frequency effects that are developed during learning in isolation would potentially preserve through to normal reading when the newly learnt words are embedded in sentences. The present thesis examines how exposure frequency effects are established during the learning of novel stimuli in isolation in a learning session, and whether the simulated exposure frequency effects would maintain to the scanning of strings with different spacing presentation formats in a scanning session. To make these research problems more tractable, the present thesis purposely stripped away aspects of linguistic information associated with language processing. Instead of constructing the experiments in the context of real language processing, the present thesis adopts Landolt-C stimuli in Experiment 1 (Chapter 2), and pseudoword stimuli in Experiments 2 (Chapter 3) and 3 (Chapter 4). Furthermore, the present thesis investigates whether the nature of learning and target identification in scanning would differ across populations (i.e., Experiment 2 examines English native speakers, Experiment 3 examines Chinese native speakers).

It is well-documented that eye movements provide an excellent indication of moment-to-moment cognitive processing (Rayner, 1998). For example, the fixation time on a word can reflect the online processing difficulty of the word. Eye movement methodology is now widely used to investigate the underlying mechanisms of varied aspects of human behaviours associated with oculomotor control, such as reading, scene perception, visual search and other information processing (Castelhano & Rayner, 2008; Rayner, 1995, 2009, 1998; Henderson, 1992). By contrast, less is known about whether eye movements are sensitive to reflect the time course of learning when the stimuli are presented in isolation or searching for a pre-learnt target that is embedded in strings during scanning.

Given that the investigation on reading using eye movement recording is very well-developed, it serves as a platform for the current thesis. Therefore, this introductory chapter will mainly examine eye movements during written language processing (i.e., reading). Additionally, one of the major motivations of this thesis was to examine an important question pertaining to word segmentation in unspaced strings, it is important to describe the existing findings obtained in reading research investigating similar questions in order to make comparisons between the previous findings in literature and the findings of this thesis. Section 1.1 will briefly describe the history of eye movement research. Section 1.2 will introduce basic characteristics of eye movements and the factors that influence eye movements in reading and other information processing. Section 1.3 will describe some commonly used eye movement measures. Some of them were used in the present thesis. Section 1.4 will review two important issues related to eye movement control in reading: Decisions of when and where to move the eyes; how much information can be extracted to the right of fixation

in reading. Section 1.5 will provide a brief description of two dominant reading models in literatures: E-Z reader model and SWIFT model. Section 1.6 will review some important studies that have adopted two approaches to examine how spacing presentation format would influence reading. One approach is to remove inter-word spaces from normally spaced languages. The other approach is to add inter-word spaces or other visual demarcation cues of word boundaries in normally unspaced languages. Section 1.7 will introduce three special issues of Chinese reading: The psychological reality of words in Chinese reading; word segmentation in the reading of unspaced Chinese texts; saccade target selection in Chinese reading. These issues are highly relevant because the major motivation of this thesis is to better understand how readers segment word boundaries in the reading of unspaced languages, like Chinese. In Section 1.8, an outline of all experiments in this thesis will be provided.

1.1 A brief history of eye movement research

Despite eye movement recording methodology being widely adopted now, the origin of using eye movements to examine cognitive processes is indeed very recent (van Gompel, 2007; Wade & Tatler, 2005; see also Wade & Talter, 2011; Venezky, 1977). Early studies on eye movements were usually concerned with visual problems, depending on subjective observation (or description). For a very long time, the eyes were considered to sweep smoothly without stops during reading until 1879 when the discontinuous nature of saccadic eye movements were described by Hering and also Javal (see Huey, 1908). The innovation of eye tracking devices provided an objective method to investigate the link between eye fixations, saccades and human cognitive processes. Rayner (1998) argued there have been three eras of eye movement research: an initial era from late 19th century to 1950s; an second era from 1950s to 1970s and a third era from 1970s to the present. In the initial era, many basic characteristics of eye movements were examined, such as saccades. In the second era, only a little research was done in relation to the role of eye movements due to the prevalence of behaviourism contemporaneously. In the third era, eye movement research has reached a unprecedented level due to the rapid innovation of computational technology. Some famous experiments that occurred across the three eras will be described below. Also, these examples might provide us with a rough idea of the explorations in relation to the link between eye movements and online cognitive processing over time.

One renowned work during 1950s is the experiment of Yarbus (translated into English in 1967) wherein he recorded the eye movements of one participant required to view the same painting (Repin's *An Unexpected Visitor*) seven times but under different

instructions. It was surprising to find that the placement of fixations differed considerably when the participants were given different instructions before each viewing. Yarbus's work is one of the best examples to demonstrate how objective eye movement recording can be used to reflect online information processing when people are engaged in tasks related to visual activities. In 1976, Just and Carpenter proposed an influential eye-mind hypothesis, that is, what the eyes are looking at is what the mind is processing, overt attention (i.e., eye fixation location) always shifts synchronously with covert attention. However, the eye-mind hypothesis was soon questioned in relation to the direct coupling of eye location and attention. In a well-known study by Posner (1980), viewers were required to hold eye fixation at one place while another stimulus was displayed somewhere else within the visual field. This elegant study showed that covert attention could be allocated independently from eye fixation location. The tasks in Posner's study (1980) was very simple, however, it was not clear whether covert attention is decoupled with eye location in more complex tasks, such as, reading, scene perception and visual search. The use of gaze-contingent techniques (McConkie, & Rayner, 1975; Rayner, 1975) provided a new approach to differentiate what is fixated (eye location) and what is processed (attention allocation) in those more complex tasks, particularly, in reading. In the late of 20th century, a large number of experiments using eye tracking techniques were carried out leading to an unprecedented growth in understanding of eye movements. A number of computational models of eye movement control during reading were proposed, less so for eye movement control during visual search and scene perception (Rayner, 2009). More detailed information about models of eye movement control will be reviewed in a later section of this chapter.

1.2 Basic characteristics of eye movements

This section describes basic characteristics of eye movements (including fixations, saccades, saccade latency, regression, return sweep and skipping) that not only occur in reading, but also might occur in visual search or scene perception. As the research on visual search or scene perception using eye tracking is far less than that on reading, the review mainly concerns findings in reading literature in relation to what factors affect aspects of eye movements.

When we read, we make eye movements about three or four times a second. Our eyes pause briefly to look directly at a word (approximately 250ms in duration) before making a rapid, ballistic rotation (a *saccade*) in order to position the fovea such that light from a point downstream in the text processed falls upon it. These stationary pauses, or *fixations*, and the rapid saccades after fixations are a universal phenomenon during natural reading, searching, and viewing etc. The reason why we have to make saccadic eye movements is because of the anatomy of the retina and the limitations of visual acuity outside the foveal region. In reading, the visual field may be considered to be comprised of three regions: the fovea, the parafoveal region, and the peripheral region (Rayner, 1998). Visual acuity is maximal in the foveal region, about 2 degrees of the quite central retina, and it drops substantially towards the parafoveal region (extending 5 degrees to both sides of the foveal region). Everything beyond the parafoveal region, that is, in the peripheral region, is very unlikely to be seen clearly. Thus, to obtain precise, high acuity, visual information, viewers have to make saccades to position the point of fixation on the new region so that light from this region falls on the fovea. Note that, it is considered that useful information is only extracted during a

fixation but not during a saccade because vision is suppressed during a saccade (Matin, 1974). These basic characteristics of eye movements hold for other visual activities, such as visual search, scene perception, however, the ranges of fixation duration, saccade length, and even visual field may have greater variability in these tasks relative to reading (Castelhano & Rayner, 2008; Rayner, 1995, 2009, 1998).

The average fixation duration in reading is about a quarter to a second, however, fixation durations can sometimes be shorter than 100ms or longer than 400ms (Rayner, 1978). Likewise, the average saccade length during silent reading of English approximates 7-9-character space, but it varies from a single character space to more than 15-character spaces. Note that, in reading, a character space is a more appropriate metric of saccade length relative to visual angle because eye movements have been shown to remain constant for text with same font size at the different viewing distances (see McDonald, 2006; Rayner & Morrison, 1981). Factors like reading skill, the age of readers, the difficulty of the text being processed, and the characteristics of the writing system have a great influence on both fixation duration and saccade length (e.g., Ashby, Pollatsek, Bolozky, Well, & Rayner, 1981; Rayner, 1998; Rayner, & Clifton, 2005; Shen, 1927; Sun, 1993; Sun & Feng, 1999). For example, less-skilled readers or child readers make longer fixations and shorter saccades relative to skilled or adult readers. Mean saccade length (measured in character space) during the reading of Chinese texts (about 2-3 characters) or Hebrew texts (about 5.5 characters) is much smaller than that of English reading.

The range of duration in visual search is larger than that in reading, substantially depending on the difficulty or ease of the task (see reviews by Rayner, 2009; Rayner,

1995). Similarly, the eyes move further in visual search tasks relative to reading, but the range of saccade length in visual search can be highly variable across different search tasks.

The duration of a saccade per se can be as short as 30ms to move approximately two degrees in reading and 40-50ms to move five degrees in scene perception (Abrams, Meyer & Kornblum, 1989; Ishida, & Ikeda, 1989; Rayner, 1978). The time to programme and execute a saccade, or *saccade latency*, is at least 150-175ms (Becker & Jürgens, 1979; Rayner, Slowiaczek, Clifton, & Bertera, 1983). However, a saccade is not just a simple reflexive movement, as much evidence has demonstrated that saccade latency can be affected by cognitive processes (for a comprehensive review, see Rayner, 1998). Recall that the average fixation duration in reading approximates 250ms, and on this basis, it might therefore initially appear that there is not sufficient time to programme and initiate a saccade if this happens after the completion of word recognition based on processing of information in the foveal region. Thus, it has been reasonably suggested that saccade programming is completed in parallel with word identification in reading (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). Different hypotheses are proposed in relation to the time course of saccadic programming and language comprehension processes. These will be reviewed in later sections of this chapter.

Some other types of eye movements, such as regressions, return sweeps and word skipping, occur quite often in reading. The eyes do not always move in a single direction during reading (e.g., from left to right, from right to left or from top to bottom), and it is a very common experience that we move our eyes backwards in text

to a place that has been viewed before. These backward movements are named *regressions*. In reading, a regression often occurs when readers fail to understand preceding content and have difficulty in sentence processing (Frazier & Rayner, 1982), or when readers overshoot the position they intended fixate, and therefore a regressive, corrective, saccade is required (O'Regan, 1990). This type of backward saccadic movement occurs on 10%-15% of saccades in reading for skilled adult readers. There is also another type of saccade that happens when the margin of the page is reached, that is, when readers have to move their eyes from the end of one line of text to the beginning of the next line. These movements are called *return sweeps* in reading (Bayle, 1942). There has been increasing recent interest in the nature of return sweeps and the processing that readers perform during fixations immediately before and after these movements (Parker, Kirkby, & Slattery, 2017; Parker, Nikolova, Slattery, Liversedge, & Kirkby, 2019; Parker, & Slattery, 2019; Parker, Slattery, & Kirkby, 2019; Slattery, & Parker, 2019; Slattery, & Vasilev, 2019).

In fact, the eyes do not fixate every word during reading. Words that have high frequency (appear often in the language), or high predictability (are probable based on preceding context) are likely to be skipped during first pass reading, that is, during the first sweep of the eyes through a sentence (Balota, Pollatsek & Rayner, 1985; Binder, Pollatsek & Rayner 1999; Rayner & Well, 1996). Other words that are long or low frequency, or have low predictability might possibly receive more than one fixation during first-pass reading (i.e., a refixation). Additionally, skipping rates are higher in short than long words (Brysbaert & Vitu, 1998; Rayner, 1979), and higher in function words compared to content words (Carpenter, & Just, 1983; Rayner & Duffy, 1988). The occurrence of *skipping* and *refixations* during first-pass reading demonstrates that

eye movement control has tight relationship with online cognitive processing, rather than simply being driven by visual and oculomotor constraints by default.

1.3 Measures of eye movements

The spatial and temporal characteristics of the human eye movement record can be used by researchers to infer moment-to-moment cognitive processes underlying various aspects of visual and cognitive behaviours. Over time, researchers have developed a set of eye movement measures that can be extracted from the eye movement record and that provide indices of different aspects of processing and their time course. The aim here is not to review all possible eye-movement measures in the current chapter. Instead, this section reviews some most important standardised measures of eye movements that have been widely adopted in reading studies (see Inhoff & Radach, 1998; Liversedge & Findlay, 2000; Liversedge, Paterson, & Pickering, 1998; Star & Rayner, 2001). It is very important to note that, the eye-movement measures reviewed here are not confined in their application to reading studies. They can also be used in other non-reading eye movement studies.

Measures of eye movements can be divided into global measures and local measures. Global measures include mean fixation duration, mean saccade amplitude, whole sentence total reading time, mean number of fixations, mean reading rate (words per second), mean number of regressions, mean number of skips. Global measures are computed on the basis of all the recorded during a single trial rather than data pertaining to a more refined sub-region of the stimulus (e.g. a word within a sentence). Compared to global measures, local measures refer to measures that are computed for data

observed in relation to only a critical region of interest (ROI). The most commonly adopted local measures are: *first fixation duration*, the duration of first fixation on the ROI during the first-pass reading; *single fixation duration*, the duration of the fixation when the ROI receives only one fixation in first-pass reading; *gaze duration* (or the first-pass reading time when the measure is computed for a ROI comprised of more than one word) refers to the sum of all first-pass fixations on a ROI, including all refixations before leaving the region; *go-past time* or *regression path time* (i.e., the sum of fixations made from the first fixation in a ROI until the eyes move to the right of the ROI – assuming a left to right reading direction); *total viewing time*, the sum of all fixations on a ROI. Eye movement recording does not just inform us of how long the eyes remain fixating a stimulus, but also gives us an indication of the location of the eye. For example, via examining eye movement data, we can easily check whether eyes skip a ROI, and if a fixation is made, we can examine the location of each fixation. In studies of reading, researchers are frequently interested in the initial location of the eyes landing on a target ROI as this is informative in relation to saccadic targeting.

Researchers are also very interested in the time course of specific effects occurring during cognitive processing. If an experimental manipulation to be examined occurs on skipping probability (the probability of skipping a ROI during first-pass reading), first fixation duration, single fixation duration, gaze duration, it is then considered that the manipulation has a relatively early effect on the cognitive process under examination. Conversely, if an effect fails to emerge on the first-pass reading measures but it does occur on total viewing time or go-past time, or appears in regressions, then it is generally argued that the manipulation has a late influence on processing. In this sense, measures of eye movements can be split into early processing

measures and late processing measures. However, it is important to note that reading time measures do not map directly onto particular linguistic sub-processes.

1.4 Eye movement control in reading

The idea that eye movements provide an excellent indication of moment-to-moment cognitive processing is now widely accepted. Since the 1970s, a large amount of research investigating eye movements during reading has been conducted leading to a better understanding of language processing. This section will describe two prominent issues that draw great attention in reading research.

1.4.1 The decisions of when and where to move the eyes

Recall that the average fixation duration is about a quarter of a second for adult readers during reading, while, the time to programme and initiate a saccade approximates 170ms (i.e., saccade latency). It seems reasonable to suggest that saccade generation (when and where to move the eyes) occurs in parallel with language processing during a fixation. Concerning saccade generation, neurophysiological evidence shows that the neural systems that encode and control spatial characteristics of a saccade (the so-called ‘where’ decision) are different from those that are responsible for triggering a saccadic movement (the ‘when’ decision). This evidence has led to the strong suggestion the pathways of ‘when’ and ‘where’ saccade generation are separate (Findlay & Walker, 1999; Liversedge & Findlay, 2000). A number of empirical studies have also demonstrated that the decisions of when and where to move the eyes are independent (e.g., Rayner & McConkie, 1976; Rayner & Pollatsek, 1981).

To date, it remains controversial in terms of which factors affect the decision of where to look next, and the decision of when to move the eyes during reading (Starr & Rayner, 2001). The ‘when’ and ‘where’ issue is a fundamental debate and the issue has sometimes been used as the basis to differentially categorise models of eye movement control. Oculomotor models claim that eye movements are primarily determined by low-level factors, whilst, high-level (linguistic) factors have little influence on the decisions of when and where to move the eyes (e.g., the Strategy-Tactics model, O’Regan, 1990, 1992; O’Regan & Lévy-Schoen, 1987). Specifically, the decision of where to look next is mainly determined by limitations of visual acuity and by visual properties of the texts, such as word spacing cues and word length. Moreover, the decision of when to move the eyes mainly depends on the position of fixation within a word. Thus, it is argued that less processing time is needed if the eyes land closer to the centre of a word as the word centre is considered to be the optimal viewing position in isolated word recognition tasks (O’Regan, 1992; Vitu, O’Regan, & Mittau, 1990). By contrast, cognitive processing/linguistic models stress the importance of cognitive/linguistic factors on making ‘when’ and ‘where’ decisions (e.g., E-Z reader model, Reichle, Pollatsek & Fisher, 1998). As such, where to move the eyes is primarily determined by low-level factors (e.g., word space, word length), whilst, when to move the eyes is determined by the higher order process of word identification (and such decisions are therefore influenced by factors such as word frequency and word predictability). Also, it is important to note, proponents of processing models do not exclude the possibility that high-level linguistic factors might also affect fixation locations. For example, removing inter-word spacing from normally spaced languages significantly increases reading time and reduces saccade extent (Rayner, Fischer, &

Pollatsek, 1998; Sheridan, Rayner, & Reingold, 2013), therefore demonstrating that making a change to the visual properties of the text (here, word spaces) can affect fixation durations and saccadic targeting (i.e., both when and where decisions). Similarly, the finding that highly predictable words are more likely to be skipped than low predictable words supports the idea that high-level linguistic factors can affect fixation locations (Balota, Pollatsek, & Rayner, 1985).

1.4.2 How much information can be extracted to the right of fixation in reading?

A further question that has arisen in reading studies concerns how much useful information can be extracted to the right of the fixated word, that is, in parafoveal vision. This theoretical question is very important because it pertains directly to the relationship between eye fixation location and attention. As mentioned before, when participants are required to hold their point of fixation at one position, they are still able to recognize a stimulus presented elsewhere in the visual field (Posner, 1980). This work, therefore, demonstrated that eye location is not bound with attention in a simple task. However, would it be the same case in more complex tasks, for instance, in reading? Perhaps, the occurrences of skipping in reading is a special case indicating that processing of a parafoveal word might take place before the eyes directly look at the word (see Fischer, & Shebilske, 1985). However, during most time of reading, words to the right of fixation are not skipped. The issue of the extent to which parafoveal word or words are processed has been examined using the boundary paradigm (Rayner, 1975). The boundary paradigm is form of the gaze-contingent technique established by Rayner and McConkie, (1975). In this paradigm, an invisible boundary is placed in the space before a target word. Prior to the eyes making a saccade that crosses the boundary, the

target word is replaced by either a preview string that can take many different forms that are more or less similar to the target itself. When the reader makes a saccade that crosses the invisible boundary the preview word almost immediately changes to the target. The display change takes just a few milliseconds and it occurs during the saccade when readers are insensitive to visual input (saccadic suppression). Thus, readers are rarely aware of the change to the display. By manipulating the nature of the preview in relation to the target, researchers are able to examine the kinds of information about parafoveal words to the right of fixation that is extracted and processed prior to direct fixation. Many studies have reported effects of parafoveal preview information on subsequent foveal processing; word length (e.g., O'Regan, 1979, 1980) as well as forms of lexical information, such as orthography, phonology, and morphology (e.g., Inhoff, 1990; Inhoff & Tousman, 1990; Pollatsek, Lesch, Moriss, & Rayner, 1992; Rayner, 1975; Rayner, Balota & Pollatsek, 1986). Valid parafoveal processing benefits subsequent foveal processing and therefore facilitates comprehension of text. By contrast, relatively fewer studies reported that a semantically related preview benefits subsequent foveal processing with the majority of such studies being conducted with participants reading Chinese or German texts (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Hohenstein & Kliegl, 2014; Hohenstein, Laubrick, & Kliegl, 2010; Hyönä, & Häikiö, 2005; Rayner, Balota, & Pollatsek, 1986; Rayner, McConkie, & Zola, 1980; Yan, Zhou, Shu, & Kliegl, 2012; for a review, see Schotter, Angele, & Rayner, 2012). However, recently, increasing studies have shown semantically related preview benefits on subsequent foveal processing in reading English texts (e.g., Rayner, & Schotter, 2014; Rayner, Schotter, & Drieghe, 2014; Schotter, 2018; Schotter, & Fennell, 2019; Schotter, & Jia, 2016; Schotter, & Leininger, 2016; Veldre, & Andrews, 2016). Most of

the time, the preview benefit findings in English reading apply in relation to the first word to the right of fixation (see a review by Cutter, Drieghe, & Liversedge, 2015; see also Rayner, Juhasz, & Brown, 2007; Rayner, Schotter, & Drieghe, 2014; Schotter, Angele, & Rayner, 2012; Schotter, Reichle, & Rayner, 2014). As to whether preview benefit can be obtained from the second word to the right of current fixated word, the results are still mixed (for a review, see Vasilev, & Angele, 2017).

1.5 Eye movement models in reading of alphabetic languages

In this section, two most important and influential models in the field of reading are reviewed: E-Z Reader model and SWIFT model. Both models claim that moment-to-moment cognitive processing has a very significant influence on eye movement control. However, the two models have different predictions regarding how attention is allocated during reading. The E-Z Reader model claims attention shifts from one word to the next serially, with only one word being lexically processed at a time (i.e., it is a sequential attention shift, SAS, model). By contrast, the SWIFT model proposes that attention is allocated to words in parallel, with more than one word being lexically processed at a time (i.e., it is a guidance by attentional gradient, GAG, model).

1.5.1 E-Z Reader

E-Z Reader is an influential processing model that has received a considerable amount of attention within the literature to date. Initially, E-Z Reader aimed to resolve problems associated with the earlier model of eye movement control put forward by Morrison (1984). In Morrison's model, the completion of word identification is the engine that drives the shift of attention. Also, the shift of the attention "spotlight"

(Posner, 1980) is coupled with programming of a saccade to the next word. Once one word is identified, attention shifts to next word, and successively, the oculomotor system is triggered to execute a saccade. Morrison's model can explain many phenomena that occur in reading (e.g., word frequency effects, preview benefit effects), however, it fails in accounting for why there are refixations on a word and why foveal processing 'spills over' to the next word. This should not occur if attention only shift to the next word when the foveal word is completely identified. The E-Z Reader model is a next generation model that overcomes these shortcomings of Morrison's model (Reichle, 2011; Reichle, Rayner & Pollatsek, 2003; Reichle, Pollatsek, Fisher & Rayner, 1998; Reichle, Warren, & McConnell, 2009).

By assuming that word identification can be divided into two stages, E-Z Reader provides sufficient flexibility to explain the phenomena of refixations and 'spill over' effects. As shown in Figure 1.1, the boxes represent the visual system, the word identification system, the attention and the oculomotor systems. Visual features of printed text are encoded at the retina, and then this information is projected from the retina to the visual cortex. Low-spatial frequency information like word boundaries obtained in the early stage of visual processing is used by the oculomotor system to make selections in relation to saccade targets. High-spatial frequency information extracted in visual processing is then conveyed to the word identification system. The attention system selects the word to be identified. Once attention has shifted to the word, the processing of this word starts. In the first stage of word identification (i.e., L₁), full information of orthography and possibly partial phonological and semantic information of the word can be obtained. Once the first stage of word identification has been finished, a signal is sent to the oculomotor system to move the eyes. In the second

stage of word identification (i.e., L_2), both phonological and semantic information about the word can be obtained. The completion of L_2 is the signal to shift attention to the next word. As mentioned, the completion of L_1 is the signal to move eyes. When the oculomotor system receives the signal to move the eyes, it makes preparations to execute a saccade to the intended location. There are two stages in saccade programming, one labile stage (i.e., M_1) that is subject to cancellation and the succeeding non-labile stage (i.e., M_2) that must be executed (i.e., it cannot be cancelled). When a new saccade to word_{n+2} is programmed while the saccade to word_{n+1} is still in the labile stage or is being programmed, word_{n+1} will be skipped, and the eyes will move to word_{n+2} . The decoupling of moving the eyes and shifting attention in E-Z Reader avoids the limitations in Morrison's model, and does an excellent job of explaining refixations and how difficulty in foveal processing might influence parafoveal preview benefits.

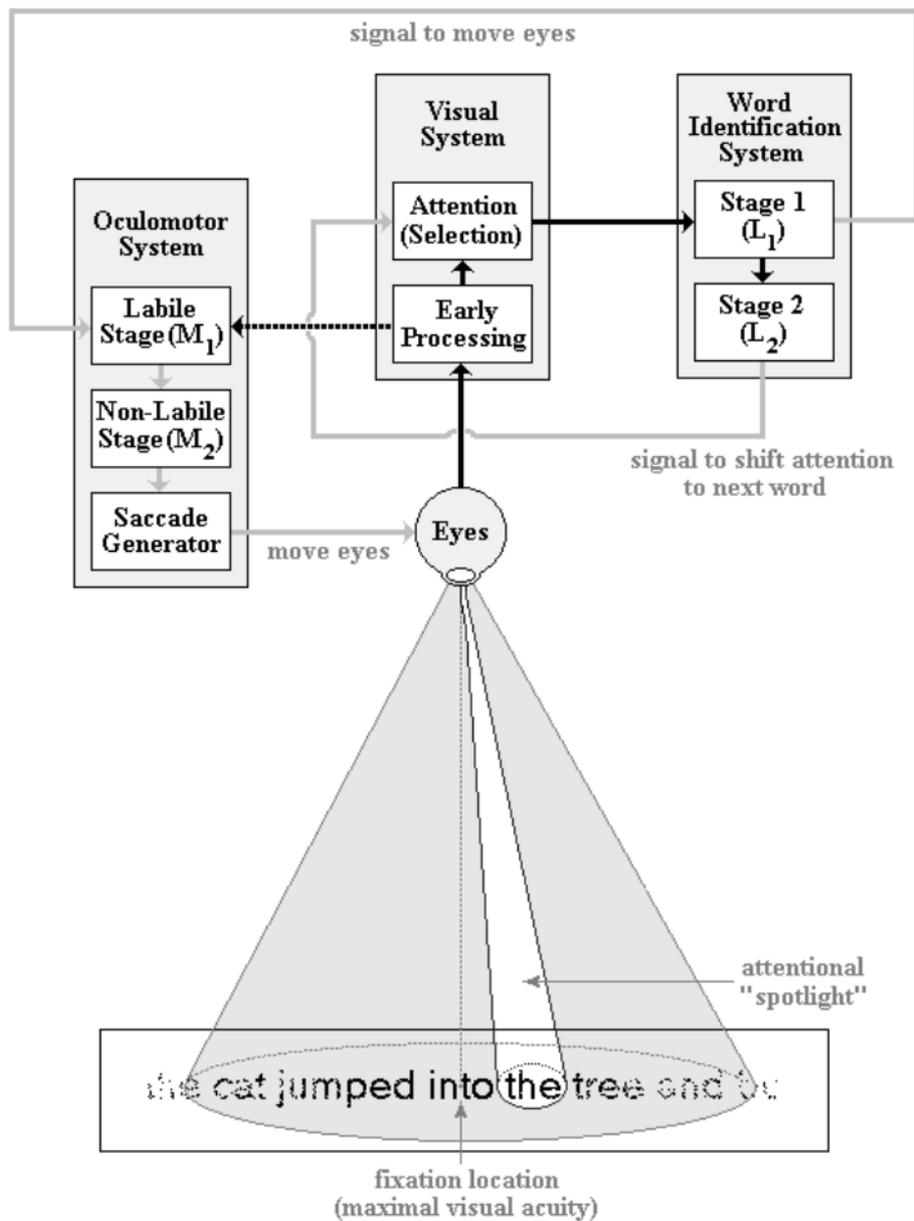


Figure 1-1 Schematic diagram of the E-Z Reader 7 (Reichle et al., 2003). (See the text for detailed description of the model's assumptions.)

1.5.2 SWIFT

The architecture of the SWIFT model (i.e., saccade generation with inhibition by foveal targets) is in some ways similar to E-Z Reader. The two models share some key assumptions. In the SWIFT model, there are two stages of word identification and two

stages of programming a saccade, as also proposed by E-Z Reader (see Figure 1.2 for a schematic diagram of the SWIFT model). The primary distinctions between the two models concerns the relationship between saccade programming and word processing and the issue of how attention is allocated across a line of text. In the SWIFT model, attention can be allocated to approximately four words at one time; that is, several words can be processed in parallel (Engbert & Kliegl, 2011; Engbert, Longtin & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Kliegl, & Engbert, 2003). By contrast, words are processed strictly serially in E-Z Reader (i.e., only one word can be identified at one time). In the SWIFT model, word identification is not the ‘engine’ to program a saccade; instead, saccades are automatically programmed at a mean rate based on a random timer ensuring the eyes move smoothly during reading (other than with the exception that there is inhibition linked to the oculomotor system when the foveal targets cause processing difficulty). Another important distinction between the two models is the selection of a saccade target. The SWIFT model posits that the initiation of saccade programming has nothing to do with the selection of where to move the eyes (they are independent decisions). In conclusion, the primary distinctions of the two models are the way to allocate attention during reading and whether the moment-to-moment word processing is the guidance of eye movement control.

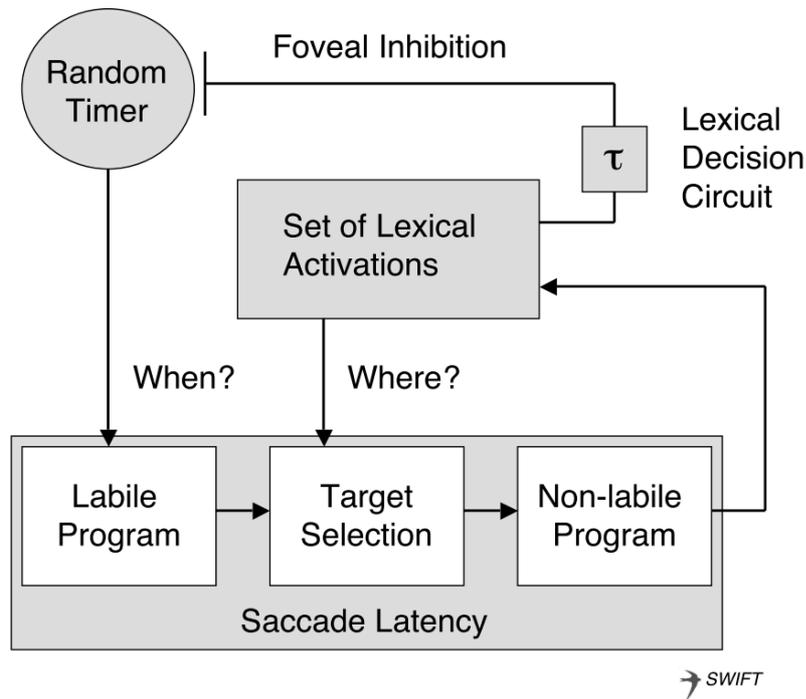


Figure 1-2 A schematic diagram of the SWIFT model (Engbert et al., 2005).

1.6 Spacing format effects on eye movements during reading

Most modern written languages are printed with word spacing (e.g., English, French, Spanish, Finnish), whereas some written languages are printed without inter-word spaces (e.g., Chinese, Japanese, Thai). The fundamental difference with respect to the presence or absence of word spacing in a language, motivates researchers to investigate what role word spacing might play in the reading of spaced languages or unspaced languages. Two main approaches have been adopted to examine this issue. In normally spaced languages, researchers have often removed inter-word spaces from the scripts in order to investigate how the removal of word spacing and word demarcation cues affects eye movement control in reading. By contrast, in normally unspaced

languages, for example, in Chinese, researchers have often investigated whether adding word spacing to normally unspaced Chinese would facilitate reading.

A wealth of evidence demonstrates that the spaces between neighbouring words play a critical role in eye movement control during the reading of normally spaced languages such that removing word spacing from the spaced languages causes substantial disruption to both word identification and saccadic targeting (Drieghe, Brysbaert, & Desmet, 2005; Mailt, & Seamon, 1978; Drieghe, Fitzsimmons, & Liversedge, 2017; Inhoff, Pollatsek, Posner, & Rayner, 1989; McGowan, White, Jordan, & Paterson, 2014; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Perea, Tejero, & Winkler, 2015; Pollatsek, & Rayner, 1982; Rayner, & Pollatsek, 1996; Rayner, Fischer, & Pollatsek, 1998; Sheridan, Rayner, & Reingold, 2013; Sheridan, Reichle, & Reingold, 2016; Slattery, & Rayner, 2013; Spragins, Lefton, & Fisher, 1976; Veldre, Drieghe, & Andrews, 2017; c.f., Epelboim, Booth, & Steinman, 1994). One important study that was conducted by Rayner and colleagues (1998) monitored readers' eye movements during the reading of English text either with word spacing or with no word spacing. They found that reading efficiency almost dropped 50% in reading unspaced text compared to normal text. Also, word frequency effect (on reading time measures) was larger in the reading of unspaced text compared to the spaced text. Furthermore, saccadic targeting was also affected by spacing format. It is important to note that, in the reading of normal spaced text, the eyes are targeted slightly left to the centre of a word – the so-called Preferred Viewing Location (PVL, Rayner, 1979). In the spaced condition, initial landing positions were more close to the centre of the word which is consistent with the typical PVL. However, in the unspaced condition, the typical centrally peaked PVL disappear, instead, readers more frequently sent their eyes

near word beginning. Perea and Acha (2009) reported similar findings in Spanish reading. Perea and Acha constructed three spacing conditions (e.g., unspaced, spaced, and alternating**bold**) and embedded either high or low frequency words in sentences with the different spacing formats. They found that unspaced compared to spaced sentences, initial landing positions were closer to word beginnings in the unspaced condition and this effect held even when word boundaries were signaled in an alternating**bold** condition. The differential patterns of landing position curves for sentences with two different types of word demarcation (word spacing vs. alternating**bold**) suggest that demarcation of word boundaries with spaces may be beneficial to reading beyond simply illustrating where words start and end.

Given that there are some languages including no spaces between adjacent words (e.g., Chinese, Thai, Japanese), the question that how native readers of unspaced languages segment word boundaries in reading of unspaced text has naturally arisen. In the past three decades, increased research has been conducted to examine this issue. For example, Sainio, Hyönä, Bingushi and Bertram (2007) investigated whether adding word spacing into unspaced Japanese texts (i.e., a mix of Kanji, Hiragana and Katakana) would affect eye movement control during the reading. It was demonstrated that the adding of word spacing into pure syllabic Hiragana texts did facilitate reading, whereas the adding of spaces into adjacent words to Kanji-Hiragana mixed texts did not produce any facilitation. Sainio et al. (2007) argued that logographic kanji characters themselves were useful demarcation cues of word boundaries, which effectively assisted with the guidance of eye movements in the reading of unspaced Japanese texts (see also, Kajii, Nazir, Osaka, 2001). Similar approach of adding spaces into adjacent words was used to examine saccadic targeting during the reading of Thai script, an alphabetic unspaced

language. Kasisopa, Reilly, Luksaneeyanawin, and Burnham (2013) reported that, in the reading of both spaced and unspaced Thai texts, adult Thai readers more frequently sent their eyes close to the centre of a word when positional frequency of either the initial or final character of a word was high. They concluded that Thai readers utilized the positional frequency of word boundary characters to guide saccadic targeting in reading unspaced Thai script (see also, Winskel, Radach, & Luksaneeyanawin, 2009). Similar patterns of eye movements were also observed for child Thai readers (Kasisopa, Reilly, Luksaneeyanawin, & Burnham, 2016).

Perhaps Chinese is the most prevalent example of unspaced languages. A series of studies have been conducted to examine whether adding word spacing in Chinese text would potentially facilitate reading. In Bai, Yan, Liversedge, Zang, & Rayner. (2008) experiments, participants read Chinese texts that were presented with four different spacing formats: text with spaces between words; text with no spaces between words; text with spaces between characters; text with spaces between non-words. Bai et al. (2008) found that sentence reading efficiency was comparable between the word spaced condition and the unspaced condition. By contrast, reading was less efficient in the character-spaced condition and least efficient in the non-word spaced condition. In their second experiment, similar results occurred when highlighting were used to create the four spacing formats. These results demonstrated that the presence of physical markers of word boundaries, either word spacing or highlighting, did not affect reading for the Chinese adult readers. Thus, Bai et al. (2008) argued that there is a trade-off between spacing facilitation effects and costs due to the readers' whole life experience of reading unspaced texts. Further studies have investigated word spacing effects in Chinese older adult readers, Chinese child readers and those learning Chinese as a

second language (Bai et al., 2008; Bai et al., 2013; Bai, Guo, Cao, Gu, & Yan, 2012; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017; Shen et al., 2010; Shen et al., 2012; Zang, Liang, Bai, Yan, & Liversedge, 2013; see also, Ma, 2017; c.f., Zhou, Wang, Shu, Kliegl, & Yan, 2018). In Blythe and colleagues experiment (2012), two groups of participants (Chinese adult readers and Chinese pupils) were required to learn new vocabularies in a learning session, after which they were required to read longer sentences that contained the newly learnt words in a test session. The participants were divided into two learning subgroups - one half read unspaced text and the other half read spaced text during learning. In the testing session, all the participants read unspaced texts. Blythe et al. (2012) found that, during the learning of new words, less reading time was spent reading in the spaced condition compared to unspaced condition for both adult readers and children. Furthermore, the spacing benefits obtained in the learning session maintained to the testing session for children though not the adult readers. Blythe et al. argued that the spacing manipulation allowed children to either form a stronger connection between existing character representations and the new vocabulary, or to form a fully specified representation of the novel word itself. More recently, Bai et al. (2013) examined whether presenting spaces between the words in Chinese sentences would benefit the acquisition of new vocabulary for those learning Chinese as a second language. They used the same paradigm as Blythe et al., (2012). The results showed that reading was much faster when spaces between the words were present compared to when the spaces were not present during the learning of novel words (see also Bassetti & Lu, 2016; Bassetti, 2009). Moreover, spacing facilitation was maintained to the later testing session in which participants were required to read unspaced texts. These findings were very similar to those observed for Chinese pupils

(Blythe et al., 2012), but the size of spacing effects was much larger for participants learning Chinese as a second language. Considering all of these results together, adding spaces between the words in Chinese texts did not facilitate overall reading for Chinese adults. However, insertion of spaces between words did facilitate the learning of novel words in reading for both children, Chinese adult readers and those learning Chinese as a second language. More importantly, the spacing facilitation that occurred in learning maintained to a later testing session in which there were no spaces between words for Chinese children and those learning Chinese as a second language, though this effect did not occur for Chinese adult readers (c.f., Bassetti & Masterson, 2012).

1.7 Special issues in Chinese reading

The history of using eye movement recording to examine the reading of Chinese spans a period that is considerably shorter than that for eye movement research investigating reading of alphabetic languages. As a result, the current state of knowledge of eye movement control in Chinese reading has not developed to the same degree as has knowledge of reading of alphabetic languages. In the past 20 years, however, an increasing number of studies have been conducted to examine the relationship between oculomotor control and online language processing in Chinese reading.

Chinese reading attracts increased research interest mainly because the nature of Chinese language is very different to alphabetic languages. One of most striking and obvious differences that exists between most alphabetic languages (e.g., English, Finnish, Spanish) and Chinese is that there is no word spacing in Chinese texts. Given

that there are no spaces demarcating word boundaries in Chinese text, a question naturally arises that how Chinese readers segment word boundaries during the reading of unspaced text. Furthermore, there is often disagreement amongst native Chinese readers as to where word boundaries lie in written text (Hoosain, 1992; Liu, Li, Lin & Li, 2013). That is to say, there is ambiguity in relation to word boundaries from one Chinese individual to another. This aspect of Chinese text and reading is very important in relation to the present thesis and it will be a central issue of investigation in the experimental work that will be reported later in the thesis.

Next, three important issues about eye movement control in Chinese reading are described. The first one concerns the question of whether words have psychological reality in Chinese reading, or instead whether processing is character-based in Chinese reading. The second concerns how readers segment words during the reading of unspaced Chinese texts. The third and final question concerns how Chinese readers target saccades in Chinese reading. These three questions are related and not mutually exclusive, and for this reason, in most studies investigating eye movement control in Chinese reading, these questions are often discussed together.

1.7.1 The psychological reality of words in Chinese reading

It is very interesting to consider the question of how readers segment words during the reading of unspaced Chinese texts. However, before examining the issue of word segmentation, the precursor question we have to consider concerns whether word units play an important role in Chinese reading. This is very important because if the word is not an important linguistic unit in Chinese reading, it is very likely that readers do not need to segment text and process it on a word by word basis when reading

unspaced Chinese texts. Alternatively, if words are critical linguistic units in Chinese reading, then it seems very likely that readers must perform word segmentation (presumably, prior to word identification) because without such a commitment, it is difficult to understand how Chinese readers might uniquely identify a lexical representation in the mental lexicon.

In linguistics, a word may be defined as the minimal meaningful unit in a language that conveys complete information and constitutes an independent grammatical component (Hoosain, 1992). The notion of a word is clear for most readers of alphabetic languages. They can easily agree on the letters that comprise a word as being those between the spaces at the beginning and end of the word. The important role of the word in alphabetic languages is also evidenced by the findings of Word Superiority Effect (Reicher, 1969; Wheeler, 1970). That is, letters embedded within a word unit are better recognized than when they are embedded in a random letter string. The word superiority effect demonstrates that the context within which a letter appears influences the ease with which it can be recognized.

Unlike readers of most alphabetic languages, Chinese native speakers have a relatively vague sense of what a word is. When Chinese readers are required to perform word segmentation by putting a slash between adjacent words in the same sentences, there are often discrepancies in their word boundary demarcations (Hoosain, 1992; Liu, Li, Lin & Li, 2013). Although ambiguity exists in off-line word segmentation tasks amongst readers, many studies reported typical word superiority effects in Chinese character perception tasks (e.g., Cheng, 1981; Li & Pollatsek, 2011; Li, Rayner, & Cave, 2009). Furthermore, increasing evidence supports the existence of the

psychological reality of words in relation to Chinese lexical representations. For instance, as mentioned before, Bai et al. (2008) investigated this issue by inserting spaces into adjacent words in normal Chinese reading. In their experiments, they created four spacing conditions by purposely inserting spaces between adjacent words, non-words or single characters (in their second experiment, highlighting was used to create the four segmentation formats without introducing a horizontal spatial extent confound). They found that reading efficiency dropped dramatically in non-word and single-character spaced conditions relative to normally presented unspaced text. By contrast, Chinese readers were able to read word spaced text as fast as normal unspaced text even though they were less familiar with spaced text relative to unspaced text based on their lifelong experience of reading Chinese. These findings indicate word units play a critical role in Chinese reading.

1.7.2 Word segmentation in the reading of unspaced Chinese texts

Given the importance of words in Chinese reading, and the fact that there are no spaces between words in Chinese reading, the question of how readers identify word boundaries during the reading of unspaced Chinese texts naturally arises. And as discussed earlier, given a lack of visual cues as to word boundaries, it seems reasonable to suggest that readers must engage in word segmentation before they are able to identify a word stored in memory. However, it is also interesting to consider how readers might determine the boundaries of a word if they have not yet identified this word. This is something of a chicken-and-egg situation (see Li, Rayner, & Cave, 2009, for more discussion). The number of studies examining how readers would possibly identify word boundaries in unspaced Chinese reading has increased rapidly in the past

two decades, however, it remains an unresolved issue. Three hypotheses have been proposed to explain how this process might occur.

Given that approximate 70% of Chinese words are two-character words (*Lexicon of common words in contemporary Chinese*, 2008), Perfetti and Tan (1999) proposed a serial parsing hypothesis in which they argued that Chinese readers tend to parse every two characters that are spatially contiguous into a word. To examine this hypothesis, Perfetti et al. compared the reading times for the same sentences under two conditions. In one condition, the sentences contained no ambiguous strings, whereas in the other condition each sentence was embedded with one overlapping ambiguous string. For example, in the sentence, there was an ambiguous string ABC such that the first two characters could comprise a word AB, whilst B might also be the first constituent of a word BC. The context required readers to segment this ambiguous string as A-BC. According to the serial parsing hypothesis, one would predict that readers would very likely segment the string as AB-C initially, and subsequently realise the inaccurate segmentation based on the context and reanalyse appropriately. If this was the case, then one would observe inflated reading times in the ambiguous condition compared to the unambiguous condition. This is exactly what Perfetti and colleagues found in their experiment, and therefore, they concluded that Chinese readers adopt a serial parsing strategy during the reading of unspaced Chinese texts.

Inhoff and Wu (2005) provided evidence against such a strictly serial parsing hypothesis. In their study, they examined the reading time on critical regions in which a four-character sequence could be either overlapping ambiguous or unambiguous. For example, the sequence “专科学生” is formed from two two-character words (“专科”

means ‘college’; “学生” means ‘student’), and this sequence should be segmented as AB-CD according to the context. However, the second and third character can constitute another word as well (“科学” means ‘science’). According to the serial parsing hypothesis, sequence ABCD should be recognized AB-CD which was the same as the context required. Thus, there should be no difference between the overlapping ambiguous condition and the unambiguous condition. However, Inhoff and Wu found that readers spent more time reading overlapping ambiguous strings than unambiguous strings. They posited that all of the potential words within the sequence are simultaneously activated, and the competition between words in relation to activation determines the decision time with respect to word segmentation.

Li, Rayner and Cave (2009) proposed an interactive-activation model of word segmentation in Chinese reading based on the earlier work of McClelland and Rumelhart (1981). In this model, all the characters in the perceptual span can be processed in parallel. But the level of activation of a certain character depends on how far it is from the fixation point (i.e., its eccentricity). There are three levels in this model: a visual perception level, a character recognition level and a word recognition level (see Figure 1.3). Visual features of printed text within the perceptual span will be initially be encoded and then character recognition will be initiated with each character being identified in parallel. The activated characters will feed activation forward to the word level such that word representations that contain activated characters themselves become activated. Activation flows between the different levels (and it is in this sense that the model is interactive), whilst mutual inhibition occurs within each level. On this basis, the word that becomes activated to the greatest degree amongst all the activated

words in the lexicon is the word that is identified. When a word is identified, this constitutes a decision with respect to word segmentation, and in this sense, word segmentation and word recognition take place simultaneously according to this model.

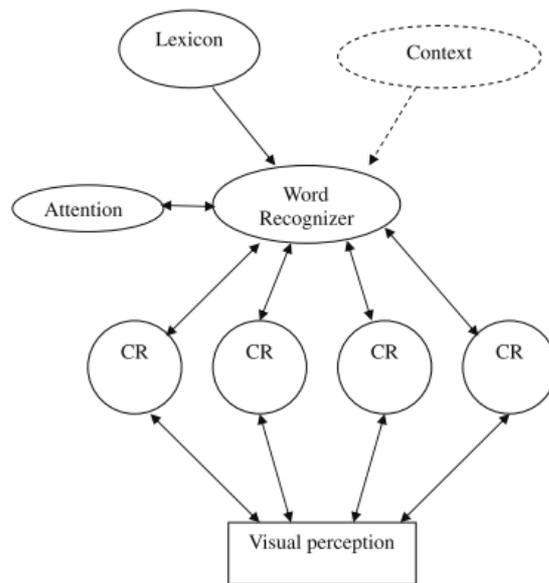


Figure 1-3 Framework of Chinese word segmentation and word recognition (Li et al. 2009). CR indicates character recognizer.

1.7.3 Saccade target selection in Chinese reading

We know that saccadic targeting in the reading of most alphabetic languages is mainly determined by low-level properties (e.g., word spacing and word length). Saccadic targeting is normally word based in spaced alphabetic languages. That is, readers prefer to send their eyes to a point slightly left of the centre of a word (i.e., PVL, Rayner, 1975). And recall that initial fixation positions shift towards the beginning of a word when word spacing is removed. In relation to Chinese reading, the mechanisms underlying saccade target selection remain controversial (Li, Liu, & Rayner, 2011; Li,

Liu, Rayner, 2015; Tsai & McConkie, 2003; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010; Zang, Liang, Bai, Yan & Liversedge, 2013).

In an early work by Tsai and McConkie (2003), it was examined whether a word or a character is selected as the target of saccades in reading Chinese. It was reported that Chinese readers do not show tendency to target a saccade to the centre of a word, or the centre of a character. The landing position distributions were flat for both single characters and two-character words. Accordingly, Tsai and McConkie (2003) argued that saccade targeting is not word-based, but it is unclear whether the character is the unit of saccade target in Chinese reading.

Given that increased studies have shown evidence that words are the primary linguistic units in Chinese reading, Yan and colleagues (2010) propose that the centre of words are more likely to be selected as saccade target in reading Chinese, but such word-based saccadic targeting is bound with successful word segmentation in parafovea. To be clear, Yan et al. (2010) claimed that if readers identify word boundaries in parafovea, they tend to send their eyes to the centre of a word, but in the case that readers fail to identify the word boundaries parafoveally, they are more likely to send their eyes to the beginning of a word. This idea was supported by splitting the initial landing positions based on the number of fixations made on the word (i.e., one or more than one fixations). Specifically, in the single-fixation situations, landing position distribution displayed an inverted-U shape with the peak near the centre of words, whilst, in the multiple-fixations situations, the initial fixations were more frequently made at word beginning. Accordingly, Yan et al. (2010) propose Chinese readers dynamically choose the saccade target depending on word segmentation in parafovea

during the reading of unspaced Chinese text – the so-called flexible saccade target selection strategy in Chinese reading.

However, the account by Yan et al. (2010) was soon questioned by the findings from other labs. Li and colleagues (2011) examined whether saccade target in Chinese reading was word-based or not by embedding either a two-character word or a four-character word (with identical meaning) into the same sentence frame. Three main findings were reported in Li et al. (2011) study: First, regardless of the total number of fixations made on the word, initial landing positions were more likely to locate at the beginning of a word. The pattern of landing position distribution was comparable between the two-character word condition and the four-character word condition. This was against with Yan et al. (2010) accounts because if word centre was the saccade target in the reading of Chinese there should produce a more right-shifted landing position distribution in the four-character word condition relative to the two-character word condition given that four-character word was more physically extended than was the two-character word. Second, when splitting the initial position data based on the number of fixations on a word, similar patterns of PVL curves that were reported in Yan et al. study also occurred. In the single-fixation duration cases, the PVL peaked close to the centre of a word, whereas in the multiple-fixations cases, initial fixations were shifted to word beginning. Third, Li et al. (2011) run simulations without considering parafoveal word segmentation and surprisingly found that these simulations predicted different PVL curves between the single-fixation situations and the multiple-fixations situations just as suggested by Yan et al. (2010). Li and colleagues therefore argued that it is still unclear whether saccadic targeting is word-based or not in Chinese reading. Alternatively, they proposed that saccadic targeting in Chinese reading involves a

combination of character-based and word based targeting contingent on word segmentation processes (see the prior section in this chapter for “interactive-activation model of word segmentation in Chinese reading” proposed by Li et al., 2009) such that the properties of fovea words will dynamically affect where to target the next saccade (see also Li, Liu, & Rayner, 2015; Ma, & Li, 2015; Wei, Li, & Pollatsek, 2013; Ma, Pollatsek, & Li, 2015). Perhaps a more direct examination on Yan et al. account in relation to a word-based saccadic targeting in Chinese reading is the experiments conducted by Zang, Liang, Bai, Yan and Liversedge (2013). Zang and colleagues (2013) recorded both Chinese adult readers and child readers’ eye movements during the reading of Chinese text that was presented in a spaced or unspaced format. It was reported that for both adult readers and child readers, initial landing positions were close to the centre of a word in the single-fixation cases, whereas initial landing positions were close to the beginning of a word in the multiple-fixation cases. The patterns of PVL curved based on the split data were consistent with previous findings (e.g., Yan et al., 2010; Li et al., 2011). According to Yan et al. (2010) account, readers dynamically select the saccade target based on whether word segmentation in parafovea is successful or not. If readers identify a word in parafovea, readers are more likely to send their eyes to the centre of the word, if readers cannot identify a word in parafovea, readers will more frequently land their eyes close to the beginning of the word. If this was the case, there should always observe centrally peaked landing position distributions in the reading of text with word spacing in Zang et al. study (2013) given that word segmentation was indicated explicitly by word spacing. However, Zang et al. found landing position effects was not affected by whether the text was spaced or unspaced. To be clear, in both spaced text and unspaced text, landing positions were close to word

beginning if the word contained more than one fixations and landing positions were close to word centre if the word contained only one fixation. These results show no evidence that Chinese readers select the saccade target based on whether they can or cannot identify a word in parafovea.

Taken together, it is still not clear whether saccadic targeting is word-based or not in Chinese reading. There are also many other research investigating this issue, however, it is beyond the capacity of the present thesis to cover them in details (e.g., Liu et al., 2019; Liu, Guo, Yu, & Reichle, 2018; Liu, Huang, Gao, & Reichle, 2017; Liu, Reichle, & Li, 2016; Liu, Yu, & Reichle, 2019a; Liu, Yu, & Reichle, 2019b).

1.8 Thesis outline

This thesis will describe three experiments for which the main manipulations are identical across experiments. In general, for each experiment, there is a learning session in which participants were required to learn target stimuli with different exposures, and a succeeding scanning session in which participants were required to search for a target stimulus (they had learnt in the learning) in longer sentence-like strings. The strings were displayed under three different formats: spaced format, unspaced format, shaded unspaced format. The primary objective of this thesis was to examine how exposure frequency effects develop during the learning of novel stimuli, and how the spacing format will affect the detection of the targets with differential visual familiarity. Chapter 2 will describe an experiment examining the learning and scanning of Landolt-C stimuli (Experiment 1). Chapter 3 will describe how native English speakers learnt pseudowords with different exposures in a learning session and how they identified

these targets when they were embedded in longer strings that were displayed under different spacing formats (Experiment 2). Chapter 4 will describe an experiment same as Experiment 2 but examining Chinese native speakers (Experiment 3). The final Chapter will discuss the findings of all three experiments more generally, and draw final conclusion of this thesis.

Chapter 2: Eye movement control during learning and scanning of Landolt-C stimuli (Experiment 1)

2.1 Introduction

In the current study, we are interested to examine how exposure frequency qualifies the rate at which abstract visual stimuli (Landolt-C clusters) are learnt cumulatively based on repeated exposures. Eye tracking methodology has been widely used to examine a variety of domains of human cognitive processing (e.g., reading, visual search, scene perception) because eye movement data provide an excellent index of moment-to-moment cognitive processing (see Rayner, 1998). Eye movement data have been demonstrated to be very informative in revealing the nature of on-line processing during reading. However, what factors drive when and where to move the eyes in reading is still controversial (Starr & Rayner, 2001).

Despite the clarity that exists regarding frequency effects during reading in the literature (e.g., Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see also Liversedge et al., 2004), it remains controversial as to whether frequency effects exist for tasks that, arguably, do not involve natural written language processing, such as mindless reading, visual search in text and proofreading (Kaakinen & Hyönä, 2010; Rayner & Fischer, 1996; Rayner & Raney, 1996; Vanyukov, Warren, Wheeler & Reichle, 2012; c.f., Vitu, O'Regan, Inhoff & Topolski, 1995). Rayner and Raney (1996) demonstrated that typical word frequency effects occurred during normal-text reading but did not occur during target word search within texts. Similar results were reported by Rayner & Fischer (1996), where they showed that word frequency affected fixation durations in normal

reading but did not affect fixation durations when the task required searching for a target word in normal text. A more recent study conducted in the context of Chinese reading also reported a lack of word frequency effects in a task where participants were required to search for a specific target within Chinese texts (Wang, Sui, & White, 2019). Thus, it has been argued that eye movement control operates according to quite different principles during normal reading and visual search, such that the determinants of when to move the eyes vary as a function of task demands (Rayner, 1995; Rayner & Fischer, 1996; Rayner & Raney, 1996; see also Vitu et al., 1995, for a different view). Most studies investigating, but failing to obtain robust word frequency effects in target search tasks, involved search through normal texts. However, Vanyukov et al. (2012) examined a similar theoretical question by using Landolt-C stimuli in a task in which participants were required to detect a target O. Interestingly, the frequency effects that failed to appear in the visual search in normal text employed by Rayner and colleagues did emerge in the Landolt-C scanning experiment reported by Vanyukov et al. Vanyukov et al. found that non-target Landolt-C clusters that were presented as distractors more frequently received shorter fixation durations than those presented less frequently. Vanyukov et al. argued that the more frequent the exposures to the distractor Landolt-C clusters, then the more robust would be the representations for those clusters in memory, and this in turn would contribute to their easier access from memory. It should be apparent that it is currently unclear as to the precise experimental circumstances that are required in order for word frequency effects to occur in a target search task. Based on existing studies, sometimes frequency effects emerge, and sometimes they fail to emerge.

One motivation of the current study is to better understand what is driving frequency effects in target search during the scanning of normal text, and Landolt-C strings (Rayner & Fischer, 1996; Rayner & Raney, 1996; Vanyukov et al., 2012). According to processing models of eye movement control, the trigger of when to move the eyes differs across visual search and reading in that these two tasks impose different cognitive processing demands (Rayner, 1995; Rayner & Raney, 1996; Reichle, Pollatsek & Rayner, 2012; Reichle, Vanyukov, Laurent & Warren, 2008). During reading for comprehension, high frequency words are accessed faster than low frequency words during lexical identification. This results in them receiving shorter and fewer fixations, alongside increased skipping relative to low frequency words. However, during visual search for a target word, it is less clear whether lexical access is, or is not, initiated. If lexical access did occur, one would anticipate that high frequency words would receive shorter fixations than low frequency words during visual search. And note that such frequency effects might also occur in respect of abstract orthographic memory representations for non-linguistic stimuli such as the Landolt-C strings employed by Vanyukov et al. (2012). In contrast, if lexical access was not necessary in the task, one might anticipate no word frequency effects, as was the case, for example, during the target word search tasks in Rayner and Raney, (1996) and Rayner and Fischer, (1996). Thus, whether frequency effects do, or do not, emerge for target words in visual search seems to depend on whether lexical access is, or is not, initiated. In the current study, we required participants to search for a target Landolt-C cluster that was embedded in a horizontally extended linear array of Landolt-C clusters. Unlike previous studies in which participants were required to search for a specific word, in this study, the targets to be detected during search were formed from a set of

Landolt-C clusters that had previously been learnt during a learning session.

Importantly, the frequency with which clusters were presented during learning, that is, the exposure frequency, was manipulated during the learning session. We assumed that in the present task, if participants were to complete the visual search task successfully, it would be necessary for them to access representations of target Landolt-C clusters that had been instantiated and stored in memory based on exposures to those clusters during the learning phase of the experiment. If accessing a representation of a Landolt-C cluster stored in memory is akin to accessing a stored representation of an orthographic string associated with a word, then it is quite possible that we might observe frequency effects during our Landolt-C target cluster search task.

Another important characteristic of previous studies that have investigated word frequency effects in visual search is that the stimuli have always been presented in normal word-spaced English texts (Rayner & Fischer, 1996; Rayner & Raney, 1996), or in horizontally extended Landolt-C strings in which spaces appeared between individual clusters giving search arrays a sentence-like appearance (Vanyukov et al., 2012). However, the presence of spaces between words or clusters in these visual search tasks might affect the emergence of any potential frequency effects. That is to say, the presence of word spacing could potentially ease the difficulty of searching for a target string (through reduction of lateral masking and crowding, and due to demarcation of the target as a distinct visual cluster), making it a relatively simple process. It was for this reason that in the present experiment we also manipulated the cluster demarcation forms of our Landolt-C strings with respect to the individual clusters comprising them.

In the current study, we developed a Landolt-C paradigm which was loosely based upon other, earlier, experiments (e.g., see Vanyukov et al., 2012; Williams & Pollatsek, 2007; Williams, Pollatsek, & Reichle, 2014). In these studies, participants were asked to search for a target O either in a single Landolt-C cluster, a linear sequence of Landolt-C clusters, or a circular Landolt-C string. In these studies, it was found that eye movements showed immediate disruption during search. Specifically, Landolt-C clusters with a smaller gap size, or those that had been presented for fewer exposures during scanning received longer fixation times. All these results demonstrate that eye movement measures reflect the immediate processing difficulties not only in language processing, but also in visual search.

In our study, we extended the target word search experiments reported by Rayner and Raney (1996), and Rayner and Fischer (1996), as well as the target O search during scanning of Landolt-C strings by Vanyukov et al. (2012) by manipulating (1) the exposure frequency of Landolt-C clusters during cumulative learning, and (2) the form of the Landolt-C cluster demarcation during target Landolt-C search. In the first session of the current experiment, participants learnt target Landolt-C clusters. During the learning session of the experiment we manipulated the exposure frequency of the targets. For high frequency targets, each cluster was encountered four times, whilst for the low frequency targets, each cluster was encountered just once. Learning accumulated over five learning blocks, giving an accumulated exposure frequency for high frequency targets of 20 presentations in contrast to an accumulated exposure frequency for low frequency targets of just 5 presentations. We used Landolt-C rings with a constant gap size, but we varied the gap orientations to create distinctive three-C

clusters (e.g., ). After learning the target Landolt-C clusters, participants then scanned through extended horizontal arrays of Landolt-C clusters that were 9 clusters long (i.e., Landolt-C strings). Target Landolt-C clusters were either present (50% of trials), or absent. Participants were required to determine whether a target Landolt-C cluster that they had just learnt was present in each Landolt-C string. The Landolt-C strings were presented to participants in three cluster demarcation forms: (1) with spaces between each individual Landolt-C cluster; (2) with no spaces, but with shading to demarcate cluster boundaries; (3) without spaces in an unspaced format (e.g., spaced strings, shadedstrings, unspacedstrings, respectively).

Using our Landolt-C learning and scanning paradigm, we first wished to simulate an exposure frequency effect during the learning of target Landolt-C clusters. The idea that humans are able to learn nonsensical visual stimuli after only a small number of exposures dates back to Ebbinghaus (1885). However, in the present study, we were mainly interested in how the degree of stimulus exposure would affect the rate of learning, and how the magnitude of any exposure frequency effect would develop across learning blocks. Our basic prediction was that the more exposures of a stimulus that a participant receives, the more robust the corresponding representation instantiated and stored in memory (Reichle & Perfetti, 2003; Vanyukov et al., 2012). Therefore, in the current study, we predicted that four exposures in each learning block would accelerate learning compared to a single exposure per learning block. Beyond this prediction, we also considered the discrepancy between the learning curves for the high and low frequency target clusters. In our experimental design, the amount of exposure to a high frequency string relative to a low frequency string is constant in each block

such that the ratio remains 4 to 1 respectively. Thus, if the rate of learning proceeds according to rate of exposure per learning block, then learning should be constant, that is, there should be main effects of learning block and main effects of exposure frequency, but no interactive relation between the two. Alternatively, if the rate of learning is cumulative (regardless of the fact that exposure across blocks is constant), then the relationship between learning block and exposure should be multiplicative, that is to say, there should be an interactive relation between the two.

Finally, as described above, we also manipulated cluster demarcations during the scanning of Landolt-C strings. Our spaced, shaded and unspaced formats allowed us to directly examine whether the presence of spacing information provides increased facilitation in accessing the representations of learnt stimuli from memory in visual search to a greater degree than demarcations that provide visually explicit cluster boundary information but no reduced lateral masking or crowding. Therefore, we anticipated that if spaces do benefit Landolt-C target search more than alternating shadings, then we would observe shorter search times in spaced strings relative to shaded strings. Such a result would suggest both cluster boundary demarcation, and lateral masking and crowding affect cluster recognition in visual search. Alternatively, if cluster boundary demarcation is sufficient to permit effective target search, then eye movements would be comparable for cluster spaced and shaded conditions relative to the unspaced unshaded condition. If this was the case, we would see comparable search times in both spaced strings and shaded strings, but longer search times in unspaced unshaded strings. If the memory for target clusters acquired in the learning session maintains through to the scanning session, we should see longer processing time on low-frequency targets relative to high-frequency targets. Furthermore, such an exposure

frequency effect would be larger in the unspaced strings compared to spaced and shaded strings.

2.2 Method

2.2.1 Participants

A power analysis was conducted, and the results indicated the minimum sample size for the current study was 15 to obtain 80% prior chance of finding a medium effect size ($d=0.5$, Cohen, 1962; Westfall, 2015). We recruited 24 participants with normal vision or corrected-to-normal vision from the University of Southampton to take part in our experiment. All of them were native speakers of spaced alphabetic languages. They gained 36 course credits or £18 for participating.

2.2.2 Apparatus

The experiments were run using a 20-in CRT monitor with a refresh rate of 60 hertz. Stimuli were displayed on a white-background screen with a resolution of 1280×1024 pixels. Participants were seated 70 cm from the monitor, and at this viewing distance 1° of visual angle extended to the approximate width of one Landolt-C ring (each Landolt-C was 30×30 pixels). A chin and forehead rest were used to minimise participants' head movements. Participants' eye movements during both the learning session and reading session were tracked using an SR Research Eyelink 1000 system with a sample rate of 1000 hertz. Viewing was binocular, but only the position of the right eye was recorded.

2.2.3 Materials

Landolt-C stimuli were used in the current study. A Landolt-C ring is a C-ring of which the gap could vary in size and orientation. In this study, we fixed the gap size of Landolt-C ring to be 6-pixels wide and created 8 unique Landolt-C rings by rotating the orientation of the gap angularly equidistantly. The Landolt-C rings were then used to compose 3-ring clusters (see Figure 2.1). In total, 504 unique clusters were constructed. Twenty-eight clusters that each contained three different rings were selected as target clusters. These target clusters were to be learnt in the first session of the experiment.



Figure 2-1 An example of a Landolt-C cluster. The gap size of each Landolt-C ring is 6 pixels.

Each Landolt-C ring occupies 30 pixels. There were 8 possible gap orientations each of which was equi-rotated through 360 deg. (e.g., 0 deg., 45deg., 90 deg., 135 deg., etc).

We constructed horizontal Landolt-C frames into which to insert the target clusters. To do this we shuffled all the clusters to construct extended horizontal strings of Landolt-C clusters.¹ In total, 56 frames of Landolt-C strings that each contained 9 clusters were constructed. Half of these Landolt-C strings contained a target cluster positioned in the second to the eighth cluster position in the string (see Figure 2.2). The same frames of Landolt-C strings were used across three cluster demarcation forms (i.e.,

¹ To avoid overlapping ambiguity appearing in successive clusters when visual cluster demarcations were absent, we ensured our Landolt-C clusters met the following criteria: (1) the final C of cluster n was different from the beginning C of cluster $n+1$; (2) in target present trials, each Landolt-C ring was unique within the target cluster, meaning the 8 distractors had no similar C elements to the target; (3) in all trials, it was ensured that all the potential clusters produced due to incorrect segmentation were different from target clusters.

spaced strings; shaded strings; unspaced strings). In the spaced strings, there was a 30-pixels gap between adjacent Landolt-C clusters. In the shaded condition, adjacent Landolt-C clusters were demarcated by shading (e.g., black and grey shadings). In the unspaced condition, no visual cluster demarcations were present. The displayed sentences occupied 862 pixels (27° of visual angle) and 1086 pixels (34° of visual angle) for unspaced/shaded condition and spaced condition, respectively.



Figure 2-2 Example Landolt-C strings presented in the three cluster demarcation forms. There might be a target cluster embedded in the string at the second to the eighth cluster position.

2.2.4 Experimental design

There were two sessions in the current experiment: an initial learning session and a subsequent scanning session. In the learning session, participants learnt target clusters displayed in isolation. During learning, we manipulated the exposure frequency of target clusters, that is, 14 targets were presented four times per learning block, whilst the other 14 targets were presented just one time per block. This accumulated to 20 exposures for high frequency clusters and 5 exposures for low frequency clusters in total over five learning blocks. We rotated exposure frequency of targets across participants and stimuli. After the 1st, 3rd and 5th learning block, a learning assessment task took place to evaluate the degree to which participants had learnt the targets. They

had to decide whether a Landolt-C cluster was one of those they had learnt in the learning blocks. In each learning assessment, 50% of the trials displayed a target cluster. The other half of trials contained a distractor. Each distractor used in the learning assessment task was unique and contained three C-rings with different orientations.

In the scanning session, participants were required to scan extended Landolt-C strings and determine whether a target cluster that they had learnt in the learning session was, or was not, present. During scanning, we manipulated the cluster demarcation form of the Landolt-C strings. Strings with the same cluster demarcation form were presented in the same block and there were three blocks. Target frequency and cluster demarcation form were counterbalanced across scanning blocks following a Latin Square design. Trial orders in both learning session and scanning were randomized.

2.2.5 Procedure

Before each learning session block, a 9-point calibration was performed until the mean error was less than 0.5 deg. Before each scanning block, a 3-point calibration was performed until the mean error was less than 0.2 deg. Recalibration was carried out if tracker loss occurred or after each break. During both sessions, we tracked eye movements.

In the learning session, each learning trial began with a box appearing slightly left of the centre of the display. Once participants fixated the box, the cluster appeared centrally on the screen, and a square box appeared simultaneously to its right. The box presented to the right could appear at one of four positions at different points on the same vertical line. Participants were required to learn the cluster displayed on the

screen and once they felt they remembered the cluster they moved their eyes to the square box on the right side of the screen to terminate the trial. The learning assessment task occurred after the first, the third and the fifth learning blocks. In each learning assessment trial, participants initiated the trial by fixating a box slightly left to the centre and terminated the trial by pressing a button to indicate whether they had learnt the displayed cluster.

After the learning session, participants were instructed to perform target detection tasks during the scanning of Landolt-C strings. Each trial started with a black circle on the left side of the screen (i.e., drift correction). Once participants fixated the black circle, the Landolt-C string appeared. Participants scanned along the string from left to right to detect whether a target cluster was present. After they had determined whether a learnt target cluster was, or was not, present, they pressed a button terminating the display and causing a question to appear asking the participant whether they had, or had not, detected a cluster they learnt in the learning session². Participants responded by pressing a button to indicate either a “Yes” or a “No” response.

During the two sessions, participants had short breaks whenever they wanted. In total, the experiment took approximately 3 hours to complete.

² During testing, participants were free to press a button to terminate a trial. In total, 15% of trials were terminated immediately participants detected a target. That is, when a button press occurred during a fixation on the target cluster. Most trials were not terminated until the eyes had moved past the target cluster.

2.3 Data analysis

Individual data points that were more than ± 3 standard deviations from the overall mean for each dependent measure were removed. In the learning session, 0.9% of data were missing due to tracker loss and 2.4% of data (averaged across different measures) were removed after the trimming procedure. In the scanning session, we removed 44 trials that contained more than 25 blinks in the scanning of the Landolt-C string (1%). For the analysis of global measures (see below), 1.45% of data were trimmed. For the local measures, 6% of trials contained no data on the target cluster and these were removed from the analysis. For the analysis of local measures (see below), the data on targets for which skipping occurred during first pass scanning were excluded (2.4%) and data beyond ± 3 standard deviations from the global mean were also removed (1.1%).

Generally, we examined the following eye movement measures: (1) first fixation duration (the duration of the first fixation on a cluster word); (2) gaze duration (the sum of fixations on a word before a saccade away from that word); (3) number of fixations in an interest area; (4) total viewing time (the sum of all fixations in a region); (5) incoming saccade length; (6) outgoing saccade length; (7) initial landing position of the eyes in the region of interest (i.e., mean landing position); (8) mean fixation duration; (9) mean saccade amplitude. Note that, incoming saccade length corresponds to the distance from the initial fixation on target cluster to the final fixation on the pre-target cluster. The outgoing saccade length refers to the distance between the final fixation on the target cluster and the first fixation on the post-target clusters. Therefore, the computation in both incoming saccade length and outgoing saccade length included in

the space between clusters for the spaced strings. However, mean landing position did not include the space between clusters as this was defined as the distance from the initial fixation on the target cluster to its' beginning.

To normalise the distributions, we natural log transformed the reading time variables before running the linear mixed-effects models. This was not necessary for the mean landing position data which were normally distributed, and therefore, no transformations were applied. To analyse continuous eye movement measures (e.g., fixation durations), we used linear mixed-effects models (LMMs, see Bates, Maechler, Bolker, & Walker, 2016) with a full random-effects structure in the first instance (Barr, Levy, Scheepers, & Tily, 2013). We included intercepts and slopes for both random factors (i.e., participants and items). When the full random-effects models failed to converge, we trimmed the full model until the model converged successfully. For binary variables (e.g., accuracy), we used logistic generalized mixed-effects models (GLMMs).

2.4 Results

2.4.1 Learning session

In this section, we will report eye-movement results from the learning blocks and then report behavioural data and eye movement results from the learning assessment task.

Learning blocks

First, we assessed the main effect of learning block that we assumed was an index of learning. Second, we examined whether shorter and fewer fixations were made on

target clusters that received 4 exposures per block relative to one exposure per block (i.e., the main effect of exposure frequency). More interestingly, we investigated how the magnitude of exposure frequency effects changed across learning blocks. See Table 2.1 for the means and standard errors of first fixation duration, total viewing time³ and fixation numbers on high frequency and low frequency clusters from learning block 1 to learning block 5. In our LMMs we set learning block as a numeric factor and built contrasts for frequency using the *contr.sdif* function from MASS package in R environment and then ran the linear mixed-effects models to examine the main effects and the interaction between exposure frequency and learning block (see Table 2.1 & 2.2)⁴.

During the learning of target clusters, first fixation durations were not affected by exposure frequency or learning block, nor was there any reliable interactive effect. As predicted, we found main effects of learning block on total viewing time and fixation number. Participants made shorter and fewer fixations in the later learning blocks relative to the initial learning blocks. Importantly, the main effects of learning block were qualified by interactive effects with exposure frequency such that the learning effects were larger for high frequency exposure than low frequency exposure (see Figure 2.3 for effect plots).

3 During each individual learning trial, participants almost always made a saccade to fixate the cluster, and then remained making fixations on the cluster until they felt confident that they had learnt it, at which point they made a saccade to the box to the right. For this reason, gaze durations were almost always identical to total viewing time on the cluster, and therefore, we only report total viewing time in these analyses.

4 All the treatments were uniform across the five learning blocks. Moreover, the total time spent learning the clusters accumulated across the blocks. We, therefore, treated block as a continuous variable.

Table 2-1 Mean first fixation duration (ms), total viewing time (ms) and fixation number on target clusters across the learning blocks.

	High Frequency					Low Frequency				
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 1	Block 2	Block 3	Block 4	Block 5
First fixation duration	373 (29)	380 (30)	395 (32)	402 (32)	398 (29)	386 (59)	357 (61)	379 (57)	419 (63)	404 (64)
Total viewing time	4453 (279)	3529 (260)	2724 (203)	2665 (213)	2361 (181)	4760 (466)	4228 (490)	3663 (467)	3618 (451)	3316 (450)
Fixation number	10.4 (0.6)	8.5 (0.6)	6.8 (0.5)	6.7 (0.5)	6.1 (0.4)	11.2 (1.3)	10.0 (1.1)	9.0 (1.1)	8.8 (1.1)	8.3 (1.1)

Note. Standard errors are in parentheses. In each learning block, high frequency clusters were presented 4 times each and low frequency clusters were presented just 1 time each.

Table 2-2 Fixed effect estimates from the LMMs for first fixation duration, total viewing time and fixation number on target clusters across the learning blocks.

	First fixation duration			Total viewing time			Fixation number		
	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>	<i>b</i>	<i>SE</i>	<i>t</i>
Intercept	5.71	0.06	94.71***	8.30	0.11	76.38***	2.23	0.11	19.92***
Frequency	-0.04	0.04	-0.97	0.06	0.04	1.31	0.06	0.04	1.43
Block	0.02	0.01	1.73	-0.13	0.02	-6.42***	-0.10	0.02	-5.33***
Frequency*Block	0.01	0.01	0.80	0.05	0.01	4.07***	0.04	0.01	3.23***

Note. High exposure frequency was treated as the baseline in the LMMs. *** $p < .001$, ** $p < .01$, * $p < .05$

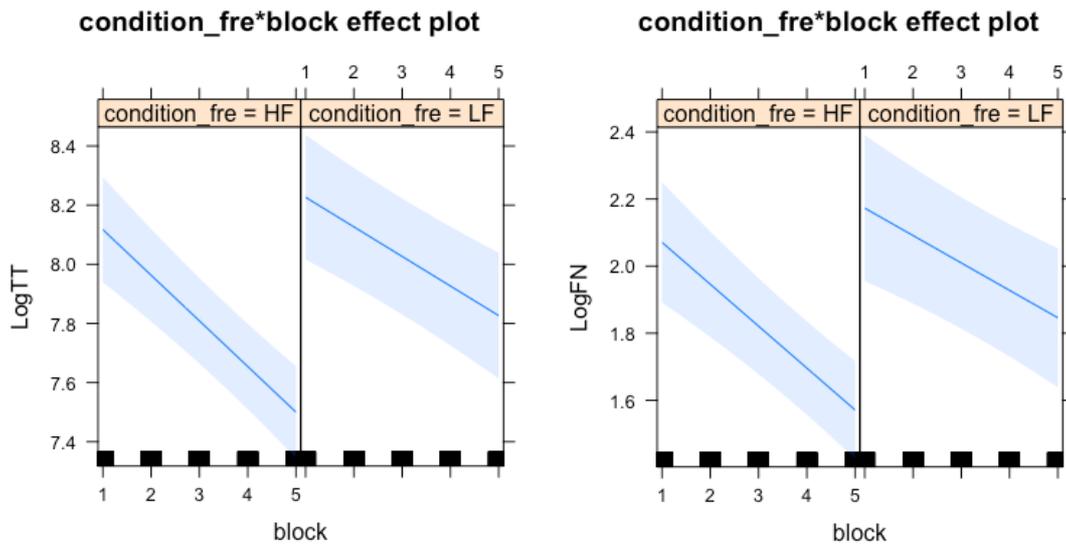


Figure 2-3 The left panel plots the interactive effect between exposure frequency and learning block on log transformed total viewing time during target learning. The right panel plots the same effect observed on log transformed total fixation number.

Learning assessment tasks

There was a learning assessment task after the first, third and fifth learning block. Participants' mean accuracy increased from 59% in assessment block 1 to 67% in assessment block 3. The false alarm rate was 18.3% in assessment block 1 and dropped to 16.9% in assessment block 3. The mean hit rate for high frequency targets reached a level beyond chance in the first block and increased to 75% in the final block. By contrast, responses to low frequency targets in the first two blocks approximated guessing and the mean hit rate in the final block reached 60%.

We built the logistic generalized mixed-effects model to formally examine mean hit rate (see Table 2.4). Robust exposure frequency effects and block effects were found on mean hit rate indicating that more frequently exposed targets were more recognizable

relative to less frequently exposed targets and mean hit rate increased across blocks. Numerically, participants took more time to decide whether they had learnt the displayed cluster for low frequency targets relative to high frequency targets. A robust block effect on reaction time was obtained indicating that participants responded faster as learning accumulated.

Eye movements in the learning assessment blocks were also examined (see Table 2.4). Main effects of block were found on total viewing time and fixation number. Consistent with the reaction time results, shorter and fewer fixations were made during the learning assessment task as block increased.

Table 2-3 Mean hit rate, means of RT, FFD, TT and fixation number in learning assessment tasks

	High Frequency			Low Frequency		
	Block 1 (4th)	Block 2 (12th)	Block 3 (20th)	Block 1 (1st)	Block 2 (3rd)	Block 3 (5th)
Hit rate	0.60 (0.04)	0.73 (0.04)	0.75 (0.03)	0.46 (0.04)	0.53 (0.03)	0.60 (0.04)
Reaction time	3914 (448)	3017 (353)	3070 (367)	4122 (406)	3540 (396)	3340 (361)
First fixation duration	296 (45)	312 (45)	302 (43)	311 (47)	334 (43)	310 (43)
Total viewing time	3568 (400)	2745 (297)	2804 (321)	3764 (361)	3242 (353)	2980 (307)
Fixation number	9.3 (1.2)	6.9 (0.8)	7.2 (0.9)	9.8 (1.0)	8.3 (1.0)	7.8 (0.9)

Note. RT = reaction time in making decisions. FFD = first fixation duration. TT = total viewing time. Fixation times are reported in millisecond. Standard errors are in the parentheses.

Table 2-4 Fixed effect estimates from GLMM on mean hit rate and LMMs on RT, FFD, TT, FN across targets in learning assessment blocks.

Dependent measure	<i>b</i>	<i>SE</i>	<i>t</i>
Hit rate			
Intercept	-0.15	0.18	-0.86
Frequency	-0.60	0.26	-2.26*
Block	0.33	0.06	5.53***
Frequency*Block	-0.10	0.12	-1.83
Reaction time			
Intercept	8.28	0.07	119.59***
Frequency	0.08	0.06	1.28
Block	-0.12	0.03	-4.56***
Frequency*Block	0.01	0.03	0.36
First fixation duration			
Intercept	5.47	0.07	74.95***
Frequency	0.11	0.09	1.19
Block	0.02	0.02	0.94
Frequency* Block	-0.02	0.04	-0.44
Total viewing time			
Intercept	8.19	0.07	124.36***
Frequency	0.09	0.06	1.56
Block	-0.12	0.02	-5.11***
Frequency*Block	0.00	0.03	0.07
Fixation number			
Intercept	2.19	0.10	22.18***
Frequency	0.10	0.06	1.61
Block	-0.12	0.03	-3.57**
Frequency*Block	0.00	0.03	0.03

Note. RT = reaction time in making decisions. FFD = first fixation duration. TT = total viewing time. FN = total number of fixations. High frequency was the baseline for the analysis of frequency effects. *** $p < .001$, ** $p < .01$, * $p < .05$.

2.4.2 Scanning session

Mean accuracy (accurate detection and rejection) was 54% in the scanning session a reduction of 13% from 67% mean accuracy that existed in the final learning assessment block. False alarm rate during scanning (Press ‘yes’ button when no target was present) was 40%. The mean hit rate (accurate detection) across all conditions

during scanning was below 50% (see Table 2.5). Formal GLMMs analysis showed that there was no difference on hit rate across all conditions (see Table 2.6). These data indicated that during scanning, participants experienced difficulty in discriminating target clusters from non-target clusters. Regardless of the poor detection performance, we analysed the eye-movement data observed on every Landolt-C cluster in the extended horizontal strings as well as the data observed solely for the target clusters⁵.

Analysis of global measures

During scanning of Landolt-C strings, mean fixation duration was shorter in the spaced strings compared with shaded strings and unspaced strings. Also, shorter mean fixation durations occurred for the shaded strings than the unspaced strings (see Table 2.5 & 2.6). Recall that a Landolt-C covered one degree of visual angle. Mean saccade amplitude was longest in the scanning of spaced strings (1.6 degrees of visual angle), and somewhat less in the shaded strings (1.3 degree of visual angle). Mean saccade amplitude was shortest in the scanning of unspaced strings, 1 degree of visual angle. The saccade amplitude data demonstrate clearly that when scanning unspaced Landolt-C strings, participants moved their eyes on average from one Landolt-C to the next. They did not move their eyes such that, on average, they fixated one cluster followed by

⁵ We undertook an additional analysis by splitting the data into two sets based on whether participants made a “hit” or a “miss” decision with respect to a target. Almost all the results between the two groups were consistent with the results we report here (when the data were not split). One subtle difference occurred on first fixation duration within the “miss” dataset. On these “target undetected” trials, significantly shorter first fixation durations were observed on high frequency clusters in spaced strings relative to shaded strings. However, no such spacing effect occurred on low frequency clusters. Overall, these analyses indicate that regardless of whether we consider the behavioural responses in relation to accuracy, or in relation to hits and misses, we obtained very similar effects.

the next. Participants were more likely to make longer saccades (and therefore, saccades between clusters) under the spaced and shaded conditions. Clearly, demarcating clusters by shading or spacing impacted saccadic targeting. Additionally, the largest effect on saccade amplitudes that occurred for the spaced condition was driven, at least in part, by the increased horizontal spatial extent of the Landolt-C strings in this condition. Thus, there were contributions to the saccade amplitude effects from both cluster demarcation and increased spatial extent. Based on all the global measures, it is clear that participants found scanning Landolt-C strings to identify a target most effortful in the unspaced condition (i.e., longer fixation durations, shorter saccade amplitudes), somewhat less effortful in the shaded condition and easiest in the spaced condition.

Table 2-5 Global measures from observations on all clusters and local measures from observations on target clusters during scanning.

Global measures				
		Unspaced	Shaded	Spaced
Mean fixation duration		358 (5)	342 (5)	327 (5)
Mean saccade amplitude		0.99 (0.03)	1.30 (0.05)	1.60 (0.05)
Local measures				
		Unspaced	Shaded	Spaced
Hit Rate	HF	0.50 (0.13)	0.44 (0.13)	0.47 (0.13)
	LF	0.41 (0.13)	0.42 (0.13)	0.44 (0.13)
First fixation duration	HF	371 (48)	348 (46)	319 (42)
	LF	359 (44)	334 (46)	333 (44)
Gaze duration	HF	1450 (290)	1022 (220)	1229 (245)
	LF	1390 (255)	1182 (265)	1233 (244)
Total viewing time	HF	2342 (346)	1745 (257)	2058 (310)
	LF	2311 (295)	1878 (298)	1946 (287)
Fixation number	HF	6.4 (1.0)	5.0 (0.8)	6.1 (0.9)
	LF	6.5 (0.9)	5.3 (0.8)	5.9 (0.9)
Incoming saccade length	HF	1.3 (0.1)	2.0 (0.2)	3.2 (0.2)
	LF	1.4 (0.2)	1.9 (0.2)	3.2 (0.2)
Outgoing saccade length	HF	1.5 (0.1)	2.2 (0.2)	3.1 (0.2)
	LF	1.5 (0.2)	2.0 (0.2)	3.2 (0.2)
Mean landing position	HF	0.7 (0.1)	0.9 (0.1)	1.8 (0.2)
	LF	0.6 (0.1)	0.8 (0.1)	1.6 (0.1)

Note. All the fixation times are reported in milliseconds. All the distances/amplitudes are measured in visual angle. The standard errors are in the parentheses.

Table 2-6 Fixed effect estimates from LMMs on global measures and local measures.

Global measure			
	<i>b</i>	<i>SE</i>	<i>t</i>
Mean fixation duration			
Intercept	5.82	0.03	210.17***
Spacing 1	-0.05	0.01	-3.85***
Spacing 2	-0.04	0.01	-4.51***
Spacing 3	0.09	0.01	6.82***
Mean saccade amplitude			
Intercept	0.18	0.05	3.58***
Spacing 1	0.26	0.03	7.77***
Spacing 2	0.20	0.02	9.97***
Spacing 3	-0.47	0.04	-12.22***
Local measure			
	<i>b</i>	<i>SE</i>	<i>t</i>
Hit rate			
Intercept	-0.25	0.18	-1.42
Frequency	-0.21	0.13	-1.69
Spacing 1	-0.11	0.15	-0.74
Spacing 2	0.11	0.14	0.80
Spacing 3	-0.01	0.13	-0.04
Frequency*Spacing 1	0.32	0.25	1.31
Frequency*Spacing 2	-0.03	0.24	-0.14
Frequency*Spacing 3	-0.29	0.24	-1.19
First fixation duration			
Intercept	5.71	0.03	194.43***
Frequency	-0.01	0.02	-0.13
Spacing 1	-0.09	0.03	-2.84**
Spacing 2	-0.06	0.04	-1.60
Spacing 3	0.15	0.04	3.64***
Frequency*Spacing 1	-0.01	0.06	-0.02
Frequency*Spacing 2	0.08	0.06	1.37
Frequency*Spacing 3	-0.08	0.06	-1.39
Gaze duration			
Intercept	6.70	0.09	78.21***
Frequency	0.04	0.04	1.03
Spacing 1	-0.35	0.05	-6.96***
Spacing 2	0.11	0.05	2.21*
Spacing 3	0.24	0.05	-4.79***
Frequency*Spacing 1	0.11	0.10	1.07

Frequency*Spacing 2	-0.04	0.10	-0.41
Frequency*Spacing 3	-0.07	0.10	-0.67
Total viewing time			
Intercept	7.31	0.11	66.01***
Frequency	0.02	0.03	0.53
Spacing 1	-0.36	0.06	-6.06***
Spacing 2	0.13	0.06	1.99*
Spacing 3	0.24	0.06	-4.06***
Frequency*Spacing 1	0.03	0.07	0.48
Frequency*Spacing 2	-0.09	0.07	-1.21
Frequency*Spacing 3	0.06	0.08	0.72
Fixation number			
Intercept	1.50	0.10	15.34***
Frequency	0.03	0.03	1.04
Spacing 1	-0.29	0.06	-5.27***
Spacing 2	0.15	0.06	2.44*
Spacing 3	0.14	0.05	2.61**
Frequency*Spacing 1	0.07	0.07	0.98
Frequency*Spacing 2	-0.11	0.07	-1.57
Frequency*Spacing 3	0.04	0.07	0.54
Incoming saccade length			
Intercept	3.97	0.05	87.77***
Frequency	0.02	0.03	0.72
Spacing 1	0.36	0.04	8.10***
Spacing 2	0.54	0.06	8.55***
Spacing 3	-0.90	0.05	-16.74***
Frequency*Spacing 1	-0.09	0.07	-1.37
Frequency*Spacing 2	0.04	0.07	0.88
Frequency*Spacing 3	0.04	0.07	0.55
Outgoing saccade length			
Intercept	4.01	0.05	84.22***
Frequency	-0.01	0.03	-0.55
Spacing 1	0.40	0.06	6.98***
Spacing 2	0.44	0.07	6.73****
Spacing 3	-0.84	0.06	-13.78***
Frequency*Spacing 1	-0.04	0.06	-0.63
Frequency*Spacing 2	0.07	0.06	1.17
Frequency*Spacing 3	-0.03	0.06	-0.51
Mean landing position			
Intercept	30.75	1.46	21.12***

Frequency	-0.49	0.84	-0.58
Spacing 1	7.09	1.31	5.40***
Spacing 2	21.06	2.14	9.84***
Spacing 3	-28.15	2.33	-12.09***
Frequency*Spacing 1	-1.47	2.06	-0.71
Frequency*Spacing 2	1.69	2.06	0.82
Frequency*Spacing 3	-0.22	2.07	-0.11

Note. Spacing1= shaded - unspaced; Spacing 2 = spaced - shaded; Spacing 3 = unspaced - spaced. *** $p < .001$, ** $p < .01$, * $p < .05$.

Analysis of local measures

In the scanning session, hit rate was quite similar between high frequency targets (49%) and low frequency targets (45%). This 4% difference on hit rate between high and low frequency clusters was considerably smaller than the 15% difference obtained in the final learning assessment task. Thus, we have two measures of target cluster recognition that show quite different effects in the same group of participants. We consider it likely that this difference in effects reflects increased difficulty associated with detecting a target cluster embedded within contemporaneously presented strings of distractor clusters. Presumably, the interference from such distractors is substantial and does not occur when non-target clusters are presented non-contemporaneously from trial to trial in the learning assessment task.

As shown in Table 2.6, there were no main effects of exposure frequency for any of the fixation time and fixation location measures. By contrast, significant spacing effects occurred for both fixation duration and fixation location measures. Longest fixation durations were observed in the unspaced condition as predicted. Surprisingly, we found longer and more fixations in the spaced condition compared to the shaded condition. However, significantly longer mean fixation durations were observed in the

shaded condition than the spaced condition when every individual cluster was included in the analyses. In relation to saccadic behaviour, we found robust spacing effects on incoming saccade length, outgoing saccade length and mean landing position. Incoming saccades were shortest for target clusters in the unspaced condition, somewhat longer for targets in the shaded condition and longest for targets in the spaced condition. Similar effects were obtained for mean landing positions on target clusters and outgoing saccades from target clusters. These results support the claim that spacing and shading effectively demarcated Landolt-C clusters relative to a lack of demarcation in the unspaced strings, and that more clearly demarcated clusters (spaced followed by shaded) were initially fixated more centrally than non-demarcated clusters. These results suggest that the more easily a participant can identify the horizontal extent of an upcoming Landolt-C cluster, then the more centrally targeted the saccade will be to that cluster. Note that this holds even in a situation where the extent of all the clusters is constant. We will return to the question of why shading is a less effective demarcation cue than spacing in the Discussion.

Next, let us consider the landing position distributions for the target Landolt-C clusters (see Figure 2.4). The most striking aspect of the data is that there are two quite distinct and differently shaped landing position distributions. For the spaced conditions, it is clearly the case that there are inverted-U shape distributions for both the high and the low frequency target clusters. In contrast, for the unspaced and shaded conditions, most fixations were made towards cluster beginning. Again, this pattern holds for high and low frequency clusters alike. Two points are obvious: First, saccadic targeting in Landolt-C cluster string scanning appears to be uninfluenced by the participant's

familiarity with those clusters. Second, differential landing position distributions appear to be driven entirely by the presence or absence of spaces in Landolt-C strings.

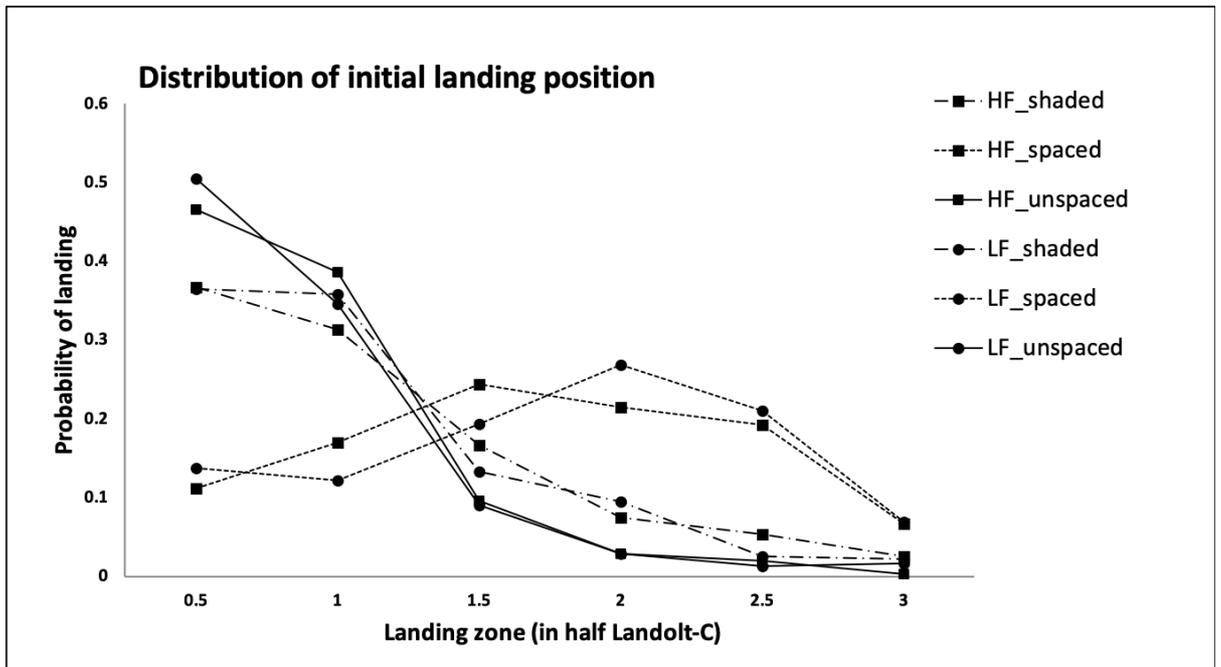


Figure 2-4 The distribution of initial landing positions on target clusters across all the conditions in the scanning session.

2.5 Discussion

In the current Landolt-C learning and scanning paradigm, we manipulated exposure frequency of Landolt-C target clusters during learning, and cluster demarcation form during subsequent Landolt-C string scanning. Using this paradigm, we initially investigated how exposure frequency modulated the rate of learning abstract Landolt-C clusters and how this modulation effect changed over successive learning blocks. More importantly, we revisited whether cluster familiarity (frequency) affects eye movement control in a visual search task using Landolt-C stimuli.

During the learning of target Landolt-C clusters, as we predicted, four exposures per learning block accelerated the rate of learning relative to just one exposure per learning block. Furthermore, the differential learning rate between high frequency and low frequency clusters increased over learning blocks. These results demonstrated that participants could learn nonsensical Landolt-C clusters after only a few exposures, moreover, they responded less effectively (i.e., less accurate responses) to targets with fewer exposures than to targets with more exposures (c.f., Vanyukov et al., 2012). The finding that participants can learn abstract stimuli is not novel, however, the finding that participants learnt stimuli with more exposures faster than those with fewer exposures is of significance. Vanyukov et al. (2012) reported similar differentially facilitative effects of fifty exposures over one exposure on processing time during target O search within linear Landolt-C strings. More recently, in relation to novel word learning, Hulme and colleagues (2019) reported that 38.5% of participants could correctly recall novel meanings of known words after just two exposures during story reading. Along with these studies, our data provide additional evidence for the claim that word frequency in

reading accumulates via repeated exposures, with more exposures contributing to more consolidated representations in memory (Hulme et al., 2019; Inhoff & Rayner, 1986; Vanyukov et al., 2012; Reichle & Perffetti, 2003). The results also suggest that how immediately exposure frequency effects occur is likely a function of the depth to which they have been processed (Craik & Tulving, 1975). Admittedly, the three studies that we focus on here are quite different in a number of respects, however, it seems reasonable to suggest that the way exposure frequency affects processing in each of the different tasks is comparable at some level. Tentatively, we suggest that searching for a target O embedded in Landolt-C strings, (Vanyukov et al., 2012), might involve the shallowest form of cognitive processing, and consequently the emergence of exposure effects was quite delayed (i.e., significant frequency effects emerged after 50 exposures). By contrast, learning novel meanings for known words almost certainly involves relatively deep linguistic processing, and presumably such processing contributed to more immediate exposure frequency effects (i.e., two exposures produced frequency effects). In the current study, we believe that the intentional learning of non-linguistic Landolt-C target clusters involved processing to a greater depth than simply searching for a target O, but shallower processing than learning novel meanings of known words during reading. Therefore, the influence of exposure on eye movement control in the current study occurred earlier than the situation of searching for a target O, but less immediately than the situation of learning novel meanings of known words.

One thing that we can be certain about in the present study is that we effectively simulated exposure frequency effects through our exposure manipulation during the learning sessions. However, despite this, we failed to obtain robust frequency effects on eye movement control when participants scanned Landolt-C strings in search for a

target cluster. Recall that in the scanning scenario, participants were required to search for pre-learnt target clusters with greater, or lesser, levels of exposure in the learning session. Also, the Landolt-C strings were presented under different cluster demarcation conditions.

Mean hit rate in every condition was surprisingly low indicating that our participants were unable to successfully perform the task. We consider that there are two major reasons why search performance was so poor during the scanning of Landolt-C strings. First, this is very likely because of the high visual similarity between distractor clusters and target clusters. Previous studies have demonstrated that search performance is substantially influenced by target-distractor similarity. Successful search is much more difficult when distractor stimuli are visually similar to the target relative to when they are dissimilar (Duncan & Humphreys, 1989; Neisser, 1963; Rayner & Fisher, 1987; Vanyukov et al., 2012; Williams & Pollatsek, 2007). In the present study, the visual distinctiveness of the current targets relative to distractors was entirely driven by unique combinations of gap orientations. Given the very high degree of similarity between targets and distractors, it is perhaps unsurprising search performance was poor in the scanning session, particularly given that target clusters were embedded within strings of 8 other Landolt-C clusters.

The second reason why search performance was poor during Landolt-C strings scanning relative to learning was because there was change in the accuracy criterion across the two tasks. To be clear, in the learning session, participants were presented with a single Landolt-C cluster and they were required to decide as to whether they had already learnt the presented cluster. That is, for each cluster participants made a single

decision. Furthermore, on 50% of trials a target was presented, and on 50% of trials a non-target was presented. To be explicit, the accuracy criterion was 50% (and we believe that under these circumstances the importance of accuracy in the task would be quite apparent to participants). In contrast, during scanning, participants were required to make up to 9 decisions, one for each successive cluster, as to whether it was or was not a cluster that they had already learnt. Only one target cluster ever appeared in each string of 9 clusters, and a target was embedded in a string on only 50% of scanning trials. Thus, participants were making a decision that a cluster was not a target on the vast majority of occasions that they considered a cluster, meaning that the accuracy criterion, at least at the level of decisions in relation to each individual cluster, in the search phase of the experiment was substantially reduced relative to that in the learning phase.

Next, let us consider why the exposure frequency of Landolt-C clusters did not affect eye movement behaviour during target search. Recall that an important motivation of current study was to investigate whether exposure frequency established during learning would be present in a sequent visual search task. There are several points to make here. As discussed earlier, for unspaced Landolt-C strings, as discussed earlier, participants had difficulty unambiguously identifying each particular set of three Landolt-Cs that formed a cluster. That is to say, as they scanned along the string, they may not have been certain where a potential target might have started and ended. Such ambiguity could have meant that identification of the target would have been very difficult and that frequency effects would have been diminished. However, the suggestion that failure to appropriately identify particular sets of three Landolt-Cs as potential target clusters could not have caused the null effects since target detection

error rates were comparable across the unspaced, shaded and spaced conditions. Cluster demarcation provided by shading and spacing removed the ambiguity participants may have experienced under unspaced conditions. Thus, it seems unlikely cluster ambiguity contributed significantly to the lack of frequency effects.

To us, there appear to be three alternative, more compelling suggestions for why we did not obtain frequency effects during string scanning. First, as mentioned earlier, our participants may have been unable to successfully identify arrays of clusters during scanning. On the assumption that cluster identification is a prerequisite for a frequency effect to occur, then a failure in cluster identification would mean that the opportunity for a frequency effect to occur never arose. Second, it may simply be the case that our manipulation of exposure frequency during the learning blocks was not sufficiently effective to induce frequency effects for Landolt-C strings stored in memory. If this was the case, then we would not observe frequency effects for target strings regardless of the cluster demarcation forms under which they were presented. However, this explanation itself raises an interesting question, namely, why did we obtain frequency effects across blocks during learning, but not during string scanning? Presumably this would have to be because it is much more difficult to identify a target cluster embedded in a string of distractor clusters relative to making a recognition judgment in relation to a cluster presented in isolation. Consistent with the suggestion that target identification during scanning posed a significant challenge to our participants is the finding that fixation durations were much longer during the current Landolt-C target search relative to fixation duration data reported in other target search tasks (e.g., Rayner & Fischer, 1996; Rayner & Raney, 1996; Vanyukov et al., 2012; Vitu et al., 1995; Williams & Pollatsek, 2007; Williams, Pollatsek & Reichle, 2014;). The inflated fixation durations

in current Landolt-C search indicated that to ascertain the presence of a target cluster amongst distractors was extremely difficult and required considerable processing beyond demands in previous studies.

A third possible explanation for the lack of frequency effects during string scanning may be that such effects simply do not occur when readers engage in scanning as opposed to reading behaviour. As mentioned earlier, several studies have failed to demonstrate frequency effects during scanning (Rayner & Fischer, 1996; Rayner & Raney, 1996; Wang, Sui, & White, 2019). However, all these studies used linguistic stimuli (words) to assess frequency effects. To our knowledge, the only study other than the present that has investigated frequency effects using non-linguistic stimuli is that of Vanyukov et al., (2012), and counter to the more general pattern of effects, this study did show effects of frequency during scanning. Recall that in the Vanyukov et al. study participants searched for a target “O” embedded in spaced Landolt-C quadruplets comprised of Cs with differing gap orientations and sizes manipulated across conditions. Here, quadruplet frequency exposure was manipulated via the frequency with which each quadruplet appeared as distractor in the strings to be scanned. To reiterate, under these conditions frequency effects did materialise. Thus, perhaps for frequency effects to occur during non-linguistic string scanning, it must be manipulated via distractor rather than target clusters. Quite why this might be the case remains unclear. To summarise, our failure to obtain frequency effects in scanning in this experiment may have arisen due to the frequency exposure effect influencing individual cluster identity decisions, but not target discrimination decisions during scanning, or more simply because our task involved participants scanning a series of non-linguistic

strings, or finally because we manipulated the frequency of target rather than distractor clusters.

Next let us consider our cluster demarcation results. The manipulation of cluster demarcation form produced very clear and robust effects on both fixation durations and fixation locations. The global analyses showed that scanning was most difficult in unspaced strings compared to spaced strings and shaded strings. More importantly, we also found a larger benefit for the spacing manipulation over the shading manipulation. That is to say, alternating shadings do facilitate scanning, but the degree of facilitation is reduced relative to that offered by the spacing manipulation. Interestingly, these data perfectly match the findings of spacing effects and shading effects on eye movement control during reading in normally spaced languages. The removal of word spaces from languages that normally have them has been shown to produce substantial disruption to both word identification and saccadic targeting during reading. Furthermore, disruption associated with removing word spaces holds even when word boundaries are demarcated by alternating shading or colours (e.g., Drieghe, Fitzsimmons, & Liversedge, 2017; Perea & Acha, 2009; Perea, Tejero, & Winkler, 2015; Rayner & Pollatsek, 1996; Rayner, Fischer & Pollatsek, 1998; Sheridan, Rayner & Reingold, 2013; Sheridan, Reichle & Reingold, 2016).

Demarcation cues such as spacing and shading may facilitate scanning for the following reasons: (1) they remove the need to perform Landolt-C cluster segmentation since cluster boundary cues are unambiguous and veridical; (2) knowing the beginning and end of a Landolt-C cluster ensures that the unit to be processed next is visually identifiable in the parafovea. This allows for optimised computation of oculomotor

control metrics in relation to visual sampling. Saccade target selection is an aspect of oculomotor control that is critical for efficient scanning, and thus, demarcation helps to reduce saccadic error; (3) explicit cluster demarcation reduces cross-cluster constituency ambiguity in Landolt-C cluster perception (i.e., which Cs belong with which cluster). Without cluster demarcation (either through shading or spacing), readers were uncertain as to whether adjacent Landolt-Cs formed strings that required evaluation against stored representations in memory for their possible identification.

Next, let us consider why alternating shadings were less effective in providing a cue to word boundaries relative to spaces between words. This is probably because processing a foveal cluster became more difficult when lateral masking and crowding occurred in the unspaced shaded conditions (see also Bricolo, Salvi, Martelli, Arduino & Daini, 2015; Slattery & Rayner, 2013). Moreover, the lateral masking and crowding occurring in shaded conditions also impaired the visual salience of parafoveal clusters, consequently, reducing parafoveal visual processing of clusters. Therefore, a more cautious saccadic targeting strategy was more likely to be initiated during the scanning of shaded Landolt-C strings relative to spaced Landolt-C strings.

The current study is the first to demonstrate that saccadic targeting was mainly driven by spacing presentations in non-linguistic Landolt-C string scanning, and this is very comparable to what has been observed in a number of reading studies. In English reading, for spaced text readers ordinarily target saccades to the middle of a word - the so-called Preferred Viewing Location (PVL, Rayner, 1979), though when text is presented without spaces, readers target saccades towards word beginnings (e.g., Rayner, Fischer & Pollatsek, 1998). Furthermore, when readers make refixations on a

word, the initial fixations are often made on word beginnings. This general pattern of findings is further qualified with respect to Chinese reading in that whether saccades are targeted to a word centre or to its beginning depends upon whether the reader makes a single fixation or a refixation on the word respectively, and this holds regardless of whether the same text is presented in a spaced or an unspaced format (see Zang, Liang, Bai, Yan, & Liversedge, 2013). Perhaps the most striking aspect of the current findings in this context is that saccadic targeting patterns were very comparable to those observed for unspaced text even though cluster units were clearly demarcated in the parafovea using shading. Taken together, the present results alongside the existing studies lead us to conclude that spacing information plays a critical role in eye guidance during reading, and this influence generalises beyond reading to a non-linguistic visual search task.

Chapter 3: Eye movement control during learning and scanning of English Pseudoword strings in English native speakers (Experiment 2)

3.1 Introduction

A very fundamental, visually striking and categorical issue in relation to any language is whether or not, in its written form, it is word spaced. Most of the alphabetic languages world-wide are presented with inter-word spaces (e.g., English), however, there are some languages without inter-word spaces (e.g., Chinese, Thai, Japanese, etc). A number of important eye movement studies that have investigated reading report highly consistent findings that the removal of word spacing in normally spaced languages disrupts word identification and saccadic targeting, and reduces reading efficiency more generally (e.g., Rayner, Fischer, & Pollatsek, 1998). Specifically, when word spacing is removed, longer and more fixations are made compared to normally spaced reading. In relation to saccadic targeting, readers are more likely to land towards a word's beginning rather than towards its centre, the location generally considered to allow for the word to be processed optimally (the Preferred Viewing Location, Rayner, 1979).

In unspaced languages a somewhat different situation exists. Whilst adding inter-word spaces to normally unspaced languages such as Chinese does not facilitate reading behaviour in Chinese adults (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008), robust facilitation does occur in children and those learning Chinese as a second language (Blythe et al., 2012; Shen et al., 2012). Without question, existing research indicates that words are very important in Chinese reading (see Li, Zang, Liversedge &

Pollatsek, 2015). Thus, a theoretical question that naturally arises in respect of unspaced languages concerns how readers make word demarcation decisions to allow them to move their eyes effectively in order to read unspaced languages like Chinese (Zang, Liversedge, Bai, & Yan, 2011).

In Experiment 1 we examined how exposure frequency affects learning and subsequent scanning of Landolt-C clusters (i.e., three Landolt-C rings with unique combinations of varied orientations) under different spacing formats (i.e., spaced strings, unspaced strings and strings with alternating shadings). Experiment 1 obtained robust exposure frequency effects during learning (faster and more accurate recognition of target clusters presented more frequently than less frequently during learning). However, those effects did not carry over to a subsequent scanning session in which participants were required to detect pre-learnt clusters embedded in longer sentence-like Landolt-C strings. Despite this, Experiment 1 did find robust effects of spacing in the scanning session such that fixations were shortest and saccades longest in the spaced condition, fixations were somewhat longer and saccades shorter in the shaded condition, with the longest fixations and shortest saccades in the unspaced condition. Also, in relation to landing position distributions, the majority of initial fixations were made close to the beginning of clusters for unspaced and shaded conditions; by contrast, the majority of fixations landed towards the centre of clusters in spaced conditions. One of the most noteworthy aspects of Experiment 1 was the absence of any influence of frequency during scanning of Landolt-C strings (and again, this despite clear exposure frequency effects during the learning phase). Experiment 1 argued that the failure to obtain frequency effects during the scanning session of the experiment was very likely due to the fact that the Landolt-C strings that participants were required to learn were

quite unlike words in many respects. Indeed, in Experiment 1 we purposefully stripped away the linguistic characteristics of the clusters that were to be learnt in order to focus on how the visual (rather than linguistic) familiarity of clusters affected processing in a reading-like visual search task. To this extent then, the stimuli in Experiment 1 of the present thesis required participants to engage in relatively shallow levels of (predominantly visual) processing rather than deeper levels of linguistic processing.

To assess whether the nature of the stimuli used in Experiment 1, contributed to the lack of frequency effects in the reading-like scanning task, we undertook the current study in which we used English pseudowords. English pseudowords are orthographically regular and pronounceable. We used such stimuli as they were much more word like than the Landolt-C clusters employed in Experiment 1 and to this extent, we anticipated that they might be easier to learn and recognise, and therefore, there may be an increased possibility of obtaining frequency effects in scanning. We suggest three reasons why novel pseudowords may be much easier to instantiate, represent and store in memory compared with Landolt-C clusters. First, all the elements that constitute pseudowords are letters of the alphabet for which there are already existing memory representations. Thus, there is no necessity for readers to create representations for the constituent elements of the novel strings. Second, pseudowords are pronounceable. When compared to unpronounceable Landolt-C clusters, pseudowords convey phonological information and thereby afford the possibility that readers may form a richer memory representation. Furthermore, the phonological form of a string will map directly onto other existing representations of phonemes stored in memory. Third, there is reduced visual similarity between the pseudowords in the current stimulus set relative to the set of Landolt-C stimuli. The reduced similarity

within the set of pseudowords should reduce interference from distractor strings, thereby increasing the likelihood that participants find them easier to remember and identify. Taken together, these characteristics of pseudowords should ensure that the stimuli in the present experiment are more memorable than those of Experiment 1, and therefore, they should provide an increased opportunity to observe frequency effects both in learning and later during the reading-like pseudoword scanning task.

To reiterate, in the current study, we wished to examine how exposure frequency effects would be established during learning of pseudowords and how alternative spacing formats might affect the ease of pre-learned target identification and saccadic eye movements to those targets during scanning in a search task. A second objective of this study was to examine whether learning and scanning effects observed in the novel Landolt-C learning and scanning paradigm developed in Experiment 1 would generalize to pseudoword stimuli. We formed the following hypotheses: First, we predicted recognition accuracy for pseudowords in both the learning and scanning sessions would be increased in the present study relative to that reported in Experiment 1. We made this prediction on the basis that since the pseudowords are more word-like than the Landolt-C clusters, then they would be more memorable and less susceptible to interference from distractors. Second, consistent with the findings of Experiment 1 we also predicted that the rate of learning should be faster for high frequency triplets than low frequency triplets. Importantly, we also predicted that a significant difference in the rate of learning for high frequency (HF) relative to low frequency (LF) triplets should appear earlier during learning for pseudowords than it did for the Landolt-C clusters used in Experiment 1. Finally, exactly as per Experiment 1, we manipulated the visual format of the strings used in the scanning task such that pseudowords were either

presented with spaces, or shading or in an unmarked unspaced format. In relation to our spacing manipulations, we predicted reading-like scanning of strings would be most difficult in the unspaced condition, less difficult in the shaded condition and easiest in the spaced condition. If frequency effects did occur during scanning, then we anticipated that HF pseudowords should be processed faster than LF pseudowords attracting shorter and fewer fixations. Most importantly, in relation to our manipulations of exposure frequency during learning of target triplets and during reading-like scanning, we predicted that spacing manipulations would have a modulatory influence. That is to say, if frequency effects occur in learning and they maintain to scanning, then the ease of identifying high relative to low frequency triplets should be modulated by spacing format such that largest frequency effects should occur in unspaced conditions, medium in shaded conditions and smallest in spaced conditions (see Rayner, Fischer, & Pollatsek, 1998). Finally, with respect to saccadic targeting, readers should have an increased likelihood of targeting saccades towards the centre of words in both spaced and shaded conditions, whilst, saccades should be more likely to land towards the beginning of words in the unspaced conditions.

3.2 Method

3.2.1 Participants

Thirty-six English native speakers from the University of Southampton with normal vision or corrected-to-normal vision took part in the experiment. The total number of observations per condition in the current study is more than the minimum number, 1600, suggested by Brysbaert and Stevens (2018) to be sufficiently powered

for an experiment with a repeated measures design. Additionally, this is the same number of participants as that tested in Experiment 1.

3.2.2 Apparatus

The experiments were programmed in Experiment Builder and run using a 20-in CRT monitor with a refresh rate of 75 Hertz. Stimuli were displayed in font Calibri size 36 on a 95% white background screen with a resolution 1280×1024 pixels. Participants were seated 70cm from the monitor, and at this viewing distance, 1° of visual angle approximated the width of one pseudoword. During testing, a chin and forehead rest were used to minimise participants' head movements. We used an Eyelink 1000 to record participants' eye movements during testing (including both the learning and scanning sessions). Viewing was binocular, but only the movements of the right eye were recorded.

3.2.3 Stimuli

We carefully constructed 552 three-letter pseudowords that were orthographically regular and pronounceable. Each pseudoword contained three different letters. The structure of the pseudowords could be one of four patterns: CVC (consonant-vowel-consonant), VCV (vowel-consonant-vowel), CVV (consonant-vowel-vowel) and VVC (vowel-vowel-consonant). An equal number of pseudowords was generated in each pattern.

We selected 24 pseudoword triplets (6 triplets for each pattern) as targets that participants were to learn in the learning session and to identify in the scanning session. The learning session was comprised of 5 learning blocks and we included three learning

assessments (one after Block 1, one after Block 3 and one after Block 5) to evaluate the extent to which participants had learnt those target triplets. A unique set of 24 distractors was selected from the pseudoword triplet database for each learning assessment block. This experimental approach is identical to that adopted in Experiment 1 other than that different stimuli (pseudowords instead of Landolt-C clusters) were used.

The remaining 456 pseudoword triplets were used to create longer sentence-like strings for the scanning session. Each string was 10-pseudowords long. In total, we generated 48 frames of sentence-like strings (see Figure 3.1). Half of the strings were embedded with a pre-learnt target, positioned equally frequently in the second pseudoword to the eighth pseudoword position. The remaining strings contained no target. In the scanning session, we manipulated the spacing format of the strings to be either spaced, unspaced or shaded. The same string frames were presented under three spacing formats in separate blocks. Therefore, 144 experimental strings were generated in total. Although pseudowords do not exist in real languages, they may vary in relation to visual familiarity. To minimise the potential influence of visual familiarity of pseudowords, we experimentally controlled the number of orthographic neighbours for both targets and distractors. The orthographic neighbours here refer to pseudowords that share two letters in the same positions (e.g., “ruz” is one of the orthographic neighbours for “ruc” and vice versa). The mean number of orthographic neighbours was 10 and 11 for each distractor and target triplet, respectively.

Spaced: jiq meo ruz auq iqa mul ola eja aoc oim
Shaded: jiqmeoruzauqiqamulolaejaacoim
Unspaced: jiqmeoruzauqiqamulolaejaacoim

Figure 3-1 Example pseudoword strings displayed under the three demarcation formats: spaced string, shaded string and unspaced strings. The target triplet in this example was in the third triplet position, 'ruz'.

3.2.4 Experimental design

As described earlier, in the current study, there was a learning session and a subsequent scanning session. In the learning session, we manipulated the exposure frequency of target pseudowords. Participants learnt these targets cumulatively over five learning blocks. Targets designated to be high frequency were learnt four times per learning block, whilst, targets designated to be low frequency were learnt once per block. Thus, after five blocks' learning, HF targets had been learnt twenty times relative to five times for LF targets. Learning assessments took place after the first, third and fifth learning block to evaluate the extent to which participants had remembered the targets.

After the learning session was completed, participants were required to undertake a target detection task during the scanning of pseudowords strings. The strings were displayed in three spacing formats (i.e., spaced vs. unspaced shaded vs. unspaced). We rotated the assignment of exposure frequency of the selected target pseudowords across participants. Furthermore, we counterbalanced the sequence of learning blocks according to a Latin Square design.

3.2.5 Procedure

During both the learning and scanning sessions, eye movements were recorded. Calibration was carried out until the mean error was less than 0.2deg for the learning session and less than 0.5deg for the scanning session. Recalibration was carried out whenever needed.

In the learning session, each trial started with a box appearing slightly left of the centre of the screen. Once the participant fixated the box, a pseudoword appeared in the middle of the screen, simultaneously with a square appearing at the right-hand side of the screen. The square would appear in any of four positions at different points on the same vertical line. Participants were encouraged to try their best to remember the displayed pseudoword. In each learning trial, the time to learn a pseudoword was self-paced. Once participants felt they had learnt the pseudoword, they moved their eyes to fixate the square on the right of the screen. This terminated the trial and initiated a blank screen. The procedure in the learning assessment trials was very similar to the learning trials. However, instead of making a saccade to a rightwardly presented square to terminate a trial, in each learning assessment trial, participants pressed one of two buttons to indicate whether they had, or had not, previously learnt the displayed pseudoword.

After the learning session, participants took a break and then continued with the scanning session. In each scanning trial, participants first fixated a box on the left of the screen causing a sentence-like string appeared on the screen. The first letter of the first pseudoword replaced the box. Participants were instructed to scan through the pseudoword string, triplet by triplet, from left to right. They were required to make a

decision as to whether the string contained a target pseudoword that they had learnt in the learning session. Participants provided a yes/no decision by initially pressing one of two buttons which terminated the trial, after which they were required to type in the detected pseudoword using the keyboard.

During both the learning session and the scanning session, participants had short breaks whenever needed. In total, the experiment took approximately 3 hours to complete.

3.3 Results

Linear mixed effects models (LMMs, see Bates, Maechler, Bolker, & Walker, 2016) including both fixed factors and random factors (i.e., items and subjects) in the structure were run in the R environment (2018) for each analysis. For binary data, such as accuracy, logistic generalized mixed effects models (GLMMs) were used. All p values were computed using the *lmerTest* package (Kuznetsova, Brockhoff, Christensen, 2017).

Separate analyses for the learning session and scanning session were conducted. In both sessions, we examined eye movement measures (e.g., first fixation duration, gaze duration) and behavioural measures (e.g., mean accuracy, hit rate). For the analysis of each continuous variable, we excluded the data beyond ± 3 standard deviations from the mean by subject and by condition. In the learning session, 2.4% of the averaged data were removed from later analyses due to this trimming procedure. In the scanning session, if skipping occurred during first-pass scanning, these trials were removed from the analysis of first-pass scanning measures (e.g., first fixation duration,

gaze duration). On average, 4.2% of the data were removed in the scanning session due to these trimming procedure.

3.3.1 Learning session

In the learning session, we examined main effects of learning block, which we regarded as an index of the degree to which pseudowords were learned effectively, main effects of exposure frequency, and the interaction between learning block and exposure frequency which we will refer to as the rate of learning effect. As the treatment in each learning block was identical we treated learning block as a numeric factor. Similar analyses were conducted with respect to learning assessments.

In the analyses of learning, we examined first fixation duration, total reading time (i.e., the sum of all fixation durations on a pseudoword) and fixation number. In the learning assessment, we examined the same eye movement measures above, and also reaction time, mean accuracy and hit rate. The means and standard errors of these variables are shown in Table 3.1. All the LMMs results were analysed using log-transformed data.

Table 3-1 Descriptive statistics in the learning session.

Learning	High Frequency					Low Frequency				
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 1	Block 2	Block 3	Block 4	Block 5
	First fixation duration ¹	515 (53)	429 (40)	367 (31)	387 (36)	343 (28)	517 (110)	463 (87)	421 (83)	420 (94)
Total viewing time ^{1,2,3}	3483 (228)	1783 (134)	1408 (101)	1164 (78)	973 (69)	4776 (510)	2940 (379)	2177 (351)	1463 (228)	1331 (258)
Fixation number ^{1,2,3}	7.5 (0.5)	4.1 (0.3)	3.5 (0.3)	2.9 (0.2)	2.6 (0.2)	10.2 (1.2)	6.8 (1.0)	5.1 (0.8)	3.6 (0.5)	3.5 (0.6)

Learning assessment	High Frequency			Low Frequency		
	Learning Assessment 1	Learning Assessment 2	Learning Assessment 3	Learning Assessment 1	Learning Assessment 2	Learning Assessment 3
	Hit rate ^{1,2,3}	0.97 (0.03)	0.99 (0.005)	0.99 (0.01)	0.71 (0.11)	0.93 (0.05)
Reaction time ^{1,2,3}	1535 (204)	1010 (102)	980 (94)	2483 (405)	1397 (198)	1124 (147)
First fixation duration	170 (10)	170 (9)	168 (11)	166 (10)	168 (10)	170 (11)
Total reading time ^{1,2,3}	1420 (200)	1030 (92)	911 (80)	2211 (352)	1273 (171)	1052 (139)
Fixation number ^{1,2,3}	4.6 (0.6)	3.5 (0.3)	3.2 (0.3)	6.4 (0.9)	4.3 (0.6)	3.6 (0.4)

Note. Standard errors are in parentheses. Time was measured in milliseconds. We use superscript to indicate the effect that occurred for each of the dependent variables. Superscript 1 refers to a significant learning block effect. Superscript 2 refers to a significant exposure frequency effect. Superscript 3 refers to a significant rate of learning effect, that is, the interaction between exposure frequency and learning block.

In the learning analyses, first fixation durations were shorter in the later blocks relative to earlier blocks (see Table 3.1), $\beta = -0.05$, $SE = 0.01$, $t = -4.74$, $P < .001$. However, neither exposure frequency, nor rate of learning effects occurred for first fixation duration ($\beta = 0.04$, $SE = 0.04$, $t = -0.94$, $P = .36$; $\beta = 0.002$, $SE = 0.008$, $t = -0.30$, $P = .76$, respectively). Similar learning block effects were also obtained on total reading time and fixation number ($\beta = -0.23$, $SE = 0.02$, $t = -11.12$, $P < .001$; $\beta = -0.16$,

SE = 0.008, $t = -9.80$, $P < .001$, respectively), indicating learning progressed substantially over the five learning blocks. For total reading time and fixation number, as we predicted, we found robust effects of exposure frequency showing that pseudowords with four exposures per block attracted shorter and fewer fixations than those with only a single exposure per block ($\beta = 0.45$, SE = 0.05, $t = 8.30$, $P < .001$; $\beta = 0.40$, SE = 0.16, $t = -9.80$, $P < .001$, respectively). Note that in the current study, high frequency was set as the baseline in the LMMs and GLMMs regarding the main effect of exposure frequency. More importantly, we found rate of learning effects (i.e., an interaction between exposure frequency and learning block) on total reading time and fixation number ($\beta = -0.03$, SE = 0.10, $t = -3.28$, $P = .002$; $\beta = -0.03$, SE = 0.10, $t = -3.63$, $P < .001$, respectively). As shown in Figure 3.2, the point at which learning started to plateau occurred approximately in block 2 during the learning of HF triplets, which was much earlier than that in the learning of LF triplets (where learning started to plateau in block 4). The pattern of the rate of learning effects suggests that learning was qualified by exposure frequency of the target triplets such that the learning rate was greater during learning of LF targets relative to HF targets. This is very different to the pattern obtained in the Landolt-C learning and scanning experiment reported in Experiment 1 where it was found learning to be faster for HF triplets than LF triplets. Thus, to formally examine whether the patterns of learning were significantly different across the present experiment and that of Experiment 1, we took the total reading time and fixation number data from both experiments and constructed full LMMs with experiment as a between-subject factor. The results demonstrated robust interactive effects between the three fixed factors (i.e., exposure frequency, learning block, and experiment). Learning rate was greater for HF targets relative to LF targets in the

Landolt-C experiment but was smaller for HF targets relative to LF targets in the current English pseudoword experiment (for total reading time: $\beta = -0.11$, $SE = 0.02$, $t = -5.83$, $P < .001$; for fixation number, $\beta = -0.10$, $SE = 0.02$, $t = -5.81$, $P < .001$). We will consider reasons for the differential curves of learning for pseudowords and Landolt-C clusters under different conditions of exposure in the Discussion.

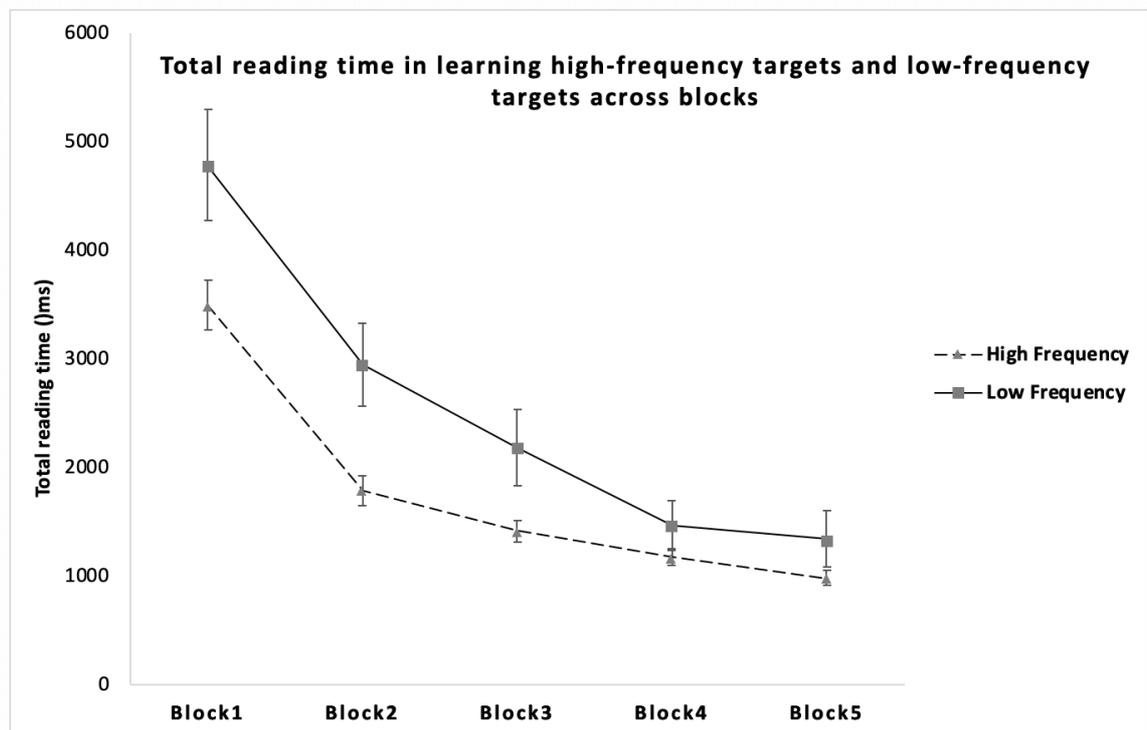


Figure 3-2 Mean total reading times during the learning of HF target and LF targets across the five learning blocks. The vertical lines represent error bars.

In the learning assessments, mean accuracy (i.e., correct recognition and rejection) was 87% in the initial assessment, increasing to 95% in the second learning assessment and reached 97% in the final learning assessment. The formal analysis of mean accuracy showed a robust effect of learning assessment ($\beta = 1.17$, $SE = 0.17$, $z = -6.99$, $P < .001$), which again demonstrated learning was very efficient for pseudowords

in the current study. In relation to hit rate (i.e., correct recognition of target triplets, see Table 3.1), we found robust main effects of learning assessment and exposure frequency such that hit rate was higher in the early learning assessments relative to the later learning assessments ($\beta = -3.13$, $SE = 0.56$, $z = -5.60$, $P < .001$), and was higher when HF targets were identified compared to LF targets ($\beta = 0.98$, $SE = 0.15$, $z = 6.34$, $P < .001$). More importantly, as in the learning blocks, we found a rate of learning effect on hit rate ($\beta = 0.68$, $SE = 0.31$, $z = 2.21$, $P = .03$). As before, we formally examined hit rates across the present study and that of Experiment 1. We predicted, the hit rate would be significantly greater in identifying pseudoword target triplets in the present study compared to that for the Landolt-C target clusters in Experiment 1, and indeed, this was the case ($\beta = 2.17$, $SE = 0.20$, $z = 10.95$, $P < .001$). For identification times in the target present learning assessment trials, similarly, we found participants spent less time on triplets that received more exposures than fewer exposures during learning ($\beta = 0.53$, $SE = 0.06$, $t = 9.0$, $P < .001$); also, shorter identification times occurred in the later learning assessments compared to the earlier learning assessments ($\beta = -0.27$, $SE = 0.02$, $t = -10.93$, $P < .001$). More importantly, the learning assessment effect was modulated by exposure frequency such that the rate of learning decreased across learning assessments ($\beta = -0.15$, $SE = 0.02$, $t = -6.55$, $P < .001$; the same pattern as shown in Figure 3.2). We also examined the eye movement measures in the learning assessments (see Table 3.1 for descriptive statistics). No reliable effects occurred on first fixation duration (learning assessment effect: $\beta = 0.001$, $SE = 0.02$, $t = 0.07$, $P = .95$; exposure frequency effect: $\beta = -0.07$, $SE = 0.05$, $t = -1.2$, $P = .22$; rate of learning effect, $\beta = 0.02$, $SE = 0.02$, $t = 1.03$, $P = .31$). However, we found robust effects of learning assessment, exposure frequency and the rate of learning on total reading time ($\beta = -0.26$, $SE = 0.02$, $t = -$

11.45, $P < .001$; $\beta = 0.48$, $SE = 0.06$, $t = 8.55$, $P < .001$; $\beta = -0.14$, $SE = 0.02$, $t = -6.38$, $P < .001$, respectively) and fixation number ($\beta = -0.20$, $SE = 0.02$, $t = -8.39$, $P < .001$; $\beta = 0.37$, $SE = 0.05$, $t = 7.74$, $P < .001$; $\beta = -0.10$, $SE = 0.02$, $t = -5.06$, $P < .001$, respectively) as we obtained across the learning blocks. The comparable patterns of results from eye movements and from off-line measures in the learning assessment tasks reinforces the fact that eye movements can provide a good index of online processing in the learning of pseudowords. Likewise, the occurrences of these effects in both learning and learning assessments indicates that our participants effectively learnt target triplets over the five learning blocks, and moreover, the degree of visual familiarity differed between HF target triplets and LF target triplets.

3.3.2 Scanning session

In the scanning session, we first examined the mean accuracy (i.e., correct detection when a target was present in a trial and correct rejection when no target was present in a trial) and hit rate (i.e., proportion of correct detections when a target was present) in relation to participants' performance in detecting target triplets within pseudoword strings. Compared to the 97% accuracy in the final learning assessment, mean accuracy in the scanning session reduced by 17% (see Table 3.2). Nevertheless, it remains the case that 80% accuracy indicates that our participants were still able to identify the pre-learnt pseudowords that were embedded in strings on the significant majority of trials. The reduced accuracy in scanning relative to that in the learning assessment is also consistent with the suggestion that identification of target pseudowords in scanning (where distractor pseudowords likely cause interference) is a more difficult task than the identification of targets in isolation. Also, note that the

mean accuracy in this experiment was much higher than that in Landolt-C scanning experiment which was at chance level (Experiment 1). We believe that the much better detection performance in the pseudoword string scanning compared to Landolt-C string scanning was mainly due to more effective learning of pseudoword triplets compared to Landolt-C clusters. We also examined the main effect of spacing format on mean accuracy. The GLMMs showed no main effect of spacing format on mean accuracy (Shaded – Unspaced: $\beta = 0.07$, $SE = 0.10$, $z = 0.73$, $P = .47$; Spaced – Shaded: $\beta = -0.04$, $SE = 0.10$, $z = -0.39$, $P = .70$; Unspaced – Spaced: $\beta = -0.03$, $SE = 0.10$, $z = -0.34$, $P = .74$). On hit rate, when exposure frequency was included as a fixed factor with spacing format in the analysis, somewhat surprisingly, there were no main effects of exposure frequency ($\beta = 0.05$, $SE = 0.11$, $z = 0.46$, $P = .65$), spacing format (Shaded – Unspaced: $\beta = 0.10$, $SE = 0.12$, $z = 0.82$, $P = .41$; Spaced – Shaded: $\beta = -0.03$, $SE = 0.12$, $z = -0.24$, $P = .81$; Unspaced – Spaced: $\beta = -0.07$, $SE = 0.12$, $z = -0.57$, $P = .56$), nor was there an interaction between the two (Frequency by Shaded – Unspaced: $\beta = -0.36$, $SE = 0.23$, $z = -1.53$, $P = .13$; Frequency by Spaced – Shaded: $\beta = 0.06$, $SE = 0.23$, $z = 0.24$, $P = .81$; Frequency by Unspaced – Spaced: $\beta = 0.30$, $SE = 0.23$, $z = 1.29$, $P = .20$). These accuracy data seems to suggest that participants were able to detect both HF and LF target triplets effectively and similarly across all the spacing conditions. The lack of exposure frequency effect and spacing format effect on hit rate may be because participants had remembered LF targets nearly as many as HF targets (see Table 3.1, in the final learning assessment, hit rate was 99% for HF targets and 95% for LF targets). The memory of those already learnt target pseudowords were relatively stable, and therefore, participants were able to identify most of them amongst multiple distractors regardless of the spacing presentation format.

Table 3-2 Descriptive statistics in the scanning session.

Global measures				
		Unspaced	Shaded	Spaced
Mean accuracy		0.80 (0.05)	0.81 (0.05)	0.80 (0.05)
Mean fixation duration ¹		306 (4.28)	283(4.66)	277 (5.17)
Mean saccade amplitude ¹		1.35 (0.04)	2.10 (0.07)	2.68 (0.10)
Local measures				
		Unspaced	Shaded	Spaced
Hit Rate	HF	0.66 (0.12)	0.71 (0.11)	0.70 (0.12)
	LF	0.71 (0.12)	0.70 (0.12)	0.70 (0.12)
First fixation duration ¹	HF	252 (32)	248 (38)	234 (38)
	LF	257 (32)	240 (36)	224 (34)
Gaze duration ¹	HF	1030 (166)	653 (138)	547 (109)
	LF	1069 (190)	681 (125)	560 (111)
Total reading time ¹	HF	1838 (286)	1395 (259)	1224 (240)
	LF	1894 (312)	1433 (247)	1170 (224)
Fixation number ¹	HF	5.41 (0.73)	4.11 (0.73)	3.80 (0.66)
	LF	5.51 (0.88)	4.12 (0.65)	3.56 (0.62)
Incoming saccade length ¹	HF	1.47 (0.26)	2.42 (0.26)	3.11 (0.30)
	LF	1.50 (0.20)	2.36 (0.25)	3.09 (0.24)
Outgoing saccade length ¹	HF	1.78 (0.26)	2.62 (0.35)	3.33 (0.34)
	LF	1.97 (0.33)	2.78 (0.34)	3.34 (0.36)
Mean landing position ¹	HF	0.67 (0.12)	1.22 (0.18)	1.72 (0.22)
	LF	0.67 (0.12)	1.14 (0.17)	1.71 (0.20)

Note. All the fixation times were measured in milliseconds. All the distances/amplitudes were measured in degrees of visual angle. One degree of visual angle equals to one triplet in the present experiment. The standard errors are in parentheses. We use superscript to indicate when a significant main effect of spacing format occurred.

We next considered the eye movement data from the scanning session. We examined two global measures that included observations from every pseudoword in the string: mean fixation duration and mean saccade amplitude. We also computed several local measures that only included data obtained from target pseudowords for which exposure frequency was manipulated in the learning session: first fixation duration, gaze duration (i.e., the sum of first-pass reading time), fixation number, total reading time, incoming saccade length, outgoing saccade length and mean landing position (see Table 3.2 for descriptive statistics).

First, let us consider the results from the global measures. There was a robust main effect of spacing format for mean fixation duration. Longest mean fixation durations occurred in the unspaced condition compared to the shaded condition ($\beta = 0.07$, $SE = 0.01$, $t = 5.50$, $P < .001$) and the spaced condition ($\beta = 0.11$, $SE = 0.02$, $t = 6.30$, $P < .001$). Moreover, mean fixation duration was longer in the shaded condition relative to the spaced condition ($\beta = 0.03$, $SE = 0.01$, $t = 3.16$, $P < .001$). The facilitation to processing of spacing and shading manipulations was also found in mean saccade amplitude. The longest saccades were made in the spaced condition compared to the shaded condition ($\beta = 0.24$, $SE = 0.02$, $t = 14.37$, $P < .001$) and the unspaced condition ($\beta = 0.66$, $SE = 0.03$, $t = 23.78$, $P < .001$). The saccades were longer in the shaded than the unspaced condition ($\beta = 0.42$, $SE = 0.02$, $t = 17.40$, $P < .001$). Longer saccades observed in the shaded condition relative to the unspaced condition indicated that the presence of visual demarcation of triplet boundaries did facilitate where to target a saccade. While, the significantly longer saccades that occurred in the spaced condition relative to the other two conditions likely arose due to two reasons. First, very clear indications of pseudoword boundaries very likely facilitated targeting

towards the centre of a pseudoword in the spaced strings. This would cause saccades to be slightly extended. Secondly, the inter-pseudoword spaces naturally increase the horizontal spatial extent of the triplet strings, and consequently, longer inter-triplet saccades are necessary as the eyes move through the string. Numerically, we did not observe a doubling of the increased saccade amplitude effect in the spaced relative to the shading condition, however, the saccade data together with the mean fixation duration data, at a global level, indicate that scanning was clearly easiest in the spaced condition and less so for the shaded condition and least for unspaced condition. Thus, it appears that the shading manipulation benefited target pseudoword search during scanning, however, the benefits were smaller relative to those observed in the spaced condition.

We examined the main effects of exposure frequency, spacing format and the interaction between the two on local measures. We found robust effects of spacing format on first fixation duration such that first fixation duration was shortest in the spaced condition, and longest in the unspaced condition (Shaded – Unspaced: $\beta = -0.08$, $SE = 0.03$, $t = -2.32$, $P = .03$; Spaced – Shaded: $\beta = -0.09$, $SE = 0.04$, $t = -2.40$, $P = .02$; Unspaced – Spaced: $\beta = 0.17$, $SE = 0.05$, $t = 3.78$, $P < .001$). Neither the exposure frequency effect ($\beta = -0.01$, $SE = 0.03$, $t = -0.52$, $P = .61$) nor the interaction between exposure frequency and spacing format (Frequency by Shaded – Unspaced: $\beta = -0.10$, $SE = 0.06$, $t = -1.59$, $P = .11$; Frequency by Spaced – Shaded: $\beta = -0.01$, $SE = 0.06$, $t = -0.22$, $P = .82$; Frequency by Unspaced – Spaced: $\beta = 0.11$, $SE = 0.06$, $t = 1.81$, $P = .07$) were robust in first fixation duration. In gaze duration, total reading time and fixation number, we found similar results as in first fixation duration. Specifically, longer gaze durations occurred in the unspaced condition compared to the spaced condition ($\beta =$

0.68, SE = 0.07, $t = 9.22$, $P < .001$) and the shaded condition ($\beta = 0.48$, SE = 0.05, $t = 9.43$, $P < .001$). Gaze duration was longer in the shaded condition compared to the spaced condition ($\beta = 0.20$, SE = 0.05, $t = 4.27$, $P < .001$). Again, there was no exposure frequency effect ($\beta = 0.03$, SE = 0.04, $t = 0.84$, $P = .41$) nor an interactive effect (Frequency by Shaded – Unspaced: $\beta = 0.06$, SE = 0.06, $t = 0.95$, $P = .34$; Frequency by Spaced – Shaded: $\beta = -0.08$, SE = 0.06, $t = -1.19$, $P = .23$; Frequency by Unspaced – Spaced: $\beta = 0.02$, SE = 0.06, $t = -0.25$, $P = .80$) for gaze duration. Likewise, most fixations were made in the unspaced condition, fewer in the shaded condition and least in the spaced condition (Shaded – Unspaced: $\beta = -0.33$, SE = 0.05, $t = -7.14$, $P < .001$; Spaced – Shaded: $\beta = -0.09$, SE = 0.04, $t = -2.19$, $P = .04$; Unspaced – Spaced: $\beta = 0.42$, SE = 0.04, $t = 20.85$, $P < .001$). No exposure frequency ($\beta = -0.01$, SE = 0.03, $t = -0.55$, $P = .59$), nor interaction between exposure frequency and spacing format were obtained for fixation number (Frequency by Shaded – Unspaced: $\beta = -0.01$, SE = 0.06, $t = -0.12$, $P = .92$; Frequency by Spaced – Shaded: $\beta = -0.09$, SE = 0.06, $t = -1.52$, $P = .13$; Frequency by Unspaced – Spaced: $\beta = 0.09$, SE = 0.06, $t = 1.66$, $P = .10$). The same pattern of effects was also found for total reading time: significant main effect of spacing format (Shaded – Unspaced: $\beta = -0.38$, SE = 0.06, $t = -6.88$, $P < .001$; Spaced – Shaded: $\beta = -0.16$, SE = 0.05, $t = -3.21$, $P < .001$; Unspaced – Spaced: $\beta = 0.54$, SE = 0.05, $t = 11.23$, $P < .001$), but no main effect of exposure frequency ($\beta = 0.01$, SE = 0.03, $t = 0.46$, $P = .65$) nor interaction (Frequency by Shaded – Unspaced: $\beta = 0.02$, SE = 0.06, $t = 0.30$, $P = .76$; Frequency by Spaced – Shaded: $\beta = -0.08$, SE = 0.07, $t = -1.18$, $P = .24$; Frequency by Unspaced – Spaced: $\beta = 0.06$, SE = 0.06, $t = -0.93$, $P = .35$).

Next, we will report results associated with saccadic targeting including analyses of incoming saccade length into the targets, outgoing saccade length from the targets and the mean landing position on the targets. Consistent with Experiment 1, the analysis of incoming saccade length and outgoing saccade length included the space between clusters for the spaced condition. In contrast, mean landing position did not include the space prior to the target cluster. The results from the fixation location analyses were quite complementary to the patterns of effects observed in the fixation times. There were robust effects of spacing format on all the fixation location measures. However, there were no exposure frequency effects on incoming saccade length ($\beta = -0.01$, $SE = 0.02$, $t = -0.38$, $P = .71$), outgoing saccade length ($\beta = 0.03$, $SE = 0.02$, $t = 1.54$, $P = 0.14$) nor on mean landing position ($\beta = -0.74$, $SE = 0.72$, $t = -1.03$, $P = .30$). Also, there were no interactive effects between exposure frequency and spacing format on incoming saccade length (Frequency by Shaded – Unspaced: $\beta = -0.05$, $SE = 0.04$, $t = -1.26$, $P = .21$; Frequency by Spaced – Shaded: $\beta = 0.05$, $SE = 0.04$, $t = 1.26$, $P = .21$; Frequency by Unspaced – Spaced: $\beta = 0.001$, $SE = 0.04$, $t = 0.02$, $P = .98$), outgoing saccade length (Frequency by Shaded – Unspaced: $\beta = -0.03$, $SE = 0.07$, $t = -0.46$, $P = .65$; Frequency by Spaced – Shaded: $\beta = -0.05$, $SE = 0.05$, $t = -0.92$, $P = .36$; Frequency by Unspaced – Spaced: $\beta = 0.08$, $SE = 0.05$, $t = 1.72$, $P = .09$), nor on mean landing position (Frequency by Shaded – Unspaced: $\beta = -2.15$, $SE = 1.76$, $t = -1.22$, $P = 0.22$; Frequency by Spaced – Shaded: $\beta = 2.07$, $SE = 1.77$, $t = 1.17$, $P = 0.24$; Frequency by Unspaced – Spaced: $\beta = 0.08$, $SE = 1.75$, $t = 0.05$, $P = .96$). The longest incoming saccade and outgoing saccade extents occurred in the spaced condition, with shorter saccades in the shaded condition and shortest in unspaced condition (for incoming saccade length, Shaded – Unspaced: $\beta = 0.48$, $SE = 0.04$, $t = 12.97$, $P < .001$;

Spaced – Shaded: $\beta = 0.29$, $SE = 0.03$, $t = 11.48$, $P < .001$; Unspaced – Spaced: $\beta = -0.77$, $SE = 0.04$, $t = 19.55$, $P < .001$; for outgoing saccade length, Shaded – Unspaced: $\beta = 0.37$, $SE = 0.04$, $t = 8.69$, $P < .001$; Spaced – Shaded: $\beta = 0.25$, $SE = 0.04$, $t = 6.94$, $P < .001$; Unspaced – Spaced: $\beta = -0.62$, $SE = 0.04$, $t = -15.21$, $P < .001$). The failure to obtain frequency exposure effects on incoming saccade extents suggests that there was no sensitivity to any increased visual familiarity of a parafoveal pseudoword based on the frequency of exposure to that pseudoword during learning. Decisions of where to target the eyes during pseudoword string scanning are clearly made on the basis of low level pseudoword boundary demarcation cues provided by shading or spacing. Such decisions are not based on the orthographic familiarity of the upcoming pseudoword.

The mean landing positions, similarly, were furthest into the target pseudowords in the spaced condition, less far into the target in the shaded condition and nearest to the target beginning in the unspaced condition (Shaded – Unspaced: $\beta = 15.18$, $SE = 1.22$, $t = 12.46$, $P < .001$; Spaced – Shaded: $\beta = 16.28$, $SE = 1.09$, $t = 14.90$, $P < .001$; Unspaced – Spaced: $\beta = -31.47$, $SE = 1.26$, $t = 25.01$, $P < .001$). As discussed earlier, to some extent, the longer incoming and outgoing saccades that occurred in the spaced compared to the other two conditions is likely due to clear pseudoword boundary demarcations alongside the increased horizontal spatial extent of the spaced string format. However, the fixation duration data observed for the target triplets clearly demonstrated that spacing produced the shortest fixations relative to fixations in the shaded condition and finally fixations in the unspaced condition. This suggests that spacing facilitated target processing when the pseudoword was fixated to a greater degree than alternating shadings even though both spacing and shading provided visual demarcation of boundaries. Thus, it seems possible that the facilitatory effects of

spacing might have also contributed to the increased incoming and outgoing saccade extent data. This argument was further supported by the patterns observed for the initial landing position distributions reported below.

When we consider the initial landing position distributions (see Figure 3.3), there are two main points to make. First, we found that exposure frequency did not particularly affect saccadic targeting. This result is entirely consistent with the saccade extent data described above. Second, in general, there were two differential types of landing position distributions. In the spaced and shaded conditions, landing position distributions presented as inverted-U shapes with a peak close to the middle of the target. Specifically, in the shaded conditions, participants more often sent their eyes to the centre of the target triplet. In the spaced condition, the peak appeared half a character beyond this point to the right of the centre of the target. By contrast, in the unspaced conditions, the landing position distribution showed a declining trend with its peak towards the target beginning. An interesting aspect of these results is that these two types of landing position distribution are very similar to distributions that have been reported in real language reading, and furthermore, these distributions are markedly different to the landing position distributions that occurred in the Landolt-C scanning task reported in Experiment 1. We will consider why the landing position patterns are different across the two studies in the Discussion.

To summarise, in the learning session, we obtained clear learning effects, exposure frequency effects, and more importantly, we found an interaction between exposure frequency and learning blocks (i.e., rate of learning effects) in the learning session. These results demonstrated that we effectively simulated exposure frequency

effects in pseudoword learning. In the scanning session, participants were able to detect approximately 70% of the target triplets that were embedded within the strings. There were no main effects of exposure frequency, nor spacing format on response accuracy. The exposure frequency effect was also absent on eye movement measures. The failure to obtain frequency effects in the Landolt-C study and during the present pseudoword experiment suggests that this was not due to the Landolt-C stimuli lacking word like orthographic and phonological characteristics. In contrast to the lack of frequency effects in scanning, in the present study we found robust spacing effects on almost every eye movement measure we examined. Both fixation locations and fixation times were affected by spacing format. The presence of triplet boundary demarcations in either the form of spacing or alternation shadings facilitated both target triplet identification and saccadic programming, though the facilitation was reduced in the shaded condition than in the spaced condition.

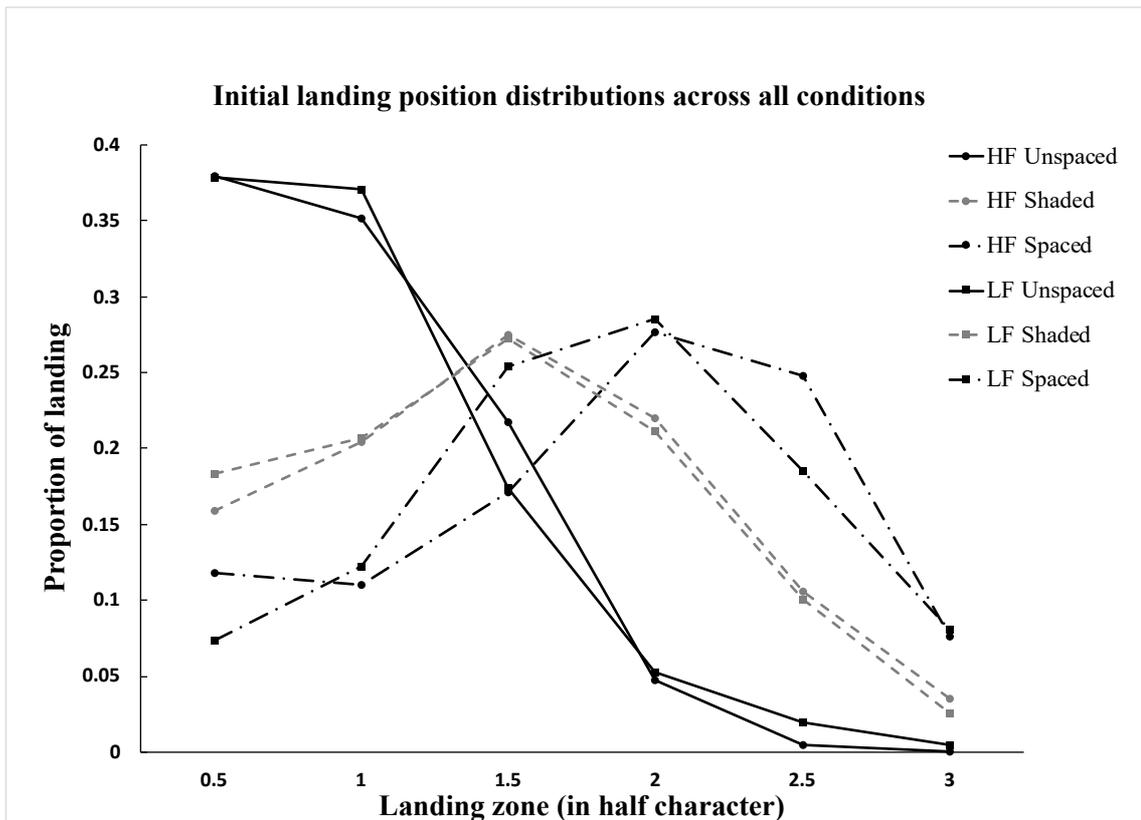


Figure 3-3 Initial landing position distributions on the target triplet across all conditions in the scanning session.

3.4 Discussion

In the current study, we adopted the novel word learning and scanning paradigm developed in Experiment 1 to examine how exposure frequency effects might become established during the learning of pseudoword triplets and how the simulated exposure frequency of target triplets affected eye movement control during the scanning of sentence-like pseudoword strings under different spacing presentation formats.

In the learning session of the present study, the majority of findings we obtained were directly comparable to those reported in Experiment 1 such that robust exposure frequency effects, learning block effects and the rate of learning effects occurred during

the learning of target pseudoword triplets. In line with our prediction, if anything, these effects were more pronounced and robust for the pseudoword stimuli used here than for the Landolt-C stimuli adopted by Experiment 1. The basic learning block effects, that is, participants spending less time fixating a triplet prior to indicating they felt that they had learnt it, in the later stages of learning relative to the earlier stages of learning, demonstrated that visual familiarity with the pseudoword triplets accumulated across learning blocks. Thus, processing of orthographic (and probably also phonological) information corresponding to each of our specific pseudowords to permit their storage and subsequent identification in memory was reduced across learning blocks. The results from the learning blocks do seem to indicate that participants were able to successfully instantiate and store representations for novel pseudowords even though these strings had no associated semantic meaning.

During learning, as predicted, target triplets that received four exposures per block attracted significantly shorter fixation times relative to the targets receiving one exposure per block. This result demonstrates, unsurprisingly, that the frequency of exposure to an orthographic string is a fundamental determinant of the ease with which it may be recalled from memory. This result is important in that it not only demonstrates the relationship between exposure frequency and visual familiarity of word-like orthographic strings, but also because it demonstrates that the learning paradigm developed in Experiment 1 was effective in simulating exposure frequency effects for stimuli beyond Landolt-C strings. To be clear, the consistency of exposure frequency effects during learning between the Landolt-C study and the present study demonstrate the reliability and replicability of such effects.

Next, let us consider the rate of learning effects obtained in the learning session of the present experiment. During the learning of pseudowords, the pattern of learning curves (as shown in Figure 3.2) indicated that the rate of learning decreased across blocks. That is to say, the difference between the time spent processing the LF pseudowords relative to the HF pseudowords decreased rather than increased across blocks. The pattern of effects we report here is opposite to our prediction, and different from the effects reported in the Landolt-C study (Experiment 1) where the difference in learning effects between LF Landolt-C strings relative to HF Landolt-C strings increased across blocks. Although these findings may initially seem somewhat incongruent, when considered in the broader theoretical context of massed and spaced presentation effects in learning, they are actually not so unusual. Over a century ago, Ebbinghaus (1885) described a temporal spacing effect showing that learning is more efficient when the information is repeated in a time spaced fashion compared to a time massed fashion. Such spaced repetition effects have been reported in many explicit memory tasks such as free recall, recognition and cued memory (for reviews, see Crowder 2014; Greene, 1989). The so-called Deficient Processing account stipulates that the second occurrence of an item repeated in a massed presentation will be processed less effectively relative to when presented in a spaced presentation (Bregman, 1967; Crowder, 2014; Cuddy, & Jacoby, 1982; Greeno, 1970). It is argued that if an item is repeated in massed practice, upon the second encounter with it, participants will still have a very familiar sense of it, and therefore, allocate reduced rehearsal time and processing resources to it on the second occurrence. In other words, processing would occur less effectively resulting in a slower learning rate when the information is repeated in a massed fashion than when it is repeated in a spaced fashion. In the present

study, participants learned pseudowords with different numbers of exposures over the five learning blocks, and therefore the learning of LF targets occurred in a more temporally spaced manner, and the learning of HF targets occurred in a more temporally massed manner. This might explain the less steep learning rate that occurred in the learning of HF relative to LF targets (see Figure 3.2). However, as mentioned previously, Experiment 1 reported different learning rate effects for Landolt-C target clusters. Specifically, the rate of learning for HF Landolt-C clusters was greater compared to that for LF targets. One might argue that if the spacing of the repetition was the cause of increased learning effects for LF targets in this study, then similar effects should have occurred in the Landolt-C study (Experiment 1), given that the manipulation of exposure frequency was identical across the two studies. We believe that the main reason for the differential effects in the Landolt-C study is probably due to the difficulty in learning the Landolt-C clusters. As described in the Introduction, Landolt-C clusters are very novel and abstract stimuli that are comprised of C-rings with a gap varying in orientation. No corresponding sound or semantic information exists the Landolt-C clusters. To this extent, these stimuli are very unlike words and therefore, compared to the pseudoword triplets used in this experiment, the learning of Landolt-C clusters was much more difficult. Therefore, in the context of learning such difficult stimuli, the spacing of the repetition would have little opportunity to exert a facilitatory effect on the learning of LF (relative to HF) targets because the effort associated with learning was simply too great. In sum, it appears that the difficulty of the learning task in relation to the nature of the stimuli being learnt is a strong modulatory influence on the rate at which those stimuli may be learnt.

Next, we will consider why participants were more effective in the learning of pseudoword triplets in this study when compared with the learning of Landolt-C clusters. Given that the manipulation during the learning session was identical across the two studies, and as argued earlier, it seems very likely that the nature of the stimuli affected the extent to which targets were effectively memorised and the rate at which exposure frequency effect were established. We provide three explanations as to why the differential learning effects occurred. First, all the constituent elements forming pseudowords are English letters that already exist in the alphabetic language of the participants that were tested in this study. Of course, this was not the case for the constituent Landolt-Cs that comprised the Landolt-C triplets. During the learning of pseudowords, participants were not required to learn novel constituent elements comprising the strings as there were existing representations for each letter in memory. By contrast, during the learning of Landolt-C clusters, participants first had to learn and represent novel, abstract, specific Landolt-C rings with different orientations that were each very similar. Presumably, the lack of familiarity with the Landolt-C stimuli alongside the lack of existing memory representations for those stimuli increased the difficulty of triplet learning. A second obvious difference between pseudoword and the Landolt-C learning is that pseudowords in the present study were pronounceable, whereas Landolt-C strings were not. Because of this, participants were able to encode triplets in relation to both their phonological and orthographic characteristics, presumably therefore, resulting in a richer and more memorable representation which would have facilitated pseudoword learning. Third, the reduced similarity between pseudoword triplets (both in relation to their orthographic and phonological forms) will have contributed to more effective learning relative to learning

of Landolt-C clusters through reduced competitor interference effects. Following these explanations, and as supported by formal statistical comparisons, in the scanning session, target detection performance was much better in this study relative to that in the Landolt-C study. This is entirely consistent with our suggestion that pseudoword learning was much more effective and successful than Landolt-C learning.

Recall that one of our objectives in our use of pseudowords as stimuli in the present experiment was to simulate exposure frequency effects more effectively during the learning session with the anticipated consequence that we might observe increased target detection performance during the scanning of pseudoword strings alongside an increased likelihood of exposure frequency effects during target detection. Indeed, target detection performance was significantly improved as discussed earlier, however, somewhat to our surprise, the exposure frequency effects that we simulated successfully during learning did not appear in the eye movement record during the scanning session of the present experiment. Recall that, in the Landolt-C study, it was also reported a lack of an exposure frequency effect in the scanning session. They argued that one possibility as to why the exposure frequency effect did not carry over the scanning session might be because memory representations of pre-learnt targets failed to persist through to the scanning session. This could be true if we assume that frequency effects only occur when target identification is successful (and, thus, a failure to identify targets would result in the lack of a frequency effect). However, this was certainly not the case in the present study since participants were able to identify the significant majority of pre-learnt pseudoword triplets that were embedded within the sentence-like strings.

We offer three alternative explanations for the lack of exposure frequency effects during scanning session of the present experiment. First, compared to the occurrence of real words in print, the range of exposures between HF and LF pseudoword strings in our experimental manipulation is small, potentially too small to induce any exposure frequency effects in the present target search task during scanning. Second, the contemporaneous appearance of multiple distractor triplets alongside the target triplet within the same string might diminish the occurrence of any exposure frequency effect. Presumably, distractor triplets might interfere with target identification making rapid, relatively automatic identification of a target impossible. Presumably, frequency effects are much more likely to appear if the identification process is quite rapid rather than being a laboured, somewhat iterative, process. The third possibility is that exposure frequency may simply not influence eye movements in a target search task in text or text-like stimuli (Rayner, & Fischer, 1996; Rayner, & Raney, 1996; Wang, Sui, & White, 2019; see also, Vanyukov, Warren, Wheeler, & Reichle, 2012, for an alternative perspective). We believe that further studies are necessary to fully understand the factors that drive frequency effects in tasks that require search for a target character string, pseudoword or word embedded within a horizontal array of comparable distractors.

Next, we will consider how spacing and shading manipulations facilitated eye movements during the scanning of pseudoword strings. Consistent with the findings reported in the Landolt-C study, we found both spacing and alternating shadings facilitated eye movement control with evidence of shorter fixation durations on, and longer saccades to, target triplets in spaced strings and shaded strings compared to unspaced unshaded strings (see also Perea & Acha, 2009; Perea, Tejero, & Winkler,

2015; Zhou, Wang, Shu, Kliegl, & Yan, 2017). The presence of either inter-triplet spaces or alternating shadings very likely facilitated scanning due to the provision of overt visual demarcations of triplet boundaries within the horizontally spatially extended strings. Knowing where a triplet started and ended allowed readers to direct their saccades towards an intended position within that triplet much more readily than when its spatial extent was not visually marked. Also, the presence of spacing/shadings eliminated the occurrence of triplet boundary ambiguity. When letters or characters are immediately adjacent, there is often ambiguity as to whether they belong together as part of a word, or do not (e.g., *understandingeniousideas* vs. *understandingeniousideas*). Also, it is important to note that the facilitatory effects of spacing were greater than those of shading. This is because reduced lateral masking and reduced crowding exist in the spaced strings relative to the shaded unspaced strings. It is well-documented that processing of foveal information is less effective when the neighbouring perceptual units laterally mask and crowd a stimulus (e.g., Wolford, & Chambers, 1983).

Interestingly, we found differential patterns of initial landing position distributions between the Landolt-C study and the present study. In both studies, saccades were more frequently targeted towards the centre of a target in the spaced strings, whereas saccade targeting was shifted towards the beginning of a target in the unspaced strings. This aspect of the landing position data was quite consistent between the two experiments. Importantly, the discrepancy between the studies occurred in the shaded strings. In the present study, participants were more likely to direct their saccades slightly to the left of the centre of a target string when alternating shadings were present. However, in the scanning of shaded Landolt-C strings, initial landing

positions were more likely to land towards the beginning of a target string. Thus, it seems that alternating shadings did not facilitate saccadic targeting in the scanning of Landolt-C strings to a similar degree to which they did in the scanning of pseudoword strings. It is very interesting to consider why the extent to which alternating shadings facilitated saccadic targeting differed across the two experiments. Once again, we believe that this is very likely due to the differential nature of the stimuli used in the two studies. As discussed earlier, Landolt-C clusters provides no information pertaining to sound, meaning, or other linguistic properties and they were very difficult to learn and to identify during scanning. By contrast, English pseudoword triplets are orthographically regular and pronounceable. That is to say, when compared to Landolt-C clusters, pseudowords appear much more word-like. Because of the word-like properties (i.e., fairly regular orthography and fairly simple pronounceability), individual pseudoword triplets are more likely to be processed as a single perceptual unit compared to Landolt-C clusters. Despite the fact that alternating shadings indicated the beginning and end of a cluster unit, due to the nature of the Landolt-C clusters, it remains likely that participants were less effective in processing the visually demarcated cluster as a single perceptual unit. Instead, it seems possible that they were more maintain more piecemeal representations of targets, perhaps resulting in a Landolt-C-by-Landolt-C identification strategy during scanning. In support of this suggestion, the refixation rate on target strings in the Landolt-C experiment was far greater than that in the pseudoword experiment. And consistent with this suggestion, the eyes were more frequently directed to the beginning of a triplet in order to process that triple on the basis of its individual constituent Landolt-Cs rather than as a unified perceptual unit. Conversely, the presence of alternating shadings in the pseudoword strings allowed

participants to capitalise upon the word-like characteristics of the triplets, meaning that participants were able to process them triplet-by-triplet (i.e., process them as more unified perceptual units rather than as their constituent parts). Under such circumstances, it is not particularly surprising to see that participants adopted a saccadic targeting strategy similar to that occurring in natural reading, that is, saccadic targeting towards the centre of an upcoming word unit.

In conclusion, in the present study, robust learning and exposure frequency effects emerged across learning sessions indicating that the novel learning and scanning paradigm developed in Experiment 1 for use with Landolt-C stimuli is also effective for pseudoword stimuli. Different patterns for rates of learning occurred in this study compared to Experiment 1, suggesting that the nature of the stimuli to be learnt directly impacts the speed at which exposure frequency effects in learning are established. Finally, consistent with previous findings, we obtained robust spacing effects but no exposure frequency effects in scanning during target search. Inter-pseudoword spaces facilitated both target identification and saccadic targeting with a reduced effect for alternating shadings relative to unspaced stimuli. Taken together, these findings alongside those of Experiment 1, demonstrate a dissociation in exposure frequency effects during target string learning relative to target string recognition, a direct relationship between the characteristics of novel stimuli to be learnt and the nature of their learning, and the efficacy of spacing as a perceptual boundary demarcation method to facilitate saccadic targeting in scanning.

Chapter 4: Eye movement control during learning and scanning of English Pseudoword strings in Chinese native speakers (Experiment 3)

4.1 Introduction

Word spacing is evidenced to play a critical role in facilitating word identification and saccadic targeting in the reading of normally spaced modern languages (e.g., Rayner, Fischer, & Pollatsek, 1998; Malt, & Seamon, 1978; Spragins, Lefton, & Fisher, 1976; see also Epelboin, Booth, & Steiman, 1994, for an alternative view). For example, removing inter-word spaces from English texts substantially increases reading time, and consequently, reading rates drop by between 30% to 50% (see also Perea, & Acha, 2009, for similar findings in Spanish reading). Similarly, the removal of word spacing disrupts saccadic targeting to a word such that the typical centrally-peaked PVL (i.e., Preferred Viewing Location, Rayner, 1979) that occurs in normally spaced English reading shifts towards the beginning of a word when inter-word spaces are removed.

Most modern languages are printed with word spacing, whereas some languages are printed without inter-word spaces (e.g., Chinese, Japanese, Thai). Given the absence of word spacing in some written languages, in the past three decades, there has been an increased amount of research that has investigated how readers segment word boundaries during the reading of unspaced script, and what factors might affect their saccadic targeting behaviours (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008; Kajii, Nazir, & Osaka, 2001; Kasisopa, Reilly, Luksaneeyanawin, & Burnham, 2013; Kasisopa, Reilly, Luksaneeyanawin, & Burnham, 2016; Li, Liu, & Rayner, 2011;

Sainio, Hyönä, Bingushi, & Bertram, 2007; Winskel, Radach, & Luksaneeyanawin, 2009; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010; Zang, Liang, Bai, Yan, & Liversedge, 2013). Chinese is the most prevalent example of an unspaced language. Modern Chinese is printed from the left to the right, as are most alphabetic languages, however, there are no spaces between adjacent words in Chinese script. The basic linguistic units in written Chinese are characters, 82% of which are standard compound characters comprising two components, that is, a semantic component (referred as a radical) indicating a broad category of the meaning and a phonetic component (referred as a phonetic) suggesting the sound (Hoosain, 1991). In written Chinese, there are about 190 radicals and 1100 phonetics (Shu, & Anderson, 1999). Usually, the semantic component is also the radical of a character, but occasionally, the phonetic component can also be a radical. This is because, historically, the radicals were set up to classify the meaning of the Chinese characters. Also, it is worth noting that, the phonetic component does not necessarily provide full and complete information about the nature of the phonological code. Amongst all phonetics, only 36% provide complete information about the pronunciation of a character, while, 48% reflect partial information overlapping with full pronunciation, and 16% provide no cue to pronunciation at all (Yin, 1991). Each character occupies equally sized box-like space regardless of its visual complexity (i.e., different characters are comprised of different numbers of strokes – basic marks that make up the radicals and characters). A Chinese word might be comprised of single or multiple characters, while 70% of the words in the Chinese language are two-character words (*Lexicon of common words in contemporary Chinese*, 2008). Another characteristic of Chinese that is pertinent to the present experiment is that, unlike most alphabetic languages (e.g., English, Finnish), the relationship between

Chinese orthography and phonology is not direct. That is to say, there is no direct, constant and consistent mapping from the orthography to the phoneme. Alongside traditional Chinese characters (i.e., *hanzi*), in mainland China, a Romanized phonetic system of Chinese characters called *pinyin* (literally, meaning “spelled sound”) was developed in 1956, in which 26 modern English letters are used as the phonetic alphabet. As a consequence, beginning Chinese language readers use *pinyin* to aid their Chinese language reading and writing. To provide an example, the two-character Chinese word “拼音”, is represented in the Romanized pin yin system as “pin yin”). As reading and writing develops, and readers become more proficient in processing Chinese characters, the use of pin yin is discontinued and is no longer used in the reading of unspaced Chinese text. The use of pin yin to support reading and writing during learning lasts for approximately a year. However, it is important to note that, pinyin is widely used in everyday life even though pin yin no longer appears in the books for more advanced readers of Chinese. For instance, the pinyin input method is the dominant method to type the corresponding Chinese hanzi in the use of computers and other digital devices.

As mentioned earlier, it is well-documented that words play an important role in Chinese reading (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008; Shen et al., 2010; see Li, Zang, Liversedge, & Pollatsek, 2015, for a review). Given the psychological reality of words in Chinese and that no word spacing is present in Chinese text, a question naturally arises as to how readers identify word boundaries in the reading of unspaced Chinese text (see Zang, Liversedge, Bai, & Yan, 2011, for a review). Bai et al. (2008) investigated how Chinese text format might potentially affect eye movements

during the reading. In their experiment four text formats were created: normally unspaced, word spaced, character spaced and non-word spaced (shading was used in their second experiment). They found that reading efficiency dropped dramatically in non-word and character spaced conditions relative to normal unspaced text, whereas reading in the word spaced condition was as easy as in the normally unspaced condition. On the basis of these results, two critical arguments were made: First, words are more important linguistic units than characters in Chinese reading; second, word spacing facilitation might be traded off against text format familiarity. That is to say, whilst spacing may play a facilitatory role in reading, it is also the case that there may be a counter-acting cost to reading due to adult Chinese readers being less familiar with spaced text due to their life-long experience of reading unspaced text. As a follow-up study, Shen et al. (2010) examined whether inserting word spacing into Chinese texts would facilitate reading for Chinese beginning readers as they had less experience of reading unspaced text compared to Chinese adult readers. The results indicated that third-year Chinese pupils were able to read spaced text as fast as normally unspaced texts, which was consistent with the previous findings from Chinese adult readers (Bai et al., 2008; Bai, Guo, Cao, Gu, & Yan, 2012; Zang, Liang, Bai, Yan, & Liversedge, 2013). Again, these findings are consistent with the claim of a trade-off between facilitation of word spacing and disruption caused by format unfamiliarity. To minimise the disruption caused by the experience of reading unspaced text, Shen et al. (2012) recorded eye movements of non-native Chinese beginning learners during the reading of Chinese text that was presented in the four spacing formats used in the Bai et al. (2008) experiment. Importantly, in the study testing non-native Chinese beginning readers, Shen et al. (2010) found reading time in the spaced text was significantly shorter than

that in the unspaced text. Note that, such a word spacing facilitation effect was absent for both Chinese adult readers and third-grade child readers. Shen et al. argued that the spacing facilitation arises because explicit word boundaries inform readers where a word starts and ends, and therefore it removes the necessity to segment word boundaries prior to word identification. Shen et al. further argued that this makes it easier to target a saccade effectively to a word for non-native Chinese readers.

Some other studies have investigated whether adding word spacing into Chinese texts might facilitate novel word learning during reading in a learning phase for Chinese children, Chinese adult readers, and those learning Chinese as a second language (e.g., Bai et al., 2013; Blythe et al., 2012; Liang et al., 2017; Liang et al., 2015; Shen et al., 2012; see also Joseph, & Nation, 2018; Joseph, Wonnacott, Forbes, & Nation, 2014; for a similar paradigm of incidental word learning during reading of English texts). Additionally, these studies examined whether word spacing facilitation (if obtained in a word learning phase) might carry over to the reading of normally unspaced Chinese texts in a later test phase. Blythe et al. (2012) reported clear word spacing facilitation during the learning of novel words for both adult and child Chinese readers, however, the spacing facilitation was maintained to the test phase only for child readers. Bai et al., (2013) examined whether the adding of word spacing would facilitate novel word learning during reading using the same learning and test paradigm (Blythe et al., 2012) in second language learners of Chinese. In their study, they demonstrated that non-native Chinese learners benefitted from word spacing during the learning of novel vocabulary, and more importantly, consistent with the findings for Chinese child readers (Blythe et al., 2012), this facilitation maintained to a test phase in which reading was unspaced. Bai and colleagues claimed that adding word spacing in Chinese text helped

to form fully-specified lexical representations of novel words in learning, and such spacing facilitation was more pronounced for less skilled Chinese readers, such as Chinese child readers and those learning Chinese as a second language.

Two other recent studies have used the same learning and test paradigm to investigate whether spacing format and positional character frequency might affect learning of novel vocabularies (Chinese pseudowords) during reading for Chinese child readers (Liang et al., 2015) and adult readers (Liang et al., 2017). Consistent with the Blythe et al. (2012) experiment, both studies found robust word spacing facilitation in novel word acquisition during reading in the learning phase. For Chinese adult readers, Liang et al. (2017) reported that spacing facilitation did not carry over to the subsequent test phase which was consistent with findings from Blythe et al. For Chinese child readers, however, Liang et al. (2015) found that the spacing facilitation failed to maintain to the test phase, which was contrary to Blythe et al. (2012) experiment in Chinese child readers. Liang et al. (2015) argued such inconsistency between the two experiments was likely due to the fact that children varied in age and reading skill across the two experiments. The Grade 3 students in the Liang et al. (2015) experiment were older and more skilled compared to the Grade 2 students in the Blythe et al. (2012) experiment. Liang et al. (2015) suggested that the presence of word spacing information facilitated learning of novel words during reading, however, the extent to which such spacing facilitation might carry over to the test phase decreases with increased age and reading skill.

The literature reviewed above suggests that most of the time, the addition of word spacing into Chinese texts does not facilitate reading for native Chinese speakers

including adult readers and third-grade child readers (Bai et al., 2008; Bai et al., 2012; Shen et al., 2010; Zang et al., 2013), but does facilitate non-native Chinese beginning readers (Shen et al., 2012). It is argued word spacing facilitation is counteracted by format unfamiliarity for native Chinese readers who are familiar with unspaced Chinese text. By contrast, spacing information increases reading efficiency for non-native Chinese beginning learners in that explicit demarcations remove confusability with respect to word boundaries which in turn assists with saccadic targeting. The literature investigating novel word learning during reading indicates that adding spaces between adjacent words in Chinese texts produce facilitation for Chinese adult readers, child readers and also Chinese as a second language learners (e.g., Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017). With respect to whether spacing facilitation that occurs during learning maintains through to subsequent reading of unspaced text, there are mixed effects. Existing findings seem to suggest that beginning Chinese learners show greater probability of carrying over spacing facilitation obtained during learning due to word spacing facilitating the formation of more fully specified lexical representations for new vocabulary. Beyond this, such facilitation effects are more pronounced for less skilled readers (Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017; see also Shen et al., 2012).

To date, little is known about how Chinese native speakers learn English pseudoword stimuli and how spacing format might affect eye movements during the reading of English pseudoword strings. This issue is of particular interest in relation to native Chinese readers given the role of pinyin during Chinese reading development. As mentioned earlier, apart from the traditional character-based Chinese (hanzi), a Romanization system of Chinese called pinyin is used to guide Chinese beginning

readers to learn to read Chinese characters and words. Pinyin is comprised of unique alphabetic forms and four diacritic tones that provide a very directly transparent correspondence to each phoneme of standard spoken Chinese (i.e., Mandarin). In mainland China, first-grade children learn how to read pinyin during the initial 10 weeks in school (Shu, & Anderson, 1999). The Chinese textbooks for first-year students are always printed with pinyin marked above characters to indicate the pronunciation of each corresponding character (see Figure 4.1). In the early stages of learning to read Chinese, pinyin is frequently used to support the acquisition of hanzi - this is largely because, to reach a basic level of Chinese reading proficiency, knowing approximately 2500 characters is necessary. The proportion of pinyin appearing in the text decreases with development of reading ability. It appears that the way Chinese native speakers (as well as non-native Chinese learners) adapt to learn pinyin is very similar to the way English participants in Experiment 2 of this thesis adapted to learn English pseudoword triplets, in the sense that pseudoword triplets are artificial stimuli that do not exist in real English. Likewise, Chinese pinyin is a loaned alphabetic phonetic system that helps those learning to read Chinese characters. Given the long-term experience of learning and using pinyin (that is alphabetic strings that appear rather like pseudowords), it might be the case that Chinese native speakers would be more efficient in learning English pseudoword triplets relative to English native speakers. Furthermore, given that pinyin is used to read character based unspaced Chinese text during a critical period of reading development, it is possible that spacing effects in the reading of English pseudoword strings might be particularly pronounced for Chinese native speakers.

yí	qù	èr	sān	lǐ
一	去	二	三	里，
yān	cūn	sì	wǔ	jiā
烟	村	四	五	家。
tíng	tái	liù	qī	zuò
亭	台	六	七	座，
bā	jiǔ	shí	zhī	huā
八	九	十	枝	花。

Figure 4-1 An example from a Chinese textbook used by first-year primary school students.

Recall that, the second experiment of the present thesis examined how English native speakers learnt novel pseudoword triplets with different exposures in a learning session and how they identified the pre-learnt target pseudowords when they were embedded in sentence-like pseudoword strings under different spacing formats (i.e., unspaced strings, triplet spaced strings, and shaded unspaced strings) in a subsequent scanning session. In the learning session, the learning block effect, the exposure frequency effect and the rate of learning effect (i.e., the interaction between exposure frequency and learning block) were analysed. Also, in the subsequent scanning session, the exposure frequency effect, the spacing format effect and the interactive effect of exposure frequency and spacing format were examined. The key findings from Experiment 2 were: (1) Robust learning effects and exposure frequency effects during the learning of target pseudoword triplets suggested effective learning and observable consequences of differential exposure frequency in learning for native English participants. (2) Robust rate of learning effects in the learning session such that the difference between the time spent processing high frequency (HF) pseudowords relative to the low frequency (LF) pseudowords decreased across blocks. (3) Despite robust exposure frequency effects and effective pseudoword identification in the learning session, exposure frequency of pre-learnt target pseudowords did not influence either

fixation durations or saccadic targeting in the scanning session. (4) Spacing format robustly affected both fixation time and fixation location measures during the scanning of pseudoword strings. Triplet identification was easiest in spaced strings, less so in the shaded unspaced strings and most difficult in the unspaced strings. Likewise, saccadic targeting was facilitated most by the presence of inter-triplet spaces, to a lesser degree by alternating shadings. Inverted-U shape landing position distributions occurred in both the spaced condition and the shaded condition. However, landing position was more left-shifted in the shaded strings relative to the spaced strings. By contrast, native English participants tended to send their eyes towards the beginning of a target triplet during the scanning of unspaced unshaded strings.

In line with Experiment 2 (and also Experiment 1) of this thesis, the present experiment aimed to simulate exposure frequency effects during the learning of pseudoword stimuli and examine how the exposure frequency of pre-learned targets might influence eye movement control during the scanning of pseudoword strings under different demarcation formats. The present experiment will examine these issues amongst Chinese native speakers, a population who actively engage with pinyin when they are moving through a critical period in their reading development – and very importantly, pinyin is formed from constituents which appear very similar to alphabetic pseudowords – the stimuli to be used in the present experiment. A second objective of the present experiment was to examine how Chinese native speakers, who are familiar with the unspaced Chinese script, would potentially benefit from the presence of pseudoword boundary demarcations during the scanning of sentence-like pseudoword strings. A third objective of the present experiment was to examine the extent to which the main findings obtained in Experiment 1 and 2 in which the subjects were native

speakers of a normally spaced language (e.g., English) might also occur for subjects that were native speakers of an unspaced language like Chinese.

To reiterate, the present experiment manipulated the exposure frequency of the target pseudowords to be learnt in a learning session and the spacing format of the strings (spaced, unspaced, and shaded unspaced) to be scanned in a subsequent scanning session. It is important to note that, the pseudoword stimuli used in this experiment (as well as in Experiment 2) were carefully designed not to be real pinyin constituents in order to remove any potential confounding effects from prior experience. The predictions of the present experiment are: (1) As we found in the learning of Landolt-C clusters (Experiment 1) and in the learning of pseudoword triplets (Experiment 2), Chinese participants should learn targets for which they receive more exposures per block more effectively than those for which they receive fewer exposures per block. That is, there should be a main effect of exposure frequency. (2) Processing time spent on target triplets should decrease over blocks, yielding a learning block effect. (3) Most importantly, as found in Experiment 2, the difference between the time spent on processing HF targets and on LF targets should decrease over blocks (i.e., there should be a decrease in the rate of learning effect). (4) during string scanning, the demarcation format of the strings should affect both target identification and saccadic targeting such that the longest processing time and the shortest saccades to words (i.e., the most leftward mean landing positions) will occur for the unspaced strings compared to the spaced and shaded strings. As Chinese adult readers have a life-long experience of reading unspaced Chinese text, it is predicted that the scanning in the shaded unspaced condition will be as easy as in the spaced condition. (5) As (pseudoword-like) pinyin plays a critical role in learning to read unspaced Chinese text, Chinese native speakers

might learn the target pseudoword triplets more effectively in the learning session, and therefore, it seems reasonable to predict that exposure frequency effects might be more likely to be observed during the scanning session in Chinese native speakers in the present experiment relative to English native speakers in the second experiment. If such effects do actually occur in the scanning session, then it is predicted that these effects will be greatest in the unspaced condition compared to the shaded condition and spaced condition. Exposure frequency effects might not differ between the shaded unspaced condition and the spaced condition given that Chinese participants are more familiar with unspaced text format.

4.2 Method

4.2.1 Participants

Thirty-six undergraduate students with normal vision or corrected-to-normal vision, from Tianjin Normal University, took part in this experiment. All the participants were native Chinese speakers. Moreover, each of them had received at least eight years' formal education of English course.

4.2.2 Apparatus, Stimuli, Experimental design & Procedure

The apparatus, experimental design and stimuli used in this experiment were identical to the second experiment in this thesis (Chapter 3). Therefore, this chapter will not describe them in detail. For full details about the apparatus, stimuli, experimental design and procedure, please see the Method Section of Chapter 3. Instead, a brief introduction of the Method of this experiment will be provided here. In this experiment,

there was a learning session in which participants were required to learn and memorise 24 target pseudowords with different exposures and after the completion of learning session, there was a scanning session in which participants were required to scan through horizontally displayed sentence-like pseudoword strings. The strings were displayed under three spacing formats: Spaced strings; unspaced strings; and shaded unspaced strings. The task was to identify whether there was a pre-learnt target embedded in the strings through scanning.

In the learning session, there were five learning blocks in which the frequency of exposure to the target pseudowords was manipulated. Three learning assessments took place after the first, the third and the fifth learning blocks. Note that, in each learning or learning assessment trial, a pseudoword was presented in isolation. In each learning block, targets designated as HF were learnt five times each, in contrast, those designated as LF were learnt one time each. Consequently, over five learning blocks, the total exposure number accumulated to twenty times for HF targets and five times for LF targets. The frequency of exposure assigned to the targets was rotated across participants. During learning, participants terminated a learning trial by gazing on a square box appearing on the right of the display screen. During learning assessment, participants made decision as to whether they had learnt the triplet presented in the middle of the screen by pressing a “yes” or “no” button. Both learning and learning assessment were self-paced.

In the scanning session, the spacing format of the pseudoword strings was manipulated. In the spaced condition, spaces were used to separate adjacent pseudowords. To some extent, the spaced strings appeared similar to spaced but

shuffled English “pseudoword text”. In the shaded condition, alternating shadings were used to indicate the boundaries of neighbouring pseudowords. In the unspaced condition, no visual demarcations of pseudoword boundaries were present.

To reiterate, none of pseudowords used in this experiment were real *pinyin* words in the Chinese writing system. Also, any consecutive three letter sequence within an unspaced pseudoword string could not form a pinyin word in Chinese. The purpose of eliminating the occurrence of pinyin words within the strings was to diminish the disruption associated with interference from Chinese participants’ prior knowledge of Pinyin in relation to the current pseudoword learning and scanning.

4.3 Results

In the learning session, analyses were conducted separately for the learning blocks and the learning assessments. Three eye movement measures were calculated for both learning blocks and learning assessments: First fixation duration; total reading time (i.e., the sum of all fixation durations made in the interest region), fixation number (i.e., the number of fixations made in the interest region). For the learning assessments, three behavioural measures were also computed: Mean accuracy (i.e., the proportion of correct response in both target present and target absent trials), hit rate (i.e., the proportion of correct response in the target present trials), and reaction time (i.e., the response latency in making a decision by pressing a button). In the scanning session, mean accuracy and hit rate were computed before the analyses on eye movement measures. The global measures of eye movements were computed across all pseudowords in a string. Two global measures were computed: Mean fixation duration

and mean saccade length. The local measures were examined in each specific interest region that contained a target pseudoword in a string. Seven local measures were analysed in the scanning session: First fixation duration, gaze duration (i.e., the sum of first-pass fixation durations), total reading time, fixation number, incoming saccade length (i.e., the distance from the first fixation on the target to the final fixation on the pre-target), outgoing saccade length (i.e., the distance from the final fixation on the target to the first fixation on the post-target), and mean landing position (i.e., the distance of the initial landing position from the left boundary of a target pseudoword). Spaces were included for the analysis of incoming saccade length and outgoing saccade length in the spaced strings. The space naturally was not included for the analysis of mean landing position across all the spacing conditions.

Prior to the formal statistical analyses, outliers that were beyond the means ± 3 standard deviations were removed. Consequently, in the learning session, 1.8 % of the data (averaged by measures) were excluded from later analyses. In the scanning session, for the global measures, 2.5% of the data were removed due to the above trimming procedure. For the local measures, 259 trials (10% of all target present trials) were excluded from the analyses in first fixation duration and gaze duration due to skipping occurring or the target pseudoword triplet during first-pass scanning. For total reading time, 55 observations (2% of all target present trials) were removed as outliers. The incoming saccade length was computed as the size of the initial saccade to the target pseudoword triplet from the pre-target pseudoword triplet. In total, 2192 data points contributed to the analyses of incoming saccade length. Similarly, outgoing saccade length was computed as the size of the initial saccade to the post target pseudoword triplet from the target pseudoword triplet. In total, 1677 data points contributed to the

analyses for outgoing saccade length. For mean landing position, there were 2189 data points remaining after the trimming procedure. Note that, only the trials in which both the pre-target triplets and target triplets were not skipped during first-pass scanning were included into the analyses for mean landing position.

Formal analyses were conducted in the R environment (2018) using linear mixed-effects models for continuous data and logistic generalised mixed-effects models for binary data (LMMs, GLMMs, see Bates, Maechler, Bolker, & Walker, 2016). All p values were estimated using *lmerTest* package (Kuznetsova, Brockhoff, Christensen, 2017). On the basis that the raw data exhibited skew, natural log transformations were performed on continuous prior to running the LMMs⁶.

4.3.1 Learning session

In the learning session, the exposure frequency of target pseudowords was manipulated during learning. That is, HF targets received four exposures each per learning block, while, LF targets received one exposure each per learning block. Moreover, the learning of target pseudowords accumulated over five blocks. In total, HF targets were learnt twenty times in contrast to five times for LF targets. This experiment examined the main effects of learning block, exposure frequency and the rate of learning effect (i.e., interactive effect of learning block and exposure frequency)

⁶ There are a few occasions that the analyses based log transformed data showed inconsistency compared to analyses based on untransformed data. The results reported here mainly focus on the log transformed analyses for two reasons: (1) there is skew and therefore a transformation is appropriate; (2) Experiments 1 and 2 reported results based on log transformed data. To perform a log transformed analysis would allow the present experiment to report meta-analyses to formalise comparisons of the nature of the effects across experiments.

in first fixation duration, total reading time and fixation number (see Table 4.1 for the means of each independent variable). The same effects were examined in both the learning blocks and the learning assessments. Note again that, as the treatment in each learning block was identical, learning block was treated as numeric factor in the analyses. Also, high frequency was set as the baseline in the analyses of exposure frequency effects.

Table 4-1 Means of first fixation duration, total reading time and fixation number on target pseudowords in learning and learning assessment. Hit rate and reaction time in the learning assessment were also included.

Learning										
	High Frequency					Low Frequency				
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 1	Block 2	Block 3	Block 4	Block 5
First fixation duration ¹	484 (45)	419 (34)	371 (30)	351 (26)	327 (24)	491 (94)	472 (80)	427 (78)	383 (65)	372 (58)
Total reading time ^{1,2,3}	2938 (271)	1545 (141)	1209 (113)	876 (77)	815 (71)	4671 (546)	3043 (498)	2229 (391)	1344 (258)	1262 (237)
Fixation number ^{1,2,3}	7.8 (0.7)	4.3 (0.4)	3.6 (0.3)	2.6 (0.2)	2.5 (0.2)	12.2 (1.5)	8.4 (1.4)	6.2 (1.1)	3.8 (0.7)	3.6 (0.7)
Learning assessment										
	High Frequency			Low Frequency						
	Learning Assessment 1	Learning Assessment 2	Learning Assessment 3	Learning Assessment 1	Learning Assessment 2	Learning Assessment 3				
Hit rate ^{1,2}	0.94 (0.04)	0.99 (0.008)	0.99 (0.01)	0.64 (0.13)	0.90 (0.06)	0.93 (0.05)				
Reaction time ^{1,2,3}	1634 (245)	1175 (166)	1006 (120)	2500 (477)	1605 (285)	1275 (206)				
First fixation duration	173 (12)	176 (16)	166 (13)	169 (12)	172 (13)	168 (12)				
Total reading time ^{1,2,3}	1433 (206)	1038 (124)	897 (95)	2118 (373)	1377 (230)	1125 (168)				
Fixation number ^{1,2,3}	5.3 (0.8)	3.8 (0.5)	3.4 (0.4)	7.3 (1.3)	5.1 (0.8)	4.2 (0.6)				

Note. All reading times were measured in millisecond. Standard errors are in the parentheses. We used superscript to indicate the effect that occurred for each of the dependent variables. Superscript 1 refers to a significant learning block effect. Superscript 2 refers to a significant exposure frequency effect. Superscript 3 refers to a significant rate of learning effect, that is, the interaction between exposure frequency and learning block.

As shown in Table 4.1, the first fixation duration was longest in the first learning block and decreased across blocks regardless of exposure frequency. The LMMs demonstrated a robust learning block effect in first fixation duration ($\beta = -0.04$, $SE = 0.01$, $t = -3.44$, $P = .001$). Numerically, longer first fixation durations were obtained on HF targets compared to LF targets. However, statistical analysis did not show a significant exposure frequency effect ($\beta = 0.01$, $SE = 0.03$, $t = 0.45$, $P = .66$), or interaction between exposure frequency and learning block ($\beta = 0.01$, $SE = 0.008$, $t = 1.35$, $P = .19$) in first fixation duration during learning. In total reading time, as predicted, robust learning block effects and exposure frequency effects occurred. Specifically, shorter total reading times occurred in the later stages of learning relative to the earlier stages of learning ($\beta = -0.24$, $SE = 0.02$, $t = -11.61$, $P < .001$). Likewise, total reading time was significantly shorter for the HF targets relative to the LF targets ($\beta = 0.64$, $SE = 0.09$, $t = 7.27$, $P < .001$). More importantly, there was a robust interactive effect between exposure frequency and learning block in total reading time ($\beta = -0.04$, $SE = 0.02$, $t = -2.54$, $P = .02$). As shown in Figure 4.2, the difference between the time spent on processing HF targets relative to LF targets reduced across learning blocks. In other words, the magnitude of exposure frequency effect decreased in the later blocks relative to the earlier blocks. This effect might be due to the fact that learning of both HF targets and LF targets was very effective. That is to say, participants learnt both HF and LF targets very well through the later learning blocks until the end of learning regardless of exposure frequency. As a consequence, the difference between the time spent fixating HF targets and LF targets during learning was successively smaller in the later blocks compared to the earlier blocks. Consistent with total reading time, target pseudowords attracted fewer fixations in the later learning

stages than the earlier learning stages ($\beta = -0.20$, $SE = 0.02$, $t = -11.48$, $P < .001$). Furthermore, there were reduced numbers of fixations on the HF targets relative to the LF targets irrespective of learning block ($\beta = 0.66$, $SE = 0.08$, $t = 8$, $P < .001$). Consistent with total reading time, robust learning rate effects occurred for the fixation number measure ($\beta = -0.06$, $SE = 0.01$, $t = -3.80$, $P < .001$) such that the difference between the total fixations made on HF targets and LF targets reduced across blocks.

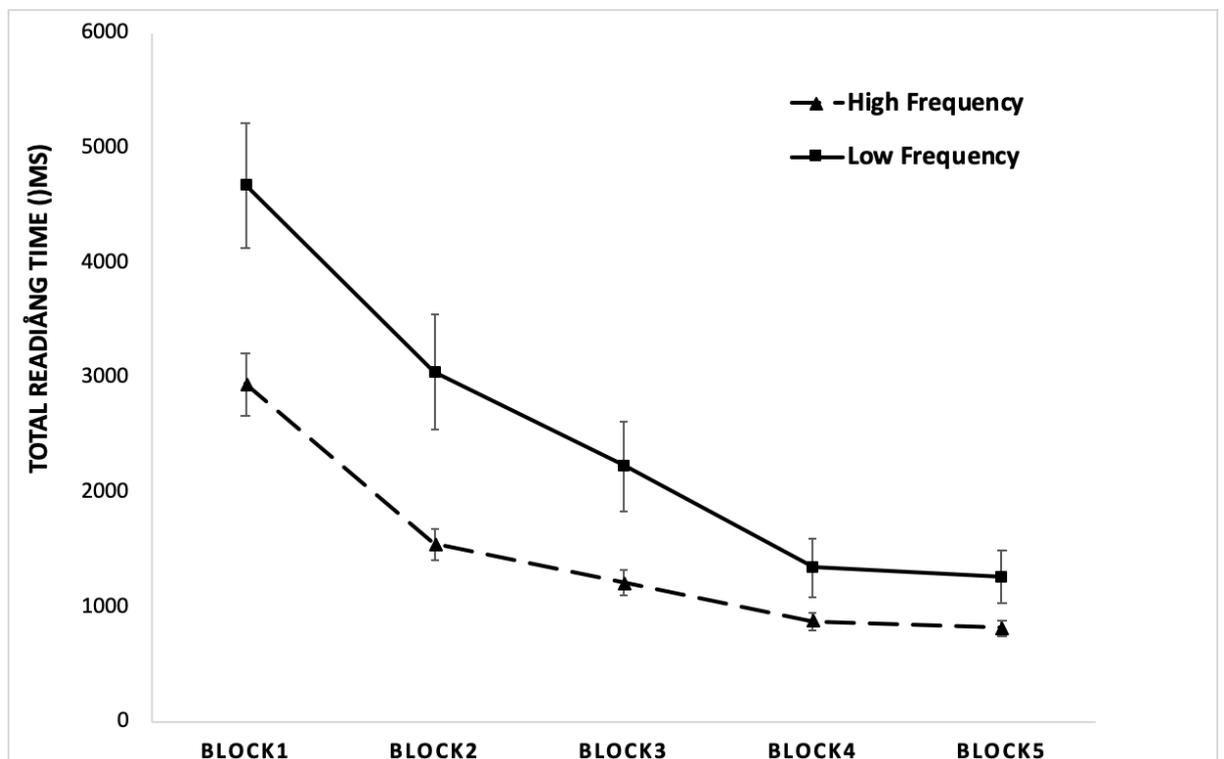


Figure 4-2 Mean total reading times on HF targets and LF targets across blocks. The vertical lines represent standard errors.

Recall that a learning assessment was included after the first, the third and the fifth learning block to evaluate the degree to which participants had remembered the target triplets. In the first learning assessment, mean accuracy was 84%. It increased to 95% in the second learning assessment and 96% in the third learning assessment.

Robust learning block effect occurred in mean accuracy ($\beta = 1.42$, $SE = 0.20$, $z = 7.30$, $P < .001$), which suggested that the learning of target pseudowords progressed significantly over the five learning blocks.

Consistent with mean accuracy, a robust learning block effect also occurred in the hit rate analyses such that greater proportion of targets were recognized in the later assessments than the earlier assessments ($\beta = 0.92$, $SE = 0.25$, $z = 3.74$, $P < .001$). The analysis on hit rate including exposure frequency as another fixed factor in the GLMMs suggested that targets that received four exposures per block were more likely to be correctly identified relative to those that received only one exposure per block ($\beta = -3.16$, $SE = 0.50$, $z = -6.40$, $P < .001$). However, there was no interaction between exposure frequency and learning block in hit rate ($\beta = 0.41$, $SE = 0.28$, $z = 1.50$, $P = .13$). Finally, a third off-line measure, namely, the reaction time in identifying target pseudowords was examined in the learning assessments. The results showed that significantly shorter reaction times occurred when the HF targets were identified relative to the LF targets ($\beta = 0.44$, $SE = 0.08$, $t = 5.76$, $P < .001$), and for the later learning assessments than the earlier assessments ($\beta = -0.25$, $SE = 0.02$, $t = -12.60$, $P < .001$). Furthermore, there was a robust rate of learning effect on reaction time ($\beta = -0.10$, $SE = 0.03$, $t = -3.08$, $P < .001$). The pattern of learning rate effect observed on reaction time was comparable to the that obtained across the learning blocks.

Apart from the off-line measures, eye-movement measures were also examined in the learning assessment. Note that, only the observations from the targets for which the exposure frequency was manipulated during learning were analysed here. In first fixation duration, there was no main effect of learning block ($\beta = -0.003$, $SE = 0.004$, t

= -0.74 , $P = .46$), nor main effect of exposure frequency ($\beta = -0.03$, $SE = 0.05$, $t = -0.57$, $P = .57$). The interaction between exposure frequency and learning block was not significant ($\beta = 0.005$, $SE = 0.008$, $t = 0.62$, $P = .54$). In total reading time and fixation number, similar patterns of results as obtained during the learning of target triplets occurred in the learning assessments. Specifically, longer and more fixations were made on LF targets than HF targets (for total reading time: $\beta = 0.38$, $SE = 0.06$, $t = 6.21$, $P < .001$; for fixation number: $\beta = 0.32$, $SE = 0.06$, $t = 5.11$, $P < .001$). Also, total reading time and fixation number decreased across blocks ($\beta = -0.08$, $SE = 0.006$, $t = -12.98$, $P < .001$; $\beta = -0.07$, $SE = 0.005$, $t = -12.94$, $P < .001$, respectively). More importantly, the exposure frequency effect was modulated by learning block such that the difference between fixations made in identifying HF targets relative to LF targets were greater in the earlier learning assessments relative to the later learning assessments (for total reading time: $\beta = -0.03$, $SE = 0.01$, $t = -3.0$, $P = .004$; for fixation number: $\beta = -0.02$, $SE = 0.01$, $t = -2.36$, $P = .02$). Recall that such a pattern of interactive effect between exposure frequency and learning block also occurred in the learning blocks of the present experiment. More about the rate of learning effects in the learning session is discussed in the Discussion of this Chapter.

Additional meta-analyses were conducted to compare the total reading times and fixation numbers that occurred for the target stimuli during learning across the three experiments reported in the present thesis. To do this, linear mixed-effects models with both subject and item as random factors were constructed. In the full LMMs, exposure frequency, learning block and also Experiment were fit as the fixed factors. These analyses allow us to formalise claims regarding the nature of change in the learning effects across the different experiments. The results showed that significantly shorter

and fewer fixations were made during the learning of pseudoword stimuli in the present experiment relative to the learning of Landolt-C stimuli in Experiment 1 (for total reading time: $\beta = -1.04$, $SE = 0.20$, $t = -5.31$, $P < .001$; for fixation number: $\beta = -0.85$, $SE = 0.18$, $t = -4.65$, $P < .001$). Also, recall that Experiment 2 (Chapter 3) reported that English native speakers learnt pseudoword stimuli more effectively relative to Landolt-C stimuli with the evidence of a robust three-way interaction between exposure frequency, learning block and Experiment on total reading time and fixation number ($\beta = -0.11$, $SE = 0.02$, $t = -5.83$, $P < .001$; $\beta = -0.10$, $SE = 0.02$, $t = -5.81$, $P < .001$, respectively). Together, these findings suggested that pseudoword stimuli were easier stimuli to learn relative to Landolt-C stimuli. Finally, learning was more efficient for Chinese native speakers compared to English native speakers as evidenced by shorter and fewer fixations made on targets during learning in Chinese participants compared with English participants (for total reading time: $\beta = 0.82$, $SE = 0.16$, $t = 5.07$, $P < .001$; for fixation number: $\beta = 0.44$, $SE = 0.15$, $t = 2.98$, $P < .001$). This is exactly what was predicted in the Introduction of this Chapter given that Chinese native speakers should be more familiar with the format of pseudoword stimuli due to the important role of alphabetic pseudoword-like pinyin in their Chinese language development.

To summarise, in the learning session, consistent with Experiments 1 and 2, the present experiment observed robust learning effects, exposure frequency effects and more importantly, the rate of learning effects in both learning and learning assessment. Together, these results suggested that learning was efficient and the exposure frequency effect was simulated successfully in the learning session in Chinese native speakers.

4.3.2 Scanning session

In the scanning session, participants were required to scan through horizontally displayed strings under different spacing formats. The task was to detect whether a pre-learned target was embedded in the string. Therefore, in the scanning session, two main effects were examined, namely, an exposure frequency effect and a spacing effect. Also, the interactive effect between exposure frequency and spacing format was examined.

As shown in Table 4.2, the mean accuracy (including correct identification and rejection) in each spacing condition was around 77%, which suggested the proportion of correct response was identical across the different spacing conditions. Formal analyses showed no main effect of spacing format on mean accuracy (Shaded – Unspaced: $\beta = -0.06$, $SE = 0.09$, $z = -0.72$, $P = .48$; Spaced – Shaded: $\beta = 0.04$, $SE = 0.09$, $z = -0.40$, $P = .69$; Unspaced – Spaced: $\beta = 0.03$, $SE = 0.09$, $z = -0.32$, $P = .75$). On hit rate, when only the

Table 4-2 Means and Standard errors of independent variables examined in the scanning session

Global measures		Unspaced	Shaded	Spaced
Mean accuracy		0.78 (0.39)	0.77 (0.06)	0.77 (0.39)
Mean fixation duration		291 (4)	277 (5)	268 (5)
Mean saccade amplitude		1.51 (0.07)	2.52 (0.12)	2.72 (0.11)
Local measures		Unspaced	Shaded	Spaced
Hit Rate	HF	0.66 (0.12)	0.68 (0.13)	0.68 (0.13)
	LF	0.65 (0.12)	0.69 (0.12)	0.67 (0.13)
First fixation duration	HF	275 (39)	279 (46)	257 (43)
	LF	270 (39)	277 (47)	263 (44)
Gaze duration	HF	700 (106)	645 (97)	642 (85)
	LF	709 (114)	645 (101)	652 (90)
Total reading time	HF	1841 (301)	1346 (255)	1349 (277)
	LF	1864 (325)	1403 (285)	1323 (269)
Fixation number	HF	5.93 (0.95)	4.20 (0.79)	4.37 (0.85)
	LF	5.97 (1.05)	4.51 (0.91)	4.35 (0.87)
Incoming saccade length	HF	1.55 (0.21)	2.48 (0.29)	3.11 (0.30)
	LF	1.57 (0.20)	2.43 (0.27)	3.07 (0.27)
Outgoing saccade length	HF	1.77 (0.29)	2.60 (0.34)	2.91 (0.36)
	LF	1.75 (0.30)	2.47 (0.40)	3.09 (0.37)
Mean landing position	HF	0.74 (0.16)	1.34 (0.22)	1.80 (0.24)
	LF	0.74 (0.15)	1.26 (0.20)	1.77 (0.25)

Note. Standard errors are in parentheses. Time was measured in milliseconds.

target trials were included in the analyses, a similar pattern of results was observed. There was no main effect of spacing format (Shaded – Unspaced: $\beta = 0.15$, $SE = 0.11$, $z = 1.34$, $P = .18$; Spaced – Shaded: $\beta = -0.06$, $SE = 0.11$, $z = -0.56$, $P = .57$; Unspaced – Spaced: $\beta = -0.09$, $SE = 0.11$, $z = -0.78$, $P = .44$), nor a main effect of exposure frequency ($\beta = -0.03$, $SE = 0.10$, $z = -0.29$, $P = .77$). The interactive effect between exposure frequency and spacing format was also not significant (Frequency by Shaded – Unspaced: $\beta = 0.05$, $SE = 0.22$, $z = 0.22$, $P = .83$; Frequency by Spaced – Shaded: $\beta = -0.05$, $SE = 0.22$, $z = -0.22$, $P = .82$; Frequency by Unspaced – Spaced: $\beta = 0.001$, $SE = 0.22$, $z = 0.007$, $P = .10$). The hit rate results, together with the mean accuracy results, suggested that participants' knowledge of memorised target triplets was relatively stable, and therefore their identification performance did not differ as a function of either spacing format or exposure frequency. Note that, the exposure frequency effect and spacing format effect were also absent on hit rate during the scanning of pseudoword strings for English native speakers in Experiment 2 (Chapter 3). It appears that this aspect of the results generalises across participant groups with native languages with very different written forms and different levels of engagement with alphabetic triplets during language learning (i.e., pinyin).

Two global eye-movement measures were used to examine whether the spacing format would affect the decisions of when and where to move the eyes during scanning. The means and standard errors of the two global measures are shown in Table 4.2. As predicted, mean fixation duration was significantly longer in the unspaced condition compared to the shaded condition (Shaded – Unspaced: $\beta = -0.04$, $SE = 0.01$, $t = -2.93$, $P = .006$) and the spaced condition (Unspaced – Spaced: $\beta = 0.09$, $SE = 0.01$, $t = 5.99$, $P < .001$). Furthermore, the mean fixation duration was longer in the shaded condition

relative to the spaced condition (Spaced – Shaded: $\beta = -11.83$, $SE = 3.03$, $t = -3.90$, $P < .001$). The robust spacing effect on mean fixation duration demonstrated that the processing of pseudoword triplets was easiest in the strings where inter-triplet spaces were present, and was most difficult when no visual demarcations of triplet boundary were available. Alternating shadings also benefited pseudoword triplet identification, however, the benefit was smaller than that of spacing. Similarly, robust spacing effects also occurred on mean saccade amplitude. Specifically, mean saccade distance was shortest in the unspaced condition relative to the other two conditions (Shaded – Unspaced: $\beta = 0.49$, $SE = 0.03$, $t = 14.86$, $P < .001$; Unspaced – Spaced: $\beta = -0.60$, $SE = 0.03$, $t = -23.37$, $P < .001$). Furthermore, saccades made in the shaded condition were shorter compared to the spaced condition (Spaced – Shaded: $\beta = 0.11$, $SE = 0.03$, $t = 3.13$, $P = .004$). It appears readers made longer saccades into the strings when those strings contained the visually demarcating information regarding triplet boundaries in the format of either inter-triplet spaces or alternating shadings. However, it is also the case that longer saccades probably occurred in the spaced condition relative to the unspaced condition because the inter-triplet spaces cause strings to be naturally extended in horizontal extent which consequently causes longer saccades to be required for effectiveness in scanning through the strings. This account is consistent with that presented in the previous Chapter. Further, as was also suggested previously, given that the mean fixation duration was shortest in the spaced condition, it is reasonable to suggest that the increased saccade extents here might not be solely due to an increased horizontally extension of the displayed string, but also due to easier scanning as a result of the clear triplet boundary demarcations. Given that there was an inconsistency in the analyses of the raw data and the log transformed data for mean saccade amplitude

between the shaded condition and the spaced condition, further comparisons of the shading and spacing manipulations will be discussed later when the other independent variables can be considered. Again, we reiterate the need for some caution at this stage in the interpretation of this measure.

Next, let us consider the results from the local eye movement measures focused on the target triplets (see Table 4.2 for descriptive statistics). We examined the exposure frequency effect, the spacing effect and the interaction between exposure frequency and spacing format for the local measures. For first fixation duration, there was no main effect of exposure frequency ($\beta = 0.02$, $SE = 0.03$, $t = 0.56$, $P = .58$). In relation to the main effect of spacing format, the analyses based on log transformed data showed that first fixation duration was significantly longer in the unspaced condition relative to the spaced condition ($\beta = 0.12$, $SE = 0.05$, $t = 2.45$, $P = .02$), whereas, a null-effect of spacing format was observed in the analyses using non-log transformed data ($\beta = 9.54$, $SE = 11.33$, $t = 0.87$, $P = .40$). The interaction between exposure frequency and spacing format was not significant in first fixation duration (Frequency by Shaded – Unspaced: $\beta = 0.04$, $SE = 0.08$, $t = 0.51$, $P = .62$; Frequency by Spaced – Shaded: $\beta = 0.02$, $SE = 0.09$, $t = 0.22$, $P = .83$; Frequency by Unspaced – Spaced: $\beta = -0.06$, $SE = 0.07$, $t = -0.81$, $P = .42$).

In gaze duration, again, there was no exposure frequency effect ($\beta = 0.03$, $SE = 0.03$, $t = 0.93$, $P = .35$) nor any interaction between exposure frequency and spacing format (Frequency by Shaded – Unspaced: $\beta = -0.02$, $SE = 0.09$, $t = -0.19$, $P = .85$; Frequency by Spaced – Shaded: $\beta = -0.02$, $SE = 0.09$, $t = -0.18$, $P = .86$; Frequency by Unspaced – Spaced: $\beta = 0.03$, $SE = 0.09$, $t = 0.37$, $P = .71$). As shown in Table 4.2,

mean gaze duration was 645ms in both spaced conditions and shaded conditions irrespective of exposure frequency, whilst, mean gaze duration was 704ms in the unspaced conditions. However, somewhat surprisingly, the analysis based on log transformed data of gaze duration suggested no robust effect of spacing format (Shaded – Unspaced: $\beta = -0.07$, $SE = 0.04$, $t = -1.55$, $P = .12$; Spaced – Shaded: $\beta = 0.06$, $SE = 0.04$, $t = 1.53$, $P = .13$; Unspaced – Spaced: $\beta = 0.0007$, $SE = 0.04$, $t = 0.02$, $P = .99$). In total reading time and fixation number, three findings were described. First, total reading time and fixation number did not differ between HF targets and LF targets ($\beta = 0.002$, $SE = 0.03$, $t = 0.06$, $P = .96$; $\beta = -0.0002$, $SE = 0.03$, $t = -0.01$, $P = .99$, respectively). Second, robust spacing effect emerged indicating that longest total reading time and most fixation number were made in the unspaced condition relative to the other two conditions (for total reading time: Shaded – Unspaced: $\beta = -0.37$, $SE = 0.06$, $t = -6.48$, $P < 0.001$; Unspaced – Spaced: $\beta = 0.44$, $SE = 0.05$, $t = 8.62$, $P < .001$; for fixation number: Shaded – Unspaced: $\beta = -0.37$, $SE = 0.04$, $t = -9.03$, $P < .001$; Unspaced – Spaced: $\beta = 0.39$, $SE = 0.42$, $t = 9.44$, $P < .001$), whereas total reading time and fixation number were comparable between spaced condition and shaded condition (for total reading time: $\beta = -0.09$, $SE = 0.05$, $t = -1.89$, $P = .07$; for fixation number: $\beta = -0.002$, $SE = 0.2$, $t = -0.009$, $P = .10$). Third, there was no significant interactive effect between spacing format and exposure frequency on total reading time or fixation number (for total reading time: Frequency by Shaded – Unspaced: $\beta = 0.06$, $SE = 0.07$, $t = 0.92$, $P = .36$; Frequency by Spaced – Shaded: $\beta = -0.09$, $SE = 0.08$, $t = -1.13$, $P = .26$; Frequency by Unspaced – Spaced: $\beta = 0.02$, $SE = 0.08$, $t = 0.29$, $P = .77$; for fixation number: Frequency by Shaded – Unspaced: $\beta = 0.11$, $SE = 0.06$, $t = 1.65$, P

= .10; Frequency by Spaced – Shaded: $\beta = -0.08$, $SE = 0.06$, $t = -1.20$, $P = .23$;
Frequency by Unspaced – Spaced: $\beta = -0.03$, $SE = 0.06$, $t = -0.45$, $P = .65$).

To summarise, the results from fixation time measures examining target pseudowords suggested that the exposure frequency of target pseudowords simulated in the learning session did not affect the time spent identifying the target in the string during scanning; on the other hand, the results showed robust spacing effects suggesting that both shading and spacing manipulation facilitated target identification. The lack of exposure frequency on fixation time measures was consistent with the findings from Experiment 2 in which English native speakers were examined (Chapter 3). However, perhaps more novel findings relate to the different patterns of spacing effects across Experiment 2 and Experiment 3. Recall that Experiment 2 showed significant differences on fixation times between the spaced strings and shaded strings. Specifically, longer gaze durations, total reading times and more fixations were observed in the shaded condition than the spaced condition in Experiment 2. The discrepancy in relation to spacing format effect on fixation times across the present experiment and Experiment 2 might be due to the fact that Chinese native speakers were more familiar with the unspaced format of the text relative to English native speakers due to the nature of written Chinese text which is unspaced. This will be discussed further in the Discussion section of this chapter.

Next, the results of three fixation location measures will be described: incoming saccade length, outgoing saccade length and mean landing positions. Consistent with the findings on fixation times, no main effects of exposure frequency were observed on incoming saccade length, outgoing saccade length, or mean landing position ($\beta = 0.003$,

SE = 0.02, $t = 0.16$, $P = .87$; $\beta = 0.003$, SE = 0.02, $t = 0.12$, $P = .91$; $\beta = -0.03$, SE = 0.04, $t = -0.79$, $P = .43$, respectively). By contrast, spacing format of the strings significantly affected the fixation location measures. The incoming saccade length to the target triplet was shortest in the unspaced condition compared to the other two conditions (Shaded – Unspaced: $\beta = 0.49$, SE = 0.02, $t = 22.32$, $P < .001$; Unspaced – Spaced: $\beta = -0.72$, SE = 0.02, $t = -33.42$, $P < .001$). Furthermore, incoming saccades length was longer in the spaced condition relative to the shaded condition ($\beta = 0.2$, SE = 0.02, $t = 10.29$, $P < .001$). There were no interactions between exposure frequency and spacing format in incoming saccade length (Frequency by Shaded – Unspaced: $\beta = -0.05$, SE = 0.04, $t = -1.25$, $P = .21$; Frequency by Spaced – Shaded: $\beta = 0.008$, SE = 0.04, $t = 0.18$, $P = .86$; Frequency by Unspaced – Spaced: $\beta = 0.05$, SE = 0.04, $t = 1.09$, $P = .28$). Similarly, the outgoing saccade targeting from the target pseudoword to the right was also shortest in the unspaced condition, longer in the shaded condition and longest in the spaced condition (Shaded – Unspaced: $\beta = 0.39$, SE = 0.03, $t = 12.30$, $P < .001$; Spaced – Shaded: $\beta = 0.17$, SE = 0.03, $t = 5.50$, $P < .001$; Unspaced – Spaced: $\beta = -0.56$, SE = 0.03, $t = -18.52$, $P < .001$). There were no robust interactive effects in outgoing saccade length (Frequency by Shaded – Unspaced: $\beta = -0.07$, SE = 0.06, $t = -1.19$, $P = .24$; Frequency by Spaced – Shaded: $\beta = 0.10$, SE = 0.06, $t = 1.59$, $P = .11$; Frequency by Unspaced – Spaced: $\beta = -0.02$, SE = 0.06, $t = -0.41$, $P = .68$). With respect to mean landing position (the distance from the first fixation on a target to its beginning), again, robust spacing effects occurred such that landing positions were furthest to the right in the spaced condition, more leftward in the spaced condition and nearest to the beginning of a target pseudoword in the unspaced condition (Shaded – Unspaced: $\beta = 0.72$, SE = 0.05, $t = 14.89$, $P < .001$; Spaced – Shaded: $\beta = 0.35$, SE =

0.05, $t = 7.09$, $P < .001$; Unspaced – Spaced: $\beta = -1.07$, $SE = 0.05$, $t = -22.51$, $P < .001$). Again, there were no interactions between spacing format and exposure frequency for mean landing position (Frequency by Shaded – Unspaced: $\beta = -0.11$, $SE = 0.10$, $t = -1.19$, $P = .23$; Frequency by Spaced – Shaded: $\beta = 0.03$, $SE = 0.10$, $t = 0.34$, $P = .73$; Frequency by Unspaced – Spaced: $\beta = 0.08$, $SE = 0.10$, $t = 0.86$, $P = .39$). Formal meta-analysis of mean landing positions between Experiments 2 and 3 was conducted showing a marginally significant interaction between experiment and shading manipulation such that shading facilitation was greater for Chinese native speakers relative to English native speakers ($\beta = 2.40$, $SE = 1.35$, $t = 1.77$, $P = 0.07$).

Finally, the initial landing position distribution will be described. As shown in Figure 4.3, exposure frequency showed little influence on where to target a target in the scanning of strings with different spacing formats. By contrast, it clearly shows that spacing format affected where to send the eyes. There were two general patterns of landing position distributions. In the unspaced condition, consistent with both Experiment 1 and 2, the majority of initial fixations landed on the beginning of a target. By contrast, in the spaced condition and the shaded condition, fixations were more likely to land to the right of the centre of a target pseudoword triplet. The present experiment replicated the general patterns of landing position curves reported in Experiment 2 where English native speakers were examined. However, there was a subtle difference in relation to the extent to which alternating shadings facilitated saccadic targeting across the two experiments.

Again, formal comparative analyses between Experiments 2 and 3 were carried out on initial landing position distributions, however, the linear mixed effects models

failed to converge. Numerically, experiment 2 showed that initial landing position distributions peaked near the centre of a target pseudoword in the shaded and spaced conditions, however, the distribution was more left-shifted in the shaded condition compared to the spaced condition. In the present experiment, for Chinese participants who were familiar with unspaced text format (due to the nature of Chinese reading), the landing position distributions were very similar between the shaded condition and the spaced condition. Potential reasons to explain this discrepancy across experiments will be discussed in Discussion section of this chapter.

Taken together, in the scanning session, exposure frequency showed no influence on either target identification or saccadic targeting despite that exposure frequency effect was simulated successfully during learning. Robust spacing effects occurred on most eye movement measures. On fixation time measures, significantly longer reading times occurred during processing of target pseudowords in the unspaced strings relative to the shaded strings and spaced strings. However, reading time was comparable in the spaced strings and shaded strings. On fixation location measures, the distance of a saccade was longest in the spaced condition, reduced in the shaded condition and shortest in the unspaced condition. Two different patterns of initial landing position distributions were generated, namely, a negative linear distribution in the spaced condition, and inverted-U shape distributions in both spaced and shaded conditions. The results from the scanning session suggested that shadings was more efficient for Chinese native speakers relative to English native speakers in providing demarcation cues for pseudoword boundaries. A plausible explanation is that this may be due to Chinese readers being more familiar with unspaced text format due to the nature of written Chinese (an unspaced language).

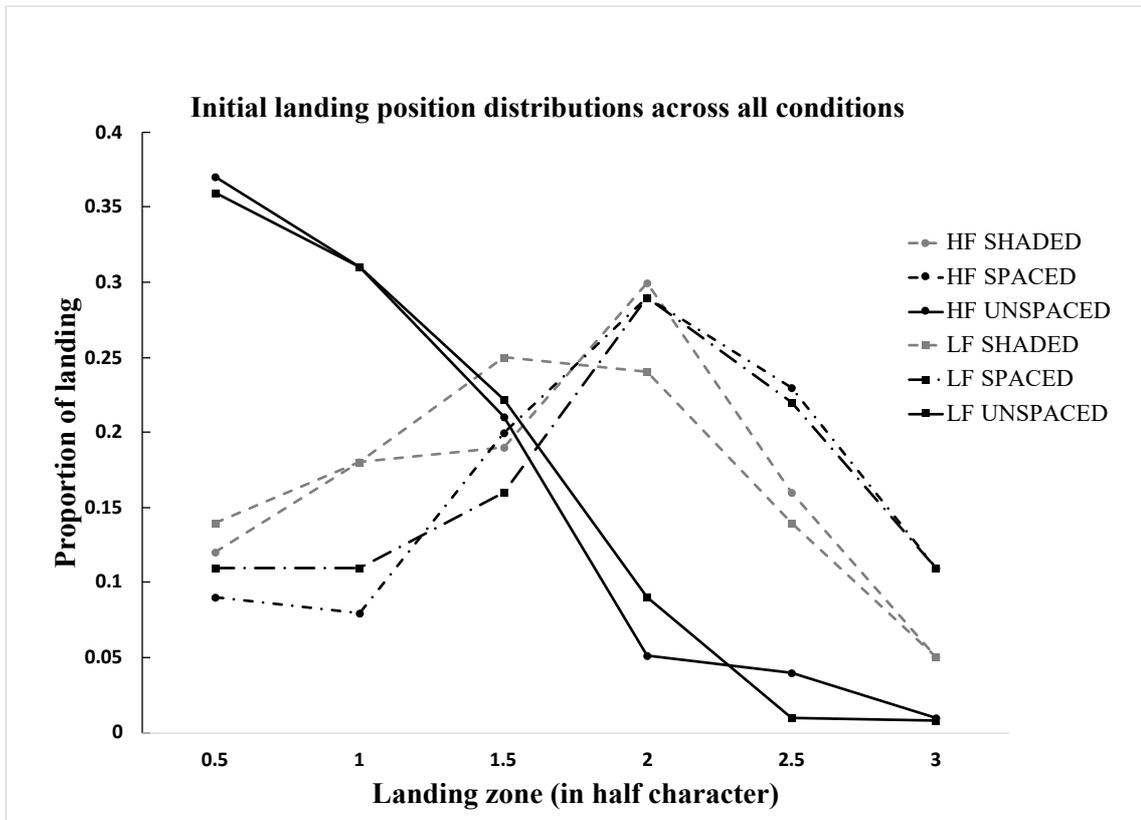


Figure 4-3 Initial landing position distributions on the target triplet across all conditions in the scanning session.

4.4 Discussion

The present experiment investigated how exposure frequency effects might be established during the learning of alphabetic pseudoword stimuli in a learning session and how the visual familiarity of these pre-learned target strings might affect eye movement control during the scanning of sentence-like pseudoword strings with or without physical demarcations of pseudoword boundaries in a subsequent scanning session. Also, the present experiment examined Chinese native speakers, a population

who use alphabetic (pseudoword-like) pinyin as a guidance to read unspaced Chinese text in their initial stages of Chinese reading development.

In the learning session, robust learning block effects and exposure frequency effects occurred in both learning and learning assessment of target pseudowords. Time spent processing target pseudowords reduced in the later stages relative to the earlier stages of learning. Moreover, HF targets that received four exposures per learning block attracted shorter and fewer fixations compared to LF targets that received one exposure per block. More importantly, robust interactive effects between learning block and exposure frequency occurred in the learning session. In general, these findings replicate and extend the findings from Experiment 1 and 2 in the present thesis.

Consistent with Experiments 1 and 2, basic learning effects occurred in the present experiment indicating that the visual familiarity of novel items increased as a function of learning block. As total exposures to the target pseudowords increased over blocks, participants were more visually familiar with the targets being displayed on the screen in the later stages of learning relative to the earlier stages of learning. Therefore, during learning, less time was required to fully represent and store the target pseudowords in memory in later learning blocks. Likewise, less time was spent identifying a target in the later learning assessments presumably since the displayed target was more visually familiar and better represented in memory. The robust learning block effects demonstrated that Chinese participants were able to learn alphabetic triplet pseudoword stimuli effectively and successfully. The occurrence of robust learning block effects across Experiments 1, 2 and 3 demonstrates the efficacy of newly

developed novel stimuli learning paradigm adopted in the present thesis to examine the nature of learning novel stimuli in isolation.

As predicted, the learning of target pseudowords was more effective for Chinese native speakers relative to English native speakers with the evidence that the mean total reading time spent processing the target pseudowords was about 156ms longer for English participants compared to Chinese participants. This may be due to two possible reasons: First, presumably Chinese readers are more familiar and practised with the process of learning this type of stimulus, given that it is something they have done thousands of times when learning pinyin in order to learn new Chinese characters for reading. As mentioned earlier, pinyin is a Romanised orthography system to represent the sound of character-based Chinese. In other words, pinyin does not exist primordially in Chinese language, but is loaned from the Roman alphabet and reformed to meet the increasing need for literacy education and international communication since the 1950s. Chinese beginning readers learn the knowledge of pinyin initially before they are able to use it to read novel characters or words in Chinese text. Also, the use of pinyin extends to broad areas in everyday life, not just as the phonetic guidance of reading Chinese text in beginning readers. It is because of the massive practice of learning and using pinyin in the early stages of learning to read Chinese and numerous exposures to pinyin in everyday life in Chinese native speakers, that Chinese participants might likely be more effective in learning similar alphabetic strings such as the pseudowords in the current study, relative to English participants. It should be clear that the pseudoword stimuli used in the current thesis were not real pinyin stimuli that exist in the Chinese language. That is to say, the pseudoword stimuli did not correspond to any existing morpheme in Chinese and this was ensured in order to avoid any confounds related to the prior

knowledge of the participants. Second, due to the process of Chinese character learning, it might also be the case that there are a greater number of existing pinyin representations in memory for Chinese readers relative to English readers. These would form an existing basis in memory within which the present novel pinyin-like pseudoword stimuli might be integrated and represented.

Again, consistent with Experiments 1 and 2, the exposure frequency effect was simulated successfully in the learning of target pseudowords in Chinese participants. Shorter and fewer fixations were made on targets that received four exposures per learning block relative to those that received only one exposure per learning block in both learning and learning assessment. The frequency of target exposures that occurred during learning determined the ease of accessing target representations in memory. This is consistent with the typical word frequency effects reported in lexical decision and reading studies (e.g., Just & Carpenter, 1980; Rayner & Duffy, 1986; for a full review, see Rayner, 2009; Schilling, Rayner, & Chumbley, 1998). Thus, the present experiment, together with Experiments 1 and 2, demonstrates that the way the experiments in the present thesis simulate exposure frequency effects (in learning and learning assessment) was reliable and produced robust effects that were replicable. Furthermore, the present experiment extended our knowledge of how exposure frequency effects might be established during learning.

A more interesting finding in the learning session of this experiment was the occurrence of robust interactive effects between learning block and exposure frequency, that is, the rate of learning effects as also detailed in Experiments 1 and 2. As predicted, the rate of learning effects obtained in the present experiment shared a similar pattern

with those reported in Experiment 2. As shown in Figure 4.2, the difference between the time spent processing the HF targets relative to the LF targets decreased across blocks, that is, the magnitude of the exposure frequency effect decreased over blocks. This might be because the point at which learning effects reached a plateau was different for HF targets and LF targets. To be clear, the learning of HF targets reached a plateau earlier relative to LF targets due to the increased number of exposures per block (four), which accelerated learning to a greater degree than just one exposure per block for the LF targets in the earlier stages of learning. Once the HF target learning performance reached a plateau, any further improvement would be comparatively small. In contrast, learning for LF targets would have taken exposures over a substantially greater number of blocks than existed in the experiment in order to reach similar levels of performance. If, for example, there had been twenty learning blocks, then it seems likely that the difference in performance levels would continue to reduce with levels of plateaued performance becoming more and more similar across the very extended number of learning blocks. However, this argument alone is not sufficient to explain why mean total reading time averaged across the first four exposures (i.e., four exposures across learning blocks 1-4) was shorter on LF targets (2821ms) relative to total time for HF targets (2938ms) averaged across a comparable number of exposures (i.e., four exposures in learning block 1). Such a difference was also obtained in Experiment 2 wherein English native speakers were examined (3483ms on first four exposures for HF targets vs. 2839ms on first four exposures for LF targets). As previously suggested, this might be due to the way the targets were presented during learning, which differed between HF targets and LF targets. Studies as early as Ebbinghaus (1885) have described a temporal spacing effect whereby learning is more effective when the same

amount of information is repeated in a time spaced fashion relative to a time massed fashion. In the present study, learning of LF targets was more temporally spaced than learning of HF targets as LF targets received one exposure per block while HF targets received four exposures per block. This could explain the increased learning effect observed for the LF relative to the HF targets across a comparable number of exposures.

Next, let us consider the findings from the scanning session in which participants were required to detect whether one of the pre-learned targets was embedded in the sentence-like pseudoword strings. It was predicted that there might be a greater probability to observe exposure frequency effects in the scanning session in the present experiment compared to Experiment 2 in that Chinese native speakers might learn pseudoword stimuli more effectively in the learning session given that they had more experience learning pseudoword-like pinyin. It was the case that Chinese participants spent less time processing the target pseudowords in the learning session relative to English participants, indeed, demonstrating more effective learning. However, the exposure frequency effects simulated effectively during learning still did not carry over to the scanning session in the present experiment. The lack of exposure frequency effects in the scanning session in Chinese native speakers was consistent with the results observed from English native speakers in Experiment 2 (and also, the results of Experiment 1, though both participants and stimuli differed in this experiment). It is noteworthy that in Experiment 2 and the present experiment, participants were able to quite effectively identify target pseudowords within the strings. Thus, the lack of exposure frequency effects on eye movements in target detection during scanning could not result from the inability to recognize the target embedded in the sentence-like strings. More likely, the lack of effects arose for similar reasons to those discussed in

Experiment 2. First, the difference between the frequency of exposures associated with HF targets relative to LF targets might be too small to induce differential exposure frequency effects in target detection during scanning. That is to say, many more exposures may simply be required to establish this form of effect in recognition. Second, detecting a target embedded in the strings was significantly more difficult relative to the identifying the target presented in isolation, which presumably diminished the likelihood of obtaining exposure frequency effects in the scanning session. Probably, recognition in a scanning situation is much less automatic and reflexive than is the case for isolated string recognition (in which situation, recall, exposure frequency effects were obtained, i.e., in the learning assessment blocks). A third possibility, consistent with arguments provided in previous chapters, is that exposure frequency might simply not affect eye movement control during a target detection task in scanning (see also, Rayner, & Fischer, 1996; Rayner, & Raney, 1996; Wang, Sui, & White, 2019). Further studies are required to investigate what determinants affect the emergence of exposure frequency effects in a task that necessarily involves lexical access during scanning.

Despite the fact that the exposure frequency effect did not maintain to the scanning session, spacing format did significantly affect eye movement control during the scanning of pseudoword strings in Chinese native speakers. The global measures indicated robust main effects of spacing format such that shortest mean fixation duration occurred in the spaced condition, durations were longer in the shaded condition and longest in the unspaced condition. Likewise, the longest saccade amplitudes occurred in the spaced condition, these were reduced for the shaded condition and were shortest in the unspaced condition. The results from the global measures replicated the findings

from Experiments 1 and 2. The fact that spacing effects consistently occurred for the global measures across the three experiments suggests that the use of physical demarcation cues was very influential in directing eye movements during search for a target in scanning, and such effects were quite similar regardless of the nature of stimuli and the native language of the participants. Moreover, the consistently robust spacing effects that occurred in this thesis demonstrate that boundary information is very important in relation to oculomotor control even in a non-reading scanning task.

Four reasons are provided here to explain why spacing exerted such a facilitatory influence on scanning relative to the situation in which no explicit pseudoword triplet boundary information was present. First, spaces between neighbouring pseudowords clearly delimited the left and right boundaries of a pseudoword, therefore, it removed the necessity to identify pseudoword boundaries necessary for segmentation in the parafovea before direct fixation. Second, given unambiguous information about the start and end of a pseudoword, the oculomotor system was enabled to direct a saccade to a target location within it more accurately and readily. Whilst this statement may appear self-evident, it remains the case that accurate targeting arose as a consequence of boundary demarcation. Third, the presence of spacing information reduced the ambiguity regarding into which pseudoword any specific letter should be grouped. Such ambiguity is not uncommon in normally unspaced Chinese text. For instance, in a Chinese sentence “鲜花生长在花园里” (meaning “Flowers grow in the garden”), combining the second character with the third character forms a word “花生” (i.e., “peanut” in English), while, combining the third character and the fourth character forms another word “生长” (i.e., “grow” in English).

The correct segmentation for this instance is the latter which contributes to the meaning of the whole sentence. Clearly, there is an analogous parsing problem for the unspaced pseudoword strings that spacing would have removed in the current experiment.

Finally, the use of spacing naturally extended the distance between adjacent pseudowords, which accordingly increased the perceptual salience given that reduced lateral masking and crowding occurred for the spaced relative to the unspaced strings.

Consistent with previous findings from the reading literature, alternating shadings facilitated the present pseudoword scanning, however, the degree of facilitation by shading was relatively smaller than the spacing facilitation (e.g., Perea et al., 2009; Perea et al., 2015; Perea, & Wang, 2017; Zhou, Wang, Shu, Kliegl, Yan, 2018). Despite alternating shadings demarcating pseudoword boundaries clearly, there remained evident lateral masking and crowding in the shaded unspaced strings compared to the spaced strings. Thus, it is no surprise to find a longer mean fixation duration and shorter mean saccade amplitudes for the shaded strings relative to the spaced strings.

As mentioned earlier in the Introduction of this chapter, a series of studies have investigated whether adding word spacing into unspaced Chinese text would possibly improve reading efficiency for Chinese native speakers across the life-span and for those learning Chinese as a second language (Bai et al., 2008; Bai et al., 2012; Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017; Shen et al., 2010; Shen et al., 2012; Zang et al., 2013; See also, Ma, 2017). Most of the time, for Chinese adult readers, including word spacing in Chinese text does not facilitate or inhibit reading efficiency. It is maintained that there is a trade-off between word spacing facilitation

and unfamiliarity of spaced text format given that Chinese readers have extensive experience reading unspaced Chinese text. By contrast, the addition of word spacing in Chinese text robustly increased reading rates for those learning Chinese as a second language. These findings from previous studies seem to suggest that reading experience and reading skill are critical determinants that affect whether word spacing facilitation will appear during Chinese reading. The present experiment found that the total time spent on target pseudowords did not differ between the spaced condition and the shaded condition, whereas in both conditions the total processing time was shorter than that in the unspaced condition. Chinese native speakers appeared to benefit from alternating shadings as much as from pseudoword spacing. However, recall that, in Experiment 2 of this thesis, total time measures showed a greater facilitation from spacing relative to alternating shadings during the identification of target pseudowords for English native speakers. That is, there is a discrepancy in the extent to which alternating shadings facilitated target identification between Chinese native speakers and English native speakers. One might expect reduced facilitation from alternating shadings relative to pseudoword spacing because of increased lateral masking and crowding in the shaded string condition (as was the case for English native speakers in Experiment 2). However, it might be unsurprising to observe similar facilitatory effects between pseudoword spacing and alternating shadings in the present experiment given that Chinese participants were more effective in learning the target pseudowords in the learning session (also, they were more effective in identifying the target pseudowords in the scanning session as evidenced by shorter processing times for the target pseudowords for Chinese participants compared to English participants). This increased effectiveness in processing shaded unspaced strings probably arose due to Chinese

readers' life-long experience of reading unspaced Chinese text. To be clear, the inhibitive effect arising from lateral masking and crowding in the shaded unspaced strings was likely to be neutralized by the familiarity of both the unspaced text format and pseudoword stimuli for Chinese participants.

The incoming saccade, outgoing saccade and mean landing position on the target pseudowords exhibited spacing effects that were very complementary to the effects observed on the global measures. Specifically, longest incoming saccades, outgoing saccades and the most rightward mean landing positions occurred in the spaced condition, to a lesser degree in the shaded condition, with the results for the unspaced condition falling in between. Whilst the current processing time results did not differ between the spaced condition and the shaded condition, the saccade extents were significantly longer in the spaced condition than the shaded condition. As discussed earlier, alternating shadings were probably less facilitatory in guiding eye movements due to increased lateral masking and crowding. However, such inhibitory effects caused by lateral masking and crowding might be counteracted by a sense of familiarity on the unspaced format for Chinese participants. Therefore, it seems unlikely that this might be the major reason for the shorter saccades in the shaded unspaced condition. A second, probably more reasonable suggestion, is that in the spaced condition the spaces between contiguous pseudowords naturally extended the global horizontal extent of a string, and therefore, saccades were naturally longer in order to effectively move the point of fixation through the spaced string relative to shaded unspaced strings.

In considering the results overall, it does appear that there is evidence to support the suggestion that the extent to which participants could benefit from either spacing or

alternating shadings was qualified by their experience in reading unspaced text . This argument was further supported by the initial landing position distributions on the target pseudowords in the present experiment. Recall that, in Experiment 2, English native speakers were more likely to send their eyes to a target pseudoword's beginning in the unspaced strings, slightly to the left of the centre of a target in the shaded strings and slightly right of the centre of a target in the spaced strings. By contrast, in the present experiment, Chinese native speakers were more likely to land towards the right of the centre of a target in both the spaced and shaded strings. It seems like that Chinese participants were able to similarly utilize alternating shadings as they were spacing as a useful cue in directing saccadic targeting in the scanning of pseudoword strings. By contrast, English native speakers who were more experienced in reading spaced text, were less effective in their use of alternating shadings in the guidance of eye movements in pseudoword string scanning.

In conclusion, the present experiment replicated and extended the findings from previous experimental chapters. In the learning session, the occurrence of robust learning block effects suggested that the learning of pseudowords and the simulation of exposure frequency were effective and successful in Chinese participants. Despite exposure effects being simulated effectively in the learning session, they did not occur in the scanning session. In the scanning session, spacing format affected both the target identification and saccadic targeting. It seems that Chinese native speakers benefitted more from alternating shadings in relation to eye movement guidance in scanning relative to English participants. Saccadic targeting was facilitated similarly for the shaded strings and the spaced strings for Chinese participants, probably due to Chinese participants' increased experience processing unspaced stimuli during reading.

Chapter 5: General Discussion

The present thesis set out to examine oculomotor control during the learning and scanning of sentence-like strings by manipulating the exposure frequency of novel stimuli in a learning session and the spacing presentation format of the strings in a scanning session across three experiments. Experiment 1 examined how native speakers of spaced alphabetic languages learnt target Landolt-C clusters with high or low exposures in a learning session and how these pre-learnt target clusters might be identified when they were embedded in longer horizontal Landolt-C strings that were presented under different spacing formats. Instead of using Landolt-C stimuli, Experiment 2 examined whether using more word-like pseudoword stimuli would be more effective in simulating exposure frequency effects in the learning session and accordingly might increase the likelihood to observe exposure frequency effects in the scanning session amongst English native speakers. Experiment 3 applied the same pseudoword learning and scanning paradigm to investigating Chinese native speakers, a population who use alphabetic pseudoword-like pinyin to assist with their initial stages of learning to read character-based Chinese text and who are also experienced in reading unspaced Chinese text. Given their unique experience, presumably, Chinese native speakers might be more efficient in learning target pseudowords, which accordingly might produce a more effective simulation of exposure frequency effects in the learning session and therefore increase the likelihood that the exposure frequency effects might maintain through to the subsequent scanning session. In this final chapter of the present thesis the key findings across the three experiments will be discussed more generally, as well as the potential implications of the present thesis as a whole

from both theoretical and practical aspects. Section 5.1 will discuss the basic learning block effects that arose consistently but with differing magnitudes across Experiments 1, 2 and 3. Section 5.2 will consider the main effects of exposure frequency that were simulated successfully in the learning sessions across the different stimuli (i.e., Landolt-C stimuli vs. pseudoword stimuli) and across participants (i.e., English native speakers vs. Chinese native speakers). Section 5.3 will discuss the rate of learning effects that were dissimilar between learning Landolt-C stimuli (Experiment 1) and learning pseudoword stimuli (Experiments 2 and 3). In Section 5.4 the finding that exposure frequency effects arose in both learning and learning assessments across experiments but did not arise in the scanning session will be considered. Section 5.5 will assess the roles that spacing and alternating shadings might play in oculomotor control during the scanning of Landolt-C strings and pseudoword strings, in English readers and in Chinese readers. Section 5.6 will discuss saccadic targeting in the scanning of strings with or without boundary information. Finally, Section 5.7 will draw general conclusions based on the overall findings reported in this thesis, discussing the potential implications of the present thesis and related research that may be worthy of investigation in the future.

5.1 Learning block effects in the learning session

The present thesis examined how the learning of Landolt-C clusters (Experiment 1) and pseudoword triplets (Experiments 2 and 3) progressed over five blocks. Regardless of exposure frequency, time spent on processing the targets decreased over blocks indicating the learning of targets progressed over exposures. This type of learning effect was observed across all three of the experiments reported in this thesis. It

is argued that learning block effects occurred because as learning block increased, participants received more exposures to the targets, with each additional exposure presumably enhancing the process of instantiating and storing the representations of the novel items in memory.

Despite the general pattern of learning effects being consistent across the experiments in this thesis, the size of learning effects appeared to vary as a function of the stimulus type being learnt and the population being tested. First, learning was more efficient when pseudoword stimuli were used relative to Landolt-C stimuli. Unlike non-linguistic Landolt-C clusters, pseudowords in the present thesis were pronounceable three-letters string in which each constituent letter already existed in the alphabet that was known by the participants. Probably, the word-like characteristics of the pseudowords contributed to the greater learning efficiency in both Experiment 2 and 3 (where such stimuli were used) relative to Experiment 1 (where Landolt-C stimuli were used). It is very likely that the more word-like stimuli were easier to instantiate and integrate into memory because they were more comparable to existing lexical representations and therefore might more readily be integrated within existing structures. This was not the case for the Landolt-C stimuli for which there were few, if any, existing memory representations, nor structured systems within which they could be readily incorporated. Second, the learning of pseudowords was more effective for Chinese participants than English participants. This was very likely because of both the format of pseudowords, that is, their pinyin-like appearance and the process of learning pseudowords in the pseudoword experiments was more familiar to Chinese relative to English native speakers since they were experienced using pinyin to spell out the sound

of Chinese characters in the early stages of learning to read character-based Chinese text.

The occurrence of learning effects across the three experiments demonstrated that the novel learning and scanning paradigm developed in the present thesis effectively captures and reflects aspects of the nature of learning novel stimuli in isolation, and then searching for them when embedded in horizontal arrays of distractors. Despite that the rate and the extent to which learning occurred, the process of actually establishing novel items in memory occurred in all three experiments and to the extent that memory representations were established and were accessible, this fundamental aspect of the results was similar across the learning stimuli and the populations that were examined.

5.2 Exposure frequency effects in the learning session

The present thesis manipulated the exposure frequency of the targets to be learnt in the learning session in order to examine how exposure frequency effects might develop during the learning of either Landolt-C clusters or pseudoword triplets in isolation. Robust exposure frequency effects occurred across all experiments in the present thesis. Targets with four exposures per block were learnt faster and more effectively relative to those with just one exposure per block. This is because the visual familiarity of the targets increased with increased stimulus exposure. The more visually familiar a target was, the less the time was required to access the representation in memory in order to recognize it during a subsequent encounter.

The finding that exposure frequency effects constantly occurred across the three experiments in this thesis was of great significance. First, it demonstrated that the novel word learning paradigm was reliable, and was effective when used to simulate exposure frequency effects during learning that were replicable. Second, it extended our knowledge in relation to the range of stimuli and participant populations that might demonstrate similar frequency effects during learning. Also, given that the exposure frequency effects appeared in the learning assessments as well as the eye movement data across learning trials, one might consider that these effects were somewhat analogous to the well-documented word frequency effects observed in learning during reading and lexical decision tasks (Joseph et al., 2014; Joseph et al., 2018; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017; Hulme, Barsky, & Rodd, 2019; Pagán, & Nation, 2019; Rayner & Duffy, 1986; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Schilling, Rayner, & Chumbley, 1998; Whaley, 1978). Third, at some level, the effective simulations of exposure frequency effects in both the learning and learning assessments of the present experiments might be informative as to how word frequency effects might become established in languages (at least during the earliest stages of novel word acquisition). Of course, an important caveat must be made here, namely, that the stimuli that were used in the present were (quite purposefully) not real words and attributes of semantic meaning were absent. Presumably, proper words would involve the development of richer lexical representations in memory, and therefore, perhaps frequency effects for real novel words might develop even more rapidly than effects reported here. This is an empirical question for future investigation. What is clear is that despite the fact that word frequency effects are prevalent, well-documented, and word frequency is considered one of the most important lexical characteristics of

words, as well as one of the primary influences over lexical processing, little is known about how such effects are established (c.f., Williams & Morris, 2004).

5.3 The rate of learning effects

Perhaps the most important effect from the learning sessions reported in the current thesis was the rate of learning effects that occurred across the experiments. Recall that the rate of learning effects reflected the interaction between exposure frequency and learning block. In general, all the experiments of this thesis found robust rate of learning effects, however, the pattern of those effects varied across the experiments. Experiment 1 showed an increase in the differences in time spent learning and identifying HF target Landolt-C clusters relative to LF target Landolt-C clusters across blocks. In other words, the rate of learning effect observed in Experiment 1 was such that the magnitude of the exposure frequency effect increased across blocks with the learning block effect being larger for HF targets relative to LF targets. By contrast, in Experiments 2 and 3, a rate of learning effect with the opposite pattern was observed during the learning of pseudoword triplets such that the magnitude of exposure frequency effect decreased across blocks, and learning for HF targets reached a reduced plateau much earlier than the learning of LF targets. Throughout this thesis, it has been argued that the major reason for the different rate of learning effects across experiments was the nature of stimuli. The Landolt-C stimuli adopted in Experiment 1 were much more difficult to learn compared with the pseudoword stimuli adopted in Experiments 2 and 3. It seems that the ease, or difficulty, of learning materials determines how the learning curve presents. Learning difficult stimuli presents a long gentle learning curve such that learning progresses at a slow rate in the initial stages as was the case in

learning Landolt-C clusters (Experiment 1). In contrast, learning relatively easy materials presents a much shorter learning curve such that the learning rate is rapid resulting in a curve that is steep in the initial stages and then plateaus, meaning that further improvements over successive learning exposures will result in only very minor reductions in processing time during learning. This was the case in the learning of pseudowords (Experiments 2 and 3). Presumably, if more learning blocks, and therefore exposures, were presented to participants when learning Landolt-C stimuli, the learning curve would likely show three clear distinctive stages of learning – a slow progressive stage in the beginning, a more steep progression in the middle, and eventually a plateau during the final stages of learning. However, as noted, to see the full pattern over extended learning would require a greater number of learning blocks than was used in Experiment 1, and consequently, the present suggestions remain speculative. Finally, it is also worth mentioning that, in line with the broader set of learning effect findings in the present thesis, any such learning curve would demonstrate qualification by exposure frequency such that HF targets would show more rapid learning effects relative to LF targets.

5.4 Exposure frequency effect in target detection during scanning

One important question that was of particular focus in the present thesis concerned whether exposure frequency effects would occur in searching for a target string during subsequent scanning. Previous studies have shown that the typical word frequency effects that are observed in reading do not appear during the search for a target word in normal text (Rayner & Fischer, 1996; Rayner & Raney, 1996; Wang, Sui, & White, 2019). To date, only one published work has demonstrated the occurrence of

exposure frequency effect in searching. In this study participants searched for a target “O” within horizontal displays of Landolt-C strings (Vanyukov et al., 2012). The present thesis argued that word frequency effects are absent in most target word search tasks because lexical access is not necessary in order to complete the task per se. To examine this argument, exposure frequency effects were simulated by training participants to learn novel stimuli with different exposures in a learning session and then requiring them to detect these targets (with differing levels of visual familiarity) in longer sentence-like strings in a subsequent scanning session. It was anticipated that there should be an increased likelihood of observing an exposure frequency effect in the present studies given that the targets to be detected in the strings were those for which exposure frequency was manipulated (and for which there were demonstrable effects in learning). And, of course, in the present study, it was the case that during the scanning task participants were required to identify targets in memory (i.e., engage in a process analogous to lexical identification) in order to identify the targets successfully. To be clear, by forcing participants to discriminate targets from distractors in the strings (i.e., engage in recognition), the task requirements were such that the likelihood of obtaining frequency effects in scanning was maximised.

In all the experiments of this thesis, the exposure frequency effect was simulated successfully in the learning session. In Experiment 1, despite learning being effective in the learning session, participants were unable to maintain their memory of pre-learnt target Landolt-C clusters through to the scanning session. This might be a likely reason that exposure frequency effects did not occur in the scanning session given that ineffective detection during the scanning suggests that identification did not often occur. This in turn means that frequency effects in scanning did not have an opportunity to

occur (since identification is likely a pre-requisite for a frequency effect to be apparent). In contrast, in Experiments 2 and 3, both learning in isolation and the target detection in scanning was effective. Nevertheless, exposure frequency effects were still absent in the scanning session. Two potential reasons were provided in this thesis to account for the lack of exposure frequency effects in searching for a target within pseudoword strings. First, the exposure frequency effects simulated in the learning session might still not be sufficient to lead to frequency effects in recognition in scanning. In the present thesis, HF targets received exposures four times more than LF targets (i.e., 20 exposures vs. 5 exposures). Whilst this is quite an amount, it remains the case that HF words in a corpus might have 100 occurrences per million relative to only 2 occurrences per million for LF targets. That is to say, the magnitude of the difference in exposure frequency, and the extent to which those differences are experienced during reading are far greater for real words than for the pseudoword stimuli manipulations adopted in the present experiment. Thus, the exposure associated with the HF targets and LF targets in the present experiments (as well as the extent of exposure) was much smaller than that for lexical stimuli that have been adopted in previous studies examining word frequency. Second, the fact that exposure frequency showed differential influences between the learning task and the scanning task might be due to the nature of the scanning task per se. The task demands in scanning, that is, the identification of a target embedded amongst similar distractors, were so much higher relative to the task demands associated with isolated target recognition. Under such circumstances any exposure frequency effects that would be relatively small and short lived could easily be swamped and lost within relatively long inspection that would be required for considered judgments associated with decisions about whether a pseudoword was, or

was not, a target. The consistency on exposure frequency effects between learning session and scanning session per se raises a very interesting question as to what factors might drive exposure frequency effects in different tasks. Whilst the present thesis cannot fully address this issue, it does appear that identification tasks that elicit rapid, quite reflexive responses are more likely to show such effects than those that elicit slower, more measured judgments. And such tasks are only likely to be viable when novel stimuli have been learnt to such a degree that they are very recognisable. Future work will be required to better understand how frequency effects in learning and recognition develop.

5.5 The roles of spacing and alternating shadings in string scanning

Another important question the current thesis investigated was whether alternating shadings might play a similar role as spacing in the guidance of eye movements during the scanning of either Landolt-C strings or pseudoword strings. Three spacing presentation formats were adopted: spaced strings, unspaced strings and shaded unspaced strings. The overall results across all of the three experiments were very consistent and demonstrated that both target identification and saccadic targeting benefitted most in the spaced condition. Alternating shadings also facilitated eye movement control, but the degree of facilitatory effect differed across stimulus type and population. To be clear, shading facilitation was smallest in the scanning of Landolt-C strings (Experiment 1), medium in the scanning of pseudoword strings in English native speakers (Experiment 2), and greatest in the scanning of pseudoword strings in Chinese native speakers (Experiment 3). It was argued that the main reason why shading facilitation was reduced in scanning Landolt-C strings relative to pseudoword strings

was due to the nature of the stimuli being used. Pseudowords adopted in Experiments 2 and 3 were orthographically regular and pronounceable. These word-like properties make it more likely that pseudowords were processed as a unified perceptual unit rather than piecemeal letter constituents. The provision of shadings might boost the salience of each individual pseudoword as an unified perceptual unit. By contrast, Landolt-C clusters contained no intrinsic linguistic information, and therefore they were less likely to be processed as a single unit. Despite shadings provided the visual cues about where a Landolt-C cluster started and ended, probably participants were less effectively utilizing them to process the cluster as a single perceptual unit, instead, the processing of Landolt-C clusters likely occurred on a Landolt-C by Landolt-C basis. In relation to increased shading facilitation in Chinese native speakers relative to English native speakers, it was suggested that this occurred due to Chinese native speakers' unique experience in learning pinyin and reading unspaced text. The format of pseudowords in the present thesis was similar to pinyin (i.e., Romanized Chinese). Also, the way of learning pseudowords that occurred in the present thesis was analogous to the way Chinese native speakers learnt to read pinyin and subsequently use pinyin as phonetic guide to read character-based Chinese text in their initial stages of Chinese reading development. Third, Chinese native speakers were more familiar with the unspaced format given their long-term experience of reading unspaced Chinese text. Given the above reasons, it was not surprising that shading facilitation was more pronounced for Chinese native speakers than English native speakers.

5.6 Saccadic targeting in the scanning of strings with or without boundary information

As reviewed in Chapter 1, it is still controversial as to whether there is a preferred viewing location in Chinese reading (Li, Liu, & Rayner, 2011; Ma, Li, & Pollatsek, 2015; Tsai & McConkie, 2003; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010; Zang, Liang, Bai, Yan & Liversedge, 2013). By splitting the initial landing position data into single-fixation cases and multiple-fixations cases, Yan et al. (2010) found that readers tend to target slightly left of the centre of words in single-fixation cases; however, readers locate their point of fixation towards word beginnings in multiple fixation cases. Accordingly, Yan et al. (2010) proposed that Chinese readers dynamically choose the place to target a saccade based on whether or not does successful word segmentation occur in parafovea. Interestingly, this general pattern of findings holds regardless of whether the same text is presented in a spaced or an unspaced format (see Zang, Liang, Bai, Yan, & Liversedge, 2013), whether the text is normal or shuffled (Ma, Li, & Pollatsek, 2015) and even holds in computational simulation (see Li, Liu, & Rayner, 2011).

The present thesis examined saccadic targeting in the scanning of strings with or without boundary information (i.e., spaced strings, shaded strings, unspaced strings). In the scanning of either Landolt-C strings (Experiment 1) or pseudoword strings (Experiments 2 and 3), the majority of initial fixations were made towards the centre of a target in spaced strings, whilst, the majority of fixations were made towards the beginning of a target in the unspaced strings. According to the account provided by Yan et al. (2010), similar PVLs should have occurred for the shaded strings across all three

experiments of this thesis given that shadings provided clear boundary information in the parafovea. However, discrepancies occurred in the shaded condition across the three experiments. In the scanning of shaded Landolt-C strings, participants made most initial fixations on the beginning of a target. By contrast, in the scanning of pseudoword strings, inverted-U shaped landing position distributions occurred for both English native speakers and Chinese native speakers. The results from the present thesis might suggest that the factor driving the changes in landing position distributions on the target was not whether participants could, or could not, identify the boundary of the upcoming target in string scanning. A flexible targeting strategy in reading unspaced Chinese (Yan et al., 2010) cannot explain the results from the Landolt-C experiment and the discrepancies across experiments in relation to saccadic targeting in the scanning of shaded strings.

5.7 Overall conclusions and implications

Briefly, the present thesis investigated oculomotor control in character string learning and string scanning. Five overall conclusions are to be drawn from the empirical findings of the present thesis. First, robust learning block effects occurred regardless of stimulus type and population. Learning was more efficient when pseudowords were used compared to when Landolt-C stimuli were used. Learning was also more pronounced for Chinese native speakers relative to English native speakers. Second, exposure frequency effects were effectively simulated in the learning session across all three experiments. Third, robust rate of learning effects occurred across all three experiments, however, the pattern of effects differed between Landolt-C learning and pseudoword learning. Fourth, despite the fact that an exposure frequency effect

occurred in the learning session, such effects did not carry over to the scanning session. Fifth, spacing manipulations provided the greatest facilitatory effects in eye movement control. The extent to which the shading manipulation facilitated scanning differed across experiments. Shading facilitation was smallest in the Landolt-C string scanning. In pseudoword string scanning, shading facilitation was greater for Chinese native speakers relative to English native speakers.

Four important key findings are noteworthy. First, the general pattern of findings in this thesis demonstrates the efficacy of the novel learning and scanning paradigm adopted in the present thesis to investigate the nature of learning and identifying novel stimuli either when they are presented in isolation or when they are embedded in strings. Second, the present thesis provides evidence showing that eye movement recording effectively reflects the online processing in learning and scanning tasks. The eye movement measures used in reading also feasibly reflect online cognitive processes in non-reading learning and scanning tasks. Third, the present thesis shows that providing boundary information is very important even in the scanning of non-linguistic strings. Fourth, the finding that differential landing position distributions occurred during string scanning with alternating shadings across experiments provides evidence against the flexible saccade target selection strategy (Yan et al., 2010). Overall, the experiments reported here represent some of the first assessments of changes in eye movement behaviour in tasks that require learning and later recognition. There are clear analogies to changes in processing that occur when individuals learn to read, though of course, processing in the present studies was quite different. Nonetheless, it seems very likely, based on the present results, that a number of important factors have a potential

bearing on the nature and efficacy of such learning and recognition. These factors deserve attention in future investigations that more directly assess reading development.

5.8 Future Directions

The final section will describe some ideas for the future directions regarding some ways that might improve the efficiency in the learning of Landolt-C stimuli. In Experiment 1, participants showed substantial difficulty in learning Landolt-C stimuli. The learning of Landolt-C stimuli was less effective and successful compared to the learning of pseudoword stimuli, however, this does not necessarily mean that the Landolt-C manipulation was not informative in reflecting the relationship between online cognitive processing and eye movements. Instead, the current Landolt-C experiment extends our knowledge about the feasibility of using eye movement recording to investigate other non-reading tasks. Moreover, consistent with previous studies, the current Landolt-C experiment demonstrates that Landolt-C manipulations are potentially very useful in examining questions relating to a broader theoretical context (e.g., learning, memory). To improve the efficiency in learning Landolt-C stimuli, three directions are considered for potential future research. First, the single learning session could be split into several sessions to be completed over several days. This might help to improve the learning of Landolt-C stimuli as evidence has shown that memory can be consolidated to a greater level during sleep. Second, a reduction in the number of target clusters to be learnt in the learning session might facilitate learning. To ensure sufficient power in any such experiments, more participants should be recruited. In this way, a reduced memory load during learning may contribute to better learning performance. Third, provision of feedback after each learning assessment trial may also lead to stronger representations of the target clusters in memory. It is

beyond the scope of the current thesis to examine all these possibilities, however, they are certainly topics worthy of future investigation.

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