An experimental analysis of braille reading using a high-resolution tracking system

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PhD 2014

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by

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NUI MAYNOOTH

Ollscoil na hÉireann Má Nuad

A thesis presented in fulfillment of the requirements for the Degree of Doctor of Philosophy

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December, 2014

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to my supervisor, Professor Ronan Reilly. His wide knowledge and his logical way of thinking have been of great value for me. His understanding, encouraging and personal guidance have provided a good basis for the present thesis. I am deeply grateful to Dr Susan Bergin for her help and Dr Charles Markham, who helped me to develop the tracking equipment. I also wish to thank Dr. Adam Winstanley, Head of the Department of Computer Science, who supported me with a budget for travelling to conferences. The financial support of John and Pat Hume scholarship is also gratefully acknowledged. I wish to express my warm and sincere thanks to Professor Denis Burnham for his support and kindness when I visited the University of Western Sydney, Bankstown. I am grateful to Professor Ralph Radach, who helped me with the language materials and took good care of me when I visited Florida State University, Tallahassee.

Special thanks should be given to the National Council for the Blind in Ireland (NCBI), the Royal Society for the Blind in South Australia, Vision Australia which helped me contact braille readers and provided a room for collecting data. In particular, I appreciate the generous support I received from Stuart Lawler, who is a manager at NCBI training center, Audrey Tormey, Samantha Ogilvie, Graeme Innes, and Peter Greco for advising and helping me and also participating in the study. Above of all, I am deeply thankful to all of the participants, without whom my study would not have been possible.

I will always be thankful for the extraordinary friendships I made while pursuing this degree. My deepest gratitude to Ruth McLoughlin, Rebecca Reilly, and Aifric Reilly for treating me as part of their family. I would like to thank Mrs Raweewan Smullen and Mrs Wilaiporn Perkins (Committee of the Society of Thai students in Ireland), and their families for providing me with delicious Thai food when I was starving here and all of their other help. I would also like to extend my thanks to Nanthana Trakarnratanakul, Patomporn Loungvara, Nattiga Silalai, Utai Uprasen, Siliang Tang, Benjawan Kasisopa, Yvonne Leung and Chee Seng Chong (Leo), Thitima Pattanapotikul, Thitapha Pitayarutsatian, Usa Saetang, Punjaporn Pojanapunya and all of my Thai friends for their friendship.

I am also grateful for the support I received from my family in Thailand, my father (Niti Aranyanak), mother (Toenchai Aranyanak), my brother (Jarungyod Aranyanak), P'Yuk (Napaporn Tantisiriseranee), Na' Nok (Supaporn Ratnoy) and Na' Man (Narumon Sirichareun). Without their encouragement and understanding it would have been impossible for me to finish this work and I am eternally thankful to my wonderful husband who always support and encourage me to achieve my PhD and my adorable little daughter Lily.

Lastly, I offer my regards and blessings to all of those who supported me in any way during the completion of this project.

Inthraporn Aranyanak

กิตติกรรมประกาศ

วิทยานิพนธ์ฉบับนี้สำเร็จได้ ด้วยความกรุณาของ Prof. Ronan Reilly อาจารย์ที่ปรึกษาวิทยานิพนธ์ ซึ่งได้ให้คำปรึกษาข้อชี้แนะและความช่วยเหลือในหลายสิ่ง หลายอย่างจนกระทั่งลุล่วงไปได้ด้วยดี ขอขอบพระคุณ Dr. Susan Bergin ที่ให้ความช่วยเหลือรวมทั้ง Dr. Charles Markham ที่ช่วยหาอุปกรณ์เครื่องมือที่ใช้ในการเก็บข้อมูล และ Dr. Adam Winstanley หัวหน้าภาควิชาวิทยาศาสตร์คอมพิวเตอร์ที่สนับสนุนทุนการเดินทางเพื่อไปประชุมงานวิชาการต่างๆ ขอขอบพระคุณผู้สนับสนุนทุนการศึกษา "John and Pat Hume Scholarship" ขอกราบขอบพระคุณ Prof. Denis Burnham สำหรับความกรุณาและช่วยเหลือระหว่างที่ข้าพเจ้าทำวิจัยที่ University of Western Sydney, Bankstown รวมถึง Prof. Ralph Radach ที่ให้ความช่วยเหลือในด้านข้อมูลเพื่องานวิจัย อีกทั้งการดูแลเป็นอย่างดีระหว่างที่ข้าพเจ้าทำวิจัยที่ Florida State University, Tallahassee

ขอขอบพระคุณ National Council for the Blind in Ireland (NCBI), the Royal Society for the Blind in South Australia และ Vision Australia ที่ช่วยติดต่อผู้ทำการทดลองและจัดเตรียมห้องเพื่อทำการเก็บข้อมูล โดยเฉพาะอย่างยิ่งคุณ Stuart Lawler ผู้จัดการศูนย์ NCBI รวมถึงบุคคลเหล่านี้ อาทิ Audrey Tormey, Samantha Ogilvie, Graeme Innes และ Peter Greco ที่ให้ความ ช่วยเหลือเป็นอย่างยิ่งและเหนือสิ่งอื่นใดขอขอบพระคุณผู้ที่เข้าร่วมทำการทดลองทั้งหมด

ขอขอบคุณเพื่อนๆโดยเฉพาะอย่างยิ่ง Ruth McLoughlin, Rebecca Reilly และ Aifric Reilly ที่ดีต่อข้าพเสมือนเป็นคนในครอบครัว คุณระวีวรรณ สมุเล็ห์น (พี่วรรณ) คุณวิไลพร เพอร์คิ้นส์ (พี่ไล) กรรมการสมาคมนักเรียนไทยในไอร์แลนด์และครอบครัวสำหรับอาหารไทยที่แสนอร่อยยามอยู่ต่างแดนและการต้อนรับที่แสนอบอุ่นจากครอบครัวของ

พี่สาวทั้งสอง ขอขอบใจ ณันธนา ตระการรัตนกุล (เจียน), ปฐมพร เหลืองวรา (ต้าร์), ณัฏฐิกา ศิลาลาย (พี่จอย), อุทัย อุประเสน (พี่อ้วน), ซิเลียง, เบญจวรรณ กสิโสภา (พี่เบญ), อีฟอน, ลีโอ, ฐิติมา พัฒนโพธิกุล (กวาง), ฐิตาภา พิทยรัตน์เสถียร(กิฟท์), อุษา แซ่ตั้ง (หนู), ปัญจพร พจนปัญญา (พี่อุ้ม) และเพื่อนๆที่อยู่เมืองไทยทุกคน

ขอขอบพระคุณ คุณพ่อนิติและคุณแม่เตือนใจ อรัณยะนาค, คุณจรุงยศ อรัณยะนาค (พี่โจ้), คุณนภาพร ตัณฑิสิริเศรณี (พี่ยุก), คุณสุภาพร รัตน์น้อย (น้านก), คุณนฤมล ศิริเจริญ (น้าแมน) รวมทั้งคุณโรแนน ไรล์ลี่ และลูกลิลลี่ที่น่ารักของมามี้ที่ได้ให้ความสนับสนุนและให้กำลังมาโดยตลอด

ท้ายนี้ความดีอันเกิดจากการศึกษาค้นคว้าครั้งนี้ ข้าพเจ้าขอมอบแด่บิดา มารดา ครู อาจารย์และผู้มีพระคุณทุกท่าน ข้าพเจ้ามีความซาบซึ้งในความกรุณาอันดียิ่งจากทุกท่านที่ได้กล่าวนามมา

อินทราพร อรัณยะนาค

ABSTRACT

The research described in this thesis had two sets of goals: (1) to carry out a baseline study of braille reading using an innovative combination of hand-tracking coupled to a computer-controlled braille display; (2) to conduct an in-depth exploration of high-speed braille readers using a range of experimental paradigms. The main results showed that using the finger tracking system permitted the exploration of the moment-to-moment cognitive processes of the braille reader with unprecedented precision. Readers showed relatively rapid sensitivity to lexical properties of the text (e.g., word frequency, lexical structure, orthographic uniqueness point) and demonstrated sensitivity to top-down context effects during reading. The final experiment provided suggestive evidence that the auditory cortex may be involved in skilled braille reading.

บทคัดย่อ

งานวิจัยที่ได้บรรยายในวิทยานิพนธ์เล่มนี้ประกอบไปด้วยสองวัตถุประสงค์หลักคือ

(1) เพื่อศึกษาการอ่านภาษาเบลล์ขั้นพื้นฐาน โดยการใช้นวัตกรรมที่สร้างขึ้นมาผสานกันระหว่างการตรวจจับความเคลื่อนไหวของมือและการควบคุมด้วยโปรแกรมคอมพิวเตอร์เพื่อใช้ในการศึกษาเป้าหมายหลักของงานวิจัยดังนี้ หนึ่ง เพื่อที่จะพัฒนาระบบการตรวจจับความเคลื่อนไหวของนิ้วมือที่มีความละเอียดสูงให้มีราคาถูกและง่ายต่อการศึกษาการอ่านภาษาเบลล์ สอง เพื่อที่จะสำรวจพฤติกรรมการอ่านภาษาเบลล์และศึกษากระบวนการการทำงานของสมอง ณ ขณะที่กำลังประมวลผลขณะอ่านข้อความ สาม เพื่อที่จะวัดผลกระทบของการอ่านตามคำสั่งในแบบที่ต่างกัน

(2) เพื่อปฏิบัติการสำรวจเชิงลึกของผู้ที่อ่านภาษาเบลล์ได้อย่างรวดเร็วดังนี้ หนึ่ง สำรวจความแตกต่างของการประมวลผลของคำ ที่ตำแหน่งจุดเอกลักษณ์ (uniqueness point) นั้นอยู่ในส่วนต้นและส่วนปลาย สอง สำรวจมือที่ใช้ในการรับข้อมูลระหว่างการอ่านภาษาเบลล์ โดยใช้เทคนิคในการเปลี่ยนส่วนของการแสดงผลบน refreshable braille display สาม ทดสอบสมมุติฐานว่าผู้ที่อ่านได้เร็วนั้นมีการใช้พื้นที่ของส่วนประมวลผลสัญญาณระดับล่างที่อยู่ในสมองส่วนของการได้ยินหรือไม่

ผลที่ได้จากการศึกษานี้แสดงให้เห็นว่า การใช้ระบบการตรวจจับการเคลื่อนไหวของนิ้วมือที่ได้ประดิษฐ์ขึ้นมานี้สามารถที่จะสำรวจการประมวลผลที่เกิดขึ้น ณ ขณะปัจจุบันของผู้อ่านภาษาเบลล์ได้อย่างมีประสิทธิภาพ ซึ่งผลจากการใช้เครื่องมือนี้แสดงให้เห็นว่าผู้อ่านนั้นมีการตอบสนองที่รวดเร็วต่อคุณสมบัติทางคำศัพท์ เช่น ในเรื่องของความถี่ของคำและโครงสร้างของคำศัพท์ อีกทั้งยังพบว่ามี top-down effect ที่เห็นได้จากการเคลื่อนไหวของ

นิ้วมือระหว่างการอ่านเบลล์อีกด้วย เรายังค้นพบอีกว่าผู้อ่านที่ใช้มือขวาเป็นหลักในการอ่านนั้นสามารถอ่านได้เร็วกว่าผู้อ่านที่ใช้มือซ้ายเป็นหลัก ตำแหน่งของจุดเอกลักษณ์ (uniqueness point) นั้นก็มีผลกระทบต่อการเคลื่อนไหวมือของผู้อ่านด้วย ผลกระทบจากตำแหน่งของจุดเอกลักษณ์แสดงให้เห็นว่า การเข้าถึงคำศัพท์ในการอ่านภาษาเบลล์นั้นคล้ายกับการประมวลผลจากถ้อยคำ (speech processing) ซึ่งเราพบลักษณะการเคลื่อนไหวมือในแบบที่เราคาดหวังไว้ คือผู้อ่านเร่งความเร็วหลังจากผ่านตำแหน่งของจุดเอกลักษณ์แค่เพียงในคำที่ยาวๆเท่านั้น ทั้งนี้อาจเป็นเพราะว่าตำแหน่งของจุดเอกลักษณ์ในคำที่สั้นนั้นอยู่ใกล้ตำแหน่งสุดท้ายของคำ นอกจากนี้เรายังพบอีกว่ามือหลักที่ใช้ในการอ่านโดยการใช้เทคนิคในการเปลี่ยนส่วนของการแสดงผลบน refreshable braille display นั้นแสดงให้เห็นว่า ผู้อ่านที่ใช้มือขวาเป็นหลักในการอ่านนั้นสามารถรับข้อมูลที่แสดงทั้งสองมือได้ดีกว่าผู้อ่านที่ใช้มือซ้ายเป็นหลัก

การทดลองสุดท้ายได้แสดงหลักฐานที่บ่งบอกได้ว่า ผู้ที่อ่านภาษาเบลล์ได้คล่องแคล่วอาจจะมีการใช้สมองส่วนของการรับรู้เสียงมาเกี่ยวข้องในการอ่านภาษาเบลล์ด้วย ซึ่งเป็นไปตามสมมุติฐานที่ตั้งไว้ จากการทดลองนี้แสดงให้เห็นว่า การใช้เสียงที่ผลิตจากช่วงความถี่ของการอ่านภาษาเบลล์ (10-30 Hz) นั้นมีส่วนช่วยในการอ่านให้เร็วขึ้นโดยเฉพาะในผู้ที่อ่านภาษาเบลล์ได้คล่องแคล่ว ดังนั้นเราอาจจะใช้ความรู้ที่ได้นี้ไปประยุกต์ใช้กับผู้ที่อ่านช้าเพื่อที่จะสร้างการเชื่อมต่อช่องทางระหว่างส่วนของการรับรู้ที่ประมวลผลในส่วนของการได้ยินกับส่วนของการรับรู้ที่ประมวลผลในส่วนของการสัมผัสเพื่อที่จะยกระดับความสามารถในการอ่านภาษาเบลล์ให้มีประสิทธิภาพมากยิ่งขึ้น บทสุดท้ายของงานวิจัยนี้จะพูดถึงการนำข้อมูลที่ได้จากส่วนที่หนึ่งและส่วนที่สองจากข้างต้นมาแนะแนวทางที่อาจจะนำไปศึกษาต่อเพื่อหาหนทางในการช่วยให้คนตาบอดอ่านภาษาเบลล์ได้มีประสิทธิภาพมากยิ่งขึ้น

Publications and Presentations

Publications:

Aranyanak, I., & Reilly, R. (2013). A system for tracking braille readers using a Wii Remote and refreshable braille display. *Behavior Research Methods*, *45*(1), 216-228.

Presentations:

Aranyanak, I., Reilly, R. G. & Radach, R. (2014). A comparison of the role of global top-down factors on local reading processes in braille and print. Paper presented to the Society for the Scientific Study of Reading (SSSR) Conference, Santa fe, New Mexico on July 16 - 19, 2014.

Aranyanak, I. & Reilly, R. G. (2013). A study of orthographic uniqueness point effects in braille reading using a high-resolution finger-tracking system. Paper presented to the Society for the Scientific Study of Reading (SSSR) Conference, Chinese University of Hong Kong, July 10-13, 2013.

Reilly, R.G. & Aranyanak, I. (2012). The dynamics of braille reading. Paper presented to the 30th Australasian Experimental Psychology Conference, University of New South Wales, April 12-15, 2012.

Aranyanak, I. & Reilly, R. G. (2010). An experimental analysis of skilled Braille reading using a high-resolution finger-tracking system. Paper presented to the biennial Research Conference on Braille Reading and Writing, Colorado, June 10-12, 2010.

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Chapter 1

General Overview

1.1 Introduction

Communication is a process of exchanging information. Writing is one of the basic skills used in communication so that humans can express their thoughts and feelings. Languages have different writing systems, orthography and syntax. Sighted people read visually, while blind people read through touch. In the early 18th century, the philosopher Bishop Berkeley assumed that the basis of perception was touch, with the hand being used as a unitary sense organ like the eye (Katz, 1925). In fact, the first dot for tactile perception was developed by Charles Barbier. Raised dots were designed to be read by touch in the dark. Later, Louis Braille learned and modified the system to be more suitable for people who have sight loss. His version was more logical and economical. Braille's version is now used widely for reading and writing by people with visual impairments. Braille characters originally consisted of a combination of six dots, but the encoding has since been extended to eight dots. Braille code was officially adopted by the Royal Institution for Blind Youth in 1854. The Missouri School for the Blind in the United States was the first institution to adopt the code. Braille reading requires a cognitive process capable of tactile perception, finger movement control, lexical and semantic processing, and pattern recognition (Sadato, 2005). Usually, braille is read during finger movements that are continuous and sequential from left to right. There are three important aspects distinguishing braille from other writing systems (Millar, 1997): the touch modality, the use of raised dots as symbols, and in some orthographic conventions contractions are used to reduce the length of words. Contractions can be used for whole word or parts of words. Foulke (1982) and

Nolan and Kederis (1969) found that contractions that occur frequently can make reading much faster since they are short and skilled braille readers can identify them quickly. On the other hand, reading speed is decreased when infrequent contractions occur (Lorimer et al., 1982). There are a number of studies that have been conducted on braille reading in order to characterise and understand the reading process. Since the mid 1970s, many studies of visual reading have been carried out using high-resolution eye movement recording systems (Rayner, 1998). The first empirical research of tactile reading was conducted by using a simple apparatus to track hand movement by Bürklen (1932). As technology advanced, various devices were developed to study braille reading. Foulke (1979) found that over the previous 30 years, three main approaches were used. One approach to braille reading research has emphasised the observation of braille reading behavior and describes the behavioural patterns of good and poor braille readers. A second approach has been concerned with the legibility of braille characters. A third has focused on reading performance as a function of variables relating to the manner in which embossed dots are displayed. Recent braille studies have focused more on cognitive neuroscience to explore online processing and brain activity during reading. Neuroscientists have used neuroimaging techniques in examining brain activity of blind readers. Increasing evidence suggests that the striate cortex in people born blind is co-opted for tactile reading. There is also similar evidence for people who are blindfolded for extended periods of time (e.g., Sadato, 2005; Cohen et al., 1997; Pascual-Leone & Hamilton, 2001).

1.2 Motivation for this research

Over the last decade, there has been a dramatic reduction in the widespread use of braille (NCBI, 2006). Of the approximately 14,000 users of the services of the National Council for the Blind in Ireland (NCBI), about 2.8% are registered users of braille (NCBI, 2006). This figure is similar to that reported for the UK (Keil & Clunies-Ross, 2002). In the US, each year approximately 75,000 people lose all or part of their sight. Nevertheless, almost 90% of blind US children are not being taught braille (the National Federation of the Blind Jernigan Institute, 2009). The main factors contributing to low braille literacy in people with sight loss are: (1) advances in technology to assist the blind to read texts, such as, screen readers, audio books, text-to-speech software; (2) improvements in medical technology that help reduce the incidence of early blindness; (3) the shortage of skilled braille teachers. For example, many teachers of blind children are not themselves fluent in reading and writing braille and some may have negative attitudes to braille and consider it a difficult system to teach and learn (the National Federation of the Blind Jernigan Institute, 2009); (4) the increasingly older age profile of the blind population.

There is a perception among educators that recent technological innovations obviate the need for braille literacy. The view is that screen readers, audio books, speech recognition software, and various software and hardware support systems for people with visual impairment have rendered braille literacy largely redundant. Nonetheless, providers of services to the blind and partially sighted have a somewhat differing view (NCBI, 2006; Keil and Clunies- Ross, 2002). Reports by both the NCBI and its British counterpart, the Royal National Institute for Blind People, argue for the enhancement of braille support. It is particularly important if young blind students are to pursue subjects such as mathematics and music with their specialised notational requirements (Keil & Clunies-Ross, 2002). Furthermore, there is evidence that literacy, irrespective of medium, is an important facilitator of cognitive development and helps maintain cognitive wellbeing into old age (Saloman et al., 1991; Eskritt, et al., 2001).

The majority of blind people in the West (approximately 58% in Ireland) are over 65 and most of them have suffered sight reduction and loss as a result of age-related illnesses such as macular degeneration (Kelliher, Kenny, & O'Brien, 2006). The current number of more than 246 million worldwide who lost their sight from diabetes is expected to increase to 380 million by 2025 (Stoker, 2009). Diabetic retinopathy can occur in people from late middle age onwards and can also be associated with a reduction in tactile sensitivity. A combination of age-related cognitive decline and reduction in peripheral sensitivity means that learning braille as an older person is an uphill struggle.

One might think that there are many assistive technologies that can substitute for braille, so why then is it still important to learn? Ryles' (1996) study found that congenitally legally blind adults who learned to read braille had higher employment rates and incomes than those who did not use braille. The majority of people with sight loss rely on screen readers or audio books. However, if you want to study subjects that make heavy use of symbols (e.g., mathematics, music), you need a symbol system like braille. Therefore, even though braille may be difficult to learn, it is very useful.

The majority of research in reading is conducted among sighted readers. In sighted reading, the use of computer-based eye tracking systems has made it possible to track precisely the location of the eyes and to manipulate the text being read as a function of eye position. This latter capability is an important tool for in-depth exploration of the nature of the perceptual and linguistic processes involved in reading. The ability to read braille at close to sighted reading speeds is a remarkable achievement and one that has received, with a few notable exceptions, scant attention in the reading research literature (Ford & Walhof, 1999). This is partly due to the relatively small community of skilled braille readers and partly to the lack of suitable technology for exploring braille reading in depth. Current technology uses a video camera to record hand movements where the frame rate is very low. This is cumbersome for any type of large-scale study. Recently, a new gaming device has been developed which is known as a Wii Remote. It comprises a built-in infrared camera that provides location information for infrared sources with relatively high temporal and spatial resolution. In this thesis, we use this device as part of a tracking system to gain insights into how braille readers accomplish the task of translating bumps on a page into meaning.

1.3 Objectives of the thesis

The main objectives of this thesis are to investigate the cognitive processes of braille readers. In order to examine the immediate processing of the braille text, a good tracking system is required to track readers' fingers. Therefore, a finger-tracking system was developed providing high temporal and spatial resolution of finger position. The system can be used with either a refreshable braille display or embossed-braille paper. Reading behaviour of skilled and less skilled braille readers was studied. One of the goals of the thesis was to try to understand how fast readers achieved the speeds they do and to use this understanding to explore the possibility of improving slower readers' performance.

Top-down contextual constraints and lexical-level effects were also investigated during a prose reading in sentences. A display change technique was used for the first time in the study of braille reading to examine hand dominance. Arising out of our initial studies, we hypothesised that fast readers might be making use of low-level speech processing areas of the auditory cortex, based in part on the observation that fast readers processed braille in a more speech-like than spatial manner. This is analogous to how visual areas are known to be used by braille readers.

The benefits of the research described here are: (1) it offers the potential to deepen our understanding of how skilled braille readers achieve the speeds they do; (2) It offers the possibility of using insights thus gained to enhance the teaching of braille reading; (3) At a broader level, the study of braille reading provides important insights into neural plasticity, which stand to benefit those working in various areas of neural rehabilitation.

1.4 Organisation of the thesis

The main goal of the thesis is to study braille reading from the perspective of cognitive processing by using a high-resolution finger-tracking system. This dissertation is composed of four parts.

Part I. Background

The first part of the thesis provides background information for the study. The history of braille and braille writing systems is described in Chapter two. The last section provides information on braille writing devices and assistive technology for the blind and visually impaired. The social and educational importance of braille is also discussed in this section.

Chapter 3 reviews previous studies of braille reading. It starts by comparing the difference between braille and print reading. It is followed by a review of early studies in braille reading. The remainder of the chapter focuses on neuroimaging techniques used in investigating visual impairment and the blind's brain activity during tactile reading.

Part II. Finger-tracking System

Chapter 4 describes a system for tracking braille readers. Older hand tracking apparatuses are reviewed at the beginning of the chapter. We then describe a cheap and convenient high-speed finger-tracking system that can track readers' finger-movements with millisecond accuracy. The system works in conjunction with either a refreshable braille display or braille paper. An equipment configuration is also described along with the methodology and procedures for data collection. Examples of the user interface are also presented in the tracker control program section. A display change technique and system limitations are discussed in the final part of the chapter.

Part III. Global characteristics of braille readers

With the development of our finger-tracking technology, it is now possible to gather data of equivalent precision to low-end modern eyetrackers for braille readers. The fifth chapter presents an experiment that was conducted in Ireland under the auspices of the National Council for the Blind of Ireland (NCBI). The study focused on braille reading behaviour. The initial phase of the study attempted to answer such questions as the nature of the reading rate in braille, the limits of the perceptual span, the degree, if any, of hand superiority, the nature of individual differences in two-handed braille reading, and so on. The combination of finger-tracking system and a refreshable braille display constructed for this project allowed us to explore in detail, the nature of braille reading and provide clues to ways of improving poorer readers' performance. Moreover, the system provides an ability to examine the online processing of text by braille readers. A study of top-down effects using a question paradigm was also examined in this experiment. Materials and methods used are described in the middle section of the chapter. Reading aloud was not used in any experiments of this dissertation because it might have affected the reading process. Many braille and print reading studies have shown that reading rates are reduced in oral reading (e.g., Knowlton & Wetzel, 1996). For example, when reading aloud, readers made more regressive movements than when reading silently (Eatman, 1942). Therefore, all participants were asked to read sentences or texts silently and naturally. The remaining part provides results and conclusions.

Part IV. An in-depth exploration of braille readers

The effects of the location of the orthographic uniqueness point (OUP) of words was investigated experimentally in Chapter 6. Another experiment focused on the feasibility of using the display change technique of the finger tracking system. The study was related to hand dominance in braille reading. This is the first braille reading experiment that used a display change technique, which is normally used in eye movement data. The braille display is used for presenting texts, as it allows the running of a program to change texts on the display while readers are still reading. Results and conclusions are described in the final section.

Recent braille reading studies have focused on cortical plasticity of blind persons either congenitally or late blind. Strong evidence from neuroimaging studies has revealed that the occipital lobe, which is normally reserved for visual input is activated during braille reading. Analogous to how skilled early-blind readers use their visual cortex, the possibility is explored in Chapter 7 that the auditory cortex may be similarly used.

The last chapter summarises the contributions of the dissertation and provides some suggestions as to how the teaching and learning of braille might be improved. Finally, I present the future work that I intend to carry out in order to explore braille reading performance and understand tactile processing more deeply.

Part I. Background

Part I is composed of two chapters. Chapter two provides background information about braille and assistive technology tools that help visually impaired readers. Background information about previous studies in braille reading is reviewed in Chapter three.

"Braille is knowledge, and knowledge is power"

- LOUIS BRAILLE

Chapter 2

Braille system and assistive technology devices

Braille is the most popular tactile writing system used by visually impaired and blind people. The first version was invented by Louis Braille in 1824. However, braille is not the only system for reading by touch. There is another embossed reading system called 'Moon', originated by Dr. William Moon. The Moon system derived symbols from Roman capital letters. They were reduced to their simplest form and in some cases new characters were created (Rex et al., 1994). The majority of elderly people who become blind later in life find the Moon system easier to learn than braille since the characters are derived from the Roman alphabet. However, braille is still the main system for the blind to use for written communication throughout the world. Loomis (1985) found that braille characters were more easily recognised than raised Roman alphabetic characters. He assumed that this might be because braille characters have lower spatial frequency representation than raised Roman characters (cited in Philips et al., 1990). Braille is not only adapted to many languages, but also supports music, mathematics, and computer use.

This chapter starts with the story of Louis Braille, who invented the six-raised dots system. The remainder of this chapter describes the braille writing system and some of the basic braille contraction rules. The International Council on English Braille (ICEB) is responsible for English braille improvement and promotion. The members of ICEB represent the various countries where English is spoken. For example, the Braille Authority of the United Kingdom (BAUK) is responsible for British braille and the Braille Authority of North America (BANA) is responsible for the English Braille American Edition (EBAE) format. There are many types of braille, including literary, mathematical and scientific, musical, and computational.

These types of braille use different sets of rules that are incompatible and also vary across English-speaking countries. BANA initiated the development of Unified English Braille (UEB) so that the code can be applied across various types of braille material worldwide. Nowadays, UEB had been adopted in the US, Canada, Australia, South Africa, Nigeria, the UK, and New Zealand. In Ireland, we have recently adopted the UEB for publications in this year, 2014.

In the final section of this chapter, the advantage and drawbacks of braille assistive devices and technology will be discussed. In addition, the so-called braille crisis will be addressed.

2.1 Louis Braille biography

Louis Braille, who invented the braille system of reading and writing for the visually impaired, was born on 4 January, 1809 in Coupvray, France. He came from a poor family. Simon-René, his father, was a harness and saddle maker. Louis had two sisters and one brother, he was the fourth child. Most of the time he liked watching his father working by using sharp tools to cut and pierce leather. He was not congenitally blind, but became unable to see at the age of three because of a self-inflicted eye injury. One day when his father was away from his workshop, he accidentally stabbed himself in his left eye with an awl. The wound became infected and within weeks the infection spread to his right eye. He was completely blind by the age of five (Donaldson, 2007; Fradin, 1997).

At that time, there was no school for reading and writing for the blind and visually impaired people. Simon-René taught his son the alphabet by guiding his fingers over strips of wood into which upholstery nails had been pounded in the shapes of the letters. When he was six, he met a priest named Jacques Palluy who worked at a local church. The priest offered to tutor Louis by reading books to him. The priest thought that Louis could study with sighted people because he demonstrated a high degree of intelligence, therefore Louis was sent to study in a local school. At the age of ten, Louis Braille won a scholarship to study at the Royal Institute for Blind Youth in Paris, which was the first school for the blind in the world. At this school, people with sight loss could learn grammar, geography, history, arithmetic, science, music, and also a trade. Primarily, they learned by listening to the lessons and repeating them. There were a few books that could be read by touch because Valentin Haüy, who was the founder of the school, had developed a printing system by which the letters were raised, or embossed. Nevertheless, the books were heavy, bulky, and letters were large so that acquiring information was very slow (O'Conner, 1997).

Louis Braille got the idea of producing a writing system for the blind from a French army captain, Charles Barbier. He had invented a system called "night writing" so that soldiers could communicate silently and without the need for light by using tactile alphabets. After that he developed a method that could be learned by the blind and renamed it to Sonography. However, Sonography was too complicated and based on phonetics. It did not provide for punctuation, capital letters, numbers, music notation, and mathematical characters. So, Louis Braille extensively modified the system by using 6 dots as opposed to 12 and the system was alphabetic, where dot patterns were used to represent a letter, number, punctuation mark, or a word. Moreover, each cell could fit under one fingertip. Louis Braille finished the first version of a braille system at age 15, in 1824, but he had not published the system yet. When he was 17 years old, he started teaching students at school. At the same time, he continued to refine his code over the next eight years and extended it to support music and mathematical symbols. In addition, he developed a writing method by using a stylus to punch a series of dots in patterns that were the shapes of the regular letters. Eventually, he published a manual of the Braille system in 1829 under the title "Method of Writing Words, Music, and Plain Songs by Means of Dots, for Use by the Blind and Arranged for Them". The system was used for blind students only in the Royal Institute for Blind Youth in Paris, but it was not accepted by sighted teachers and officials at that time. He kept modifying the code and produced a second version of Method of Writing Words, Music and Plain Songs in 1837.

Louis became seriously ill with tuberculosis, when he was 26. In 1844 his health became worse and he had to stop teaching. Louis' health got better in 1847 and he began to teach in the institute again for three further years. His health worsened again and could not teach much, only a few piano lessons. Finally, he died on January 6, 1852, two days after his 43 birthday. Two years later, France officially recognised braille as the system of reading and writing for people with visual impairment. After that, the system was adopted in schools for the blind in many countries; Austria, Belgium, Denmark, England, Germany, Spain, Scotland, and the US. In addition, Braille was adapted to more than 200 languages all around the world and became a universal writing system (Meyer, 1995).

2.2 The braille writing system

The braille system is a raised dot system of reading and writing for visually impaired people. The raised dot patterns are used to represent alphabetic characters. It is a spatial code, which comprises six dots in each cell; three dots in the left column and three dots in the right one as in Figure 2-1.

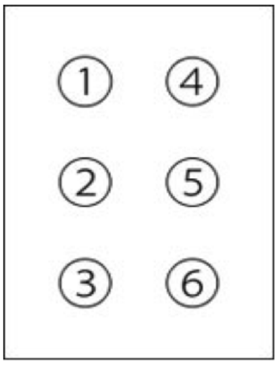
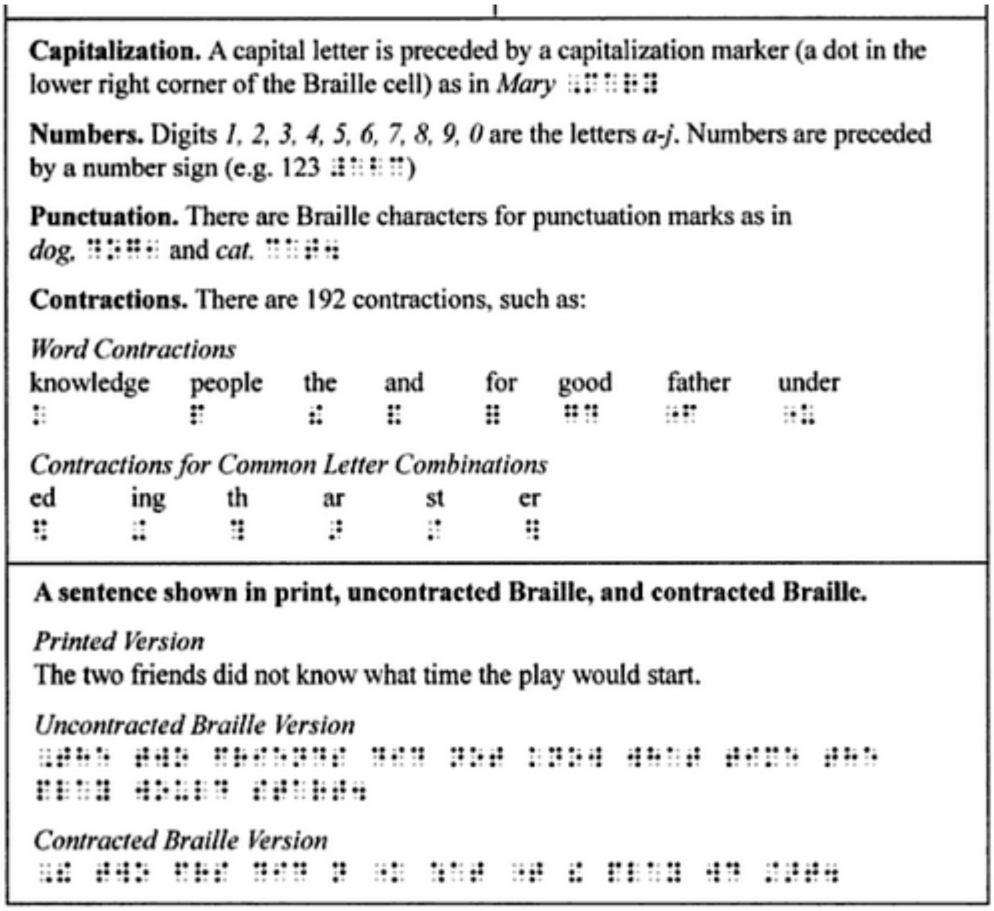


Figure 2-1: A braille cell.

A particular permutation can be described by naming the positions where dots are raised; from the top to the bottom left is called dot one, two, and three respectively; from the top to the bottom right is called dot four, five, and six respectively. Each country uses a different standard size of braille dimension. Gill (2008) summarised the different braille dimensions used in the major braille-producing countries and for specific applications. The height of a dot is between 0.25 to 0.53 mm. The space in horizontality and verticality is between 2.3 and 2.5 mm. The cell-to-cell spacing to be 6.0 to 6.2 mm (Gardner, 2005). For braille used for reading by a visually impaired person, the dots of each cell must be easily distinguishable from the background. The format of English braille is the same as in the standard English writing system. Namely, letters are written from left to right and there are spaces between words. The braille system is divided into three levels.

Grade 1 braille is where the combinations of the raised dots stand for each character in the Roman alphabet. There is a one-to-one correspondence between each dot pattern and a character (e.g., letter, digit, punctuation). This level is typically used for new braille readers. Books or documents produced in Grade 1 braille will be a lot larger and bulkier than print. It is not, therefore, generally used for publications.

Grade 2 braille also called contracted braille, is a shorter form that makes use of contractions to reduce the length of words. It includes Grade 1 characters plus contractions and short-form words. The British English braille alphabet (BAUK style) is shown in Appendix A.


Capitalization. A capital letter is preceded by a capitalization marker (a dot in the lower right corner of the Braille cell) as in *Mary*

Numbers. Digits *1, 2, 3, 4, 5, 6, 7, 8, 9, 0* are the letters *a-j*. Numbers are preceded by a number sign (e.g. 123)

Punctuation. There are Braille characters for punctuation marks as in *dog.* and *cat.*

Contractions. There are 192 contractions, such as:

Word Contractions
knowledge people the and for good father under

Contractions for Common Letter Combinations
ed ing th ar st er

A sentence shown in print, uncontracted Braille, and contracted Braille.

Printed Version
The two friends did not know what time the play would start.

Uncontracted Braille Version

Contracted Braille Version

Figure 2-2: Examples of braille contractions in words and a sentence (Legge, 2007).

Figure 2-2 shows contracted braille examples of capitalisation, numbers, punctuation, and word and part of word contractions in the top panel. The bottom panel shows a printed version of an English sentence and its corresponding uncontracted and contracted braille versions (Legge, 2007).

Grade 3 braille is a braille code for shorthand beyond Grade 2 braille. This system has more abbreviated words and is more complicated than Grade 2. It is often used for writing diaries or personal notes. It has not been standardised.

All braille beginners in Ireland are recommended to start learning with braille Grade 1, and then move to braille Grade 2 when they reach an advanced level. At present, there is an extension of dots from six (64 possible combinations) to eight (256 possible combinations) in order to use music notation, or a shorthand code used by blind stenographers in Austria and West Germany. Moreover, eight-dot braille is used to support computer-based technology and most refreshable Braille use this system to identify highlighted items and the position of the computer cursor.

2.3 British braille primer

A standard braille primer is used for beginners to learn braille rules of contractions in Ireland (Royal National Institute of Blind People, 2008). Braille beginners start learning dot patterns for each letter of the alphabet and digits and practise writing and reading in Grade 1 braille. After learning the letters of the alphabet in Grade 1 braille they go on to learn Grade 2 braille (contracted braille). This is the form of braille used for publications. There are a number of rules for use of contractions. Most of the alphabet is used to represent whole words; usually it is the first letter that is used. For instances, the braille symbol of the letter “l” is a contracted word for “like” and “w” is abbreviated for “will”, etc. Moreover, short-form words that are abbreviated spellings of common longer words are also employed in the braille code. For example, “yourself” is contracted into “yrf” - ⠽⠗⠋, “tomorrow” is contracted into “tm”- ⠞⠍ in Grade 2 braille. In addition, some common words are formed by using only one character instead of the whole word, such as “and” - ⠯, “for” - ⠿, etc. They can also be used as a part of words; “band” - ⠃⠯, “force” - ⠿⠉⠑ (BAUK, 2004). There are also contractions for some parts of words that occur frequently in English as prefixes and suffixes (ch, sh, gh, th, ed, ar, ing, con, ance, etc.). Some contractions are fixed to be written at the beginning of a word or braille line (“com” - ⠤ in “computer” - ⠤⠏⠥⠞⠻), in the middle of a word (“ea” - ⠂, “dd” - ⠲), or in any part of a word (“en” - ⠢, “in” - ⠔). Furthermore, there is a special rule for braille contraction that the word signs for “to” and “by” must always be written as part of the following word. However, they must not be contracted if they occur at the end of a braille line, immediately before a punctuation mark, or joined to another word by a hyphen to form a compound word. Some punctuation marks use only one cell to represent the signs, such as, comma and period The contractions described above involve just one cell to form a contraction. Braille rules also include composite signs, which occupy two or more consecutive cells. They are divided into three main classes as follows:

2.3.1. Composite word signs

The whole word is expressed by two cells in sequence. The first cell can be started with one dot in dot 5 and f, such as, “father” - ⠐⠋, started with two dots in dots 4 5 and the contraction of “the”, such as, “these” - ⠘⠮, and started with three dots in dots 4 5 6 and s, such as, “spirit” - ⠸⠎.

2.3.2. Composite group signs

These group signs may be used only medially and terminally. In this class there are some letters expressed by the same dot sign, but preceded by a different dot sign. For examples: “ance” is represented by dots 4 6 and followed by the letter e - ⠨⠑, such as “adv<u>ance</u>” - ⠁⠙⠧⠨⠑ .

2.3.3. Composite punctuation signs

Braille contains the same punctuation marks as is found in print. Most of them use two combinations of dot patterns to represent the punctuation signs, such as compound quote signs, square brackets, asterisk, etc. There are only two punctuation signs represented by more than two cell combinations, such as double dash (--) - ⠤⠤⠤⠤ (four bottom c signs in sequence), ellipsis (…) - ⠄⠄⠄.

2.4 English braille authorities

The International Council on English Braille is responsible for improving standards for braille usage for all English-speaking users of braille. BAUK is an organisation that set out the rules of Standard English braille for publications (Englebretson, 2009). The British braille code has been used in the United Kingdom, Australia, South Africa, Nigeria, and many other countries where English is a formal language including the Republic of Ireland.

The Braille Authority of the North America (BANA) is an organization, which is responsible for controlling braille publications and versions used in the United States, Canada, and New Zealand. It is supported by seventeen different blind or visually impaired organisations. The goal of BANA is to develop braille code standards and make it easier to use and teach. The main difference between British and American braille is British braille uses contractions, regardless of word morphology. For instance, the word “smoothest” in British braille is contracted as “smoo/the/st”, but American braille contracts as “smoo/th/e/st”. However, both authorities use similar music and literary braille codes and have developed their own codes for mathematics and science, computer, and chemistry. Students who use BANA or BAUK need to learn four major codes in school within each jurisdiction (Bogart and Koenig, 2005):

Literary braille: this is an English braille code used for writing regular text in books, magazines, and novels. It consists of over 250 contractions represented in single braille cells or multiple braille cells for letters, numerals, punctuation marks, composition signs, contractions, single-cell words, and short-form words;

Nemeth Code for Mathematics & Science Notation: this is used for transcribing mathematics, and science notation into braille which contains symbols not available in Literary braille. It was developed by Dr. Abraham Nemeth in 1946 as part of his doctoral studies and adopted in 1972 for use in US;

Computer Braille Code (CBC): This was originally designed by Tim Cranmer. It was developed to encode materials relating to computers. This code provides all braille character, one-to-one mapping between braille cells and the ASCII keyboard characters;

Music Braille Code: This was originally devised by Louis Braille, but in 1998 BANA approved changes in the braille music code. Although most of the codes are unchanged, some modifications had been made, such as, in title pages no contractions are used and words in braille are placed above the music.

Not only is English braille different between British and the United States, but even within the same authority, braille characters do not have universal meaning across the four major types. For instance, Arabic numerals (1-9 and 0) are represented differently in English literary braille, Nemeth code, and computer braille code (Englebretson, 2009).

In 1992, BANA established a project, so-called the Unified Braille Code (UBC) Research Project (Bogart et al., 2000). The main purpose of the project was to develop a unified code that could be applied for Literary braille, the Nemeth and Computer braille codes with a few changes. For instances, the dollar sign, the percent sign, the square brackets, which are represented differently in the three codes would be combined into one symbol in UBC (Cranmer and Nemeth, 1991). Lots of changes that would affect literary code were designed not to be abbreviated (Bernard and Franklin, 2003). The International Council on English Braille (ICEB) is the organization responsible for countries where English is spoken. It has a membership that includes Australia, Canada, New Zealand, Nigeria, South Africa, United Kingdom and United States (Simpson, 2010). Ireland has recently participated in the organisation in 2014.

2.5 Braille writing devices and assistive technology for the blind and visually impaired

Most visually impaired people rely on braille writing devices and assistive technology in work, for entertainment or other activities of daily life. At present, there are a number of assistive devices and technologies developed to help them live as normally as sighted people in terms of reading, writing, browsing the Internet, using a phone, etc. Some devices are simple and inexpensive and are still used by people who cannot afford expensive assistive technologies.

2.5.1 Slate and stylus

The cheapest tool in braille writing is a slate and stylus. They are the oldest tools used to produce braille and are adapted from Barbier's writing frame. A slate is a small plate made of metal or plastic, around 8.5 x 11 inches comprising 4 lines of 28 cells each. A writer has to insert a paper into the slate and use it as a guide. Raised dots can be made by using a stylus to punch holes into the slate. Each dot of each braille character is written individually by using the slate and stylus in order to form letters to words. Braille writers have to write from right to left and reverse dot order because they have to flip over the paper to read the raised dots, which is the main disadvantage of this method. The speed of taking notes on the slate with the stylus is about half the average speed for pencil writing (Cheadle, 1994).

2.5.2 Perkins brailler

Braille is also produced by a machine, which looks like a regular typewriter. The braille typewriter was invented by Frank Hall in 1892 (Carlisle, 2004). The most common braille typewriter is called the Perkins Brailler. It was first produced in 1951 (Mellor, 2006). Braille characters are typed on paper with a key corresponding to each of the six dots of the braille code. This is similar to a typewriter, but with only 7 keys. The first three positions are on the left and last three positions on the right, and a space key in the middle. To form a braille letter, the user simultaneously pushes the keys corresponding to the required dot combinations. Users compare a stylus and slate to handwriting, while using a Perkins Brailler is more like typing. Compared to the slate and stylus, the Perkins Brailler is harder to carry around, more expensive, and noisier. However, it can produce all the dot in a braille character at one time. Therefore, it is faster for writing braille. These devices are also useful for braille learners to practice remembering dot patterns.

2.5.3 Braille translation software

Nowadays, there are many technologies that help the visually impaired to read information on computers, read documents, print documents and surf the web. All assistive technologies, such as, braille printers, braille displays, braille note takers, etc., need software to convert the electronic text from, say, MS Word into braille characters and vice versa. In order to operate these devices, you need to install braille translation software. There are a lot of such products on the market. The most commonly used include Duxbury Braille Translator, MegaDots, and Braille2000. Some products are open source, for example, NFBTrans or LobLouis. However, current open source products do not translate into braille Grade 2 perfectly.

2.5.4 Braille embossers

To produce hard copy braille from a computer, software documents can be printed as embossed dots by a braille printer. The embosser has to connect to a computer and braille translation software must be installed to translate text into braille code, which is then typically printed on heavyweight paper. It is similar to a regular printer, but slower and noisier.

2.5.5 Refreshable braille displays

Instead of reading braille from bulky books, a refreshable braille display is one of the tools that can be connected to personal computers that enables the user to read the contents of the computer screen. There are three sizes of braille display; some have 40, 65, and 80 cells to display raised dots. Most of them support six-dot and eight-dot braille. Each pin is electronically controlled to move up and down in order to form the braille characters from the incoming text stream. However, they can only present one line of text at a time and they are expensive. Generally, the products raise dots through holes in a flat surface. Recently, Dr. Neil Di Spigna and his colleagues from North Carolina State University have been developing a full-page braille display that allows the display to represent a text in a full page and images as raised dots. They use a “hydraulic and latching mechanism” concept to make it cheap to produce. There are numerous advantages of using the device, for example, it is paperless and mobile.

2.5.6 Braille notetakers

Braille notetakers are electronic braille writers similar to the Perkins brailler with braille keys for entering information. They use a speech synthesiser for auditory output of what has been typed or braille display for checking the output. The information is then stored in the notetaker. However, the memory in the notetaker is not as big as a regular computer. If the users want to store large amounts of data, it can be transferred to a computer via a USB cable or Bluetooth. The information can also be printed on a Braille printer. They are light and mobile, so they are suitable for students to take notes in a classroom. They also provide basic organizational tools, such as a calendar and they can also be used to send or receive email.

2.5.7 Screen readers

People with visual loss who need to read texts displayed on a computer screen can use a screen reader. This program uses a speech synthesiser to convert text on the screen to speech. Some of the screen readers have graphical user interfaces (GUIs), with the ability to handle buttons, menus, and other visual screen elements. There are many commercial screen readers, for example, JAWs from Freedom Scientific. It uses an integrated voice synthesiser and the computer's sound card to output the content of the computer screen to speakers. Window-Eyes from GW Micro converts components of the Windows operating system into synthesised speech allowing for complete and total access to Windows-based computer systems. At present, screen readers are popular because they are easy to use. Since the largest population of visually impaired became blind in old age from Glaucoma, Macular degeneration, and diabetes (Jackson & O'Brien, 2008), this is a good option for them in reading texts. However, there are some disadvantages to using screen reader. For instance, it reads everything even punctuation marks and when the screen reader does not recognise a word it will spell it out. It uses a computer-sounding voice, and this may irritate listeners. Reading data from graphs or tables may confuse the screen readers and also it does not support texts in PDF format.

2.6 What has caused the decline in braille usage?

In the past, there were many illnesses that caused childhood blindness, such as, the congenital rubella syndrome (CRS), but since 1970 when rubella immunisation was introduced the number of babies born with CRS decreased dramatically. Moreover, these days there are many medications and technologies to help people with blindness. A recent study has successfully made an artificial retina to restore normal vision in mice, and it is hoped a similar success will be had with humans soon (Nirenberg & Pendarinath, 2012).

Since 1963 the number of braille readers has declined significantly (National Federation of Braille, 2009). According to the National Federation of Braille (NFB), 90% of blind children in the US are not taught to read braille. In Australia, there are no special schools to teach braille. Children with blindness or low vision have to go to a regular school and learn with sighted children. Some reasons for this are: (1) there are not enough teachers who can read and write braille fluently; (2) some of the teachers that are available have not received enough training; and (3) many braille teachers think braille is unnecessary to learn because these days there are various technologies to help them read. They tend to have negative attitudes to braille (Holbrook and Koenig, 1992; Rex, 1989).

The number of congenitally blind people, who would tend to use braille more than the late blind, has been significantly reduced by the development of better medication. One of the commonest causes of vision loss in Ireland is diabetes (Jackson & O'Brien, 2008). More than 90% of people with diabetes will suffer from retinopathy (Feit-Leichman, Kinouchi and at al., 2005). People in Ireland who have sight loss suffering from diabetic eye disease has increased by 120% between 1996 and 2003 (Kelliher et al., 2006). According to the Diabetes Federation of Ireland, there are more than 200,000 people with diabetes in Ireland and over half of them are unaware of the serious long-term risks associated with the condition (Jackson & O'Brien, 2008). Diabetic retinopathy often occurs from middle to old age. In addition, fingertip sensitivity can be reduced due to peripheral neuropathy. This is a significant obstacle to learning braille.

2.7 Why is braille still important?

Even though text-to-speech software is broadly used for people with blindness to read text, listening is not the same as reading. The blind do not learn spelling or punctuations from listening and also their reading and writing skills are not being practiced. A neuroimaging study has shown different patterns of activation of the brain between reading and listening comprehension tasks in sighted subjects; there tends to be more activation in the left inferior occipital cortex and left-lateralized activation during reading comprehension, while the temporal cortex is more active in listening comprehension task (Buchweitz, Mason, Hasegawa, & Just, 2009).

Assistive technology is still useful for people with vision loss, but there are some drawbacks in using it. For instance, some people who use audio books might get distracted more easily while listening to a book than reading by themselves. Moreover, if you want to reread a part that you misunderstand, it is hard to find the exact point you want to re-read. In contrast, braille literacy enables people with vision loss to function more independently in their life. They can keep notes and locate places such as toilets and use elevators when braille signs are available.

Braille helps people with visual impairments understand the fundamentals of language. Braille is essential to the study of a high level of mathematics, music, and computer programming. In addition, braille is indispensable for deaf-blind people since they cannot use screen readers or audio books. It is also an essential tool for communicating with others.

Chapter 3

Previous studies of braille reading

Empirical studies of braille reading are reviewed in this chapter. In the past, many researchers studied braille reading to attempt to understand how braille readers perceive information and the characteristics of their reading style (e.g., reading speed, style of hand movements). In the early 1990's, research in cognitive neuroscience became increasingly common in order to better understand the brain processes that occurred during tactile tasks and specifically braille reading. Recently braille studies using neuroimaging techniques have found evidences that in congenitally blind people, touch activates not only the primary sensorimotor cortex (SM1) and secondary somatosensory area (SII), but also the occipital lobe that mainly functions for visual perception (e.g., Sadato et al., 1996, 2002; Hamilton & Pascual-Leone, 1998; Cohen et al., 1999; Lanzenberger et al., 2001; Burton et al., 2002). Some studies (e.g., Sadato et al., 1996; Cohen et al., 1997) reported that there was activation in primary and secondary visual cortex in early blind subjects during tactile discrimination tasks. However, these studies did not include a sample of late blind participants. The comparison was between early blind and sighted subjects. Another PET study was carried out by Büchel, Price, Frackowiak, & Friston (1998) who found activation of primary visual cortex in late blind subjects, but of the extrastriate visual areas in early blind subjects. Cohen et al. (1999) and Sadato, Okada, Honda, and Yonekura (2002) found there was a stronger activation in visual cortical areas in subjects who lost their sight before their early teens.

In 2004, Sadato and his colleagues conducted an experiment among late blind persons who had not learned braille before. The result demonstrated that visual cortex showed activation during tactile discrimination tasks in people who had lost their sight late in life, but not in a sample of sighted readers. More interestingly, a study with blindfolded normal sighted subjects was conducted over a period of five days. The results indicated some activation in participants' occipital visual cortex during tactile information processing (Pascual-Leone and Hamilton, 2001).

3.1 Braille versus print reading

Sighted people learn to experience the world through their eyes, whereas, the sense of touch is the main window on the world for people with visual impairment. Even though sighted and blind people use the different sensory modalities in reading, both systems generate information that is eventually mapped onto the same linguistic representation (Schiff & Foulke, 1982).

3.1.1 Sensory channels

The sense organs used for vision are both eyes working in synchrony. In braille reading, one or both hands may be employed and one or more fingers on each hand. In reading by touch, detecting characters or pictures is determined by the height of the embossed dots or lines comprising the figure. Vision, however, depends on the contrast between background, foreground, and figure. Although the modality of perception is different, the underlying linguistic processing is in almost all respects the same.

3.1.2 Picking up information

In the case of tactile reading, most information is acquired during hand movements. It involves fingers, hands, and arms and the coordination of these movements. Reading braille happens continuously and sequentially. Words are assumed to be perceived through the movement of fingers and become grouped successively in perception. The process is called “chunking”, which is a grouping from small elements to form a bigger unit (Rex et al., 1994). During braille reading, pauses are rare, however, they are found near word intervals or at beginnings of words. When the finger pauses, only the letter under the finger is read and no perception occurs (Kusajima, 1974). In visual reading, eyes do not move continuously and smoothly along a line of text, but the move in a series of rapid jumps called saccades and between those jumps the eyes make short pauses called fixations. During a fixation, several words or letters can be perceived in one fixation. Therefore, the intake of the information doesn’t occur when the eyes move or during saccades because the movement is too rapid, but it happens during fixations (Rayner, Carlson, & Frazier, 1983). Nolan and Kederis (1969) stated that the perceptual unit for braille reading seems to be a character or a single cell at one time, while sighted readers can perceive 4 to 6 unrelated characters in one fixation duration or more if they form a word (Healy, 1980; Johnson, 1975).

3.1.3 Reading speed

As several studies have demonstrated, reading by means of the visual channel is more rapid than reading by means of the tactile channel. Foulke (1991) has argued that braille reading is mostly slower than print reading because only one character is recognised at a time. Nevertheless, some braille readers can read as fast as the average reading speed of sighted readers. To achieve these speeds, fast braille readers must be able to integrate tactile information over a larger time window and thus use higher-level lexical and linguistic information to help with recognition (Schiff & Foulke, 1982).

Wetzel and Knowlton (2000) showed that average braille reading rates were slower than the print rates when conditions are matched and the methods of measurement are the same. Taylor (1965) studied reading performance of 12,359 first year students. The reading speed showed the average of 280 words per minute (WPM). Foulk's (1982) study demonstrated that the conventional estimate of braille reading speed is about 100 WPM. Legge and his colleagues (1999) studied reading speeds from 44 skilled braille readers. They compared Grade 1 and Grade 2 braille and found that the mean reading speed of Grade 2 braille was 80.34 WPM, which was faster than Grade 1 braille at 57.08 WPM. However, when measured in terms of characters per second, the reading speeds of Grades 1 and 2 are not significantly different. Troxell (1967) conducted an experiment that compared visual and tactile reading speed when text was presented a character at a time. He found that the average braille reading speed was similar to visual reading at 19.5 wpm in visual readers and 18 wpm in tactile readers. Moreover, context conditions were examined by comparing the reading of normal and scrambled sentences. The result demonstrated that speeds for normal sentences were faster than for scrambled sentences. In terms of words per minute, the result showed that unscrambled sentences were read 31% faster for Grade 1 and 40% faster for Grade 2 texts, agreeing with the findings of Nolan and Kederis (1969) on braille word recognition. Knowlton and Wetzel (1996) compared braille reading in four different reading conditions: oral reading, silent reading, studying, and scanning. The participants performed the best in the scanning task (203 WPM), oral reading (136 WPM), studying (106 WPM) and silent (105 WPM), respectively. The findings revealed that reading rates altered, depending on the task that readers were asked to perform. Wetzel and Knowlton (2000) compared reading rates between print and braille on three reading tasks: oral reading, silent reading, and studying. The analyses indicated that there was a significant difference in the reading rates of print and braille reading under each condition. The average reading rate decreased across oral reading, silent reading, and studying. Hensil and Whittaker (2000) examined 30 sighted participants in reading by asking comprehension questions after silent reading. The result showed that the mean rate was 246 wpm.

In summary, the average reading speed of expert braille readers is between 90 to 115 WPM, compared to 250-300 WPM for sighted readers (Rosa et al., 1994). Mousty and Bertelson (1985) stated that reading rate was affected by the choice of hand for reading and the legibility of words. Moreover, the reading speeds vary widely, depending on methods, materials, context (e.g., prose, scrambled sentences), reading task (e.g., oral reading, silent reading, scanning, comprehension), braille reading experience, and braille code used (Grade 1 and Grade 2; Knowlton & Wetzel, 1996; Millar, 2004).

On average, tactile reading is certainly slower than visual reading. Tactile acuity is poorer and primarily affords sequential character-by-character reading. The eyes, on the other hand, can jump from one line position to another. The average saccade length in English is about 7-9 characters, or about one and a half words (Morrison & Rayner, 1981; O'Regan, 1983). Foulke (1982) stated that we might expect braille reading speeds to be equivalent to print reading speeds if only one character is visible in print reading at a time.

3.2 Braille reading behaviour

Between the 1920's and 1990's, braille reading studies mainly involved investigating reading performance rather than its underlying cognitive processes (e.g. Bürklen, 1917, 1932; Holland, 1934; Eatman, 1942; Foulke, 1964; Lowenfeld et al., 1969; Kusajima, 1961, 1974; Fertsch, 1974; Millar, 1984, 1987; Bertelson, Mousty, & D'Alimonte, 1985). The knowledge from these investigations was typically used to determine the most appropriate teaching strategies for improving reading speeds.

Many devices were designed to track finger movements in order to explore braille reading behaviour. The first device was invented by Bürklen and was called a *tastschreiber*. It was a simple device that drew lines with pencils mounted on the reader's index fingers (Bürklen, 1917, 1932). The Kymograph, used by Kusajima (1974), records the downward pressure of the readers' fingertips on the braille cell as it varied during reading (cited in Foulke, 1979). In 1985, Mousty and Bertelson used two television cameras for filming the subjects' hand movements both horizontally and vertically. Millar (1997) used a transparent surface supporting a transparent braille sheet and recorded a video form underneath the surfaces. The Automatic Finger Tracking System (AFTS) is a computer-based system for automatic finger tracking of braille readers developed by Breidegard el at. (2008). In general, the trend in recording techniques has been towards less intrusiveness and greater temporal resolution.

Empirical research of braille reading has demonstrated that the most efficient readers read braille with both hands, thus contributing to high reading rates. However, there is controversy about the relative contribution of the hands when both are used to read. Do both hands perceive braille simultaneously? This is a question that many researchers have addressed. Bertelson et al. (1985) claimed that fluent braillists mostly used disjoint exploration in their reading style in taking information from two hands in parallel. Since these readers had the highest reading speed, it might be assumed that both hands perceived input simultaneously. However, Millar (1987) found that index fingers perceived letters sequentially since while one finger was on a letter, the other finger was touching a space or a gap between letters or words. Therefore, she claimed that perceiving information by using both hands in braille reading did not involve simultaneous processing. Moreover, another question related to using both hands is the precise function of each hand during braille reading. Some researchers consider that there is no difference in function between the left and right hand in braille reading. Others assume that each hand has a special function. For example, Smith (1929) suggested that only one finger perceived the information and the other one was employed as a guide. According to Kusajima (1970), two-handed reading is faster than one-handed reading since both hands perform different function in parallel. He argued that the right hand was used for scanning gist and left hand for checking individual words. Millar (1997) concluded that both hands were used in reading and both of them take in spatial information, although individuals vary in the hand they use most.

> "Hand movement is a very individual matter, depending on such factors as the effect of asymmetry in the brain (which is partly responsible for which hand is dominant), the relative sensitivity of each finger, and possibly the effect of any training received at an early stage of learning. Some read with the left or right hand alone; with the other one merely marking the place, and some use both hands at the same time. " Lorimer (2002, p.76)

Researchers have attempted to investigate fast and slow braille readers' behaviour in order to find out how good readers perform, so poor readers could be taught to use the same techniques. Eatman's (1942) study revealed that fast readers employed two index fingers rather than one finger. His results demonstrated that using both hands independently in reading is faster than using only one hand and using multiple fingers when reading was found in proficient braille readers. Index fingers of both hands are the primary reading fingers, middle fingers may be used to help the index fingers in recognising braille characters, and other fingers are used to sense the end of the line and punctuation (Burklen, 1932; Wormsley, 1997). Foulk (1979) perceived that using all fingers in the braille reading process would assist in improving reading speed. Most fluent braille readers divide the reading task between their two fingers; at the middle of the line, the left index finger searches for the beginning of the next line while the right index finger still reads the current line until the end of the line (this is referred to as a disjoint exploration pattern by Bertelson et al. (1985)). Eatman assumed that the reason why readers who employed both index fingers read faster was because they had learned to involve both fingers cooperatively in the same perceptual process. During reading, fast readers move their reading fingers steadily and smoothly, applying light pressure on the raised dot patterns and making fewer regressions (Eatman, 1942; Fertsch, 1946; Nolan and Kederis, 1969; Kusajima, 1974; Millar, 1997). On the other hand, slow readers usually employ only one index finger in reading, but if two index fingers are used, they are not used independently. There is no division of the reading task. This technique often causes readers to stray off lines (Bürklen, 1932).

Many educators have hypothesised that increasing reading speed in poor readers can be achieved by encouraging behaviours found in good readers (Schiff and Foulke, 1982). Many researchers have conducted experiments to train poor readers by using rapid reading techniques. Umsted (1972) and Wallace (1973) demonstrated that training the rapid recognition of the braille cell increases reading speed significantly. Cates and Dennis (1986) examined the effectiveness of using a computer generated self-paced tachistoscope-like display of sentences and phrases to improve braille reading speed. He stated that the device might serve as vehicles for improving skills such as reading rate. Nolan (1964) and Grunwald (1966) trained braille readers to use a device developed to study ways of improving the efficiency of braille reading. The device consisted of a supply reel that moved sheets of paper (embossed with braille characters) continuously from right to left. The raised dot braille was moved across a display surface and onto a take-up reel. The reader's index finger was placed on the paper tape in a fixed position. The speed of the supply reel could be controlled and increased gradually when the readers were reading so that they could be trained to read at faster rates. Nevertheless, Nolan (1964) stated that increased rates by training did not survive long. Grumwald (1966) demonstrated that braille readers who have acquired the ability to identify several characters, syllables or words, come to read at about 250 wpm. Moreover, the size of fingers is also important in tactile acuity. Ryan, Erik, and Daniel (2009) studied 50 women and 50 men on a tactile grating orientation task and measured the surface area of the participants' index fingertips. The result showed that haptic perception improves with decreasing finger size. The women had better tactile acuity than men because their finger size is smaller.

In summary, most researchers have observed that using both hands leads to better performance than using only one hand. The left hand might be better for new braille learners because it is dominant in spatial processing. However, if the readers want to speed up their reading, the right hand might be better to take in linguistic information. Braille reading needs both spatial and language skills. In general, we cannot identify which hand is the best in reading braille because it depends on task demands, stimulus materials, reading habits, and individual preferences (e.g. Bradshaw, Nettleton, & Spehr, 1982; Millar, 1984).

3.3 Neuroimaging techniques in the blind

The parts of the brain that are used for processing tactile and visual information are known as the primary somatosensory cortex and the primary visual cortex (V1), respectively. In the past, studies of braille reading emphasised various aspects of hand performance, since it was not possible to observe brain activity during reading at that time (e.g., Fertsch, 1947; Harris, 1980; Millar, 1984). In the late 1980's, new techniques based on functional neuroimaging started to be used to understand more deeply the behavioural characteristics of tactile reading. The techniques were used to pinpoint areas of neural activities in the brain, such as,

Positron emission tomography (PET): a technique for measuring radioactivity in the brain and produce images of neural activity;

Transcranial magnetic stimulation (TMS): a technique based on using a magnetic field that induces a current in the brain; it can be used to alter or disturb brain activity;

Functional magnetic resonance imaging (fMRI): it is a technique to image brain activities;

Parts of the brain involved in a particular mental process can be studied by fMRI. This technique detects changes in blood flow and oxygenation that occur in response to neural activity. These techniques can be used, among other things, to demonstrate cross-model reorganization in the brain after sensory deprivation.
The first experiment that showed cortical plasticity in braille reading was carried out using the PET technique. This technique works by injecting radioactive material and can be dangerous to participants who are sensitive to radiation, so it was only used briefly in the early 1990s . It was used to examine the effects of early onset blindness on cortical metabolism in the first experiment conducted by Wanet-

Defalque et al. (1988). The result showed that glucose metabolism was higher in the occipital cortex of early blind participants than in sighted participants. Sadato et al. (1996) studied the neural networks used by braille readers blinded early in life compared with sighted readers by using the PET technique. The results showed that there was activation in primary visual cortex during haptic tasks among the blind subjects; on the other hand, deactivation was found in the sighted subjects. This suggested that reading braille in early blind people is supported by the functions of primary visual cortex. Transcranial magnetic stimulation (TMS) was used by Cohen et al. (1997) to disrupt the function of different cortical areas in early blind participants during a tactile discrimination task. The findings showed that TMS applied to subjects' visual cortical areas induced errors during identification of braille letters, whereas sighted subjects were not disrupted when they read embossed Roman letters. It suggests that the visual cortex in the blind subjects is used to process tactile stimuli. In 1999, Cohen used PET and repetitive transcranial magnetic stimulation (rTMS) to observe periods of susceptibility for cross-modal plasticity in the blind. His results demonstrated that age of onset of blindness was a critical variable in rerouting of tactile information to the visual cortex and the susceptible period did not extend beyond 14 years. Nevertheless, a previous PET studied by Büchel et al. in 1998 found that participants who had vision early in life but were told that they would become completely blind also demonstrated a cross-modal reorganization of the occipital cortex. Therefore, Büchel claimed that not only the age of onset of blindness causes cross-model reorganization, but tactile experience early in life was also an important factor. In 2008, a study reported by Ptito et al. showed that TMS administered to the left and right occipital cortex induced tactile sensations in the fingers of blind braille readers related to the number of hours of braille reading per day, their dexterity, and their reading speed. Sadato et al. (2002) and Sadato (2005) used fMRI to explore the neural substrates activated during tactile stimulation. The results were in accord with Cohen et al.'s (1997) study. The findings correspond to the previous studies of braille tactile discrimination tasks, where there was activity seen in the occipital lobe, which occurred in the primary visual cortex in early blind subjects, but not in late blind participants. In sighted participants, there was no activation in the occipital lobe. In contrast, Büchel et al.'s (1998) study showed that the primary visual cortex was activated in late-onset blind subjects, but not in congenital and early-onset blind subjects. This might be because of differences in the control conditions and discrimination tasks, and the age of exposure to braille reading (Sadato et al., 2002).

Increasingly, findings using the brain-scanning techniques to present activity inside the brain of congenitally blind people suggest that the traditional visual cortical areas are not just reserved for vision but also for other sensory modalities. There is evidence in the occipital lobe in the blind's brain that takes on language-processing tasks (Hamilton et al., 2000). Important factors in activating cortical visual areas are not only the age of early-onset blindness, but a reader's motivation to learn braille. After visual sensory deprivation the human brain has an ability to re-organise itself, known as 'plasticity of the occipital cortex'. In addition, researchers have shown that when individuals with blindness learn to read rasied-dot patterns, the brain reorganises itself and uses the visual cortex in processing tactile information (Hannan, 2006). This evidence indicates a remarkable degree of functional plasticity in the visual cortex.

Part II. Finger-tracking system

The following chapter describes the finger-tracking system used to record finger movement data for all experiments conducted for this thesis.

> “The tiny bumps, they mean everything. They jump and twist, likes waves of the sea. They roll and dip, like hills on flat ground. They tell a story too, of fire and ashes, of flowers that bloom. And wilt just as fast. You can read it, If you try.”
>
> \- NINJA CAT

Chapter 4

Instrumentation and software

This chapter[1] describes a cheap and easy-to-use finger-tracking system for studying braille reading. It provides improved spatial and temporal resolution over the current available solutions and can be used with either a refreshable braille display or braille-embossed paper. The system has been developed for measuring the moment-to-moment processing of behaviour of braille readers and exploring ways of enhancing the braille reading experience. Setting up the system and software used for the system are described in this chapter. The software developed to control the display of text and the logging of finger location are also described. This software can also dynamically change the displayed text, contingent on the reader's finger position. This is called a display-change paradigm and was originally developed for use in eye movement studies. This technique was used for the first time in braille reading study for an experiment in Chapter 6. This finger tracking system will allow researchers to probe skilled braille reading in significantly more depth than has heretofore been possible.

[1] Note that some parts of this chapter are published in Behaviour Research Methods in 2012 (Aranyanak & Reilly, 2012)

4.1 Introduction

Sighted reading has been investigated scientifically for well over 100 years (e.g., Huey, 1968). In the last 30 years or so, the precision with which sighted reading can be studied, at least at the perceptual level, has undergone a revolutionary change with the development of modern eyetracking technology (Rayner, 1998). Research on tactile reading was first conducted around the turn of the last century (Bürklen, 1932). The dominant tactile writing system has, for nearly two centuries, been braille. However, technological developments have not made a significant impact on the study of braille reading. Much of the research over the last 30 years has entailed the laborious analysis of video recordings, collected typically at around 25 frames per second (FPS). In general, the sampling rates of most of the video recording techniques used to study braille reading have been too low to capture any subtle alterations in reading speed that might, for example, reflect online language processing. Previous studies of braille reading have been hampered by the technology available to track readers' fingers (e.g., Legge, 1999; Millar, 1997; Mousty et al., 1985; Pring, 1982). Therefore, to study braille reading with close to the sampling rate of some of the low-end modern eyetrackers (e.g., the Tobii X60 and X120 from Tobii Technologies AB, Danderyd, Sweden), a high-resolution finger-tracking system utilising affordable components was designed. It provides high temporal and spatial resolution of finger movements. The aim of this chapter is to describe this new finger-tracking system in detail.

4.2 Review of braille tracking devices

The first attempts at recording the hand movements of braille readers were described in Bürklen (1932). The measurement device, referred to as a *Tastschreiber* or touch writer, was quite crude and consisted of a pen-like instrument clamped to the braille reader's finger, the tip of which scratched a trace of the hand movements on smoked paper. The Tastschreiber was reportedly uncomfortable to wear and would quite likely have interfered with fluent reading. In more recent times, Mousty and Bertelson (1985) used two video cameras to record braille readers' hand movements. The frame rate for both cameras was 25 FPS. The braille text to be read was displayed on a tablet with one of the cameras placed above the tablet, so that the left-to-right hand movements could be recorded. The other camara was set up at the same level as the tablet facing the reader, in order to record finger movements. A digital clock with a resolution of 100 ms was mounted on the tablet, and its output was recorded by the cameras while subjects read.

A higher-resolution recording system was used by Bertelson and his colleagues in the early 1990s (Bertelson, Mousty, & Radeau, 1992; Mousty & Bertelson, 1992). The tracking component had originally been developed by Noblet, Ridelaire, and Sylin (1985). Although Noblet et al.'s tracking solution was arguably the best available until recently, it required considerable expertise in the area of circuit fabrication and video technology to construct a workable device. In Bertelson et al.'s use of the Noblet et al. tracker, the braille text was presented using an Active Line braille display controlled by an Apple II microcomputer. The recording device consisted of a solid-state video camera (Hitachi KP120U) located above the display. A small lightemitting diode (LED) attached to the nail of the reading finger flashed every 40 ms. The location of each flash was recorded as x–y coordinates by the camera, allowing finger movements to be captured with reasonable accuracy. Millar (1997) described a videotaping technique to collect data from braille readers that involved a transparent surface (66 x 30 cm) supporting a transparent sheet of plastic embossed with braille text. The readers' hands were recorded from below. The video camera and a monitor were connected to each other. The monitor could display text and hand movements in real time. In each frame, the cumulative time, at 10-ms resolution, was digitally displayed on the monitor. The data were collected at a rate of 40 FPS and analyzed by hand, frame by frame (Millar, 1997). Breidegard et al. (2008) introduced an automatic finger tracking system (AFTS) for identifying finger location in video recordings of braille readers. Previous users of video based systems (e.g., Millar, 1997; Mousty and Bertelsen, 1985) had had to analyze each video frame manually to determine finger positions. The AFTS used an algorithm based on template matching and filtering to detect and track the readers' fingertips. The system had two cameras. The first camera was placed underneath a semi transparent braille sheet mounted on a transparent glass plate. Its spatial resolution was 768 x 576 pixels, and the resolution of a second camera, located at an angle above the fingers, was 320 x 240 pixels. The frame rates of both cameras were 25 FPS. Hughes (2011) constructed a device for examining the movement kinematics of braille readers. The equipment comprised a digitising tablet about 30 cm square with a spatial resolution of 0.1mm. The tip of a digitising pen was attached to the end of the dominant reading fingertip and connected to the pen's electronics, which were mounted separately on the reader's forearm. The tip of the pen was 3–10 mm distant from the reading finger's center, and the reading surface was not touched by the pen. The sampling rate of the system was 100 Hz.

While Hughes's (2011) system is innovative in its use of hardware and has a good sampling rate, it appears to be limited to tracking just one finger. In addition, the arrangement of the pen tip at the end of the reading finger precludes the use of certain finger positions favored by some readers. For example, in the studies conducted for this thesis, one reader was found who used the very tips of the fingers rather than the bulbous pads. Also, some reader studied preferred to angle their fingertips several degrees off vertical, where vertical is with respect to the orientation of the braille characters. This is presumably to increase the fingertip surface area in contact with the text. However, Hughes's pen arrangement would be likely to give erroneous cell location information in this case. Correcting for any offset in location would be complicated by the tendency for readers to dynamically alter their finger orientation as they sweep across the cells.

4.3 A Wii remote–based tracking system

As can be gathered from the foregoing brief review, modern recording techniques have been based on either the manual or automatic analysis of video recordings or from the active generation of signals by LEDs (or other devices) attached to readers' fingers. The latter approach is more suitable for a precise, in-depth analysis of braille reading. However, until recently, signal generation approaches have had the disadvantage of either requiring custom built hardware (e.g., Noblet et al., 1985) or limiting the number of hands tracked and the mode of reading (Hughes, 2011). The aim in building the system used for this thesis was to overcome these limitations and to create a high-resolution finger-tracking system approximating the temporal and spatial resolution of modern eye-trackers, but constructed from off-the-shelf components. For example, entry-level eye-tracking solutions start with a sampling rate of 60 Hz (e.g., the ASL H6 from Applied Science Laboratories, or the Tobii x60 from Tobii Technology AB). At the top end, eye-trackers of course can sample at much higher rates. For example, the EyeLink 1000 from SR Research Ltd can sample from one eye at 2000 Hz. A sampling rate of 100 Hz is acceptable for a braille tracking application, given that hand movements are significantly slower than saccadic eye movements. This finger tracking system is similar to that of Noblet et al. (1985) by using trackable infrared LEDs with a high-resolution camera. However, instead of having to construct an LED tracking camera from scratch, as they did, developments in the gaming industry were exploited and it was possible to use a relatively cheap, ready-made input device in the form of Nintendo's Wii Remote (or Wiimote as shown in Figure 4-1, to use its more popular name).

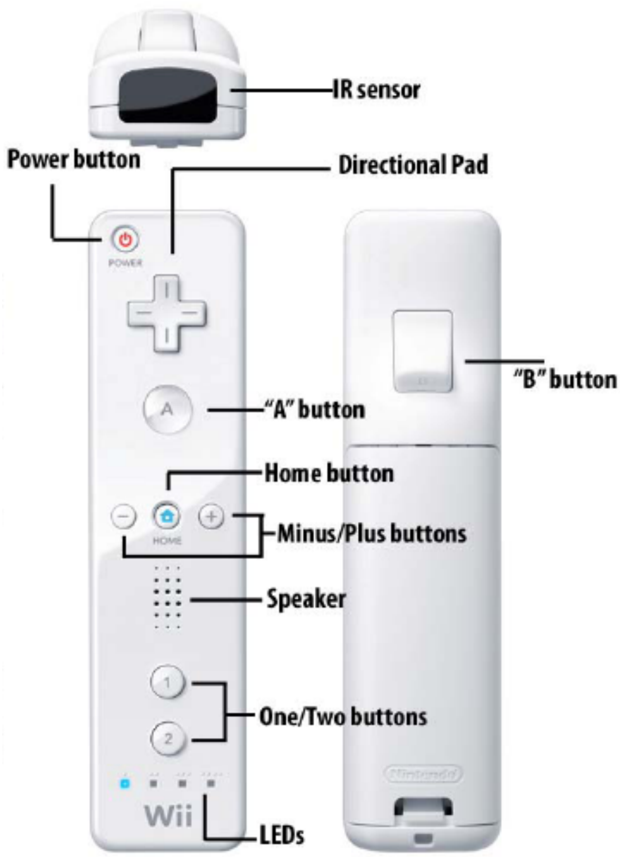


Figure 4-1: Nintendo's Wii Remote.

The Wiimote is a new-generation input device for Nintendo gaming software and is relatively cheap, at less than €40. From the perspective of the research described here, its most appealing feature, apart from cost, is its built-in infrared camera, which can calculate the positions of up to four infrared light sources. The camera sensor provides location data with a resolution of 1,024 x 768 pixels at a 100 Hz sampling rate. The sampling rate is greater than a standard webcam, which is typically in the 25-40 FPS range, and is comparable to the entry-level eye-trackers discussed.

The tracking system as a whole comprises a refreshable braille display (Handy Tech Elektronik GmbH, Horb-Nordstetten, Germany), a Wiimote, four infrared LEDs, and a laptop that integrates the components, provides an easy-to-use software interface, and logs the reading data. Hand tracking is accomplished by attaching an infrared LED to one or two of a subject's reading fingers and using feedback from the Wiimote's infrared camera to determine the locations of the two light sources. The vast majority of readers use at least one of their index fingers for reading. From the overall data collected in this thesis, all participants used at least their index fingers, although some readers used one or more additional fingers. Note that there is no reason, in principle, why one could not track the positions of more than two fingers. Careful consideration of the fingers that multifingered one-handed readers use should allow for the determination of which finger to track. In the case of someone using two or more, the rightmost finger is the most reasonable one to track. Thus, even when one-handed readers use multiple fingers, in principle we could recover the positions of the other fingers from a single tracking LED on the reading hand.

Figure 4-2: Easy Braille refreshable display (version 3.1).

To display braille characters under computer control, the Easy Braille refreshable display (version 3.1; see Figure 4-2) was used. This is an electromechanical device that comprises 40 braille cells (6.5 mm wide, cell to cell, for a six-dot cell). The dimensions of the display are 30.5 cm wide by 9.0 cm deep by 2.9 cm high. To display the braille dot patterns, small rounded pins are raised and lowered through holes in the cell surface. However, like the majority of refreshable braille displays currently on the market, the Easy Braille display is only able to present text one line at a time. Nonetheless, the big advantage of this type of display is its potential for dynamically altering text contingent on finger position. Why this is important will be discussed in a later section.

In addition, the system described here could be readily adapted for use with a multiline refreshable display. A paper mode was implemented in which our system can study multiline braille reading in its more typical form. As already mentioned, the main point of integrating a refreshable display with this tracker was the potential offered for more powerful experimental paradigms, such as, display change technique, than are possible with currently available systems.

4.4 Equipment configuration

Figure 4-3 is a schematic representation of how each of the hardware components were integrated into the tracking system. Text is presented using the refreshable braille display. The fingers to be monitored are tagged with infrared LEDs and tracked by a Wiimote. A control program running on a laptop is used to read the finger coordinates from the Wiimote camera and to control the text displayed. The system described supports the tracking of one or two reading fingers, depending on the reader's reading style.

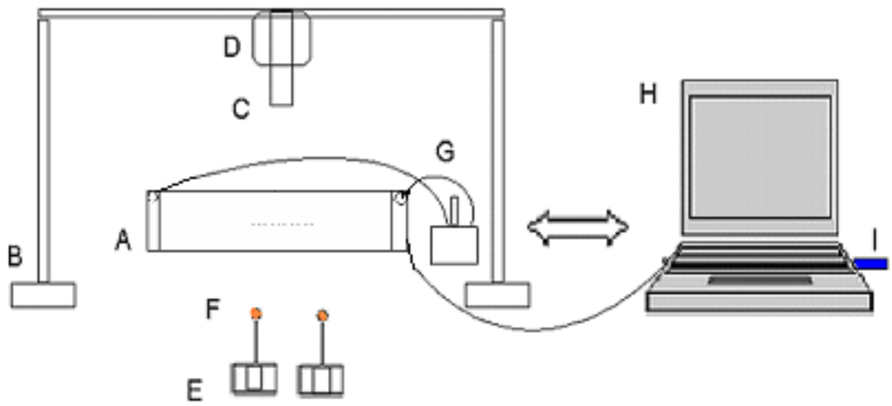


Figure 4-3: A schematic representation of the tracking system: (A) refreshable braille display; (B) retort stand for supporting cameras; (C) Wiimote; (D) video camera; (E) elastic wrist straps; (F) light-emitting diodes (LED); (G) switch box; (H) laptop; (I) bluetooth receiver

The tracker components are configured as follows. First, a horizontal bar approximately 50 cm in length is clamped to the top of two retort stands at approximately 45 cm from the table surface. The braille display is placed exactly between the two stands. The Wiimote is clamped to the middle of the horizontal bar, with the infrared camera aimed at the braille display. The height above the surface of the braille display or braille-embossed paper is approximately 40 cm. It is important to ensure that the lens of the Wiimote's camera is parallel to the surface; otherwise, the mapping between braille cells and camera pixels can be uneven across the camera's input range. A video camera is also attached by a clamp to the horizontal bar and pointed toward the braille display. It was found useful to have a complementary video recording of the readers' performance to record any idiosyncratic reading styles that the subjects might have used.

Two LEDs are attached to the braille display just to the left of the first cell and the right of the last cell, in order to facilitate calibration. They are linked to a switch box, which allows them to be switched on one at a time during the calibration process and switched off during tracking. The braille display and the laptop are connected via a USB cable, while communication between the Wiimote and the laptop is via a Bluetooth connection. A standard infrared LED with a round cross-section of 3 mm, 850 nm peak wavelength, and an emission angle of ±13º was used. The infrared camera maps the light sources onto a 1,024 x 768 planar grid. Given the configuration of the Wiimote and display described above, a single 6.25-mm-wide braille cell subtends approximately 20 pixels. In theory, 1,310 braille cells can fit into a 1,024 x 768 grid. However, if the braille display is placed near the boundary of the grid, tracking accuracy declines. It was determined that the optimal location for the display is between 100 and 900 pixels on the x-axis and centered around pixel 380 on the y-axis.

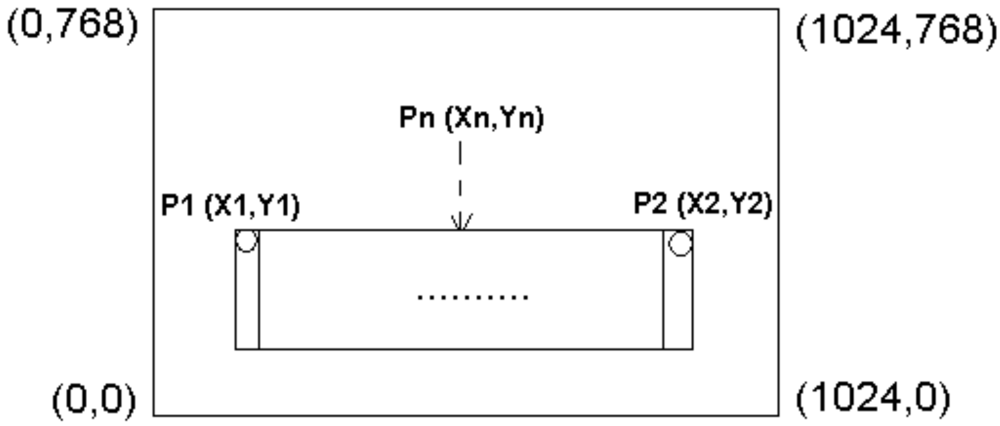


Figure 4-4: The layout of Wiimote resolution and calibration points on the refreshable braille display. The outer box represents the X and Y resolution of the Wiimote with values ranging from 0 to 1024 and 0 to 768, respectively. The inner box represents calibration points on the refreshable braille display.

In order to trace finger movements on the Easy Braille, the program must be calibrated. Calculating finger positions need two calibration points as showed in Figure 4-4: P1 is the first point on the top left corner of the first cell of Easy Braille and P2 is the second point on the top right corner of the last cell of Easy Braille. Pn is a current position, which a finger is on the braille display. It can be updated along finger movements. Pn position is a mapping point of Pn onto segment P1 and P2 which is converted to cell numbers by using this equation;

$$\left(\frac{((X2-X1)(Xn-X1)+(Y2-Y1)(Yn-Y1))*40}{(X2-X1)(X2-X1)+(Y2-Y1)(Y2-Y1)}\right)+1$$

To track readers using braille paper, the physical configuration of the system is the same as for the refreshable display (see Appendix G). The paper should be anchored to the table with tape and oriented square-on to the Wiimote camera. It will help to mark out the location of the page on the table in order to maintain calibration consistency. The main difference when using paper is that calibration requires three points rather than two (1) just above the first line at the leftmost cell, (2) just above the first line at the rightmost possible cell position, and (3) just below the last line at the first cell. For Points 1 and 2, the LEDs were used and they were controlled by the switch box, and for Point 3 an LED was used and attached to the end of a wand. These LEDs are switched on sequentially by the experimenter under direction from the calibration routine.

There are two common sizes for printed braille pages 8.5 x 11 inches, which can be embossed with up to 34 characters per line and 25 lines per page, and 11.5 x 11 inches, which can be embossed with up to 40 characters per line and 25 lines per page. The number of characters per line and lines per page are adjustable in the program in order to reflect this variation. The optimal region for positioning the braille page is between 200 and 825 pixels along the x-axis and between 45 and 740 pixels on the y-axis. Therefore, the three calibration points need to be inside the rectangle defined by this boundary.

The limitation of using braille paper is that the camera can track braille precisely only for 23 lines per page (just short of the standard number per page), but can track up to 40 cells per line. Therefore, each line is very close to each other, which can lead to LED location confusion. In order to decrease the confusion, printing the text double spaced helps. Furthermore, the system needs calibration every time there is a new page. Therefore, data collection is a little more time-consuming in paper mode than in display mode.

4.5 Calibration methodology

During reading, subjects are asked to place elastic straps on their wrists that carry the batteries to power the LEDs (see Figure 4-5). The LEDs themselves are generally placed at the center of a reader's index fingernails using Blu-Tack (a putty-like glue). Care should be taken so that the LEDs are placed along the vertical axis of the nail so as to get accurate cell location readings, particularly for readers who read with their fingertips, causing the nail to be held almost vertically to the plane of the display. Because of the nipple-like shape of the LEDs (see figure 4-5), the tracker can cope well with these variations in finger orientation. Note that the camera must have an unobstructed view of the LEDs for accurate recording. However, the system is tolerant of transient loss of signal.

Figure 4-5: Photograph of a reader with LEDs attached to the index fingers and batteries attached to the wrists.

Another two LEDs are attached at just above the first cell at the leftmost possible cell position and just above the last cell at the rightmost possible cell position. The

LEDs are linked to an on/off switch. Before calibrating cell locations, the system needs to calculate the location of the first and the last cell. The left LED is switched on first, followed by the right LED. The system calculates the cell positions by computing the (x,y) coordinates of the two LEDs on the display. During this calibration, subjects were asked to put their hands under the table to avoid confusion between the LEDs attached to subjects' index fingers and the two fixed calibration LEDs. After finishing calibration, the program computes its estimate of the braille cell locations and displays them on the screen. Readers are then asked to put their hands back on the braille display to confirm the cell locations.

In the cell location validation phase, braille letters a, b, c are presented at the first three cells and c, b, a on the last three cells. Subjects are asked to place their left index finger on cell 1 and right index finger on cell 40, then to move their fingers sequentially to the letters b and c. If the cells on the user interface do not correspond to the index fingers' positions on the braille display, the cells were re-calibrated. The validating calibration usually occurs every ten sentences with a full recalibration when necessary. If the cell location is correct, the subjects are asked to hit a right spacebar to start reading. A video recorder is turned on when the actual experiment starts. The subject's name and type of experiment are written on a sheet of paper placed on the easy braille as identification. The participants are asked to read silently. After finishing each line a right bottom space bar of the braille display needs to be pressed by readers to get the next line. Before starting the actual experiment, participants practice six trials to familiarise themselves with the experiment and also to confirm the configuration of hands and fingers that they prefer. The results of the practice trials are then used to determine how many fingers to track (one or two) and which is the dominant braille reading finger. As already mentioned, in some cases readers will use more than just their index finger on one hand. In this case, the leading, preferred reading finger is tracked.

Generally calibration is stable and only in need of adjustment if the readers have accidentally nudged the display or if one of the LEDs has come loose. However, in order to verify the stability of the calibration, a series of calibration checks were run every minute over a 30 minute period and it was found that the reported positions of two static LEDs shifted by just one pixel. Since calibration accuracy is checked every 10 sentences during experiments (approximately every 3 min) and one braille cell subtend approximately 20 pixels, this level of calibration drift is unlikely to cause problems in tracking accuracy.

In the case of paper reading, an abc–cba validation line is printed on the first and last lines of the page. The calibration starts from point 1 which is just above the first line at the leftmost cell, point 2, which is just above the first line at the rightmost possible cell position, and point 3, which is just below the last line at the first cell, respectively. Before starting reading, readers are asked to put their index fingers on the calibration validation lines on the first line and then on the last line. If they are one-handed readers, they move their index finger from the left to the right of each calibration validation line. Subjects are asked to locate their left index finger on the letter a on the first cell and right index finger on the letter a on the last cell, then they are asked to move their fingers sequentially to the letters b and c. However, if the cell numbers are not shifted, readers are asked to locate their index fingers only on the letter a at the first and the 23rd line of the following pages. If the cells on the user interface do not correspond to the index fingers' positions on the braille display, the cells are re-calibrated.

4.6 Tracker control program

The code controlling the tracker was written in Visual C# running on Microsoft's .NET platform. This system was constructed using Microsoft's Visual Studio 2005 and run on Window XP. The system uses two main external libraries: (1) a library to read LED source coordinates from the Wiimote (Peek, 2008) and (2) a library for writing to the braille display (Handy Tech Electronik GmBH, Horb-Nordstetten, Germany). Listings 1 and 2 are examples of the C# code used to control the tracker. They illustrate methods involved in the calibration of the Wiimote (Listing 1) and in the initialization and output of text to the braille display (Listing 2).

The following code excerpt illustrates interfacing with the Wiimote and the Handy Tech braille display. This sample C# code initialises communication with the Wiimote and updates the infrared sensor locations (this example is used as part of the calibration routine for the tracking system)

```
private void FirstCalibrationWindow_Load(object sender, EventArgs e){
Wiimote m_mote;
int sb = 0;
float x, y;
float x1, y1, x2, y2;
String a, b, c, d;
// mWC holds the list of all wiimotes
WiimoteCollection mWC = new WiimoteCollection();
m_mote = null;

try {
            mWC.FindAllWiimotes();
   }
catch (WiimoteNotFoundException ex)
   {
            MessageBox.Show(ex.Message,
```

```
                    "Wiimote not found error",
                    MessageBoxButtons.OK, MessageBoxIcon.Error);
    }
catch (WiimoteException ex)
    {
                 MessageBox.Show(ex.Message, "Wiimote error",
           MessageBoxButtons.OK, MessageBoxIcon.Error);
    }
catch (Exception ex)
    {
                 MessageBox.Show(ex.Message, "Unknown error",
           MessageBoxButtons.OK, MessageBoxIcon.Error);
    }
foreach (Wiimote wm in mWC)
          {
                    m_mote = wm;
                    break;
          }


if (m_mote != null){  // connect it and set it up as usual
            m_mote.WiimoteChanged +=
                    new EventHandler<WiimoteChangedEventArgs>
                              (m_mote_WiimoteChanged);
          m_mote.Connect();
          if (m_mote.WiimoteState.ExtensionType !=
                    ExtensionType.BalanceBoard) {
                    m_mote.SetReportType(InputReport.IRAccel, true);
    }
}}
delegate void UpdateDelegate(IRState irSensor);  //update sensor
void m_mote_WiimoteChanged(object sender, WiimoteChangedEventArgs e){
          try {
          this.BeginInvoke(new UpdateDelegate(UpdateUI),
                    e.WiimoteState.IRState);
          }
          catch (Exception) {
          }
}
```

```
void UpdateUI(IRState e){
            UpdateIR(e.IRSensors[0]);
}
private void UpdateIR(IRSensor irSensor){  //get data from Wiimote
            if (irSensor.Found) { //Wiimote detects infrared
                        // get X and Y coordinates
                        x = irSensor.RawPosition.X;
                        y = irSensor.RawPosition.Y;
                        textBox3.Text = irSensor.RawPosition.ToString();
            }
}
```

This excerpt initialises the braille display, reads key presses from it, and displays a line of text

```
Wiimote newGetWii;
public Thread thrd;
//declare braille class
HtBrailleDriverClass braille = new HtBrailleDriverClass();
private void _Fingers_Load(object sender, EventArgs e)
{
            braille.initialize(); // Initialize the braille display
            Array a = new byte[] { };
            braille.displayText(ref a);
            braille.onKeysPressed += new IHtBrailleDriverSink_onKeysPressedEventHandler
            (braille_onKeysPressed);
}
public delegate void brailleRead(ref System.Array keys);
void braille_onKeysPressed(ref System.Array keys, int
                        cursorRoutingPosition){
this.BeginInvoke(new brailleRead(GetKey), keys);
}
void GetKey(ref System.Array keys){
int keyCount = keys.GetUpperBound(0);
    String key = "NULL";
    HtBrlKeys a = (HtBrlKeys)(keys.GetValue(0));
    key = a.ToString();
```

```
    if (key == "KEY_RIGHT") {
        if(line ==1){
                end = 2; // starting recording the data
        }
        ShowSent(); // calling method ShowSent
    }
}



private void ShowSent(){
if (wrBrl.Peek() != -1){ // not the end of the file
        string Sent = wrBrl.ReadLine();
        string Text = wrEng.ReadLine();
        textBox3.Text = Sent;
        textBox4.Text = Text;
    char[] s = Sent.ToCharArray();//cut the text into characters
    for (int i = 0, i1 = 0; i < Sent.Length && i < 40; i++){
                PutIntoSH(s, ref SH, ref i1, i);}//get the ascii code
        Array st = new byte[40];
                 // put the characters into the array
        for (int i = 0; i < 40; i++){
                st.SetValue(SH[i], i);}
        // show the characters on the display
        braille.displayText(ref st);
        }
        else
        { // the end of the file
                textBox3.Text = "The End of File!!";
                Array st = new byte[] { };
                braille.displayText(ref st);
        }
}
```

A simple user interface was developed for configuring, calibrating, and recording reading data. The flow of control of the tracking software is driven by a simple forms interface. There are two versions of the program, one for use with the refreshable display, and one for use with braille-embossed paper. When either version of the program starts up, the first form presented (Figure 4-6) gathers data about the subject: his or her name, the experimental condition, the dominant reading hand, and so on.

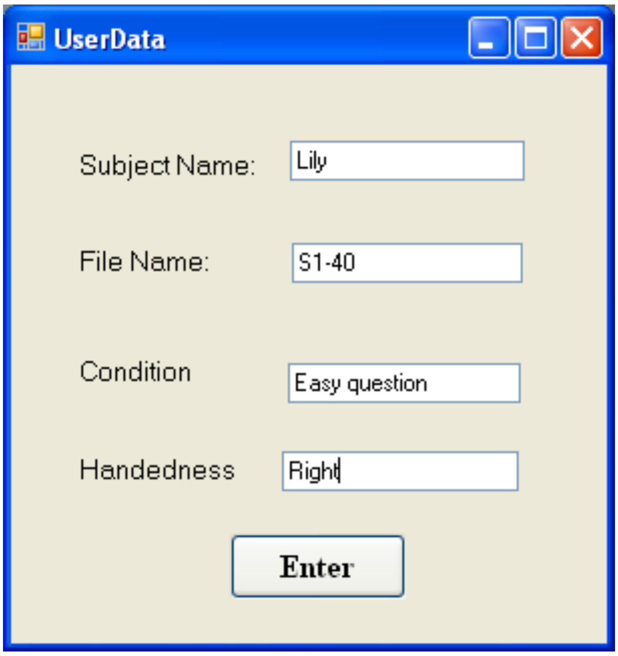


Figure 4-6: Form interface for recording subject and experimental information.

The form includes the subject's name, the file name in which the recorded data will be stored, the experimental condition under which the data are being collected, and the dominant reading hand of the subject. This is then followed by a calibration window (Figure 4-7), which facilitates the calibration of the braille display with respect to the camera and allows hand positions to be associated with specific cells in the display.

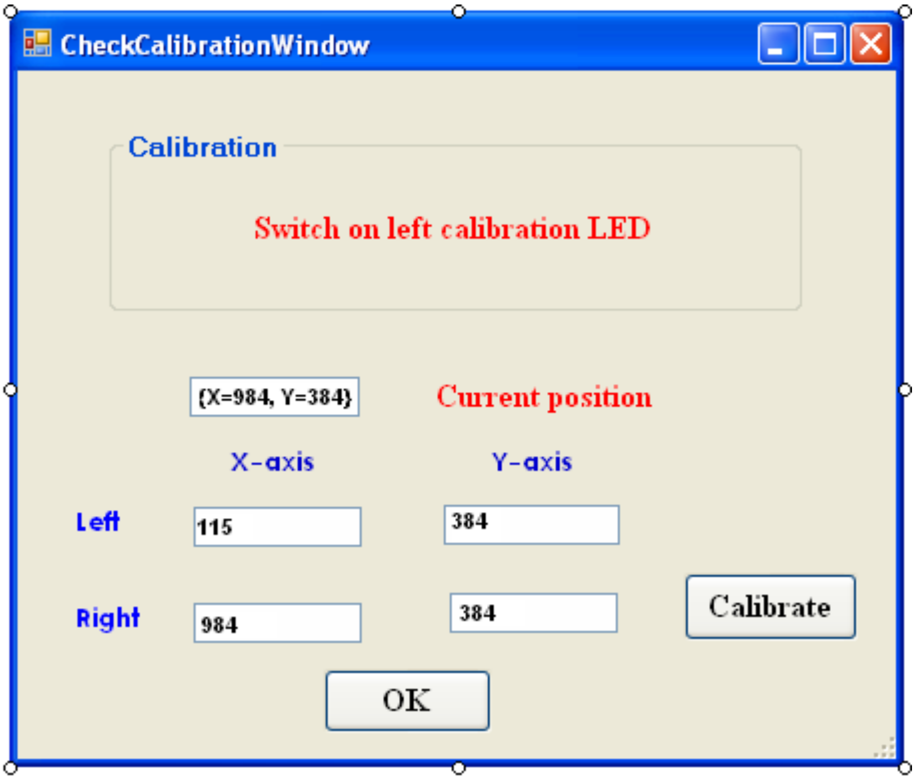


Figure 4-7: Calibration form for refreshable display mode. The top left box displays the x–y coordinates of the current position of the LED. The fields labeled "Left" and "Right" contain the x–y coordinates of the left and right calibration points at either end of the cell array on the braille display. These points are set using the Calibrate button on the form.

For the paper version, the calibration process is a little more complicated, involving the use of three landmark points (see Figure 4-8).

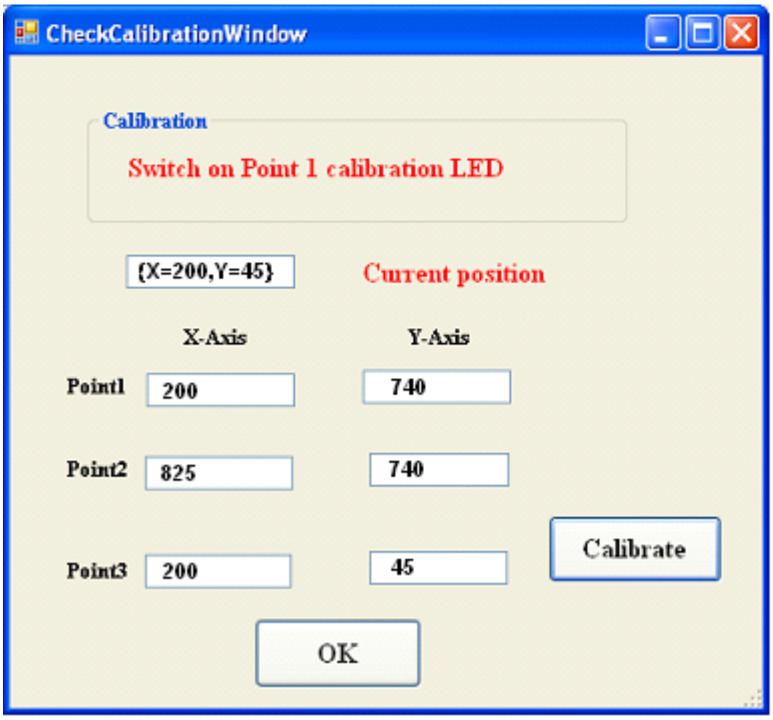


Figure 4-8: Calibration form for braille paper mode. The top left box displays the x–y coordinates of the current position of the LED. The fields labeled "Point1" and "Point2" contain the x–y coordinates of the left and right calibration points at either end of the first line on a braille page. Point 3 contains the x–y coordinates of the left calibration point below the first character of the last line on the page.

The points are registered in turn by using the Calibrate button on the form. Once calibration is complete, the experimenter makes the choice of reading mode. The control program supports the tracking of one or two fingers. The form in Figure 4-9 is used to indicate the reader's preferred reading mode. This form is for controlling the program that supports the tracking of one or two index fingers, depending on the reader's style.

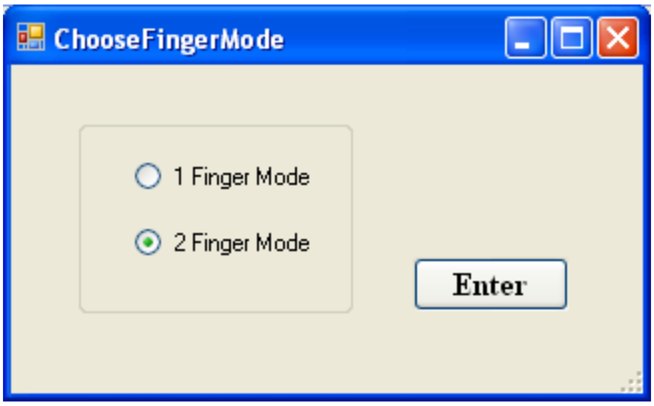


Figure 4-9: Finger mode form for selecting a finger/fingers used by the subject.

Finally, the system is ready to record data. Figure 4-10 shows the line of text that is being read. The braille display can only present a single line at a time, but sentences can be presented as a series of single lines, where the reader steps through the lines using a space bar. In Figure 4-10, the ASCII codes corresponding to the braille translation of the text are displayed. One ASCII code corresponds to one braille cell. However, there is not a one-to-one mapping between these codes and regular text, because the braille encoding includes various contractions for common letter sequences (e.g., in Figure 4-10, the character pair ",:" represents the word "Which," where the comma indicates capitalisation and the colon is a contraction for the word "which"). This form also allows the experimenter to progress to the next line of text by means of the Next Line button. However, the usual mode of progression is for the reader to press a bar on the braille display. The Calibrate button on this form allows the system to be recalibrated if the experimenter detects some variation in tracking accuracy. When reading is complete, the Exit button is clicked in order to close the application and save the recorded data to file.

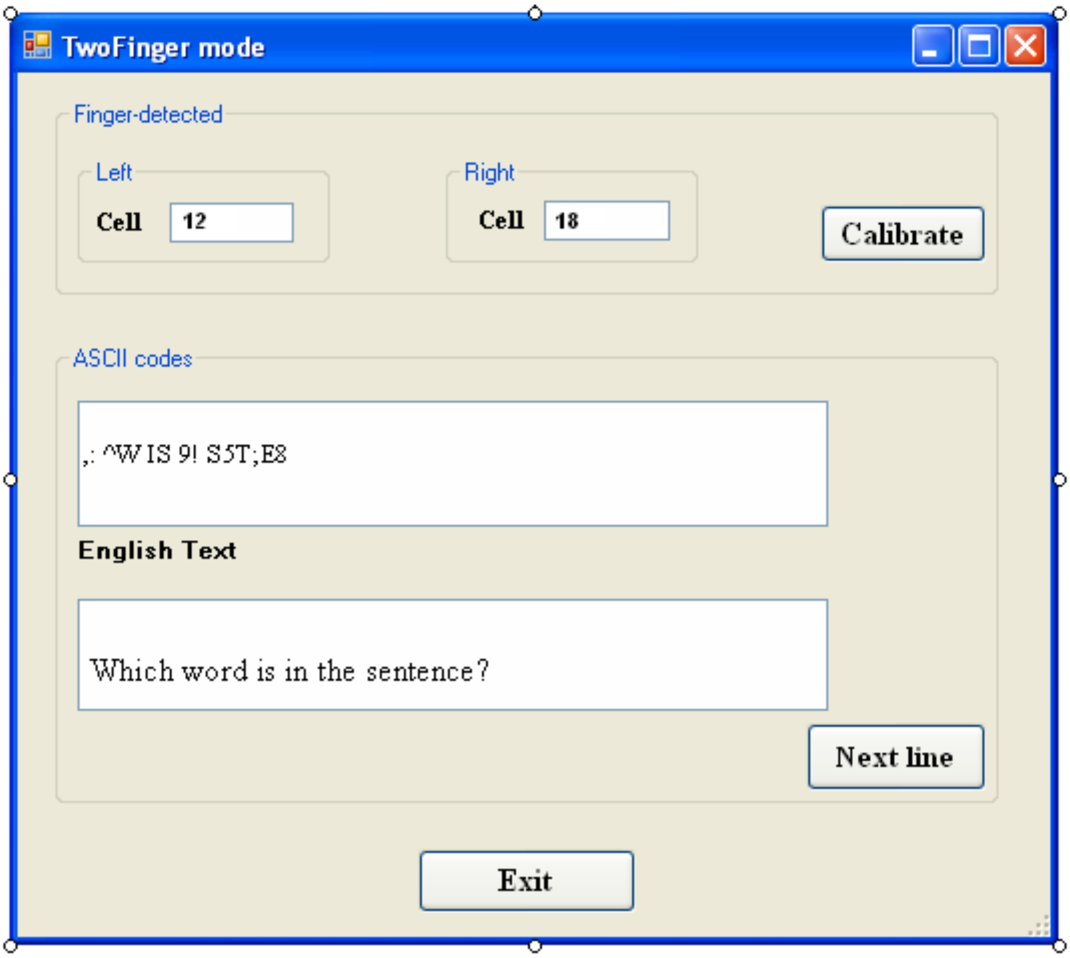


Figure 4-10: Two-finger mode form for refreshable display mode.

Figure 4-10 presents the display of the text line currently being read using the refreshable display in two-finger mode. The one-finger form has a similar layout. The ASCII codes in the box are the Grade 2 braille encodings of the text and include various contractions for common letter sequences.

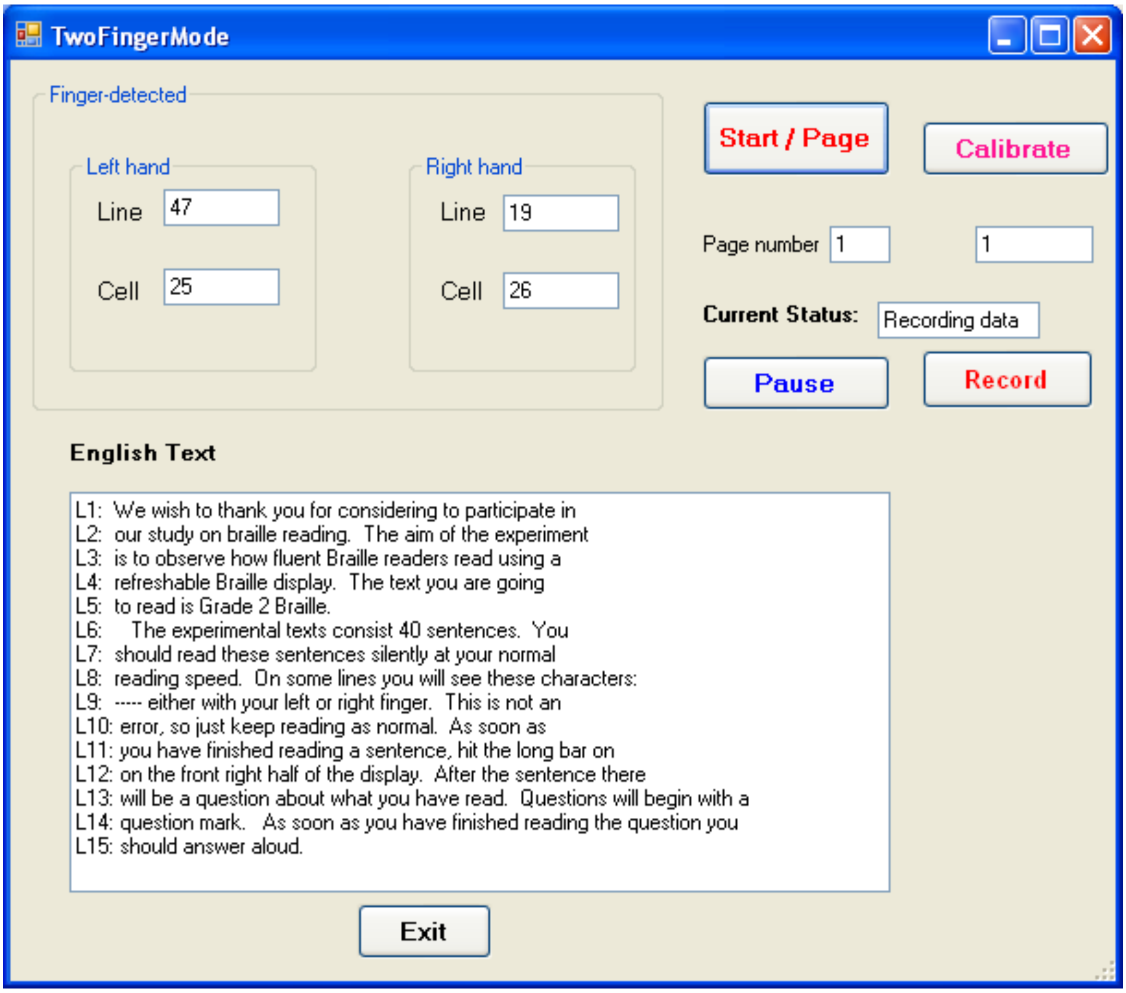


Figure 4-11: Two-finger mode form for braille paper mode.

Figure 4-11 is the corresponding form for the paper mode of the program. Note that the interface provides dynamic feedback about both the line and cell number for each hand tracked. The form shows cells and lines being read in braille paper mode by the left hand and the right hand. The English text is shown in the textbox. The Calibrate button initiates the calibration sequence, and the Start/Page button is for starting to record the cell and line numbers in an output file.

4.7 The output data

The output data file records in ASCII format both subject details and the position of the finger(s) every 10 ms. Following an initial header giving subject details, each line in the file represents the location of one or both fingers at 10-ms intervals. If two fingers are being tracked, the output will consist of two sets of location information. In the case of paper mode, this location information includes both line and cell numbers.

4.8 Display change

An especially useful feature of the system is its capability to make changes to the displayed text contingent on the position of one or both fingers. For example, the tracker control program implements a boundary paradigm similar to that commonly used in sighted reading (Rayner, 1975). This could be useful, for example, for the study of which of several fingers is the most sensitive in readers who use more than one finger on a single hand. The latter style tends to occur among fast one-handed readers. Another application of the display change capacity might be to provide different inputs to the left and right hands, in the case of two-handed readers. This would be especially helpful in answering questions about the division of labor between the hands of two-handed readers. For example, do the hands process the text in a complementary way, or is one hand more dominant? One possibility is that processing effort is spread over both hands and that the allocation of effort alters dynamically in response to the changing demands of the reading task.

Another scenario is that the roles of the hands are relatively fixed throughout the reading process. One way to explore this issue would be to split the braille input stream across the two hands so that each hand only picked up, say, every alternate word. This can be achieved by dynamically masking words depending on whether they are being read by one or the other hand. This forces the reader to integrate inputs from both hands to make sense of the text. By comparing the impact that masking has as compared to a non-masked condition, we can gauge the relative contribution of each hand. Furthermore, by altering the task demands on the reader by varying the text difficulty, It is possible to determine the distribution of processing across hands is static or dynamically dependent on the task demands.

The display change feature is only feasible due to the relatively high-speed infrared camera of the Wiimote in conjunction with the real-time control program that supports the integration of the camera and the braille display. We believe that the system described is currently the only tool available for answering, in a relatively direct way, questions concerning the relative roles of multiple fingers in braille reading.

4.9 Caveats and limitations

The system proposed here represents a significant advance on what is currently available to braille reading researchers. Nonetheless, there are a number of aspects of the system requiring fine-tuning. While one of the goals of the finger tracking system was to afford as normal a reading environment as possible, without sacrificing accuracy, the tracking hardware does impose some constraints on the reader. To ascertain whether the wearing the LEDs and batteries impacted on reading, participants were asked to rate on a 5-point scale the impact on their reading of wearing the LEDs and batteries (1 no impact, 5 significant impact). Out of the sample of 20, 70% gave a response of 1 (no impact), while the remainder gave a response of 2 (some impact).

Since the LEDs are bright, when readers' index fingers are located too close to each other the LED signals occasionally merge. To deal with this, a program to detect and correct this problem was written (see CorrectCellNumbers in Appendix F).

The finger-tracking system can track only two LED signals as the most, but some readers use multiple fingers in reading. Related to this point, a useful additional feature for our system would be an extra video camera to monitor the mode of contact of the readers' fingers with the braille text. Our current configuration uses a video camera mounted above the reading plane. A camera that viewed the reader's hands from the front would help in identifying which fingers to track in the case where several fingers on one hand are used. Crucial to much of the effective use of our system is the reliability and accuracy of our infrared sources. In addition, the LEDs used are smaller than the average finger width, so this leaves open the possibility of underestimating the transit time of the finger through a cell. This may be less of a problem when looking at aggregated transit times through words, since it would be a constant error. However, the issue becomes more important in the case of display change manipulations, in which one could change a displayed cell while the reader's finger had not left it or had already encroached upon it. Again, this issue could be dealt with by finer tuning of the system's code to take account of individuals' finger widths.

4.10 Conclusion

This chapter has described a cheap and easy-to-use finger tracking system for studying braille reading, either from a refreshable display or from embossed paper. It provides spatial and temporal resolution close to that found in modern entry level eyetracking systems. With its capabilities to implement display change paradigms on a refreshable display, it has the potential to allow researchers to probe in significantly more depth the remarkable achievement that is skilled braille reading. While some compromises were made in designing our system, overall it has better performance, greater generality, and significantly better ease of use than any other system currently available. The code that used to conduct experiments, manuals for setting up a refreshable braille display and braille paper can be downloaded as supplementary materials for this thesis (see in Appendix F).

Part III. A global characteristics of braille readers

The following part presents an empirical study of braille reading conducted in Ireland. The main purpose of the experiment focused on braille reading behaviour of proficient and slow braille readers in contracted braille reading. The effects of word frequency and a question paradigm were also examined.

"Braille, a system of tiny dots
Offers freedom of learning and lots,
To those who can't access ink,
So, reflect, for those of us who cannot see!
At how limited we'd be,
Without Braille?"

- AUDREY TORMEY

Chapter 5

Experiment 1: Braille reading behaviour and task demand effects

Visual reading can be investigated by tracking eye movements, which mostly involve left to right movement of both eyes in parallel over the text. The eyes do not move smoothly during reading. Pauses occur frequently in order to acquire new information; these are called visual fixations. No information is acquired during eye movements. On the other hand, tactile reading requires movement to pick up information. Even though reading information from vision and touch is derived from different modalities, linguistic processing is assumed to be identical (Millar, 1997). Thus, finger movement data can be analysed using approaches similar to those used in eye movement data analysis.

This chapter describes an experiment conducted in Ireland using the Wii-remote tracking system and a refreshable braille display. Two main aspects were examined in this experiment: (1) the online processing of reading texts by braille readers using a high-resolution finger tracking system and comparing reading behaviour between fast and slow readers; (2) the effects of top-down task factors on braille reading (i.e., word verification vs. comprehension).

5.1 The characteristics of finger movement in reading braille

Generally in the majority of braille readers, the pads of the index fingers are used in tactile reading. Nevertheless, there are a minority of people who also use other fingers, such as, middle and ring fingers (Bürklen, 1932; Lowenfeld et al., 1969). Foulke (1964) conducted an experiment by asking the blind people to read braille with all fingers except their thumbs. He found that it was possible to read with all fingers, but their dominant index finger was faster than others.

Bertelson, Mousty and et al., (1985) studied patterns of finger exploration in reading uncontracted braille. The experiment involved 24 blind readers reading aloud in three conditions: prose, statistical approximations of text, and scrambled words. Their hands were recorded on video from two angles: one camera recorded the horizontal movements of the hands on the page, while the other, recorded the vertical position of readers' fingers. The results demonstrated two major classes of hand usage: (1) one-handed reading, where readers read with the left or right hand alone, and (2) two-handed reading, where readers used both hands. In general, there are three main categories of hand movements that can be identified during text exploration:

Forward movements. These involve reading along the line from left to right. This movement is used to acquire information and its function is equivalent to fixations in visual reading (Breidegard et al., 2008).

Return movements. These involve readers making a return sweep to go to the next line. Therefore, there is no gaining data during this phase and the speed is faster than the forward scanning. Most readers leave left hand from the current line to find a new line while right hand is still reading to the end of the current line and join with left hand on the new line. Sometimes the finger misses the next line or does not land on the first character of the new line. The earlier cells are sometimes skipped during scanning. The end of the current line is often overshot before the return sweep. The skip occurs at the end of the current line when the last cell presents a punctuation mark, but it happens less frequently (Bertelson et al., 1985).

Regressions. These occur when one or both hands go back to reread some parts of text that has previously been read. Obviously regressions reduce reading speed because new material will not be read while readers spend time in re-reading. This is often found among slow or poor readers (Holland & Eatman, 1933; Fertsch, 1947). It also happens when readers are not sure if a word or words have been interpreted correctly and they retrace to the difficult words before continuing. Some braille readers use only their left or right hand in reading text. One hand is employed in reading along the text from left to right until the end of the current line, then the same hand returns to the next line. There are no differences between the operating modes of the using left or right hand (Bertelson et al., 1985). Some readers use both hands in reading braille. Basically, readers hold both index side-by-side sometimes touching or having a short space between them. Wormsley (1979) catagorised the patterns of two-handed reading into four groups: (1) left marks: the left hand is used as marker while the right hand reads, it is called "*assisted one-handed reading*" by Bertelson et al. (1985); (2) parallel: it is called "*conjoint exploration"* by Bertelson et al., (1985), both index fingers scan along the line and move to the next line side by side; (3) split: at the end of a current line, the left hand returns to the new line while the right keeps reading the current line until finishing the line, then the right goes to meet the left at the margin; (4) scissors: the left hand starts reading from the beginning of the next line as the right returns from the end of the previous line to the next line, then both hands meet nearly at the middle of the line, where they read together briefly before separating. Split and scissors patterns are included in the category *disjoint exploration* by Bertelson et al. (1985).

A number of studies have suggested that using two hands in reading braille is more efficient than one-handed reading (e.g., Eatman, 1942; Fertsch, 1947; Bertelson et al., 1985; Devidson et al., 1992; Millar, 1997; Wright, Wormsley, & Kemai-Hannan, 2009). Wright, Wormsley, and Kemai-Hannan (2009) conducted a longitudinal study, which showed that most braille reading participants changed their hand movement patterns to be more sophisticated. For example, those who started with a conjoint pattern often progressed to a disjoint pattern. Wormsley (1979, 1996) found that the scissors pattern is the most efficient, followed by split and parallel patterns. Bertelson et al.'s (1985) result confirmed Fertsch's (1947) findings that using hands independently in reading braille was strongly associated with reading speed. Return sweeps of the left hand to the next line saved 6-7% of reading time (Fertsch, 1947).

The goal of this part of the thesis is to observe how braille readers use their fingers in reading braille on the braille display by using the Wii-remote finger tracking system and describe general behaviour and performance of fast and slow braille readers. Various idiosyncratic techniques used by fluent readers are also examined.

5.2 The use of reading strategies

In general, the purpose of reading is to understand the meaning of the text by linking existing knowledge with the information derived from the text. It involves a complex set of cognitive processes. Psychologists have divided the reading processes into two aspects: (1) bottom-up; mapping the low-level aspects (e.g., word recognition, eye-movement control) to meaning; (2) top-down; mapping readers' prior knowledge or high-level features (sentence comprehension, discourse structure) and experiences to the low-level information. In general, these two processes work together in processing the information being read (Rayner & Pollatsek, 1989; Stanovich, 2000).

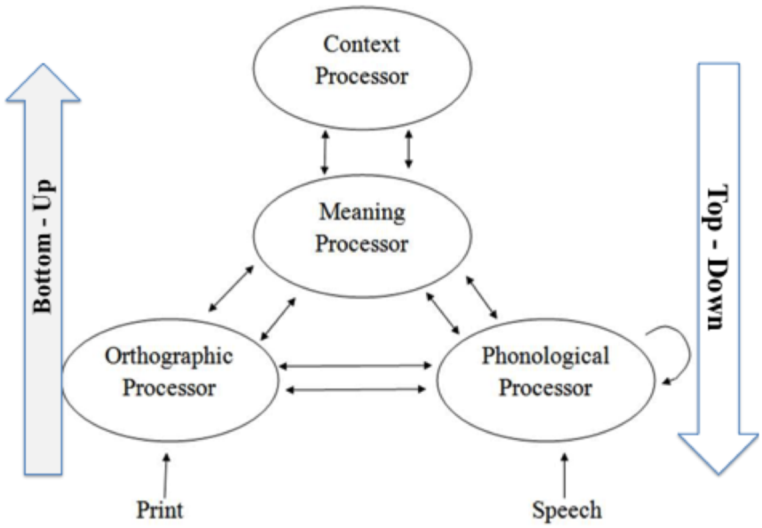


Figure 5-1: The bottom-up and top-down processing in reading and listening (Adapted from Adams, 1994).

During the reading process, readers use a variety of reading strategies and skills to help them construct and maintain meaning (Paris, Wasik, & Turner, 1991). The use of a particular strategy depends on reading tasks, materials, and individual variations. In visual reading, these can be observed by examining readers' eye movements during a reading task, how the eyes move when readers try to comprehend what they are reading and how they behave when readers do not understand parts of a text. A lot of research has been conducted in eye movement studies to measure eye movement behaviour in visual reading (e.g., Rayner & Pollatsek, 1989; Pollatsek, 1993; Rayner, 1998; Reilly & O'Regan, 1998; Radach & McConkie, 1998). Data analysis is based on inspection duration (e.g., single fixation duration, first fixation duration, or gaze duration) and inspection probabilities (e.g., single fixations, multiple fixations, or skippings) (Kliegl, Grabner, Rolfs, & Engbert, 2004). The eye movement patterns in reading silently and aloud are different. The mean fixation durations while reading aloud were longer than reading silently (Rayner, 1998). The difficulty of texts also impacts the characteristics of the eye movements influenced by the lexical variables, such as, word length, word predictability, and word frequency, etc (Wotschack, 2009). Short words are skipped more than longer words, likewise, high-frequency words are skipped more than low-frequency words (Radach & Kempe, 1993). Rayner and Well (1996) demonstrated that low-predictability words had longer fixation durations and also attract more regressive movements than higher-predictability words.

Eye movements are also influenced by reading instructions, such as, visual search (e.g., proofreading, letter cancellation) or comprehension reading (e.g., summarising, synthesising). There are a few studies that have investigated how reading instructions impact eye movement behaviour during silent reading. One of these was conducted by Kaakinen and Hyönä (2008) who demonstrated that the duration of fixations in proofreading task was greater than reading for comprehension. On average, reading speed is faster in reading for gist than comprehension (Wotschack, 2009). Rayner and Raney (1996) examined the difference in word frequency effects in two tasks; reading for meaning compared to a search task. The result indicated that a frequency effect was not significant in the search task, but was in the reading task. Readers spent longer fixating low-frequency words than high-frequency words. Wotschack (2009, p.144) stated that "Given the definition of reading strategy as a parameter specification in accordance with an identified reading intention, all these effects are causally related to top-down influences." Radach, Huestegge, and Reilly (2008) examined the different effect of the reading task on eye movement patterns. Reading materials were identical for each task instruction, but participants could be asked to answer two types of question: word verification and comprehension. The results indicated that top-down factors clearly influenced eye-movements in the specific reading task as expressed in word-viewing time. Single fixation durations, gaze durations, and rereading time were significantly shorter for the word verification as compared to the comprehension question.

Very few braille reading studies have investigated bottom-up and top-down effects. Millar (1988) studied whether speed in braille prose reading for comprehension involved bottom-up processes (‘letter-by-letter’ processing) or top-down processes related to context. The result suggested that speed in braille prose reading depended on a combination of context and orthography, in accordance with models of visual prose reading. Since there are not many braille reading studies that explore top-down effects, this experiment was designed to examine whether or not top-down factors influence tactile reading.

The purpose of this part of the thesis is to examine the online processing of braille reading by using the different kind of task instructions (word verification vs comprehension) paradigm investigated by Radach et al (2008). The paradigm was used to explore a high-level factor and low-level factor that might influence finger movement on braille reading. Moreover, another low-level aspect of braille processing involving with low and high word frequency was also investigated.

5.3 Materials and methods

5.3.1 Participants

Twenty three Grade 2 braille readers were recruited through the National Council for the Blind of Ireland (NCBI) by sending an email to readers registered with the library at NCBI (see Appendix B) . Three were removed from the data analysis -- one because he had a stroke, one withdrew from the study before completion, and one was found to have a large number of reading errors. The remaining 20 proficient braille readers were visually impaired, 10 male and 10 female. Fourteen of them were congenitally blind and six were blind from an early age. None of them had any residual vision. Two subjects were left-hand dominant and the remaining subjects were right-handed, as assessed by a handedness questionnaire (modified from Oldfield, 1971; see Appendix G). Twelve participants used both hands and eight readers used one hand in reading. To determine reading finger preference, they were asked to indicate which finger they would use to read braille. All participants identified their index finger/fingers as the preferred reading finger/fingers. Most readers' preferred reading hand was the same as their dominant hand. Nonetheless, three participants were right handed, but preferred the left index finger in reading braille. Participants were paid 10-40 Euro for the study.

	Mean	S.D.	Range
Age when Tested (yrs)	45.25	14.12	16 to 69
Age braille was Learned	6.15	2.54	4 to 12
Years Reading braille	39.15	13.43	12 to 58

Table 5-1: Group characteristics of the 20 braille readers (see Appendix D).

5.3.2 Materials

Eighty stimuli were used in testing which were derived from a set provided by Ralph Radach's laboratory at Florida state University (Radach et al. 2008). Six stimuli were provided to familiarise participants in a practical part before an actual experiment. The 80 test stimuli including a question after each sentence were converted to Grade 2 braille by NFBtrans777. Each sentence was presented in two lines; one at a time on a refreshable braille display. All 80 stimuli, including questions both in print and ASCII braille format are listed in Appendix D.

There were two aspects to the experiment carried out:

(1) *Question paradigm:* Each sentence was followed by one of two types of question, one asking if a particular word had occurred, another requiring deeper analysis. The comprehension questions were slightly harder because readers needed to answer from their understanding. All of them began with Wh-questions, such as, why, what, etc.

Order	Grade 2 braille in an ASCII format	Print
Line 1	,AT ! ZOO ! B1UTI;L **P1COCK** /RUTT$ BACK	At the zoo the beautiful **peacock** strutted back
Line 2	& =? _M "TS :ILE P WAT*$4	and forth many times while people watched.
Hard Question	8 ,:Y DID ! P1COCK /RUT BACK & =?8	? Why did the peacock strut back and forth?

Table 5-2: An example of a sentence followed by a comprehensive question. The target word is “peacock”, which is a high frequency word.

Order	Grade 2 braille in an ASCII format	Print
Line 1	,! "Y BOY 0 GIV5 /R;G **MORPH9E** AG/ !	The young boy was given strong **morphine** against the
Line 2	9T5SE PA9 F 8 BAD 9JURIES4	intense pain from his bad injuries.
Easy Question	8 BOY OR GIRL8	? Boy or girl?

Table 5-3: An example of a sentence followed by a verification question. The target word is “morphine ”, which is a low frequency word.

(2) *Frequency paradigm*: Noun target words were embedded in each declarative sentence. The statistical word frequency was computed from an English corpus (British National Corpus, 2014; see FindWordFreq.java in Appendix F). Target words that had a log frequency of more than 7.0 were identified as high frequency, and those less than 7.0 were assigned to the low frequency group. The average of the low frequency words was 3.47 with standard deviation (SD) of 1.77, the average of the high frequency words was 7.95 with SD of 0.9. The lengths of the target words were in the range of 5-7 cells and were all nouns.

5.3.3 Design

The study was run in two reading sessions. Each session comprised 40 sentences of 80 lines in total. The sentences in Session 1 and 2 were not the same. The order of questions and sentences were counterbalanced across participants. Six practice trials mixing three easy and hard questions were presented before starting the actual stimuli. The experimental sentences were grouped as follows:

A. Session 1: Set 1 (1-40) : Easy questions
   Session 2: Set 2 (41-80) : Hard questions

B. Session 1: Set 1 (1-40) : Hard questions
   Session 2: Set 2 (41-80) : Easy questions

C.Session 1: Set 2 (41-80) : Easy questions
   Session 2: Set 1 (1-40) : Hard questions

D. Session 1: Set 2 (41-80) : Hard questions
   Session 2: Set 1 (1-40) : Easy questions

Participants were assigned to one of the four groups above. There were 20 subjects, with five subjects assigned to each group. Each sentence was followed by a question.

5.3.4 Procedure

All braille readers were tested individually in a private room. Prior to testing, participants were put at their ease and asked for some basic demographic information such as, the age they started reading braille, number of years of reading braille, hand-dominance, etc. This information was required because it could affect reading speed (Legge et al., 1999, Wetzel & Knowlton, 2000). Subjects were informed about the aim of the experiment and were instructed on how to use the refreshable braille display. They were also instructed about the instrumentation used in tracking hands and procedures of the experiment (see Appendix D). The participants were asked to read the instructions for the study and had six practice trials before starting the actual experiment to familiarise them with the refreshable braille display and the procedure of the experiment. All participants were informed that they could withdraw from the study at any time.

The readers were asked to adjust their seat position for comfort. Then they were asked how many hands they normally used in reading. LEDS were attached to their relevant index finger(s). A calibration routine was executed at the beginning of each experimental session. The calibration method has already been described in Chapter 4, p. 65. Wh- questions or two-word choices were displayed after each sentence beginning with a question mark to indicate it was a question. Readers were asked to answer the question orally, then to press the spacebar after responding. The sentences were separated by an empty line. Readers could not go back to read previous lines. The two experimental blocks were separated by a rest period (10-15 minutes). The total time to complete two sessions was 45 to 60 minutes, depending on the subject's reading speed.

5.4 Data analysis

The programs for data analysis in Appendix F were executed on the raw output data to compute durations that fingers were on cells and lines. The R statistical language was used for data analysis and for plotting graphs. Before analysis, 0.9 % of data were eliminated due to signal loss or inaccurate tracking. Cell durations of more than 1000 ms were also removed from analyses. This represented approximately 0.5 % of the data. In addition, the first and last word of each line and return sweeps were excluded from analysis. For readers who used two fingers in reading, only their preferred reading hand data were selected for analysis. Most of them preferred their right hand in reading.

The data comprise four finger-movement measures. *Single-pass times* are those in which the reader makes only one pass on the word; there is no regression in the word. *First-pass reading times* (red line) are the sum of initial times on each cell in the word, following the first entry into the region, until the word is first exited. *First-visit reading times* (green line) are the sum of initial times spent on the word before exiting it to the next word to the right. *Re-reading time* is defined as the remainder of the time spent on the word after it has already been exited to the right.

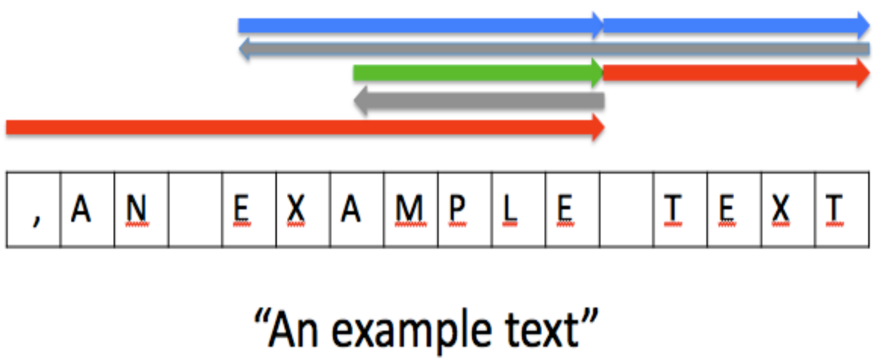


Figure 5-2: Finger-movement measures

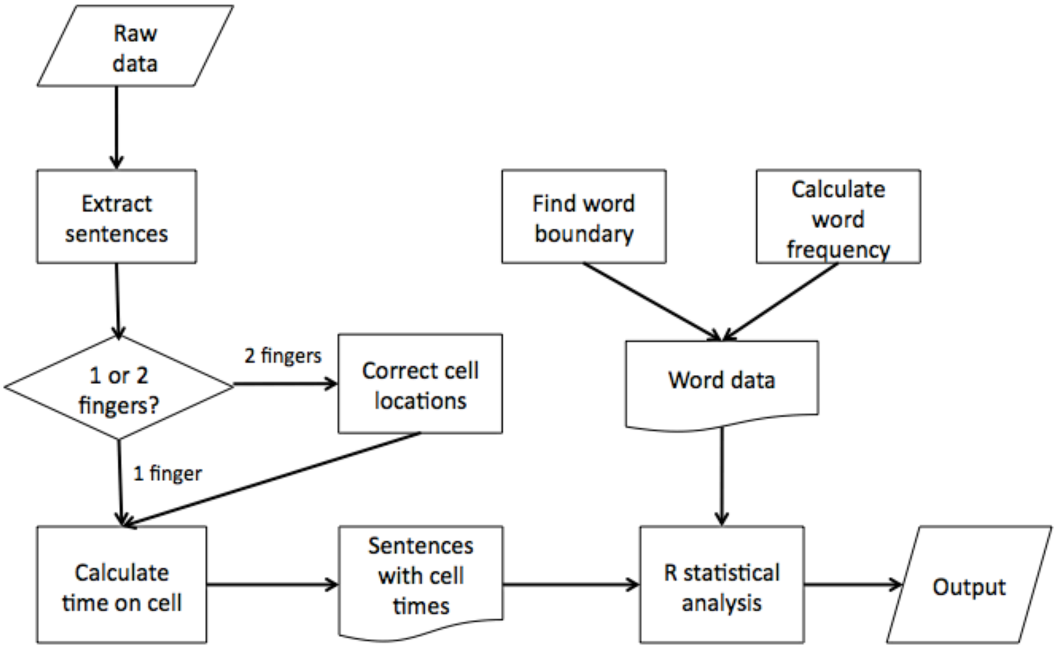


Figure 5-3: The processes of cleaning up the refreshable braille display data.

Figure 5-3 presents the processes of cleaning up the refreshable braille display data. Raw data derived from the finger tracking system were input to a program to select lines that contained the target words and also add sentence numbers to the file. Then, if the data were from two-fingered readers, a program was used to correct the cell numbers that had been swapped between left and right finger due to occasional tracking errors where the right and left fingers became confused. This program checked if the cell number of the right finger position was less than the cell number of the left finger position and made an appropriate correction (Appendix F). Cell transit times were then calculated from the corrected raw data, which were analysed using linear mixed-effects models. Programs to find the word boundary and add in word frequency were written and the data combined into one file for analysis in R.

5.5 Results

5.5.1 Finger-movement patterns

Finger tracking analysis

All participants preferred using their index finger(s) in reading. Their choice of hand can be divided into 2 main groups:

(1) One-handed reading. This group contains two sub-groups: only left (1FL) or right hand (1FR). The size of the dots in the following graphs represents transit times through the cell. It should be kept in mind here that, with skilled braille readers, the hand does not "fixate" or pause on a cell. It is continually in motion. The x-axis represents cell location, and the y-axis represents cumulative time, going from top to bottom. The left index is in red and the right index is in blue.

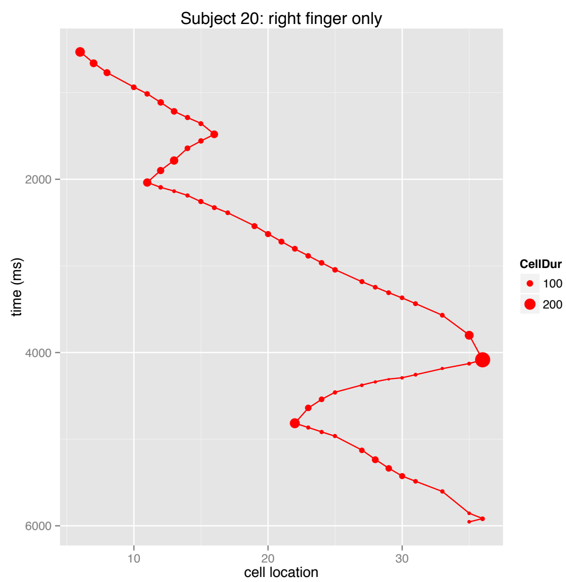


Figure 5-4: An example of using only the left hand in reading.

(2) Two-handed reading. These readers can be divided into three sub-groups;

(a) those that mainly used one hand for reading. If the right was the main, the left was mostly kept at the beginning of the line as presented in Figure 5-5 and if the left was the main, the right was mostly kept at the end of the line. However, both hands were used together sometimes when readers re-read to confirm previous information. In this case, the LED was attached only to the main reading finger;

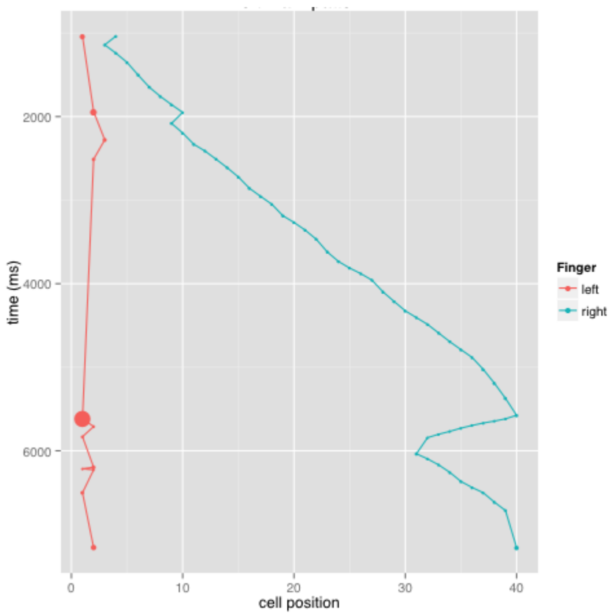


Figure 5-5: An example of using the right index finger as a main reading finger while the left finger is used as a marker.

(b) the use of completely joined fingers (2FCJ), where both index fingers read jointly along the line side-by-side either including return sweeps, as shown in Figure 5-6 or not including them, as shown in Figure 5-7; and

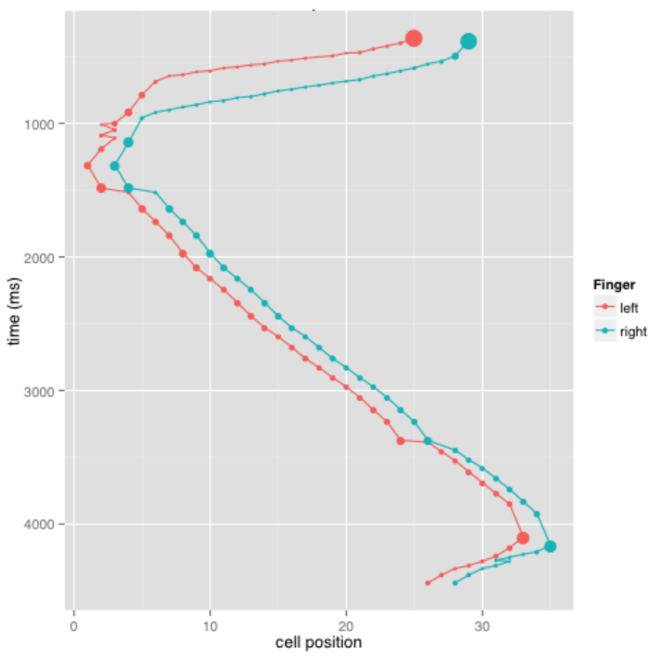


Figure 5-6: An example of using both index fingers reading along the line side-by-side including return sweeps.

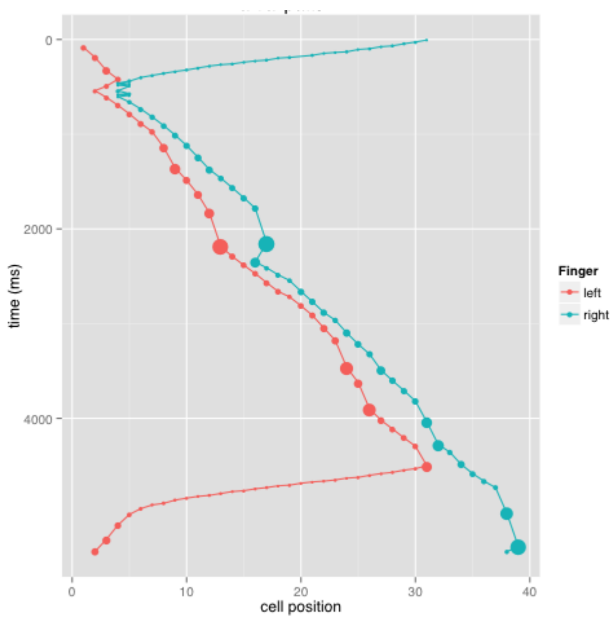


Figure 5-7: An example of using both index fingers jointly from the beginning to near the end of the current line then split.

(c) those that used partly joint fingers (2FPJ) so that from the beginning of the line, both index fingers were used together side-by-side until near the middle or the end of the line when the fingers split; the left moved to the beginning of the current line whereas the right is still reading continuously until finishing the line as shown in Figure 5-8.

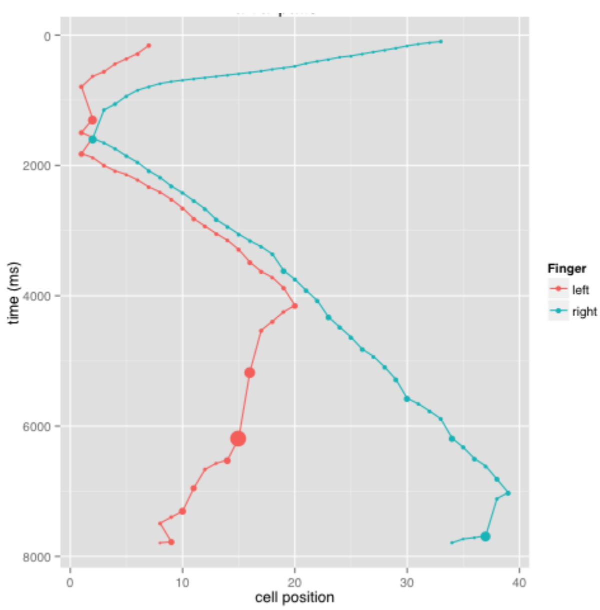


Figure 5-8: An example of using both index fingers jointly from the beginning to the middle of the line then split.

Figure 5-9 is another example of the partly joined finger style. It is also called a scissors style by Wormsley (1979). Fingers start from opposite ends of the line, then both move towards each other and met approximately in the middle of the line then split, with the left returning to the beginning of the line and the right proceeding until the end of the line.

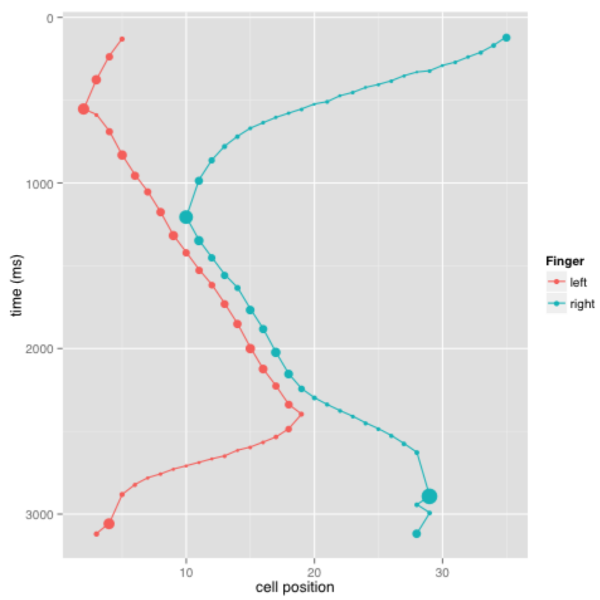


Figure 5-9: An example of using both index fingers jointly in the middle of the line. The left and the right index fingers came from different sides, moved towards each other, joined near the middle of the line, read along the line briefly then split.

Visual analysis and descriptive statistics

Of the 20 participants, eight used one-handed reading. Of these, five used the right finger while the left was placed at the beginning of the line, two used the left finger while the right was located at the end of the line, and one reader used just their left hand. The remaining 12 readers used two-handed reading. Eight of them employed a completely joined style with the two index fingers only ever about one or two cells apart as in Figure 5-5, 5-6. Four readers employed a partly joined style. There were two subjects who were left-handed; the remainder were right-handed. Twelve of the participants employed only index finger(s) in reading, six of them employed index and middle finger(s), one used index fingers and right ring finger, and the last person used all three fingers; index, middle, ring fingers of his right hand.

The characteristics of slow and fast braille readers are found to be similar to those found by previous researchers (e.g., Bürklen, 1932; Eatman, 1942; Wormsley, 1979). Slow readers touched the braille dots heavily and made lots of “scrubbing” motions, moving the reading fingers up and down over a braille cell, and also retracing the line. In contrast, good readers read smoothly, made less regressions, and used less downward pressure. Moreover, some fast readers adopted their own reading styles to get a higher speed. These are discussed in the next section.

Individual techniques to achieve reading speed

In addition to the general reading patterns shown above, interesting individual techniques to achieve fast speeds were also observed.

Subject 3, a left-handed reader, used only index fingers in reading, and preferred her left finger. She angled her left and right index fingers to point towards each other almost parallel with the line of cells. This may serve to expand the surface area under her fingers and allow her to acquire more braille cells.

Subject 8 used both hands in reading. Not only were both index fingers employed, but also her right ring finger. The right ring finger was positioned next to the right index finger while the right middle finger raised in the air during reading. One possibility for the adoption of this configuration is that is would reduce interference from the cortical projections of neighbouring fingers.

Subject 19 used a form of assisted one-handed reading. His left index finger was mainly placed at the beginning of each line and used to read the beginning of the line and occasionally to re-check it. The other hand, however, used four fingers in contact with the braille cells: index, middle, ring, and little finger. He used their tips to lightly touch the braille cells when reading. He said he developed his own way to increase reading speed by practicing this everyday and his reading speed was the highest of all of the readers in this study.

Subject 20 was congenitally blind but became deaf five years before participating in the study. His reading style was similar to subject 19 (his brother), but he used fewer fingers when reading. Interestingly, because he was deaf and blind, the only way he could communicate was using a braille typewriter. The machine looks similar to a print typewriter but with braille characters. There is a slot for displaying only one braille cell at a time. So, he placed his right index on the slot while his interlocutor typed. He often answered the questions before they were completed, which meant that conversations were not as impeded as one might have expected.

5.5.2 Task demands

The scores (based on 40 two-choice items) were almost perfect in the verification word task, the comprehension scores showed more errors (M = 99.21%, SD = 1.46 versus M = 94.56%, SD = 6.15, respectively), $t(19)$ = 0.005. Figure 5-9 presents the average on cell transit time for word lengths 4 to 7 as a function of reading mode. One-handed left finger readers spent longer time reading compared to others. In contrast, one-handed right finger readers read as fast as two-handed readers.

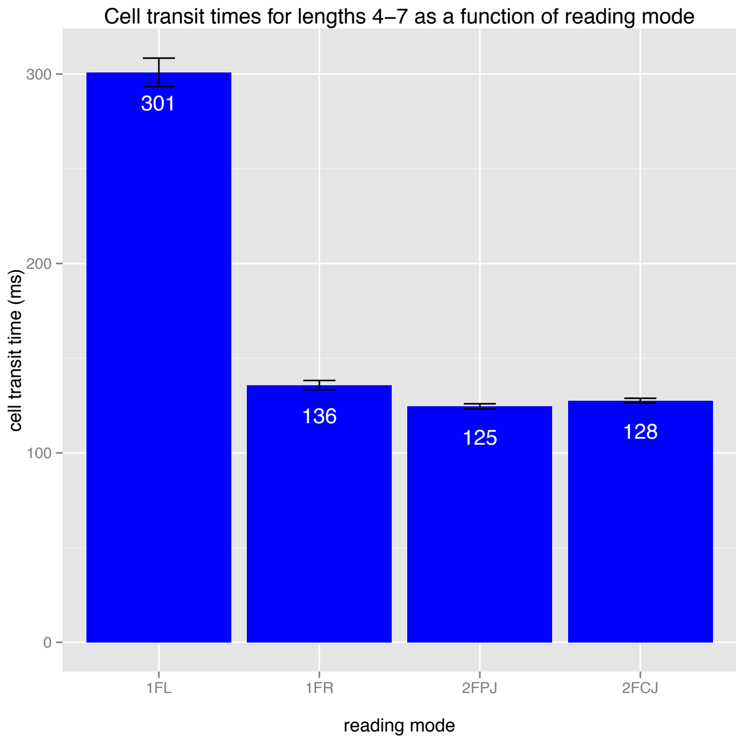


Figure 5-10: Cell transit times as a function of reading mode.

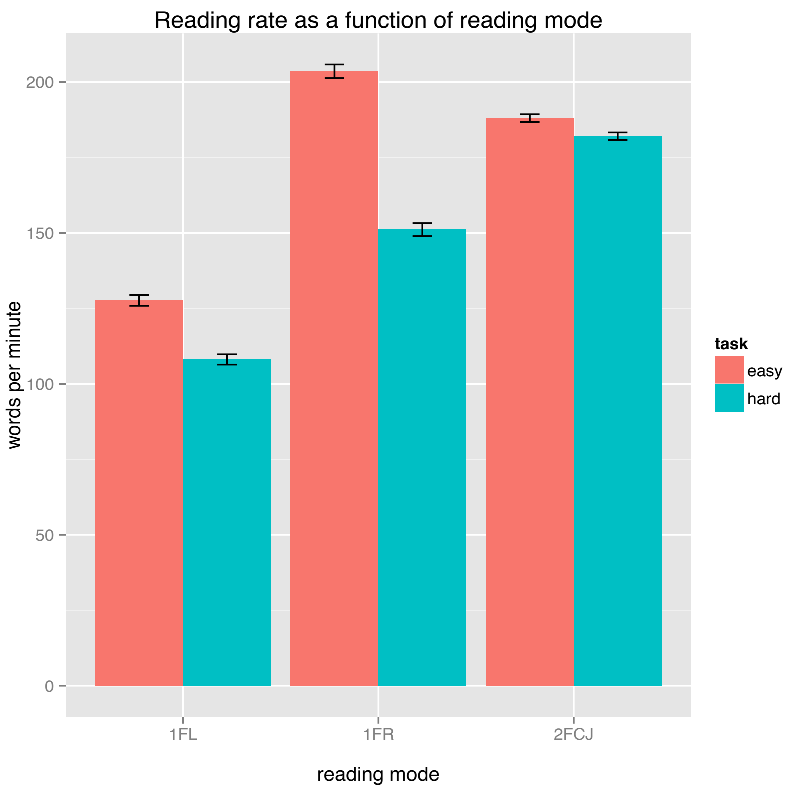


Figure 5-11: Reading rate as a function of reading mode.

To compare the average reading speed to visual reading, the data was presented in words per minute as shown in Figure 5-11. This graph does not show two-handed partly joint reading style (2FPJ) because the reading speed of this style could not be accurately calculated in words per minute. The words-per-minute calculation was carried out over all of the words in the experimental sentences, excluding the questions. The average braille reading speed of one-handed left finger readers was about 128 words per minute on the easy question and 108 words per minute on the hard question. One-handed right-fingered readers read about 203 words per minute on the easy questions and 151 words per minute on the hard questions. Two-handed completely joint readers' reading (2FCJ) rate was approximately 188 words per minute on the easy question and 182 words per minute on the hard question. There was a significant effect of task difficulty: hard questions affected the reading more than easy questions ($t=13.64$, $p_{MCMC} < 0.0001$)[2].

[2] Unless otherwise state, the *p* values will be calculated using Markov Chain Monte Carlo (MCMC) estimation (Baayen, Davidson, & Bates, 2008).

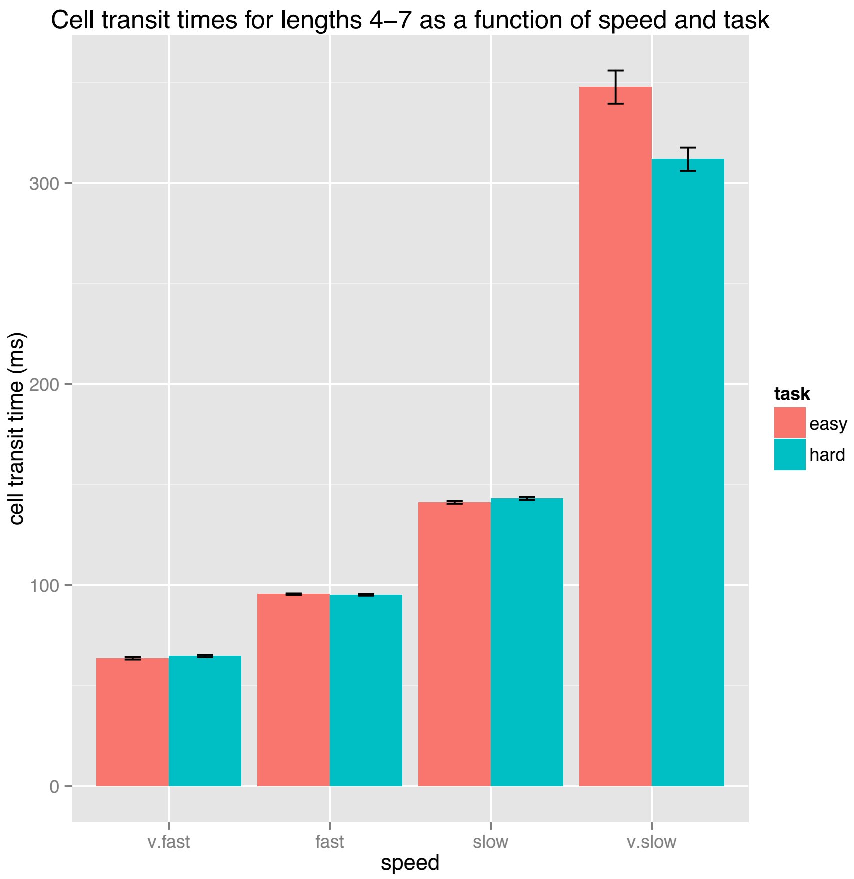


Figure 5-12: Reading rate as a function of task difficulty and readers' speed. The x-axis represents a range of fast and slow readers, the y-axis represents cell transit times.

There was no significant interaction of reading speed and task difficulty, t<2. However, the interesting point of Figure 5-12 is the slowest group shows that they spent a longer time on the easy task which would not be as expected. This may be due to higher word verifying demands in the slowest readers.

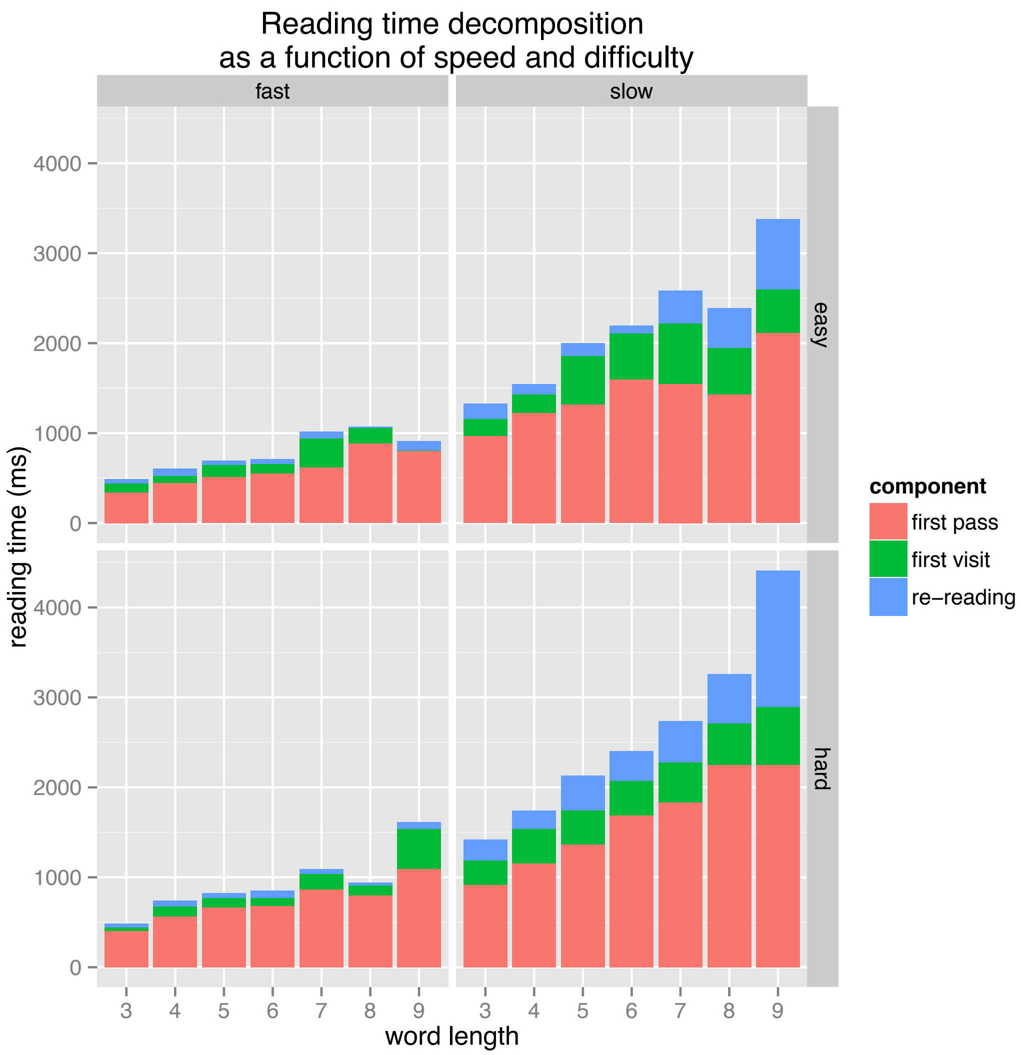


Figure 5-13: Reading time decomposition as a function of speed and difficulty.

To visualise the proportion of time spent for different components over the range of word lengths, Figure 5-13 presents the decomposition of word-based reading times into time spent in the first pass (red), additional time on the same word before leaving it (green); the remainder of the total time on the word (blue). Four panels show data for two levels of speed (slow vs. fast) and difficulty (easy vs. hard). As we expected slow readers reread more than fast readers and also reread more on comprehensive task than the verification task.

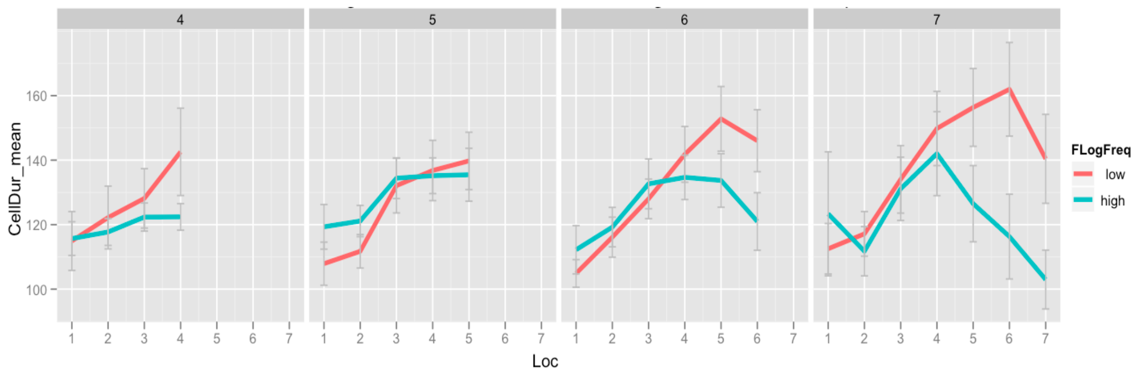


Figure 5-14: Two-handed completely joint reading mode: cell duration for word lengths 4-7 as a function of frequency on single pass times. The panels represent different word length; the x-axis represents character positions, the y-axis represents reading durations. The red line represents the low frequency words and the green represents the high frequency words.

Figure 5-14 shows word frequency effects on single pass times for two-handed completely joint reading readers. A linear mixed-effects (LME) analysis was carried out on the data, with cell location in word and log frequency of the word as covariates. Linear, quadratic and cubic terms for the covariates were tested in the model. The significant terms were log frequency ($t = 2.68$, $p_{MCMC} = 0.005$) and the quadratic term for cell location ($t = 4.82$, $p_{MCMC} = 0.001$). There was also a highly significant interaction between frequency and the quadratic location term ($t = -4.02$, $p_{MCMC} = 0.001$) as shown in Table 5-4. The locus of this latter interaction is clear in the comparison between the first and last pairs of panels in Figure 5-13. The word length of five at the character position four to five does not show much significant difference between the two lines. However, the word lengths of six and seven show that readers spend more time on low frequency words than high frequency words after the fourth character. This graph demonstrates the rapid effects of language processing on the movement of the readers' fingers. The effects show the difference between low- and high-frequency words in equal or less than 40 milliseconds. This would be difficult to pick up with a normal video camera because the sampling rate is only 25-40 frames per second. These rapid effects are, therefore, only detectable because of the high-resolution tracker that we have used.

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	113.595393	12.754712	8.906
LocSq	3.175095	0.658235	**4.824**
LocCb	-0.346550	0.166311	-2.084
CLogFreq	1.978915	0.738276	**2.680**
LocSq:LocCb	-0.002342	0.001711	-1.369
LocSq:CLogFreq	-0.503513	0.125089	**-4.025**
LocCb:CLogFreq	0.027364	0.019353	1.414

	MCMCmean	p_{MCMC}	Pr(>|t|)
(Intercept)	86.1426	0.0001	0.0000
LocSq	1.8395	**0.0001**	0.0000
LocCb	-0.6625	0.0366	0.0372
CLogFreq	0.5187	**0.0052**	0.0074
LocSq:LocCb	-0.0055	0.1754	0.1711
LocSq:CLogFreq	-0.7530	**0.0001**	0.0001
LocCb:CLogFreq	-0.0101	0.1514	0.1574

Table 5-4: LME analysis of cell transit times as a function of frequency and cell location in word.

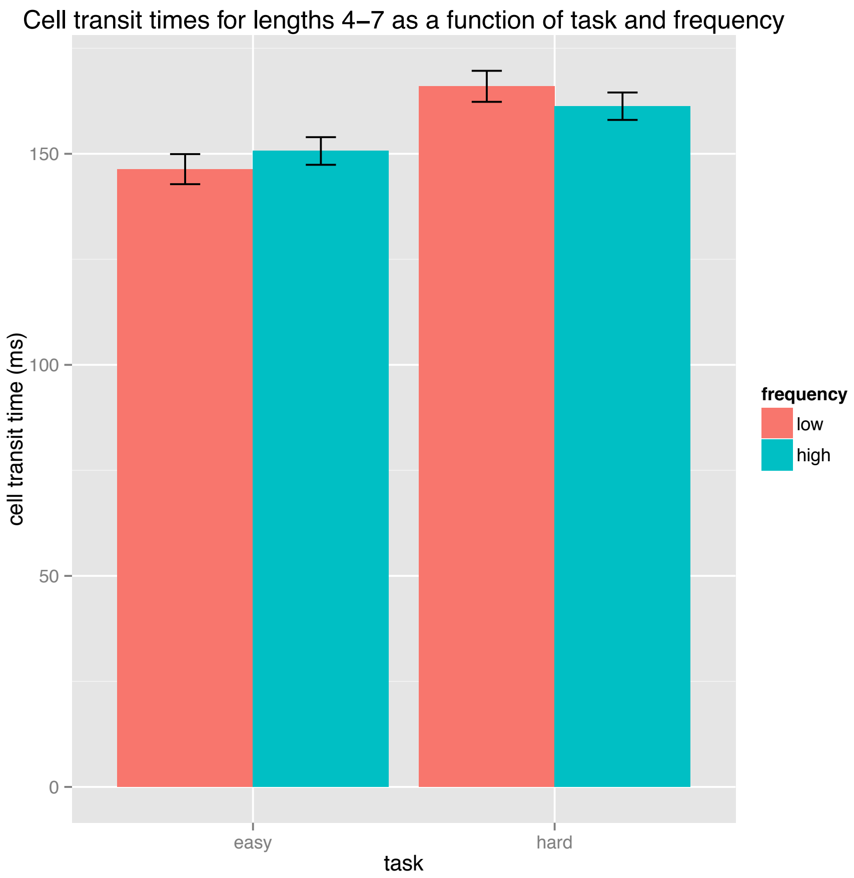


Figure 5-15: Cell durations as a function of word frequency and task difficulty.

The statistical analyses of the above figure showed that there was a highly significant task effect (t = 15.31, p_{MCMC} = 0.0001), a significant effect of frequency (t = 2.78, p_{MCMC} <0.01), and a significant interaction between frequency and task (t = 2.55, p_{MCMC} = 0.01).

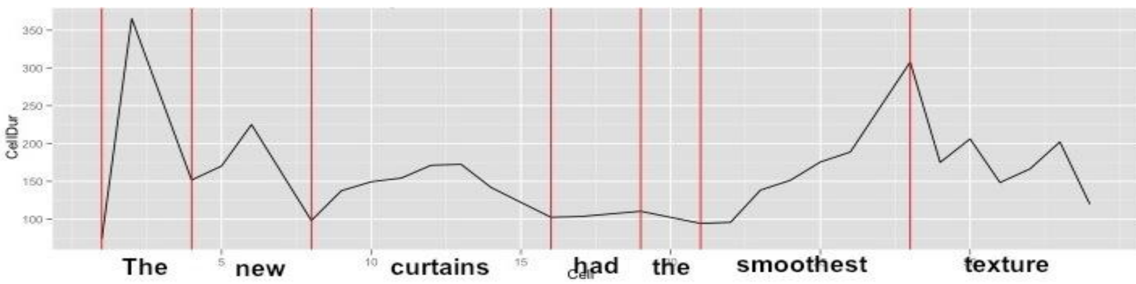


Figure 5-16:An example of the global pattern of hand movement.

Figure 5-16 is an example of the global pattern of hand movement over one sample sentence, with results averaged from single passes (i.e., where there was no rereading). The sentence is “The[3] new curtains had the smoothest texture”, which maps to the ASCII coding sequence “,! NEW CURTA9S _H ! SMOO!/ TEXTURE”, where each character represents a six-dot pattern. The inverted-U shape over some of the words (e.g., “new” and “curtains”) indicating a subtle slowing down in mid-word is a common pattern found with high-speed readers (Aranyanak & Reilly, 2013). These speed variations can be of the order of 50 ms and would be hard to detect in devices using lower sampling rates, such as those reviewed in the preceding sections. Figure 5-15 shows an interesting contrast in the words between “curtains” and “smoothest”. In the case of “smoothest” the multiple possible endings may be causing a slowing near the end of the word, so it suggests sensitivity to lexical predictability.

[3] Note that “The” is represented by a single-cell contraction, and that at the beginning of the sentence it is preceded by dot 6 to denote capitalization.

5.6 Conclusion

Using a cheap and simple tracking system it has been possible to explore the moment-to-moment processes of the braille reader with high resolution. The hand movement patterns that we found accorded well with those from previous studies (Eatman, 1942; Wormsley, 1979; Mousty and Bertelson, 1985). The main findings of this chapter support earlier taxonomies of finger movement patterns of braille readers. All participants used their index finger(s) as their main reading finger(s). One common feature across all fast readers is that they used multiple fingers at a time; a minority used two or more fingertips on the one hand, while the bulk of them used the index finger of both hands adjacently during reading. While readers using one hand adopted a more or less homogeneous approach to reading, those using two hands used a variety of different reading styles. These can be broadly categorised as (1) using both hands conjointly to read lines, followed by a return sweep involving both hands; (2) using both hands to read from the beginning of the line to the middle or near the end, and then parting their left and right hands, with the right continuing, the left returning to the beginning, followed eventually by the right when it reaches the end of the line; (3) using the left hand to rescan text that has already been traversed by the right hand. Most braille readers combine those modes together in reading. Most of the two-handed readers in these samples used completely joint mode or conjoint exploration, while only a few used a combination between completely joint and partly joint in reading. We noticed that people who used mixed modes often used the completely joint mode when they would like to read carefully or confirm the information that have read.

The characteristics of efficient and poor readers reading on a refreshable braille display found in this study are similar to previous studies where materials were printed on embossed papers (e.g., Eatman, 1942; Kusajima, 1974; Mousty and Bertelson, 1985; Wormsley, 1996). It has been found that fast braille readers can achieve reading speeds comparable to average sighted readers. A striking characteristic of the fast readers is that they rarely re-read, usually just making one fast pass through the line of cells. Poorer readers, on the other hand, frequently did lots of scrubbing, touching on the braille characters heavily, and with a tendency to go over and back on a word as they read. Poor readers spend more time in backtracking through the text than good readers. This also happens with sighted reading. Longer regressions occur when readers do not understand the text (Frazier & Rayner, 1982; Murray & Kennedy, 1988). Text difficulty strongly affects the number of regressions. This occurred more frequently in reading scrambled words than prose (Mousty & Bertelson, 1985). Moreover, in both visual and tactile reading, retracing of reading is also caused by ambiguous sentences (Rayner et al., 1983; Mousty & Bertelson, 1992).

Based on data from one-handed readers, it was found that readers who employed their right hand read faster than readers who employed only their left hand and the mean reading rate of right one-handed readers is in the same range as two-handed readers. The finding is similar to some researchers (e.g. Hermelin & O'Connor, 1971; Rudel, Denchu, & Hirsch, 1977) who found that most beginning readers performed better when they used their left hand, while the right hand was superior in fluent older readers (Fertsch, 1947). Nevertheless, the average age of left and right one-handed readers in the present study is in the same range. There are a number of reasons to perhaps explain this finding. This might be because four out of five right one-handed readers used more than one fingers in reading while all three left one-handed readers used only their index finger in reading. The functional asymmetry of the cerebral hemispheres may also play a role. The right hemisphere is more involved in spatial processing, while the left hemisphere appears to play a more important role in language or verbal processing in most people (e.g., Sperry, 1982; Gazzaniga, 1988). Millar's study (1984) found that braille readers performed better in naming tasks with their right hand. In contrast, using the left hand was better for letter discrimination tasks. Therefore, one could suggest that beginners should start reading with their left hand because it will be faster in recognising braille patterns. However, if they wish to read faster, they should use their right hand as the main one for reading. Furthermore, we noticed that reading performance is related to their reading experience: the more reading hours per week the more efficient as well as the more fingers are used.

From eye movement studies, task demands can be a factor that affected reading. Therefore, the task instruction was investigated during reading isolated sentences. Hand movement data of two samples with identical sentence materials but different reading instructions (verification vs comprehension tasks) were compared. The data were analysed in detail patterns of local movements. The results revealed top-down effects on braille reading as expressed in finger movements. The time of first visit on words were longer when readers had to answer comprehensive questions. This finding is not surprising because readers have to read more carefully to answer detailed questions than word-choice questions. It indicated that task effects similar to those found for sighted readers are also a feature of braille reading (Radach et al., 2008). Slower readers were affected by task difficulty to a greater extent than fast readers as shown in Figure 5-11.

There are a number of sighted reading studies investigating the effects of word frequency on reading rates (e.g., Kliegl et al., 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Miellet, Sparrow, & Sereno, 2007), as well as in recent braille reading studies (Huges, 2011; Perea, García-Chamorro, Martín-Suesta, & Gómez, 2012). Our finding on word frequency effect during braille reading supports those studies that readers spent longer time reading low-frequency than high-frequency words particularly. One important discovery by using our Wiimote tracking system is that the readers slow down imperceptibly as they pass through a word; the less common the word, the greater the deceleration, as shown in Figure 5-13. With the traditional tracking device, it wasn't possible to detect these subtle online adjustments in speed because the frequency effect size was less than 40 ms.

Turning to the global pattern of hand movement shown in Figure 5-15, we can see a variety of movement patterns for different words. A possible source of this variation will be explored in the next chapter.

Part IV. An in-depth exploration of braille reading

The following chapters emphasise the cognitive processes underlying braille reading. The data were collected in Australia. Materials in Chapter 6 were designed to combine two experiments into one data collection due to time constraints. The first experiment is related to the orthographic uniqueness point (OUP) effect. The second experiment focuses on the feasibility of using the finger-tracking system for finger-movement contingent display change experiments. The study explored hand dominance in braille reading using this technique.

Chapter 7 presents evidence that the auditory cortex may be implicated in supporting reading via an existing pathway between the somatosensory and auditory cortices. This hypothesis is in keeping with a metamodal theory of the brain where functions developed for one domain can be re-purposed for another (Pascual-Leone & Hamilton, 2001).

“My image of the table is exactly the same as a table, it has height, depth, width, texture; I can picture the whole thing all at once. It just has no colour.”

- PAUL GABIAS

Chapter 6

Experiment 2: Orthographic uniqueness point effects

The previous chapter demonstrated readers' sensitivity to lexical predictability in the global pattern of hand movement as shown in Figure 5-14. This might be related to the effect of orthographic uniqueness point on word latency. A post-hoc analysis of the previous study was investigated and some evidence was found that braille readers spent a longer time in words with a late orthographic uniqueness point than in those with an early one. Therefore, this current study explored the orthographic uniqueness point (OUP) effect experimentally.

6.1 A study of orthographic uniqueness point effects in braille reading

Word recognition or lexical access has been studied in terms of different modality of input based on visual, tactual, and auditory processing. The well-known model used for describing lexical access, proposed by Marslen-Wilson (1987), is called the Cohort Model. It was originally designed for on-line spoken word recognition. The Cohort Model initially starts with bottom-up processing. Once listeners are provided with initial acoustic-phonetic information of a word, they would activate a set of possible words in the lexicon that begin with the same phoneme as illustrated in Figure 6-1.

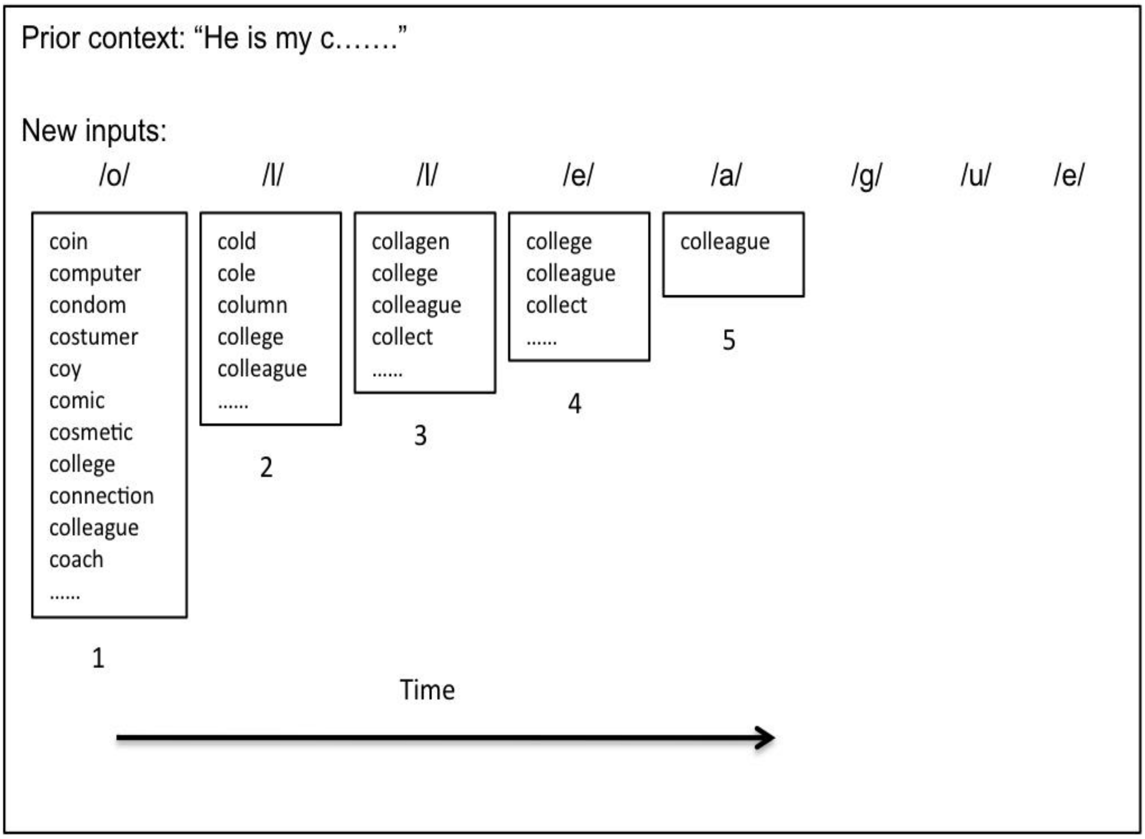


Figure 6-1: An example of a sentence when a listener is processing the word "colleague" according to the cohort model description.

In recognising a spoken word, at the start there are many possible word candidates. As more of the input is heard, the number of candidates is reduced. Figure 6-1 illustrates the Cohort model in action. Once the /o/ is encountered, listeners activate a cohort of words with an initial /co/. After the phoneme /l/, the cohort is further reduced until a critical point is reached where listeners can identify the word because there is just a single candidate remaining. The critical point is called a "uniqueness point (UP)". In this case, the spoken word "colleague" would be recognised once /collea/ is perceived. Therefore, the UP is the phoneme /a/. This suggests that words can be recognised before perceiving all of the input data. The location of the uniqueness point can be different from word to word. Sometime it is located early and sometimes near the end of the word. Previous experiments in spoken-word recognition have shown that listeners' speech recognition speed is affected by the location of the uniqueness point (e.g., Marslen-Wilson,1987; Radeau, Mousty, and Bertelson, 1989; Marslen-Wilson, 1990).

The concept of the uniqueness point (UP) has also been applied to measure response times in visual word recognition. It is used to explore whether visual words are recognised in parallel or serially. Kwantes and Mewhort (1999) and Lindell, Nicholls, and Castles (2003) demonstrated results that supported the cohort model of word recognition. Early-OUP words were processed on average about 29 milliseconds faster than late-OUP words in naming and lexical decision tasks. From the findings, they suggested that visual word recognition was supported by evidence for sequential processing that the letters of a word are encoded in left-to-right order. This might be because the nature of the task encouraged readers to encode letters sequentially. For example, if we assume that visual word recognition involves accessing a lexicon that has been organised around the speech experience of the listener and therefore involves left-to-right serial retrieval, we would then expect faster responses to words with early, rather than late, orthographic uniqueness points (Kwantes & Mewhort, 1999). In contrast, recent studies (Radeau, Morais, Mousty, Saerens, & Bertelson, 1992; Lamberts, 2005; Miller, Juhasz, & Rayner, 2006) reported opposing results to the previous studies, with predictions derived from the cohort model not supported. Lamberts (2005) reviewed those studies and stated that the letters of a word in visual word recognition were not processed purely sequentially, because the intake of information in visual word recognition is usually simultaneously obtained from more than one letter. However, at some stage, letters are also processed sequentially. He concluded that it is still not clear whether letter identification is processed in parallel or serially because the nature of the processes is related to the details of the reading task. Many researchers describe the nature of visual word processing by using serial and parallel components in their models (e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Reilly & Radach, 2006). Lamberts (2005) suggested that using eye movement recording could provide some useful insight into the online processing of words in reading. Miller et al. (2006) examined eye movements while readers read in a natural reading context where early and late OUP words were embedded. The results did not indicate any OUP effects on target words. They explained their finding of no effect compared to that of previous studies due to the fact that the experimental methodology used was different. Their experiment used an eye tracker to record eye-movements while previous studies used response time in a naming task and reaction time in a lexical decision task. Regarding braille word recognition, most of the previous studies measured response time by reading aloud and focused on reaction times of regular words versus pseudo words, degraded versus undegraded braille, contracted versus uncontracted braille involving high versus low familiarity and also different task demands (e.g., Nolan & Kederis (1969); Pring, (1982); Pring, (1984); Millar, (1987); Legge et al., 1999; Veispak, Boets, & Ghesquière, 2012). Obviously, braille reading is primarily sequential from left to right. The information-processing mechanisms in braille reading involve serial processing more than parallel processing (O'Connor & Hermelin, 1978; Nolan & Kederis, 1969; Bertelson et al., 1992; Veispak et al., 2012). On the ‘letter-by-letter’ hypothesis, braille is a ‘bottom-up’ hierarchical process. Foulke (1982, p. 194) stated “the braille reader must have to identify and remember all the letters in a word sequentially and integrate them in order to identify that word”. The characteristic of tactile reading is similar to speech (Bertelson, 1995). The Cohort model might be, therefore, the most appropriate approach to exploring braille word recognition. One other piece of research by Bertelson and colleagues (Bertelson et al., 1992) had looked for an OUP effect in braille reading. This study examined isolated recognition times of French nouns to find out if they were impacted by the location of the uniqueness point. Subjects' finger movements were recorded using a solid-state video camera (Hitachi KP-12OU) combined with a system developed at the Université Libre de Bruxelles (Noblet et al., 1985). A small diode producing a one millisecond flash every 40 milliseconds was attached to each reading finger. The following three experiments were carried out on the same blind participants:

(1) *Gender classification and pronunciation of braille words.* The targets included 42 early and late OUP words. Subjects were asked to name the gender of the noun or pronounce the word aloud as soon as possible after starting to read the word and their response latencies were recorded. The result showed that recognition reaction times (RT) for each task was significantly faster in words with an early OUP than to words with a late OUP. This finding provides evidence of on-line lexical access in braille word recognition;

(2) *Gender classification with braille versus spoken words.* This experiment tried to extend the preceding experiment to determine if similar on-line processing also occurred in listening. The experimental trials consisted of two sets of 34 tri-syllabic nouns that were used in Radeau et al.'s (1989) study. The procedure of identifying gender was identical to Experiment 1. For the spoken words part, the target words were pronounced by a French male native speaker. Subjects were asked to identify the gender of the target words as soon as possible. The results replicated those of the first experiment and found significant effects of UP location even through the target words were presented in a different modality;

(3) *Gender classification of braille words, effects of uniqueness point location, and frequency of occurrence on RT and scanning speed*. Thirty-six French nouns were used as stimuli. Half of them were low-frequency words and another half were high-frequency words. The procedure of identifying gender was similar to

Experiment 1 except subjects used a manual response on a toggle switch with their non-reading hand for the vocal response. The results showed that the uniqueness point effect was more distinct in high-frequency words rather than low-frequency words. The mean scanning time per character in the pre- and post-OUP regions showed that there was no difference in scanning speed between the two regions. This finding is of particular relevance to the current study, since we want to examine if the lack of difference between the pre- and post-OUP regions during scanning movement might be because the tracking system used was not sensitive enough to pick up the subtle effect.

The global pattern of hand movement described in Chapter 5 demonstrated some lexical sensitivity (e.g., to frequency). Therefore, a post-hoc analysis tested for an orthographic uniqueness point (OUP) effect. The result is shown in Figure 6-2.

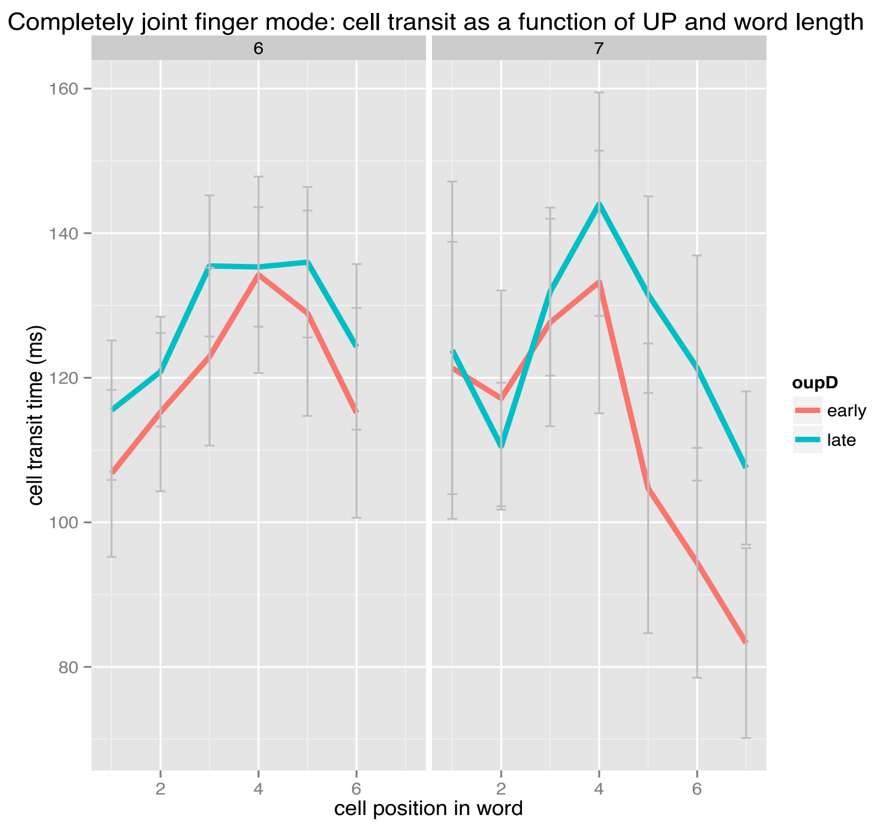


Figure 6-2: A post-hoc analysis of an OUP effect.

Figure 6-2 shows cell transit time as a function of the uniqueness point and word length (6 and 7) of completely joint finger reading mode. The red line represents early OUP words and the blue represents late OUP words. The result from this post-hoc analysis revealed that readers left the early OUP words earlier than late OUP words as shown in Figure 6-2. This post-hoc analysis needed now to be confirmed by an experimental study.

The aim of the this study is to determine if there are orthographic uniqueness point (OUP) effects in a prose Grade 2 braille reading task. It was hypothesised that the stimulus at the fingertips of the braille readers has speech-like properties because braille letters are perceived sequentially and it was assumed that readers would spend longer in late OUP words than early OUP words. The presence of an OUP effect (e.g., an acceleration of the hand following the uniqueness point) would indicate that online language processing is used by readers to modulate their finger movements. The preceding research showed evidence that braille word recognition supported the on-line processing view of speech recognition. However, it was carried out on isolated words, so the stimuli in this study were designed for more natural reading. On-line language processing was investigated by recording finger movements during sentence reading. Grade 2 braille was used because it is commonly used by experienced braille readers. Thirty sentences were chosen from Miller et al., (2006)'s study. The early and late OUP words in the study were selected from the MRC psycholinguistic database (Coltheart, 1981). However, the position of early and late UP was re-calculated to take account of the different lexical structure of contracted braille words. Finger movements were assessed in terms of the four parameters described in Chapter 5: single-pass time, first-pass reading time, first-visit reading time, and total reading time.

6.2 Materials and methods

6.2.1 Participants

Seventeen braille readers participated in the study, four male and thirteen female. Participants were recruited from the Vision Australia organisation, the Royal Society for the Blind in South Australia, and the Association of Blind Citizens of NSW Inc. by email (see Appendix B). Two females were excluded from the data analysis. One was because of a brain injury and the other one did not complete the experiment. Thus, only the data of 15 subjects were analysed. Eleven of the 15 subjects were considered congenitally blind. Two of them had lost their sight gradually between birth and the age of 8. Two participants became blind late in life. All subjects were English native speakers who could read Grade 2 braille in the UK format. Three of the readers employed only one hand in reading. All subjects were administered the handedness questionnaire modified from Oldfield (1971). Participants were paid AUS$25-50 for the study.

	Mean	S.D.	Range
Age when tested (yrs)	44.65	8.85	35 to 57
Age when braille was learned	7.35	7.19	4 to 32
Years reading braille	36.7	10.3	14 to 53

Table 6-1: Group characteristics of the 15 braille readers (see Appendix E for details).

6.2.2 Materials and design

Five sentences were used to familiarise participants with the procedure before the actual experiment. Sentences comprised between one and two lines. These materials were converted into British Grade 2 braille in an ASCII format by a braille translator called NFBtrans, which was first developed in 1990s. It is freeware running under MS-DOS.

The stimuli were adapted from the materials used by Miller et al. (2006). Miller had target words rated for familiarity by 32 participants on a 7-point scale (higher values indicating greater familiarity). The mean familiarity for early OUP target words was 5.8 and 5.7 for the late OUP ones. However, the locations of early and late OUPs were recalculated using a Perl program that processed a large corpus of words in UK contracted braille format (see Appendix F). Thirty pairs of early and late OUP words were selected from these materials (see Appendix E).

Early - OUP

“Fay wanted an immediate *divorce* after the last fight with her husband.”

“,FAY WANT$ AN IMM *DIV**O**RCE* AF ! LA/ FI<T) H] HUSB&4”

Late - OUP

“Fay wanted an immediate *apology* after the last fight with her husband.”

“,FAY WANT$ AN IMM *APOLOG**Y*** AF ! LA/ FI<T) H] HUSB&4”

The average length of the target words was 5.8. The average early OUP location was letter 3.8, while the late OUP was at letter 5.5. Target words were closely matched on their log frequency, number of syllables, and word length. Target word pairs were embedded in the same sentence and selected to fit the context. Each participant read 15 sentences with early OUP words and 15 sentences with late

OUP words. Ten simple questions were asked at random points during the experiment to check on readers' understanding of the materials.

6.2.3 Procedure[4]

Participants were tested individually in a quiet room. They were asked for their demographic details, read a consent form (see Appendix C), and signed their name before starting the experiment. They were seated in front of the tracking apparatus and familiarised with it. Each subject was instructed to read the texts silently and naturally, but to answer the questions aloud. They were told that sometimes they might feel the display change on some words and they were told to try not to reread. LEDs were attached to the readers' reading finger/fingers and the batteries were switched on.

Prior to the actual experiment, five practice trials were run to familiarise them with the task. A calibration routine was initiated at the beginning of the experimental session. Calibration accuracy was checked every 10 sentences throughout the experiment. A calibration was carried out when the actual and displayed cell numbers were inconsistent. The calibration method was identical to the study described in Chapter 4, p.65. Readers were told to read a new line by pressing the long bar under their right hand. This software did not provide a button to reread the previous line. Two kinds of stimuli were mixed in random locations. Subjects who were assigned to participate only in the OUP study were asked to answer 10 simple comprehension questions. This task was usually completed with one-handed readers in 20 minutes. Subjects who participated in both OUP and hand dominance studies were asked to answer 12 questions only related to the hand dominance study due to time limitation. They normally took about 45 min because they were

[4] Note that the OUP and the hand dominance studies were conducted in the same session.

also examined for the hand dominance study.

6.3 Results

The data were manipulated and cleaned in the same way as described in Chapter 5, Figure 5-2. Only first passes through the target words were selected for analyses. First and the last words on a line were also eliminated from the data analysis. For two-handed readers, only right-hand data were used in the analysis since most of participants preferred their right hand and employed completely joint mode in reading. At first, only the target words were analysed, but we needed more data for a wider range of word length. Therefore, all words were analysed except words located at the beginning and the end of each line. The data analysed focused on words of length 4 through 6 inclusive. Length 4 was chosen as the minimum length at which an OUP effect might be detected, and length 6 was the maximum chosen for which there were sufficient data points to carry out the analysis. The means of the early and late OUP of length 4 to 6 are presented in Table 6-2.

Length (letters)	OUP (letters)
4	4.23
5	4.74
6	4.98

Table 6-2: A mean OUP location by length of current word.

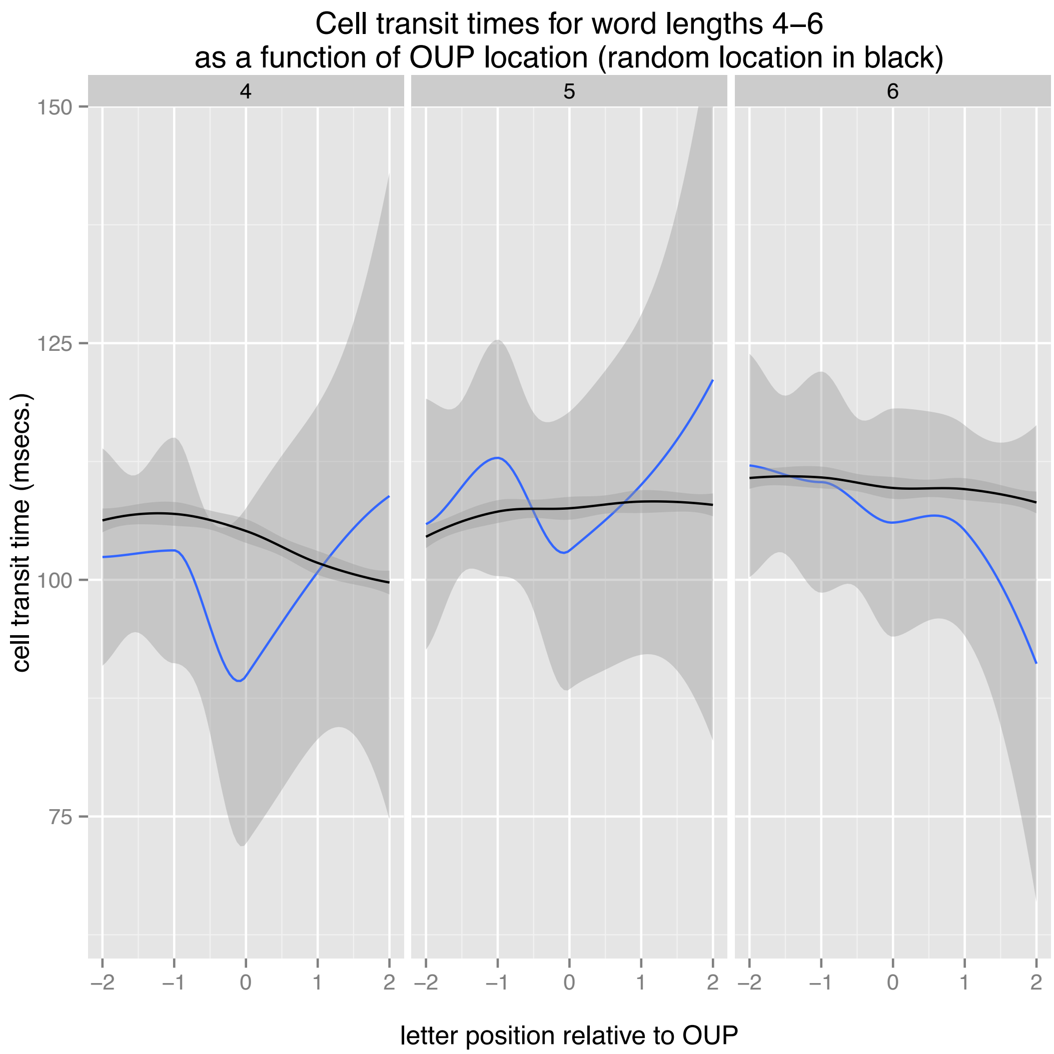


Figure 6-3: Cell transit times for word length 4 and 6 as a function of OUP.

Figure 6-3 shows the cell transit times in 4, 5, and 6-letter words. In each panel, 0 represents the UP and negative numbers are locations in the word before the UP, positive numbers are locations after a specific word's UP. The blue line represents the actual OUP data, while the black curve represents the transit times around a randomly selected letter location. This was intended to provide a default against which to compare data from the actual OUP. In the case of the default curve, a letter location excluding the first letter was randomly selected 100 times as a zero point for each of the words in the text.

Figure 6-3 shows that the dip associated with the OUP position as compared to the control is significant for lengths 4 and 6 ($t = 2.51$, $df = 12$, $p < 0.03$; $t = 2.12$, $df = 15$, $p = 0.05$, respectively), but not for 5. The slopes of the actual data in word length 4 and 5 decreases before the location of UP but after the UP there is a steeper positive slope, whereas, for length 6 there is a small climb before the graph declines after the location of the UP. One explanation for the v-shaped pattern for lengths 4 and 5 is that it may be due to the OUP in shorter words coinciding with the word boundary, as can be seen in Table 6-2. Since the average OUP for length 6 words is before the word boundary, the length 6 data may provide a purer measure of an OUP effect. The OUP data and the cell transit times at word boundaries are compared, as shown in Figure 6-4. We can think of word boundaries as being the definitive OUP, since the word is uniquely defined once the reader encounters the space at the end.

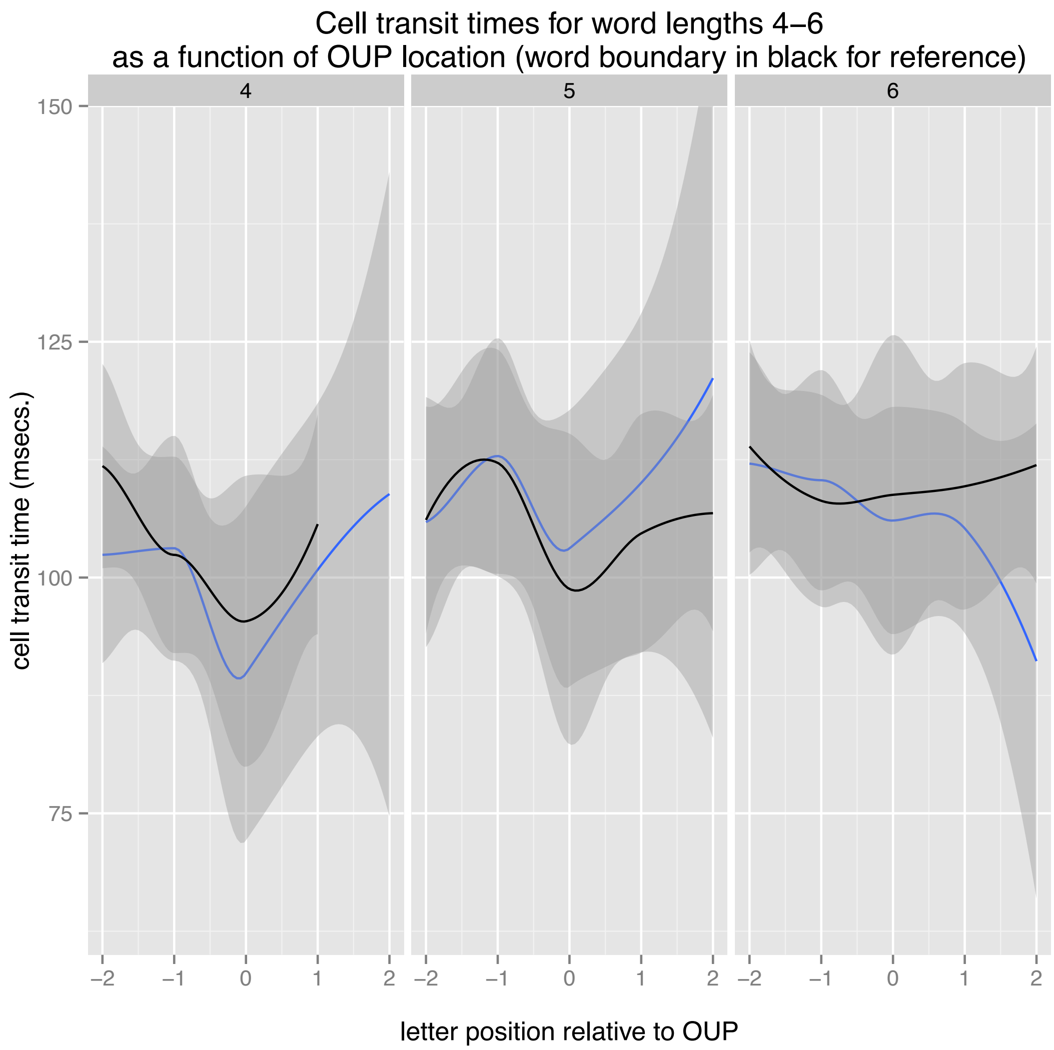


Figure 6-4: Cell transit times for word length 4 and 6, comparing the actual OUP data and the OUP that occurred at the end of words.

We can see that for lengths 4 and 5, the OUP location and the word boundary location show very similar patterns. It is only for length 6 that we see the OUP and word-boundary patterns diverging.

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	-747.778	832.043	-0.899
OUPloc	396.736	120.700	**3.287**
pOUPloc	905.313	135.830	**6.665**
WordLen	295.700	133.274	2.219
logFreq	-390.043	66.660	-5.851
OUPloc:pOUPloc	63.242	9.325	**6.782**
OUPloc:WordLen	-73.737	19.509	-3.780
OUPloc:logFreq	-33.255	5.149	-6.459
pOUPloc:WordLen	-243.461	18.480	-13.175
pOUPloc:logFreq	-6.062	7.325	-0.828
WordLen:logFreq	113.470	10.404	10.907

Table 6-3: LME analysis of word reading times as a function of word length and the location of OUP.

Table 6-3 shows the statistical analysis of word reading times. There are many factors that might affect the reading time on a specific word, such as the OUP location of the current word, the OUP location of the previous word, word length, etc. The analysis indicates a significant effect due to the OUP of the current word (t = 3.29), where readers spend longer on a word the later the OUP. Interestingly, the location of the previous OUP has as similar but stronger effect on reading time (t= 6.67). In addition, there were significant interactions between most of the covariates. One of the more interesting interactions is that between the previous and current OUP locations (t=6.72). This is graphed in Figure 6-5 below. The prediction was that the later the OUP, the longer would be spent on the word.

Moreover, it was predicted that there could be a word-lag effect, whereby a late OUP in the previous word would increase reading times on the current word.

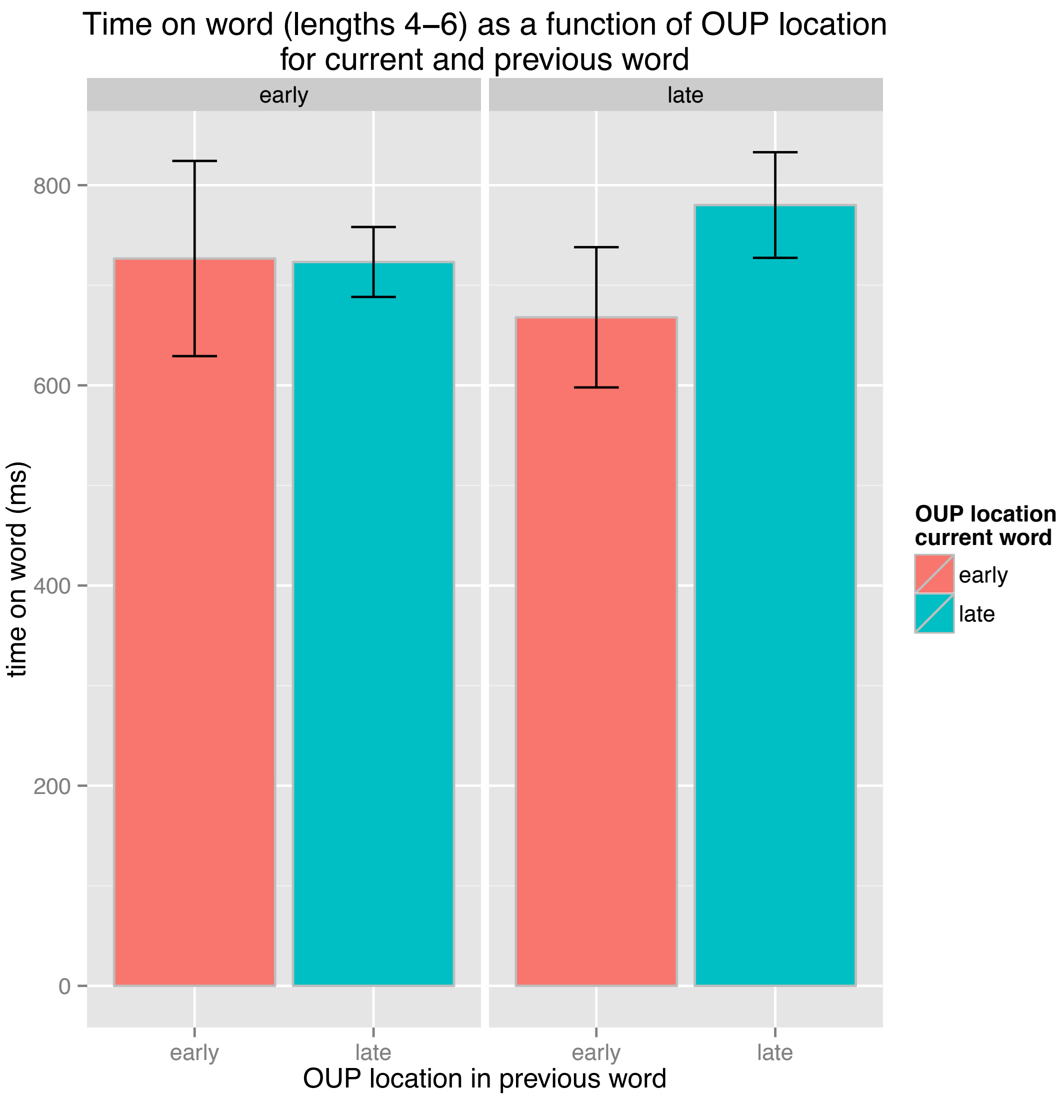


Figure 6-5: Word reading times for word length 4 and 6 for current and previous word

The red bar in Figure 6-5 represents words with early OUP and the blue bar words with a late OUP. The two panels represent the OUP location in the previous word. The bar graph shows the longest reading times on the late OUP in the previous word followed by the late OUP in the current word, as expected. We also expected to find the best reading performance for early OUP in the current word and previous words. However, it appears that an early OUP in the previous word combined with a late OUP in the current word gives best reading performance. This unexpected result may be due to confounding of the previous word's OUP with word length and frequency effects of the previous words.

6.4 Conclusion

Compared to visual reading, braille reading seems to be more continuous, with the hand moving smoothly along the text, with no word skipping. However, these characteristics seen by the naked eye may be deceptive. The finger movement is not steady all the time. The velocity of finger movement continuously alters (Hughes, 2011; Hughes, McClelland, & Henare, 2013). This might be caused by many factors, such as word frequency, word predictability, etc.

According to Bertelson et al. (1992), lexical access for braille words could be described by the cohort model, which was normally used for speech recognition. Bertelson revealed online processing occurred by showing an effect on mean reaction time of OUP location. However, they did not find significant effects in scanning speed between before and after the UP region.

The current findings clearly show that the location of the OUP affects cell reading times, as shown in Figure 6-3. The graph of the default and actual OUP are significantly different. The pattern of the default or control OUP data is similar across word lengths. However, in the case of the actual OUP data, there is an increase in the cell transit times after the OUP in word length 4 and 5, but an overall decline reading time for word length 6. This is most likely because the location of the OUP in word lengths 4 and 5 is at the end of the words as evidenced in Figure 6-4. The V-shaped pattern is characteristic of reading times at word boundaries.

Note that our measure of the OUP effect is confounded by sentence context, since context will also help readers more rapidly recognise words. However, because we looked at many words in a of variety different contexts, sentence effects should be averaged out.

It was also found that overall word-reading times were affected by the OUP location in previous word (Figure 6-5). The results show a lag effect of the previous word's OUP on the current word – the later the OUP in the previous word, the longer time spent on the current word.

Taken together, these results demonstrate a surprising sensitivity of braille readers' finger movements to local variations in lexical structure. It is now only possible to study such effects because of the greater precision of the hand tracking system that has been developed for this research.

Experiment 3: Hand dominance in braille reading by using the display change technique

This experiment focuses on a feasibility study of the display change technique. Hand dominance in braille reading was examined by using the technique to control the presentation of texts under left and right index fingers. This present study is the first to adopt the display change technique for braille reading, a technique normally used in visual reading.

6.5 Hand dominance in braille reading

The relative role of the two hands used by braille readers who use both hands is still unclear. Bürklen (1932) stated that the left and right hands processed two different parts of the text in parallel, whereas Kusajima (1970) suggested that those two hands were employed in different functions, one hand for scanning gist and the other hand for checking individual words. Some researchers are of the view that each hand has a particular function in reading braille and one hand may be more effective than the other (e.g., Hermilin & O'connor, 1971; Rudel et al., 1977; Fertsch, 1947). In the early 70's, some studies supported different hand specialisations for each hand. According to Hermilin and O'Connor (1971), blind children under the age of 10 could read braille faster and more accurately than visually impaired adults by using their left hand in letter-naming tasks, similar to what we found in Lowenfeild et al.'s (1969) study. Moerover, in reading tasks, Benoit-Dubrocard, Liégeois & Harlay (1997) found that the left hand read more accurately than the right hand and that left-handed subjects read more efficiently in meaning-matching tasks. In contrast, Fertsch (1947) found that the right hand was superior to the left hand in the process of reading braille during comprehension reading tasks.

The right cerebral hemisphere controls movement of the left side of the body and is associated with spatial processing and non-verbal information processing. In contrast, the left cerebral hemisphere controls movement of the right side of the body and is associated with language processing (e.g., Nunn et al., 1999; Ploner et al., 1999). Based on the lateralisation of brain function, it might be assumed that using the left hand for braille reading would be superior for spatial perception. Nevertheless, reading also needs language processing, hence the right hand should be superior for the verbal aspects of reading (Albrecht, 2009). In 1984, Millar studied letter discrimination and letter-naming tasks as spatial tasks and verbal processes, respectively. The findings showed that, in letter discrimination, slow readers read faster with their left hand, and fluent readers were significantly faster with their right hand in letter naming. However, she argued that “it is not sensible to assume functional representation solely from hand advantages” (Millar, 1997, p.68). For example, hand advantage might not only arise from left and right brain functional asymmetries, but also from other factors, such as, practice, being taught to use a specific hand, and so on. For instance, aimed movements using the right hand are more accurate than with the left in right-handed people even though this is essentially a spatial skill. In addition, type of task and stimulus materials must be considered. For example, using one finger is more effective in a scanning task, but in reading prose, two hands are better (Millar, 1997). Most studies demonstrated that using both hands in reading is better than one hand (e.g., Foulke, 1982; Millar, 1984; Bertelson et al., 1985).

Fertsch (1947) raised the question about which hand plays a greater part in reading when both hands share the task. He introduced the term “hand dominance” which referred to the superiority of a given hand in braille reading. Specifically, if readers used their right hand more efficiently than their left hand, it could be said that they were right-handed in braille reading, and vice versa. His study found that using both hands in reading was classified into three groups by reading time: readers were catagorised as 'hands equal' if the reading times were within 20% of each other, the right would be termed dominant if the times of the right were greater than the left hand by more than 20% and vice versa. The findings demonstrated that subjects who were classified as hands equal could read faster than the other two groups. Moreover, the 'left dominant' category of subjects were the least efficient readers and contained about twice as many poor readers as good readers.

The aim of this study is to demonstrate the feasibility of the tracking system's display change program and also investigate hand dominance in braille reading. McConkie and Rayner (1975) developed various eye-contingent display change techniques: moving-window, moving-mask, and boundary paradigms (McConkie and Rayner, 1975; Rayner and Pollatsek, 1989). These techniques have been used to examine cognitive processes during visual reading. In this study, I have used the moving-mask technique to display target words only on the left while braille readers were reading sentences, and vice versa with their right hands. Each sentence contained a target word. Only the target word was masked with a hyphen sign for different hands. If the input to the left index finger was masked for the target word, the target word could be read by the right index finger, and vice versa. The finger tracking system software could detect when the index fingers moved onto the target words so that the braille display could dynamically change the text. This study reports evidence from readers' answers. Target words were embedded in sentences and participants were asked to read silently. Only subjects who employed completely joint fingers were selected for analysis. Stimuli were carefully matched for word length and frequency

6.6 Materials and methods

6.6.1 Participants

Participants were identical to Experiment 2, but three readers who used one-handed reading were excluded. Therefore, there were 12 subjects remaining.

6.6.2 Materials and design

Forty sentences were presented in this study. The experiment was designed to explore only two-handed readers. Each sentence contained a target word ranging from 3 to 5 characters. The average log frequency of the target words was controlled to be as similar as possible at 11.81 and 10.19 respectively.

The target words were masked by a hyphen (dot 3 and 6) for different hands. They were never positioned at the first and the last position of the line. Mostly they were located between the third word after the beginning and before the end of the line. Regarding Figure 6-6 and Figure 6-7, the blue circle represents the location of the left index finger reading on the letter and the green circle represents the location of right index finger. Figure 6-6 shows an example of masking the word *photo* on the left index finger. As the left index finger moved through the word was masked, but was unmasked on the right index finger. Figure 6-7 shows an example of masking the word *photo* on the right index finger. As the right index finger moved through the word was masked, but was unmasked on the left index finger. The sentence is shown in ASCII code. The blue circle represents the left index finger and the green circle represents the right index finger.

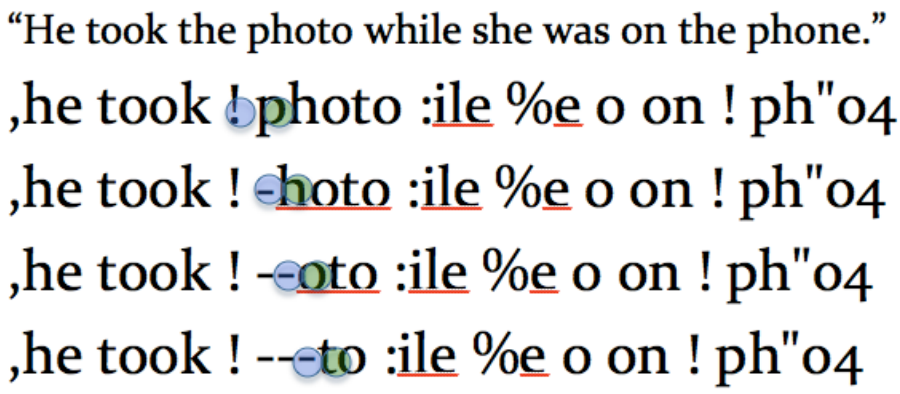


Figure 6-6: An example of masking on left index finger.

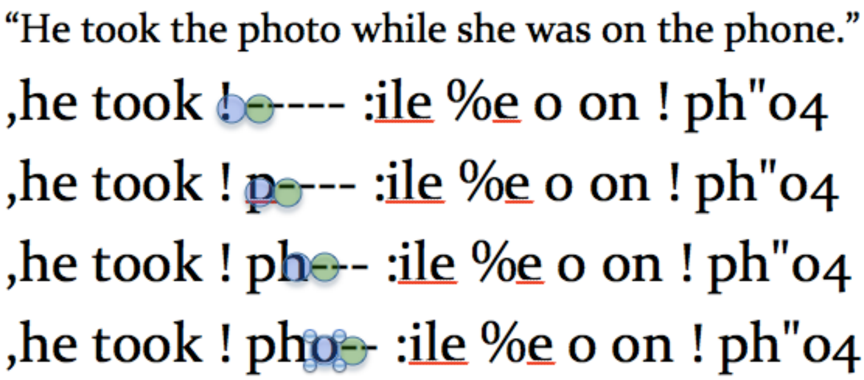


Figure 6-7: An example of masking on right index finger.

The stimuli were completely counterbalanced. Twelve sentences used in the hand dominance task were followed by a question where the answers were related to the target words. Each of the following materials were read by six participants. There were two lists of materials; Sentence 1-20, target words were masked on the left index finger. Sentence 21-40, target words were masked on the right index finger, and vice versa (See Appendix E). The participants were assigned to read one list of the materials.

Twelve questions were asked at random locations in the experiment. Subjects were simply asked to decide which of four word choices had been in the sentence just read. Three choices were related to the target word in the sentence but the last choice was always “none”. For instances, the multiple choices of the sentence such as, “phone piano photo none”.

6.6.3 Procedure

The procedure was already described in Experiment 2.

6.7 Results

The data used for the analysis of hand dominance in braille reading were only the question responses. The preferred reading hand, the dominant hand, and the display location of the target words were factors in the analysis.

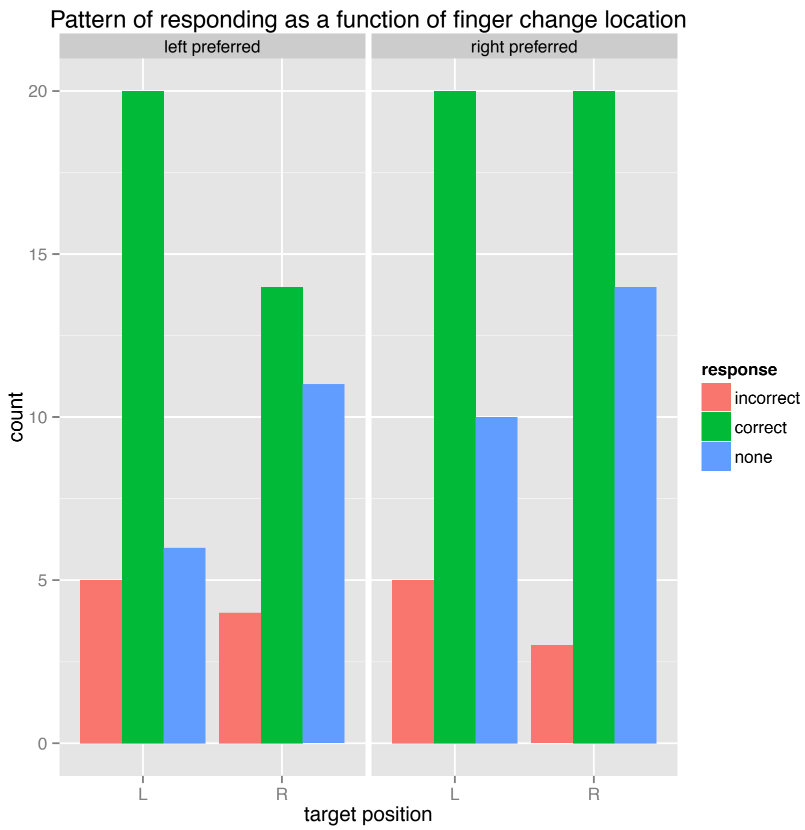


Figure 6-8: Pattern of word identification as a function of preferred braille reading index finger and the finger to which the word was presented.

The left panel of Figure 6-7 represents subjects who preferred their left hand in reading and the right panel represents subjects who preferred their right hand. The L and R under each panel represent the finger to which the word was presented. The above figure shows that the main numerical difference in performance is when words are presented to the right finger of those who indicate that their preferred reading finger is the left index (left panel of figure). The main source of difference here is an increase in "none" responses at the expense of correct ones. This interaction is marginally significant ($z = 1.41$; $p < 0.08$).

6.8 Conclusion

Many researchers have tried to address which hand plays a superior role in braille reading when readers use both hands. Performance was mostly examined using reading time and accuracy of question answering. Yet no research was found that investigates hand dominance in braille reading in real time. This is the first study to show the possibility of using the display change program provided in the finger-tracking system software as a tool for exploring hand dominance in braille reading. It appears that readers who prefer to read with their right finger are equally at ease with the left. However, the reverse is not the case. It was found that reading performance of the readers who preferred reading with their left hand is less efficient than the other group. This likely reflects the fact that readers of braille tend to start learning with their left hand as a dominant hand and moving to their right as they get more skilled.

This finding is consistent with the observations of Millar and others (e.g., Fertsch, 1947; Hermelin and O'Connor, 1971; Millar, 1984) who have observed a difference in reading performance for left and right hand readers. Fertsch (1947), for example, found that most fluent braille readers used their right hand in reading.

On the other hand, braille beginners performed better when they used their left hand (Hermelin & O'Connor, 1971). Moreover, Millar (1997) indicated that the left hand was superior in spatial tasks while right hand was more efficient in verbal tasks. A range of evidence shows that while beginning readers find it easy to start learning braille with the left hand (irrespective of their hand dominance), fast reading speeds are only achievable by also engaging the right hand. In the case of the present experiment, the preferred left fingered readers are slower than the preferred right fingered readers, similar to that found in Chapter 5. The mean cell transit times from the 5-7 length words, on the first pass for those who favour left is 96.8 versus right hand is 83 milliseconds. The asymmetric performance shown in Figure 6-7, suggests that skilled braille reading requires accurate performance for both left and right finger. This interpretation is also supported by an fMRI study of braille discrimination tasks by left and right index fingers (Sadata et al., 1998). The study found that readers who preferred the left index finger for reading activated clearly the right primary sensorimotor area, whereas, readers who preferred the right index finger activated both primary somatosensory regions of the brain equally.

In the next chapter, the argument that data from the left and right hand are being processed by separate brain mechanisms and that this is at the root of the significant speed advantage that right-handed braille readers demonstrate, will be explored.

Chapter 7

Experiment 4: Braille and the metamodal brain: evidence of auditory involvement in skilled braille reading

Figure 5-11 in Chapter 5 showed that the information pick-up strategy of slow and fast readers was strikingly different. While slow to average readers tend to concentrate on the spatial features of individual characters as evidenced by repeated passes over cells (referred to as "scrubbing") and lots of regressive reading, on the other hand, the faster readers tended to make a single high-speed pass across the cell array smoothly. These latter readers appear to attend to the global pattern of stimulation made by the dot sequence. It seemed that the stimulation arising from the sequential pattern of raised dots was being processed more as a speech-like pattern than a spatial one. This suggests that perhaps these highly skilled readers were recruiting the auditory areas of the brain to support their processing of this speech-like signal. Therefore, we postulated that the auditory cortex might be also involved in the processing of braille reading in fast readers. Neuroimaging studies of blind people have shown that the primary visual cortex is activated during braille discrimination tasks (e.g., Uhl, Franzen, Lindinger, Lang, & Deecke, 1991; Sadato et al., 1998; Büchel et al., 1998; Cohen et al., 1999; Burton et al., 2002; Amadi et al., 2004). In addition, there is growing evidence to support the metamodal theory of brain function which argues that the kind of co-option found in the visual cortex is a pattern across the entire cerebral cortex (e.g., Pascual-Leone & Hamilton, 2001; Kauffman, Théoret, & Pascual-Leone, 2002).

In this chapter, evidence that the auditory cortex may also be implicated in supporting reading via an existing pathway between the somatosensory and auditory cortices is presented. The hypothesis is that once the vibro-tactile stimulus generated at a reader's fingertip goes above the audible threshold (around 20 Hz), the signal processing machinery of the auditory cortex can then be engaged to help with reading. This hypothesis is in keeping with a metamodal view of the brain where functions developed for one domain can be re-used for another (Pascual-Leone & Hamilton, 2001).

7.1 Brain plasticity

The cerebral cortex consists of four lobes, each lobe being associated with different processing functions. This is a general description of the brain commonly found in anatomy textbooks. It was previously believed that the structures and functions of the brain were static by adulthood. Over the past few decades, neuroscientific studies have found evidence that brain function is not static, but can be reorganised throughout a person's lifetime. This phenomenon is known as brain plasticity or neuroplasticity. New neural pathways can be activated by repetitive learning. The neuroimaging methods discussed in Chapter 3 have enabled neuroscientists to examine cognitive re-organisation non-invasively. Recent studies have shown striking images that the brain is able to re-route neural pathways from a damaged area to intact neurons in an undamaged area. For example, patients with early left hemispheric brain lesion indicated activation in their right hemisphere that took over language functions (Duchowny et al., 1996; Booth et al., 1999; Staudt et al., 2002). Boatman et al. (1999) also discovered that children aged between 7-14 could recover their speech discrimination after surgery even if the left hemisphere had been damaged after the critical period for language acquisition. Moreover, these neuroimaging tools can also be applied in assessing the potential in stroke patients for recovery of meaningful speech. The most common symptom in stroke patients is speech deficits, so-called aphasias. Fridriksson (2010) demonstrated that the brain has an ability to show significant recovery in chronic stroke patients with aphasia. Patients' communication improved after 30 hours of speech therapy emphasising anomia treatment. His results showed that the regions surrounding the damaged areas took over the damaged area's function helping to support recovery. In addition, Maguire, Woollett, and Spiers (2000) discovered that London taxi drivers who had experience of driving taxi on average for 14 years had significantly larger posterior hippocampi, a brain area involved in navigation and spatial representation, compared with a control group.

Furthermore, there is evidence of the plasticity of the brain in areas relevant to braille reading. For example, if one region in the brain that usually supports processing one sensory modality is deprived of input, that region can be used to process different sensory modalities. This type of brain plasticity is initially found in humans who have had early-onset sensory deprivation. Cross-modal plasticity resulting from visual deprivation is reviewed in the following section.

7.2 Cross-modal plasticity

Sensory deprivation can give rise to situations that make brain plasticity more clearly evident. It is known as cross-modal plasticity. There is growing evidence of cross-modal re-organisation in both animals and human studies. Monkeys with nerve transection where either vision or auditory inputs have been profoundly diminished have been used to observe the resultant brain activity. These studies showed that undamaged sensory systems can compensate for sensory deprivation in other areas (e.g., Laemle, Strominger, & Carpenter, 2006; Bengoetxea, Argandoña, & Lafuente, 2008; Brussel, Gerits, & Arckens, 2011). In humans, increasing evidence from visually deprived individuals shows activation in the visual cortex during non-visual tasks, such as sound or tactile discrimination tasks, hearing words, braille reading, and tone and phoneme matching tasks (Schlaug et al., 1999, 2000; Burton et al., 2002a,b). Over the last 20 years, neuroscience studies of brain processing in the blind have found that during tactile discrimination tasks, activation in visual cortex is found in both early blind and blind-from-birth subjects (e.g., Cohen et al., 1997, 1999; Sadato et al., 2002; Sadato, 2005).

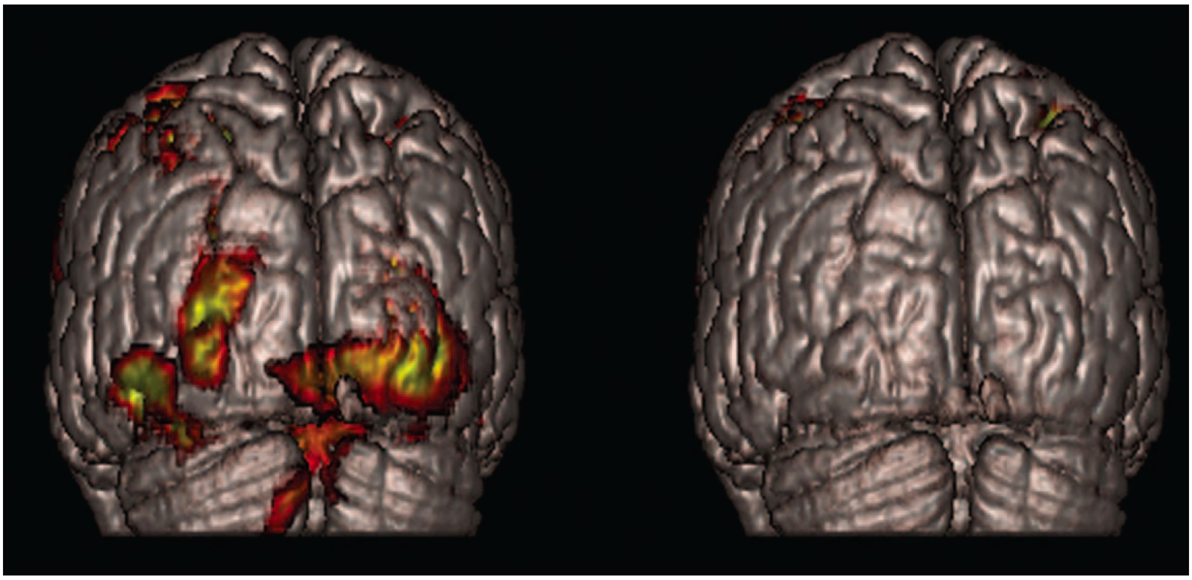


Figure 7-1: Areas activated during braille tactile discrimination task comparing an early blind participant (left) and a sighted reader (right) (Sadato, 2005).

The above figure shows extensive occipital activation, involving area V1 in an early blind subject, but the activation was not found in a sighted subject during braille tactile discrimination tasks. Moreover, Pascual-Leone and Hamilton (2001) cited a case of a proficient braille reader who suffered a stroke in the occipital area that rendered her alexic. There is some debate over the issue of a critical period in the use of the deafferented occipital cortex to support braille reading. There is strong evidence that early visual experience changes its subsequent adaptability for braille (Burton, 2003; Buchel et al., 1998). However, even in circumstances where people have lost their sight late in life, the visual cortex shows activation during tactile discrimination tasks (Sadato, Okada, Kubota, & Yonekura, 2004). Brain plasticity not only occurs in the occipital area during tactile reading, but also in the somatosensory cortex. Moreover, an enlargement of the sensorimotor cortical representation for the preferred braille reading finger but not for non-reading fingers was discovered by Pascual-Leone and Torres (1993) and Giriyappa, Subrahmanyam, Rangashetty, & Sharma , (2009).

7.3 Metamodal brain

A traditional unimodal view of brain function would suggest that different brain regions are responsible for different functions. However, increasing evidence supports a new model referred to as the metamodal model. The metamodal theory conceives of the brain as organised as a set of operators that can process information irrespective of sensory input modality (Pascual-Leone and Hamilton, 2001; Reilly, 1995). Pascual-Leone and Hamilton (2001) described experiments with subjects blindfolded for five days and noticed significant increases in visual cortex involvement in tactile tasks through the course of the blindfolded period. There was a subsequent reversion to normal levels of activity after removal of the blindfold. Kauffman et al. (2002) noticed a steady improvement in braille discrimination tasks for blindfolded versus non-blindfolded sighted subjects, where subjects were monitored over a period of five days. These results support a metamodal theory of cortical computation whereby the computational resources that underlie sensory and motor activities can be applied to different input domains, rather in the way software functions designed for one application domain can be generalised to others (Reilly, 1995). Thus, somatosensory input from a braille text can be processed by, say, the visual or auditory cortices depending on task requirements. This theoretical position, alternatively referred to as cortical software re-use, has been articulated in several forms in the last two decades (Reilly, 1995 ; Jacobs, 1999 ; Pascual-Leone and Hamilton, 2001; Reilly, 2002; Anderson, 2010).

For example, the extrastriate cortex seems especially implicated in fine braille discrimination tasks. Conceivably, this region has latent functionality that is best adapted to this task, independent of modality. Invoking metamodality further, it is also possible that other cortical regions may simultaneously contribute to skilled braille reading. There is reliable evidence to suggest that vibrotactile stimulation is normally projected, inter alia, to the caudomedial (CM) region of the auditory association cortex (Yau, Olenczak, Dammann, & Bensmaia, 2009 ; Foxe et al., 2002).

More recently, Reich, Szwed, Cohen, and Amedi (2011) observed activity in the ventral stream of the visual cortex, the so-called visual word-form area (VWFA), during a braille reading task. The authors suggested that this was an instance of metamodality at work whereby the VWFA has specific functionality that makes it suitable for co-option by braille readers. They hypothesised that the VWFA may support the linking of complex feature patterns with the language areas of the brain irrespective of their provenance.

7.4 The hypothesis

In this study, it is hypothesised that skilled braille readers exploit the already existing cortical “ bridge” between the somatosensory area and the auditory cortex located in the left CM region of the auditory association cortex. There is also strong neuroscientific evidence of a link between the somatosensory cortex and the auditory cortex in non-human primates (e.g., Schroeder et al., 2001; Budinger, Heil, Hess, & Scheich, 2006; Smiley et al. 2007; Escabi, Higgins, Galaburda, Rosen, & Read, 2007; Higgins, Escabi, Rosen, Galaburda, & Read, 2008) and in humans (e.g., Foxe et al. 2002; Schürmann, Caetano, Hlushchuk, Jousmäki, & Hari, 2006; Ro et al., 2012). In the case of braille readers, the proposed benefits are that readers can exploit the brain functions that are already in place to process the speech stream. One possibility is that the readers use these functions to tune into the higher-order, word- and phrase-level features of the vibrotactile stimulation produced during reading. Slower braille readers, on the other hand, concentrate more on the lower-order sequencing of the braille cells. One clue that this might be happening comes from brain scans from Büchel et al. (1998) that show distinct differences between early and late blind braille readers. In the case of the more skilled, early-blind readers, the involvement of the visual cortex is reduced and the pattern of activation shows hemispheric asymmetry, with the faster readers engaging more of their left visual cortex than their right. While the late-blind, slower readers, engage both left and right visual cortices more or less equally.

According to the general view of brain lateralisation, the right brain is dominant for spatial abilities and left brain is dominant for verbal processing. Using a divided visual field (DVF) technique, the left brain is found to be more sensitive to high spatial frequencies whereas the right brain is more sensitive to low spatial frequencies (Motz, James, & Busey, 2012). This evidence suggests that beginning readers may start learning braille with the left hand easier than the right, but if they want to increase their reading speed, reading only with the right hand might be more efficient. This shift to overall left-hemispheric dominance for fast readers is supported by data from our earlier participants among whom the fastest typically used their right hand. This was despite many of them having started learning braille with their left hand. One possible reason for the switch is that the left hand has an early advantage for picking up spatial arrangements of the cells, but the right hand is better equipped to process the speech-like stream of vibrotactile stimulation.

Yau et al. (2009) showed that tactile frequency vibrations interfere with tone perception when they were in the same frequency range. Moreover, Ro et al. (2009) also revealed that during a discrimination task participants increased their performance 12.8% when the sound was the same as frequency as the vibrotactile stimulus. So if the vibrotactile aspect of the braille input is being used to speed braille reading and if a tone sequence in the same frequency range (i.e., 10-30 hz) is played, it should interfere with the reader's ability to use the auditory modality to process braille.

The following experiment was designed to test the conjecture of auditory involvement in braille reading by presenting readers with a range of auditory stimuli in the hope of interfering with the use of these auditory circuits. It was hypothesised that faster readers made use of the auditory cortex to help them achieve their reading speeds, consequently, they should find the braille noise more disruptive than noise unrelated to braille stimulation and there would be no difference between the two classes of noise for slower readers. This hypothesis will be referred to as the auditory cortex re-use (ACR) hypothesis. The ACR hypothesis was tested by using sound analogues of the same frequency range as the vibrotactile input from the braille readers' fingers, which was calculated from the data collected in Chapter 5. The vibrotactile input was in roughly the same frequency range as that made by the braille dots on their fingertips, approximately 10-30 Hz. The braille frequency was computed from the reading time per line divided by the number of braille cells multiplied by two, since each cell consisted of two vertical columns. Another sound in a different range (40-60 Hz) from the braille reading frequency was presented to readers over headphones. The aim of the paradigm is to interfere with the low-level speech circuitry of the brain, which should result in differential inhibition of performance if the fast readers make use of this region and slow readers do not.

7.5 Materials and methods

7.5.1 Participants

Participants were the same as in Chapter 6, but only 12 braille readers volunteered to participate in this experiment. A new mean of the demographic details was recalculated as showed in Table 7-1.

	Mean	S.D.	Range
Age when tested (yrs)	45.6	8.7	32 to 57
Age braille was learned	8	8.15	4 to 32
Years reading braille	37.46	10.73	14 to 53

Table 7-1: Group characteristics of the 13 braille readers.

7.5.2 Materials and design

Reading materials for this study were selected from scientific texts that readers might not be too familiar with but which were also not too technical (see Appendix E). Nine scientific passages were used. They were printed in contracted UK braille on embossed-braille paper. The page dimensions were 34 characters per line and 23 lines per page. Each passage consisted of two pages. The average number of words in each text is 220 words. In order to calibrate the finger tracker, calibration characters were located on the first and last line of each page, consisting of the letter sequence “abc” at the line beginning and “cba” at the line end.

To test the ACR hypothesis, the materials were divided into three groups depending on the order of the auditory stimulus they received: (1) Braille noise (in the range 10-30 Hz) was produced by generating from prime numbers of frequency range between 11 to 29 Hz. The reason for using prime numbers was to prevent resonance effects. The following figure shows a screenshot of the Audacity program used to generate the braille noise;

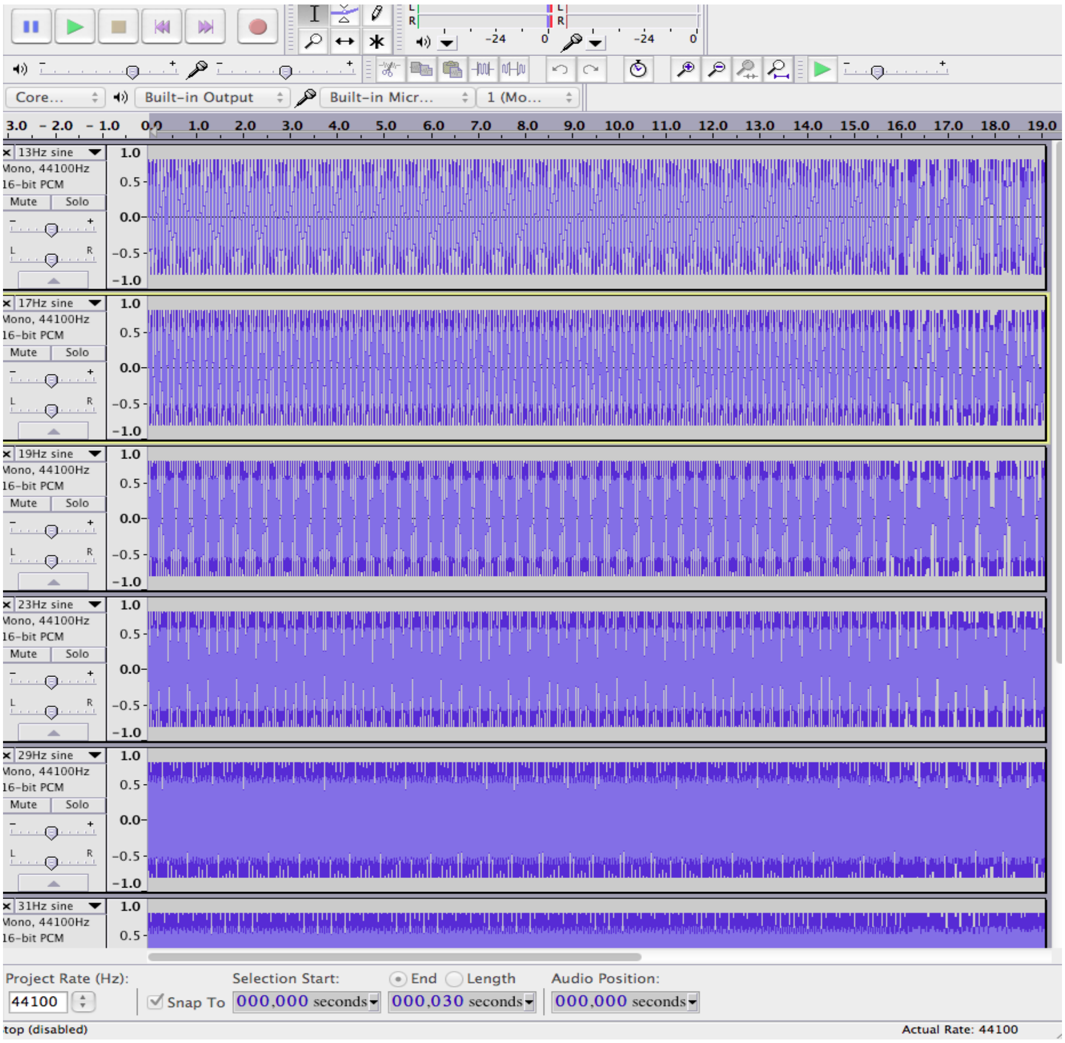


Figure 7-2: Producing Braille-Noise by using prime numbers.

(2) Non-braille noise (40-60 Hz) was slightly offset from the braile noise frequency range; (3) silence as another condition. The order of the noise conditions was counterbalanced across subjects, but the order of the passage in each group was fixed. Braille noise and non-braille noise was delivered from an external headphone which linked to the Audacity program used for generating the noise. A

comprehension question was asked at the end of each text.

Each Subject read three narrative texts for each of the three auditory conditions for total of nine texts comprising 18 pages. The order of each auditory stimulus was counterbalanced across the subjects, but the order of each text was identical as follows:

Braille noise: Autism, Sun, Gestures

Non-braille noise: Stem cells, Bilingualism, Greenhouse Effect

Silence: Mars, Coconut Oil, Wrinkles

7.5.3 Procedure

All subjects were tested individually in a quiet room. They were asked for some basic demographic information (e.g., preferred reading hand, hand dominance, reading hours per week, age at which they were taught to read braille). They read a braille consent form (see Appendix C) and signed their name. The consent form emphasised that they could discontinue their involvement at any time during the course of the experiment without any cost to themselves. The participants were seated in front of the apparatus and familiarised with it. All of them were instructed in the experimental procedure. They were told they were going to read nine texts on different scientific topics silently for comprehension so that they would be able to respond a comprehension question that immediately followed each passage.

During reading they heard two types of auditory stimulus over headphones and silence as a control. Prior to the actual experiment, they were told to listen to the two forms of noise and were asked if the volume was too loud for them, if so, the volume was turned down slightly. When the participants were ready, the researcher attached an infra-red LED to the nail of their index finger (both index fingers in the case of two-handed readers) and attached elastic wrist straps containing batteries to the participants' wrists. An infra-red camera situated above subjects' hands tracked their finger movements. When the experiment started, participants were asked to read the texts silently. Each text was followed by a simple question to be answered orally. A calibration check of the system was normally performed at the first page of the nine passages in order to ensure that the line and cell numbers were being accurately measured. Participants were asked to put the headphone on and leave their hands under the table to cover the LEDs on their fingers so as not to interfere with the calibration LEDs on the paper. The calibration method is already described in Chapter 4, p. 68.

Once the noise started playing, readers were instructed to start reading the text. Even though it was in the silence condition, subjects still had to put the headphone on to cut down the noise from outside. The start recording button was pressed to record the cell, line, and page numbers while reading and pressed a pause button when changing page. The noise was stopped during page changes and question answering. The experiment was typically completed in 60 minutes.

7.6 Data analysis

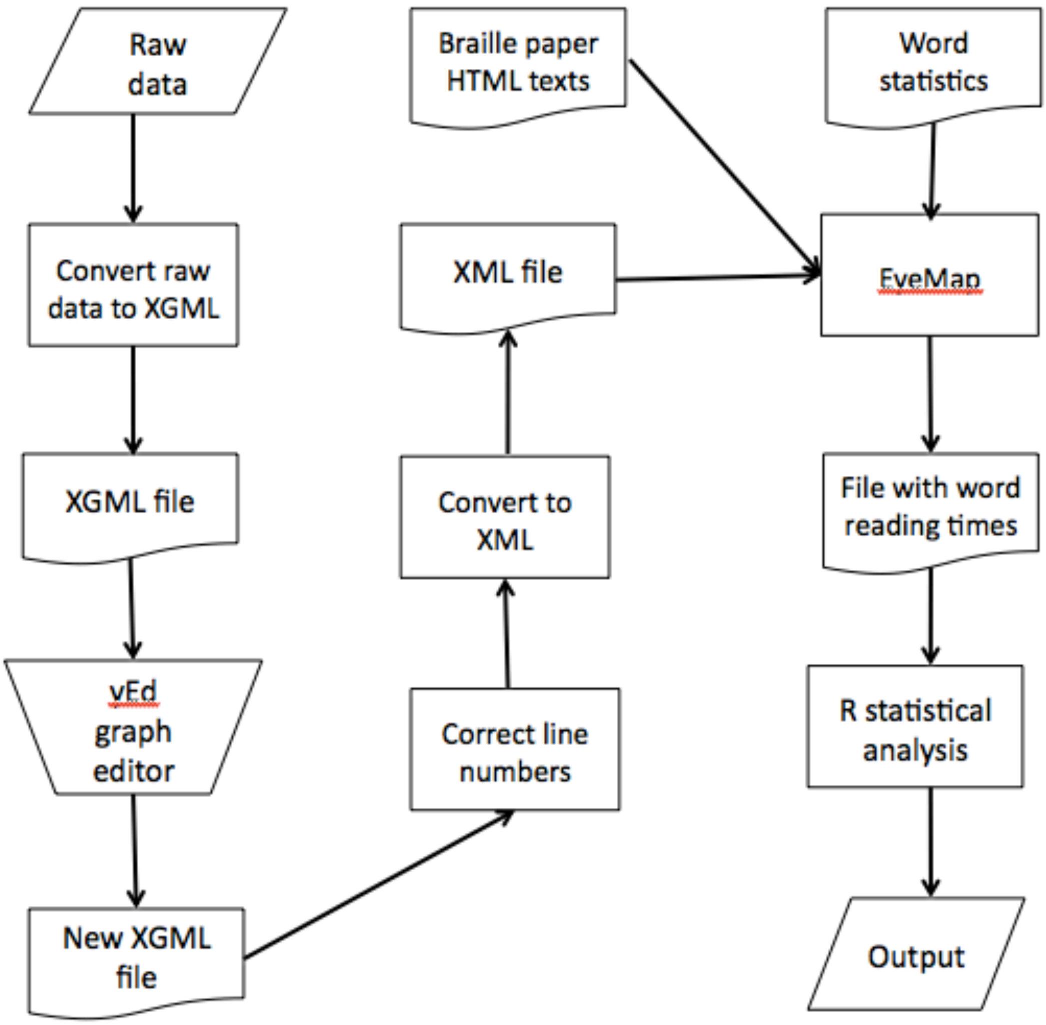


Figure 7-3: The processes of cleaning up the braille paper data.

The raw data derived from the finger tracking system were converted to XGML in order to import the data into the yEd graph editor. This graph editor was used to visualise the overall reading pattern and to eliminate return sweeps and correct line number errors that sometimes arose due to loss of LED tracking. A Perl program (Appendix F) was written to convert the raw data into XGML format as shown in Table 7-2. The left and right hand data were separated into different files.

Subject 1, Left hand, BraillNoise-Silient-NonBrailleNoise, Page 1


```
<section name="node">
                <attribute key="id" type="int">2</attribute>
                <attribute key="label" type="String">L4.4
13.3</attribute>
                    <section name="graphics">
 <attribute key="x" type="double">409.0</attribute>
  <attribute key="y" type="double">1164.0</attribute>
<attribute key="w" type="double">35.0</attribute>
<attribute key="h" type="double">35.0</attribute>
   <attribute key="type" type="String">ellipse</attribute>
   <attribute key="fill" type="String">#00FF00</attribute>
       <attribute key="outline" type="String">#000000</attribute>
                    </section>
                    <section name="LabelGraphics">
                              <attribute key="text" type="String">L4.4
13.3</attribute>
                              <attribute key="fontSize" type="int">8</attribute>
                              <attribute key="fontName" type="String">Dialog</attribute>
                              <attribute key="anchor" type="String">c</attribute>
                     </section>
              </section>
```


Table 7-2: An example of the XGML format of node 2, line 4, cell 4, start time at 13.3 ms.

This XGML format was imported into the yEd graph editor that displayed the raw data in the program (http://www.yworks.com/en/products_ yed_about.html). An example of a graph from raw data is presented in Figure 7-4 and Figure 7-5 shows modified data in which the return sweeps have been deleted and confusing lines corrected manually.

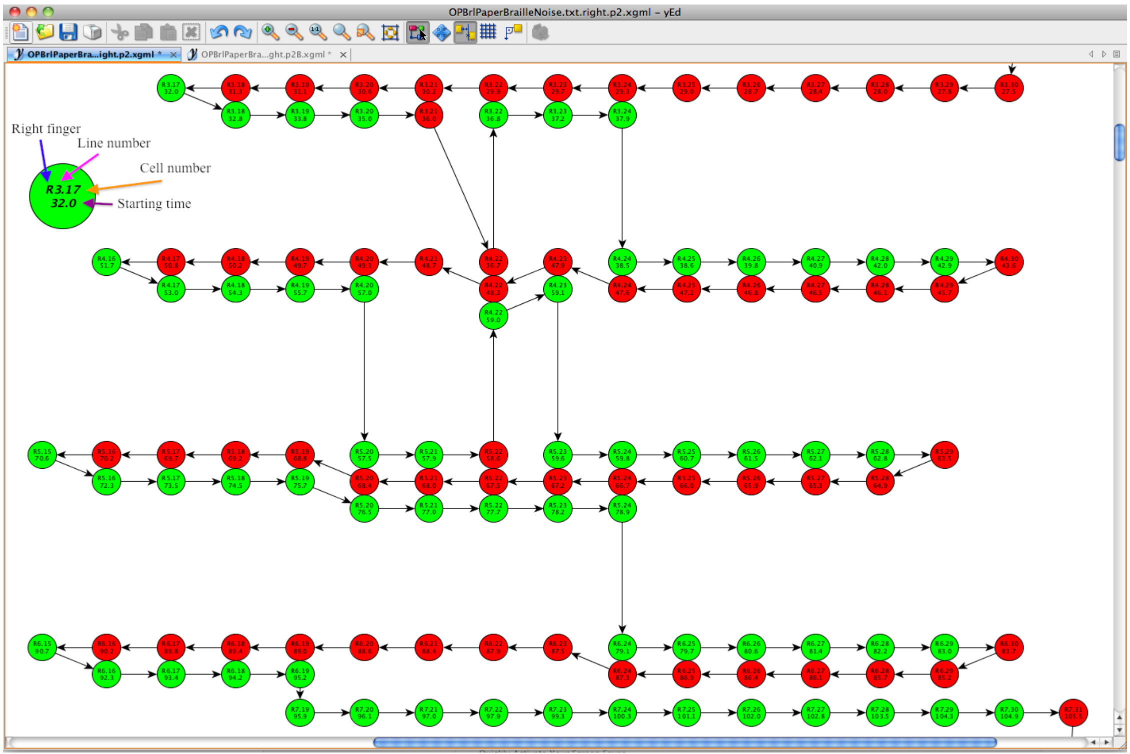


Figure 7-4: An example of raw data presented in the yED graph editor. The red dots are return sweeps. The green dots are cells that the reader spent time on while reading from left to right. .

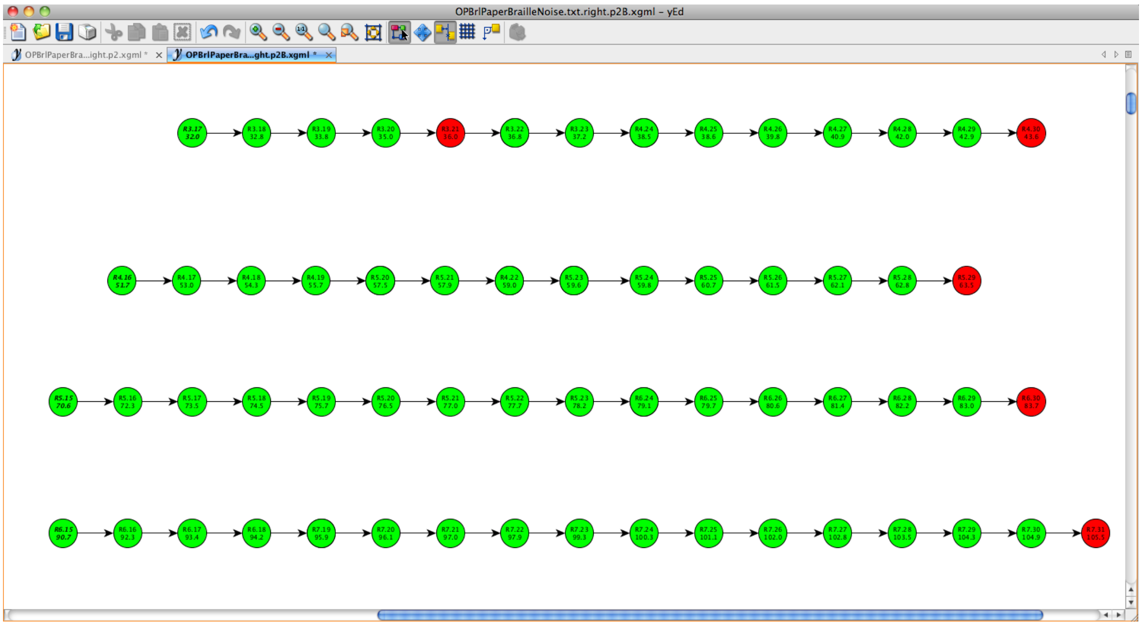


Figure 7-5: An example of modified data presents on yED graph editor.

After editing the graph, the new graph was saved and then converted to another XML format by another Perl program (Appendix F) so that the new data could be processed by the reading visualisation and analysis software EyeMap (Tang, Reilly, & Vorstius, 2011; http://openeyemap.sourceforge.net/). Eyemap was developed for visualising and analysing eye movement data but was adapted to analyse braille data for this study because the program provides basic tools for visualisation, word segmentation, and also producing eye movement related reading measures, such as, gaze duration, fixation duration, saccade length, etc. Texts on paper in braille were also imported into Eyemap for the generation of various reading measures. In addition, word frequency values taken from a database derived from a subtitle corpus (Brysbaert, et al., 2012) were also imported into Eyemap.

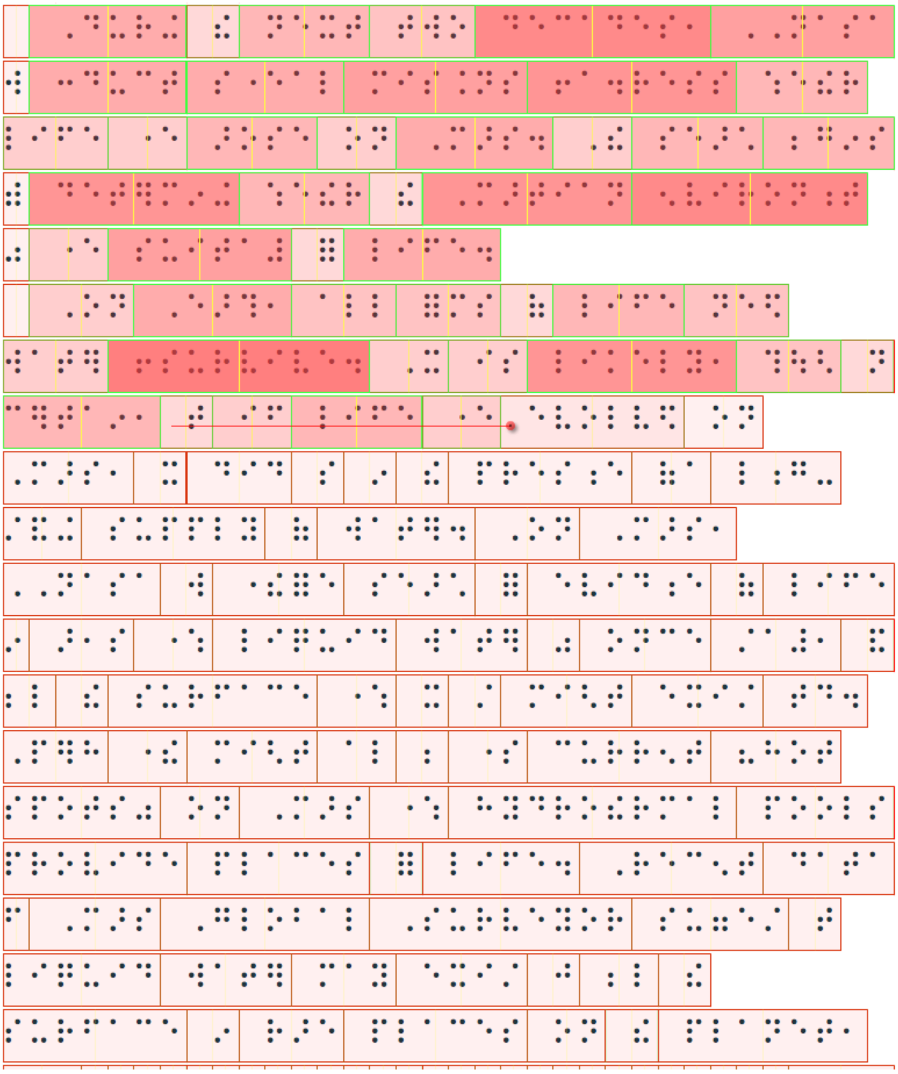


Figure 7-6: An example of braille paper data on Eyemap.

Figure 7-6 is an example of braille paper data displayed in Eyemap. The red line is the reader's right index finger. The depth of the red in each word represents the total time spent on the word. Eyemap provides word reading times used for analysis in R.

7.7 Results

After cleaning the data, 10 of the 12 subjects data were usable. Those two participants' data were too noisy to be analysed because of LED signal loss. In the case of two-handed readers, only the right-handed data was used because all of them preferred their right hand in reading. The data was analysed using the R package. Outliers were excluded from the analysis. Data less than 10 ms and greater 2.5 SDs above the mean were removed. For the cell transit analysis only times that were part of uninterrupted sweeps from left to right were used. The subjects were divided into two groups based on whether they were above or below the mean reading speed for the group as a whole. By this measure, four of the readers read below the average and six readers were above the average. Figure 7-6 shows an average of cell transit times between fast and slow readers in each noise condition: braille noise, non-braille noise, and silence.

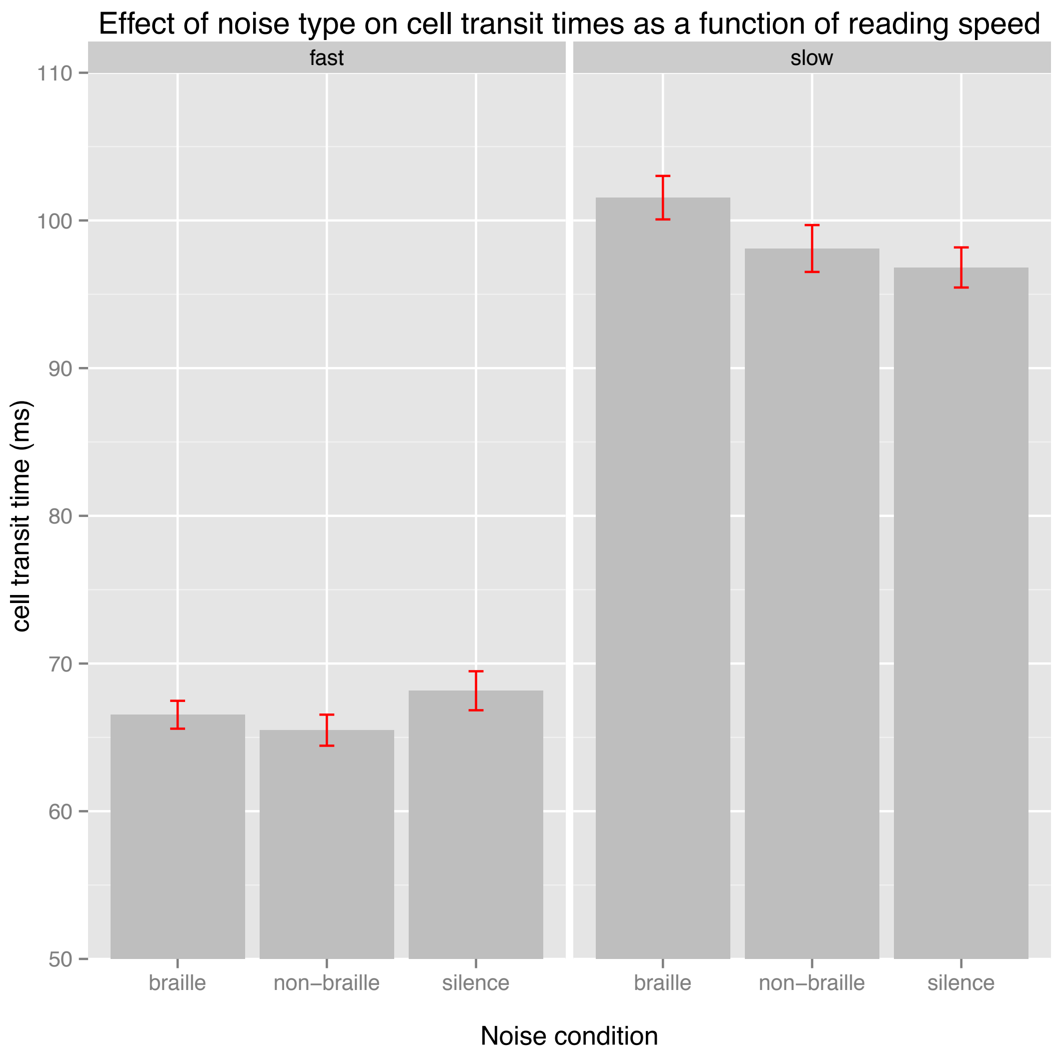


Figure 7-7: Effect of noise type on cell transit times as a function of reading speed.

Figure 7-7 shows that noise had a differential effect on readers depending on whether they were fast or slow readers as measured by their average cell transit time. Braille noise significantly slowed the slow reader group, while having no such effect on fast readers. This interaction was significant ($t = 2.72$, $p_{MCMC} = 0.01$).

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	84.5134	4.1378	20.425
non-braille:braille	-1.0045	0.7225	-1.390
silent:braille	0.3668	0.7056	0.520
slow:fast	34.2925	8.1862	4.189
non-braille:braille : slow:fast	-3.6486	1.3422	**-2.718**
silent:braille : slow:fast	-1.9975	1.3152	-1.519

	MCMCmean	p_{MCMC}	Pr(>|t|)
(Intercept)	84.5594	0.0001	0.0000
non-braille:braille	-0.9856	-0.1816	0.1645
silent:braille	0.3646	0.5978	0.6031
slow:fast	34.1598	0.0018	0.0000
non-braille:braille : slow:fast	-3.6289	**0.0100**	0.0066
silent:braille : slow:fast	-1.9420	0.1464	0.1288

Table 7-3: LME analysis of the effect of noise type on cell transit times as a function of reading speed.

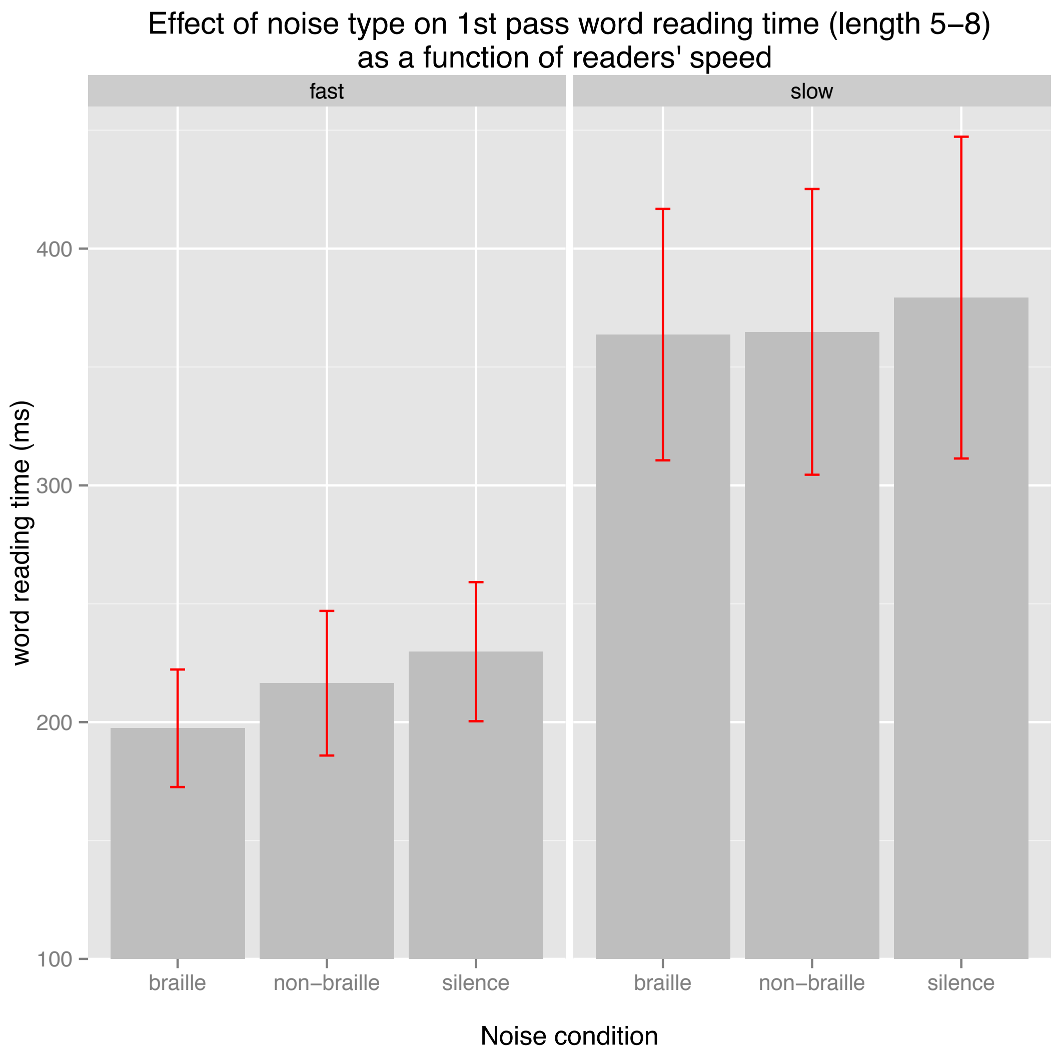


Figure 7-8: Effect of noise type on first-pass word reading time as a function of readers' speed.

Figure 7-8 represents the analysis of word-level of length 5 through 8 in order to get a more accurate picture of the impact of the noise condition on word processing. The graph demonstrated that there is clear benefit for fast readers from braille noise. The statistical analysis also indicated that there is an interaction between the braille noise and reading speed ($t = 1.94$, p_{MCMC} approximately 0.05). Even though it is not strong, it is significant.

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	264.002	61.438	4.297
non-braille:braille	114.991	80.132	1.435
silent:braille	6.549	88.792	0.074
slow:fast	69.050	74.253	0.930
logFreqWF	-4.293	28.342	0.151
non-braille:braille :slow-fast	-34.743	53.728	-0.647
silent:braille : slow-fast	-102.468	52.703	**-1.944**
non-braille:braille : logFreqWF	-38.339	36.438	-1.052
silent:braille : logFreqWF	4.426	40.151	0.110

	MCMCmean	p_{MCMC}	Pr(>|t|)
(Intercept)	260.205	0.0001	0.0000
non-braille:braille	119.223	0.1370	0.1518
silent:braille	5.507	0.9482	0.9412
slow:fast	69.302	0.3588	0.3528
logFreqWF	-3.289	0.9138	0.8797
non-braille:braille :slow-fast	-33.854	0.5350	0.5181
silent:braille : slow-fast	-98.869	0.0680	**0.0523**
non-braille:braille : logFreqWF	-38.724	0.2856	0.2932
silent:braille : logFreqWF	5.588	0.9000	0.9123

Table 7-4: LME analysis of the effect of noise type on first-pass word reading time as a function of readers’ speed.

7.8 Conclusion

The results show that braille noise did indeed selectively affect reading performance. We hypothesised that braille noise would have a stronger effect on faster braille readers. The present findings suggest that braille noise may enhance reading speed in fast participants but not in slow participants. There is also some evidence that braille noise may affect slow readers' reading speed, but in the opposite direction to fast readers. The perception of vibrotactile stimulation appears to be enhanced by noise in the same frequency, thus, braille noise did not increase slow readers' speed because their reading range was lower than the average. This is different from the findings of Yau and his colleagues (2002)'s study where they found sound stimuli of similar frequency to the vibrotactile input caused perceptual interference.

In both the cell-level and word-level analyses, as evident from Figures 7-7 and 7-8, there is a significant interaction between reading speed and the impact of noise, where braille noise in particular tends to benefit the fast readers and impede the slower readers. This interaction is support for the hypothesis that fast braille readers are using the somatosensory-auditory channel. However, why the noise appears to be facilitatory rather interfering for fast readers is a surprise. One explanation is that it is an effect of a phenomenon called Stochastic Resonance (SR; Usher and Feingold, 2000) whereby an optimal amount of noise added to weak signals allows them to be better detected. Many studies have found that noise increased vibrotactile sensitivity due possibly to a SR phenomena (e.g., Liu et al., 2002; Moss, Ward, & Sannita, 2004; Wells, Ward, Chua, & Inglis, 2005).

In summary, this experiment is the first study to show that the hearing part of the brain may be implicated in the braille reading process. This finding supports the metamodal view that brain regions, in this case the auditory cortex, can also be used to process information from different modalities. These findings open up the possibility of using this phenomenon to develop techniques that use auditory feedback to enhance readers' reading speed. If we could reinforce the link between the somatosensory cortex and the auditory cortex in slow readers by adding braille frequency noise it may help the auditory cortex to become engaged in the reading task. This current study is a relatively crude test of the auditory link to braille, but nonetheless with very promising results.

Chapter 8

Discussion and future work

This chapter highlights the key results from conducting the research described in this dissertation. It also hints at a way of improving the teaching and learning of braille by the utilisation of findings from these experimental results. This dissertation started with a concern over declining braille use. Currently, most people become blind later in life and there is a range of text to speech software to help the blind to read. This comes at the cost of the downgrading of their literacy skills. Given the perceived benefits of braille literacy and the various obstacles to its uptake, there is a need for support systems to aid in its teaching and use. Therefore, rather than technology being used to replace braille, it could be used in a complementary fashion to enhance its learnability and usability. To study braille reading behaviour, we need a hand-movement tracking device to explore online processing of tactile information during braille reading. Traditional approaches have involved the manual, frame-by-frame analysis of video recordings, but this is too slow and cumbersome for any type of large-scale study. The finger tracking system was, thus, developed to investigate the moment-to-moment processing of braille text. The system can be used with a refreshable braille display or braille-embossed paper. It has allowed the measurement of more subtle details of readers' hand movements, such as acceleration and deceleration patterns in low-frequency words, as shown in Figure 5-12. The details of the finger tracking system are already described in Chapter 4.

With greater access to high-resolution reading data, we are now in a position to focus on a detailed analysis of high-speed braille reading. The thesis contribution includes several braille reading experiments performed using the finger-tracking system. The study started from a global analysis of braille readers that focused on braille reading behaviour to explore hand movement patterns used in braille readers. The hand movement patterns found accorded well with those from previous studies (e.g., Eatman, 1942; Kusajima, 1974; Mousty & Bertelson, 1985) as described in Chapter 5. Experiment one examined the role of a global top-down factor in reading braille. A question paradigm was used to examine whether top-down factors influenced the temporal and spatial aspects of finger movement control. Other factors, such as, frequency effects and individual reading styles were also investigated. Top-down effects showed clearly in reading behaviour through finger movements, reflected in differences in reading speed, as well as in word reading times (e.g., first pass times, single pass times). We determined that readers spent more time traversing infrequent words than more familiar ones, controlling for word length, which was found to be the same as in visual reading. In the case of task difficulty, in general when braille readers had to answer a comprehension task, as opposed to responding to a verification task, the number of words read was much less. Moreover, task difficulty particularly affected slower readers. This finding is unsurprising, since the more demanding task required more careful reading. In summary, braille readers show on-line sensitivity to lexical properties of the text (e.g., word frequency and lexical structure) and top-down task demands.

In terms of reading speed, readers who used multiple fingers in reading read faster than one-finger readers who have read braille in everyday life more than the others. This finding accords with previous studies (e.g., Burklen, 1932; Eatman, 1942; Kusajima, 1970). It was also found that one-handed readers who used their left index finger in reading read more slowly than one-handed readers who used their right index finger in reading. This finding is in agreement with Harris (1980) who found that proficient braille readers tended to use their right hand in reading.

The remainder of the thesis focused on an in-depth exploration of braille reading. The orthographic uniqueness point technique was used to investigate braille word recognition. The results indicate that lexical access of braille can be described by the cohort model. The findings show the different online processing of the regions before and after the OUP location, this online effect was not found in previous studies (Bertelson et al., 1992). In general, we expected to see the OUP emerge for longer rather than shorter words because there is a greater chance to pick up evidence for a speed-up when measuring over longer words. Braille readers spent longer time in the late and the early OUP words. However, the word reading times of the current word were also affected by the OUP location in the previous word.

Hand dominance in braille reading was also examined in Chapter 6 by using a display change technique analogous to that used in eye movement studies. This technique was feasible for braille reading due to the use of the computer-controlled tracker and linked braille display. The data were only collected from two-handed readers, since the task depended on presenting different information to fingers of the left and right hand. The results indicated that readers who preferred their left index finger performed less effectively when they were asked a question about target words presented to their right as opposed to left index finger, whereas, readers who preferred their right index finger performed the identification task equally well with both index fingers. Moreover, readers who preferred the left hand were slow readers on the whole. This finding supports previous studies (e.g., Fertsch, 1947; Hermelin & O'Connor, 1971).

In the final experiment described in Chapter 7, the characteristics that might distinguish fast from slow readers were investigated. From casual observation, it was apparent that the fastest braille readers rarely re-read a line of text and usually made just one fast pass through the array of cells. It seemed that they were tuning into the vibrations on their fingertips generated by the movement across the braille dots rather than attempting to decode the spatial arrangement of the dots in the individual braille cell. In contrast, slower readers moved their fingers back and forth, and seemed to be trying to get a sense of the spatial arrangement of the dot patterns. Fast braille readers seemed to be processing braille in a manner more similar to speech than text.

There is considerable evidence of a neural connection between the auditory and somatosensory cortices (e.g., Foxe et al. 2002; Schürmann et al. 2006; Ro et al., 2012). Auditory stimuli of the same frequency has been found to interfere with vibrotactile discrimination tasks (Yau et al., 2009). We know that not only is the somatosensory cortex activated during braille reading, but also the visual cortex (e.g., Uhl et al., 1991; Cohen et al., 1997, 1999; Sodato et al., 2002; Sodata, 2005). It is not inconceivable, therefore, that readers might be able to exploit the neural functions that are already in place in the auditory cortex to process the speech stream. To explore this possibility, an experiment was designed to try to use noise to interfere with braille reading. Two kinds of noise were played over headphones to readers (braille noise and non-braille noise). There was also a silent condition. The study revealed that noise appears to enhance fast readers, but disturb slower readers. This might be due to a stochastic resonance phenomenon (Usher and Feingold, 2000) that occurs when noise is added to weak signals causing them to be detected more easily. However, a defining characteristic of stochastic resonance is that noise can make things worse if the frequency is not coherent with the signals. This finding also lends support to the hypothesis that fast readers exploit the connection between the somatosensory cortex and the auditory cortex. It suggests that the hearing part of the brain may also be recruited for processing braille, but primarily by fast readers.

A corollary of this finding is that if we use an auditory stimuli that is synchronised with the vibrotactile stimulus at the reader's fingertips, we might enhance their processing of the braille signal. Therefore, a future line of research could explore the use of auditory feedback to enhance reading performance in slow or new braille readers. One possibility is to develop a device to convert the vibration under the fingertips to sound, so that readers can hear sound with the same pattern of variation as vibrotactile stimulus. The device could consist of an accelerometer attached to the readers' fingertips. Software would produce a synchronous auditory stimulus converted from vibrations under the reader's fingertips as they read. The aim would be that the combination of the two signals, vibrotactile and auditory, would get the attention of the auditory part of the brain earlier than might happen naturally, and would consequently help slow readers read faster. It is also hoped to modify the finger tracking system by using a newer technology, such as a high-speed touch screen that can track multiple fingers or a refreshable braille display that can detect pressure on the display so that we will know more precisely where and what fingers are being used.

In summary, this dissertation has made several unique contributions to the field of braille research. A high-resolution finger tracking system has been developed supporting a refreshable braille display and embossed paper. The system also provides software for a display change technique that has not been used in braille reading before. Moreover, it was the first study that found evidence for the recruitment of auditory cortex during braille reading, which holds out some promise for use in teaching slow and new braille readers.

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Appendix

Appendix A

The British Braille chart (BAUK).docx

Appendix B

Recruitment email of the first data collection.docx

Recruitment email of the second data collection.docx

Appendix C

Participant consent form.docx

Information sheet.docx

Demographic questionnaire.docx

Appendix D (Documents for the data collection of experiment 1)

Explanation of the experiment.docx

Irish subjects.docx

Materials for experiment 1.xls

Appendix E (Documents for the data collection of experiment 2 to 4)

Australian subjects.docx

Materials for experiment 2 & 3

- OUP.docx
- Hand dominance.docx

Materials for experiment 4

- Braille paper texts.docx

Appendix F (Programs)

Programs for the experiments

- NFBtran777

- Wiimote Driver1.7
- EasyBraille Driver
- Program of experiment 1
- Program of experiment 2 & 3
- Program of experiment 4
- Examples of texts for the programs
  EnglishBraillePaper.txt
  Data1_1to40_easy.txt
  TextData1_1to40Easy.txt
- Manual for setting up Program
  ReadmeBraillePaperProgram.docx
  ReadmeBrailleTrackProgram.docx

Programs for data analysis

- All experiments
  myFuncs.R
  myFuncs2.R
  myFuncs3.R
  myFuncsJJ.R
  genBrailleUnicode.pl
  IterGenBrailleUnicode.pl
- Experiment 1
  SelectandAddSentenceNumber.java
  CorrectCellBetweenLnR.java
  CalculateCellTransitTimes.java
  FindWordBoundary.java
  FindWordFrequency.java
  Analysis05.R
- Experiment 2 & 3
  calcOUP.pl
  calcOUP2.pl
  OUPAnal03.R
  Analysis06.R

- Experiment 4

  brailleAnal04c.pl

  GenFixHashXML.pl

  IterGenFixHashXML.pl

  parseXML2.pl

  IterParseXML2.pl

  braillePaperAggAnal2.pl

  genEyeMapXML2.pl

  IterGenEyeMapXMLTwo.pl

  PaperAnal02.R