READING IS IN THE EYE OF THE BEHOLDER: EYE MOVEMENTS AND EARLY WORD PROCESSES IN DEAF READERS OF FRENCH

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Abstract

For the present dissertation, three studies were conducted to investigate various aspects of reading in severely to profoundly deaf individuals who use Quebec Sign Language as their main mode of communication and who were categorized as skilled or less skilled readers. A group of skilled hearing readers also participated so that their results could be compared to existing literature. Two studies investigated the use of orthographic and phonological codes during early French word processing, with a masked primed lexical decision task (Study 1) and with the observation of eye movements (Study 3). The second study served as a bridge between the first and the third studies. The participants' eye movements were recorded to determine their eye movement characteristics, such as their reading speed and the size of their perceptual and word identification spans.

The results of the first and third studies converged to show that deaf readers, skilled and less skilled, process orthographic (Studies 1 & 3) and phonological (Study 1) codes very early during word processing. Importantly, skilled and less skilled deaf readers did not differ in the way they encode words relative to the control group of hearing readers. The observation of the participants' eye movements in the second study revealed that reading-level, not hearing status (hearing or deaf), was the main factor determining the characteristics of the participants' eye movements (such as reading speed, size of the word identification span, etc). However, hearing status was a determining factor in the size of the perceptual span of skilled deaf readers, which, unexpectedly, was wider than that of skilled hearing readers. An overarching finding in the three studies is that the three participant groups differed mainly in the speed at which they read or recognized words. Skilled deaf readers, even when matched on reading level with skilled hearing readers read more slowly than the latter group. It was concluded that the main difference between the three groups of readers, apart from the size of the perceptual span in the skilled deaf readers, was one of speed of processing which could be related to low general language competence in many deaf readers.

Résumé

Trois études ont été réalisées afin d'examiner différents aspects de la lecture chez deux groupes de personnes ayant une surdité sévère ou profonde et utilisant la langue des signes québécoise comme mode de communication principal : un groupe de bons lecteurs et un groupe de lecteurs faibles. Un groupe de bons lecteurs entendants a aussi participé aux trois études afin de servir de point de comparaison avec des études existantes. Deux études ont vérifié l'utilisation des codes orthographique et phonologique lors des premiers moments de la reconnaissance des mots, l'une à l'aide d'une tâche de décision lexicale masquée avec amorce (Étude 1) et l'autre à l'aide de l'observation du mouvement des yeux des participants (Étude 3). L'Étude 2 a servi de pont entre la première et la troisième étude. Dans le cadre de cette étude, le mouvement des yeux des participants a été enregistré et plusieurs mesures de bases ont été recueillies, telles que la vitesse de lecture, la largeur de l'empan perceptuel et la largeur de l'empan de reconnaissance des mots.

Les résultats de la première et de la troisième étude convergent et montrent que les lecteurs sourds, bons et faibles, utilisent l'information orthographique (Étude 1 et 3) et phonologique (Étude 1) très tôt lors du traitement des mots. Il faut toutefois souligner le fait que les lecteurs sourds (bons et faibles) ne différaient pas du groupe de lecteurs entendants dans la manière dont ils encodent les mots. L'observation du mouvement des yeux des participants lors de la lecture (Étude 2) a révélé que le niveau de lecture, et non le fait d'entendre ou pas, sous-tendait les différences entre les groupes en ce qui a trait aux mesures recueillies (vitesse de lecture, empan de la reconnaissance des mots, etc.) Le fait de ne pas entendre a toutefois eu une influence sur la largeur de l'empan perceptuel qui, étonnamment, chez les bons lecteurs sourds, était plus large que celui des bons lecteurs entendants. De façon globale, les résultats des trois études ont permis de constater que les groupes de participants se distinguaient principalement par la vitesse de lecture (ou de reconnaissance) des mots. Les bons lecteurs sourds, même s'ils avaient un niveau de compréhension en lecture équivalent à celui des bons lecteurs entendants, lisaient plus lentement que ces

derniers. Il est suggéré que la différence de vitesse de traitement entre les trois groupes est peut-être liée à des connaissances langagières non-optimales chez plusieurs participants sourds.

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Statement of Originality

The three studies conducted for the present dissertation present a novel portrait of how adult deaf individuals read, with a special focus on how skilled and less skilled deaf readers use orthographic and phonological information during early word processing. This question was examined with a masked primed lexical decision task (Study 1) and by observing the participants' eye movements during sentence reading (Study 3). A secondary goal of the present work was to examine the eye movement characteristics of skilled and less skilled deaf readers (Study 2). The three studies have been written in manuscript format. At the time of official submission of this dissertation to McGill University, Study 2 has been submitted to the *Journal of Experimental Psychology: Human Perception and Performance*. Parts of the results of Study 2 have also been presented at the *14th European Conference on Eye Movements*, in August, 2007. Study 1 and Study 3 were submitted for review before the oral examination for the present dissertation.

Contribution of Authors

Study 1

Bélanger, N., Mayberry, R.I., & Baum, S.R. (submitted). Unmasking the use of orthographic and phonological information by skilled and less skilled deaf readers of French.

I (Nathalie Bélanger) was responsible for the development of the ideas, questions and hypotheses at the basis of this study, for stimuli preparation, for the design of the study, for data collection/analysis, for the interpretation of the results and for manuscript writing. Dr. Rachel I. Mayberry provided guidance at all the stages of this work. Dr. Shari R. Baum also provided guidance, but principally during the stages of data collection/analysis and manuscript writing.

Study 2

Bélanger, N., Mayberry, R.I & Baum, S.R. (submitted). Casting an eye on skilled and less skilled deaf readers: Eye movement patterns during sentence reading. *Journal of Experimental Psychology: Human Perception and Performance.*

I was responsible for the development of the ideas, questions and hypotheses at the basis of this study, for stimuli preparation, for the design of the study, for data collection/analysis, for the interpretation of the results and for manuscript writing. Dr. Rachel I. Mayberry provided guidance at all the stages of this work. Dr. Shari R. Baum also provided guidance, but principally during the stages of data collection/analysis and manuscript writing.

Study 3

Bélanger, N. & Mayberry, R. I. (submitted). Orthographic and phonological information in early word recognition by skilled and less skilled deaf readers: focusing on eye movements.

I was responsible for the development of the ideas, questions and hypotheses at the basis of this study, for stimuli preparation, for the design of the study, for data collection/analysis, for the interpretation of the results and for manuscript writing. Dr. Rachel I. Mayberry provided guidance at all the stages of this work. Dr. Shari R. Baum also provided guidance, but principally during the stages of data collection/analysis and manuscript writing.

Chapter One

1.1 Introduction

In spite of over four decades of research, the determinants of deaf[1] individuals' reading skills are still the source of many questions. Indeed, despite being the center of such research, deaf children and adults still achieve, as a population, a level of literacy well below that of their hearing peers (Allen, 1986; CADS, 1991; DiFrancesca, 1972; Gallaudet Research Institute, 2004; Reinwein, Dubuisson & Bastien, 2001; Traxler, 2000; Trybus & Krachmer, 1977). Some deaf individuals, however, do reach expert reading levels. The reasons why certain deaf people become excellent readers and others do not are unclear. One of the main hypotheses to explain poor reading skills in deaf individuals is related to the fact that deaf people lack (completely or not) the auditory input necessary to develop fully specified sound-based (or phonological) representations and that this underlies their reading difficulties (Perfetti & Sandak, 2000). If that were the case, good deaf readers would necessarily be the ones who have the best phonological decoding skills during reading. In the literature on reading and deafness, however, it is not clear that this is the case. There are numerous conflicting findings and some studies show that good deaf readers (adults or children) do not use a phonological code at all (e.g. Chamberlain, 2002). It is suggested in the present dissertation that such an unclear pattern of results may be in part related to three factors: (1) the possible confound between effects of orthographic and phonological codes during word recognition, (2) the primary use of tasks that do not tap early word recognition processes or that promote the

[1] Throughout this document, the term *deaf* will consistently be used to refer to people with severe to profound hearing loss.

explicit use of a phonological code to resolve the task (e.g. rhyme judgement), which may not necessarily be involved in reading, and (3) the lack of control of reading level within studies. Based on these observations, the goal of the present dissertation is to further investigate the unique contribution of phonological and orthographic codes during early word recognition by adult deaf readers as a function of their reading level. A secondary goal of the present project is to investigate the eye movement behaviour of skilled and less skilled deaf readers and how this may be driven by their reading level, or by their enhanced visual skills in peripheral vision (Bavelier, Dye & Hauser, 2006, for a review).

This introductory chapter will present detailed background for the three experiments that were conducted. In the introduction, several bodies of literature will be reviewed. First, research on reading development and expert reading in hearing readers will be summarized, with a special focus on phonological and orthographic coding, and how these codes are involved in reading development and expert reading. Two models of expert word recognition will also be presented and compared. Following this section, a detailed review of the main factors leading to skilled or less skilled reading in deaf people will be presented. Again, focus will be placed on the role played by phonological and orthographic information, and whether such codes are used by deaf readers, but other factors leading to reading difficulties in deaf individuals will be reviewed to provide a broader context of the hurdles deaf individuals face when reading. Furthermore, a section will be devoted to visual processing in deaf people as this may affect how they process text when reading. Because studies investigating eye movements were conducted for the present dissertation, a section reviewing the basics of eye movement research will follow. Finally, three eye movement control models will be introduced and discussed. The following chapters will present the three studies that were conducted for this dissertation, but they are briefly described here.

The first study (Chapter 2) explored the use of phonological and orthographic codes in early French word recognition as a function of the reading level of signing deaf adults using a masked primed lexical decision task. The second study (Chapter 3) served as a bridge between the first and third experiments and investigated the basic eye movement characteristics of signing deaf adults according to their reading levels. The results of this study served as a basis to interpret the results of the third study. This last study (Chapter 4) addressed the same question as the first study (the use of orthographic and phonological codes in early French word recognition in relation to the reading level of signing deaf adults), but in this case the experimental stimuli were inserted in sentences and eye movement measures were gathered while the participants were reading.

Following the presentation of these three studies, a detailed discussion will place the results of the three investigations in a broader context.

1.2 Hearing Readers

To better understand and contextualize the challenge faced by deaf readers, it is important to first present the processes and linguistic factors involved both in developing and successful reading in hearing children and adults. It is not the goal to present extensive reviews of such broad fields; rather an overview will be laid out to set the stage for the issues at stake for deaf readers.

1.2.1 Development

Learning to read is a complex task requiring the mastery of many components to achieve expert reading. Hoover and Gough (1990) proposed the *Simple View* of reading, in which reading amounts to two components: decoding and spoken language comprehension. According to Hoover and Gough (1990), of the two abilities, only decoding is specific to reading; however, both components are equally important. Oakhill and Cain (2007) specify that spoken language comprehension can be broken down into different components (i.e.: phonology, semantics, syntax and pragmatics). More specifically, such aspects as phonological skills, vocabulary knowledge, syntactic knowledge, and discourse level skills are involved in spoken language comprehension, and overall there is a strong relationship between spoken language and reading comprehension, as many skills are likely shared between the two (Oakhill & Cain, 2007). However, recent work by Cutting and Scarborough (2006; see also Joshi & Aaron, 2000;

Jenkins, Fuchs, van den Broek, Espin & Deno, 2003) has shown that above and beyond word decoding skills and language comprehension skills, part of the variance in reading comprehension was significantly accounted for by reading speed. Based on such results, Joshi and Aaron (2000) suggested a revised version of the *Simple View* of reading, the *Component model*, where reading speed is also a factor. The model is therefore operationalized as Reading = Decoding x Comprehension + Speed. Because Joshi & Aaron (2000) did not really describe the decoding and language comprehension components of the model per se, but only added the speed component to the *Simple View* model (Hoover & Gough, 1990), the present work will refer to the *Simple View* model, but will also take into account the speed component of reading.

Much focus in the reading development literature has been placed on the role of phonological information in the process of learning to read. Frost (1998; p. 74) proposes the "speech primacy axiom", meaning that when learning a language, individuals primarily form associations between meaning and spoken word forms. The written form of a language is a secondary representation of speech that must necessarily match visual symbols (letters) to phonological units of the spoken language (see also Harm & Seidenberg, 2004). Because the mapping between the symbols and sounds is more systematic than the mapping between symbols and meanings (Van Orden, Pennington & Stone, 1990; Ziegler & Goswami, 2005), phonological information is suggested to play a determinant role in reading. Wagner and Torgensen (1987) suggest that there are three kinds of phonological information processing: phonological awareness, phonological decoding, and phonetic recoding in working memory. *Phonological awareness* is defined as the ability to perceive and manipulate the sounds of spoken words (Goswami & Bryant, 1990) or, as Vellutino, Fletcher, Snowling and Scanlon (2004; p. 4) put it, "the conceptual understanding and explicit awareness that spoken words consist of individual speech sounds and combinations of sounds (syllables, onset-rime units)." *Phonological decoding* (the focus of the present work) is defined as the process of print-to-sound conversion during visual word recognition. Finally, *phonetic recoding in working memory* is defined as the transformation of written symbols into a speech-based code so that information can be maintained in working memory for further processing. When observed in preschool children, phonological awareness is widely accepted as a very important predictor, or even as a causal factor to better reading achievement at a later stage (Perfetti, 1991; Torgesen, Wagner, & Rashotte, 1994; Wagner & Torgensen, 1987). However, this is disputed by some researchers who suggest that phonological awareness may instead be a product of reading (see Castles & Coltheart, 2004 for a review; Morais, 2003) or may also be partly derived from orthographic knowledge (Castles, Holmes, Neath & Kinoshita, 2003). As for phonological decoding, the principal reading development models suggest a logographic/pre-alphabetic phase/stage of reading where children rely mainly on visual features to recognize words. This is followed by the alphabetic phase/stage (Ehri, 1998, Frith, 1985), where children "crack the code" or figure out the print-to-sound relationship. According to these models, orthographic knowledge consolidates after the letter-sound associations are mastered as whole-word orthographic representations emerge. Share (1999; p. 96) proposes a similar process, the *self-teaching hypothesis*, where "phonological recoding performs a self-teaching function enabling the learner to acquire the detailed orthographic representations necessary for fast, efficient visual word recognition."

Such a reliance on phonological information in reading development has led researchers to suggest that reading deficits in dyslexic children are mainly based on their difficulty in representing and using phonological information. The dominant hypothesis to explain dyslexia has been termed the *phonological core deficit* (Stanovich, 1986; see Snowling, 1998, and Vellutino, Fletcher, Snowling & Scanlon, 2004 for reviews). More specifically, due to deficient phonological processing, it has been shown that dyslexic children generally have lower phonological awareness skills, have constraints on short-term memory, may be weaker at nonword reading than reading-age matched controls and also have word-finding difficulties, as shown in rapid naming tasks where they are generally slower (Snowling, 1998 for a review).

However, coming back to the *Simple View* of reading (Hoover & Gough, 1990), reading breakdown can also occur at other levels than at the word decoding level. Several studies have focused on the language basis of reading. Research with normally reading children and young adults (1st to 10th graders) has shown that spoken language skills are a significant contributor to reading comprehension (Catts, Fey, Zhang & Tomblin, 1999; Cutting & Scarborough, 2006; Nation & Snowling, 2004), but also to word recognition (Nation & Snowling, 2004). In a large-scale study involving 2nd grade children, it was found that 70% of the children who had been classified as poor readers had been reported as having language deficits when they were in kindergarten (Catts et al., 1999), indicating that language skills are also a source of reading difficulties. Catts, Adolf & Ellis Weismer (2006) studied a large sample of 8th grade readers in whom they measured word recognition skills and reading comprehension. In their sample, they found that some of the teenagers fell into a group with poor word recognition and good comprehension, but others had good word recognition skills and poor reading comprehension skills. These poor comprehenders (as labelled by the authors) had mild deficits in receptive vocabulary and in grammatical understanding (as measured by the ability to comprehend verbal commands involving syntactic structures differing in complexity; Catts et al., 2006).

Overall, the studies presented above show that reading comprehension is based on three main skills: decoding, oral language comprehension and reading speed. Word recognition itself is based on decoding skills, but oral language comprehension is also predictive of efficient word recognition. In a nutshell, good reading comprehension and good word processing skills, besides decoding skills, rely on good language skills, which, it will be shown in the *Deaf Readers* section, are not always well developed in deaf readers. Before introducing research on deaf readers, however, it is important to present an overview of research on expert hearing readers.

1.2.2 Expert Readers and Models of Word Recognition

How exactly expert hearing readers read is a vast domain of inquiry. As Hoover and Gough (1990) point out, only word decoding is highly specific to reading and numerous other processes are related to spoken language comprehension. Because the main focus of the present dissertation is word-level processes, the following section will only present information on word processing in expert readers. Specifically, emphasis will be placed on how orthographic and phonological information processing operate during early word recognition. The role of phonological information is quite disputed and has been the center of much research. Two main views on the role of phonology during word recognition, and indirectly on the role of orthography, have been proposed in recent years. In the first view, represented specifically by the Dual-Route Cascaded model (DRC-Coltheart, 1978; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001), word recognition processes vary based on the dichotomy between regular and irregular words (i.e.: words for which the pronunciation is derived through regular grapheme-phoneme conversion - *maid* or *cave* - versus words for which grapheme-phoneme conversion would lead to an erroneous pronunciation – *said* or *have*). The DRC model is principally a naming model, although the recently implemented version also accounts for lexical decision task results (Coltheart et al., 2001). In the DRC model, both routes start with visual (*Visual Feature Units* – see Figure 1) and letter (*Letter Units*) processing and split from there. Importantly, the *Letter Units* level encodes letter positions with a slot-based procedure. In other words, letter positions are coded according to their absolute position within words (i.e. the word "word" has the letter "w" in the first slot, "o" in the second slot, "r" in third slot and "d" in final slot). It will be shown below that this is not consistent with recent findings on orthographic coding during word processing. The first, *Lexical Nonsemantic*, route has direct mappings from whole-word orthographic representations (*Orthographic Input Lexicon*) to whole-word phonological representations (*Phonological Output Lexicon*) and then to the *Phoneme System* to prepare for pronunciation. The second, *GPC* (for grapheme-phoneme conversion), route assumes rule-based grapheme-to-phoneme conversions (*Grapheme-Phoneme Rule Systems*) prior to the access to the *Phoneme System* leading to pronunciation (S*peech*). Prelexical processing through phonological subword units therefore only happens via the *GPC* route, whereas in the *Lexical Nonsemantic* route, the orthographic and phonological codes are addressed (i.e., not determined by the assembly of smaller units - as in the *GPC* route - but rather directly activated as whole-word unparsed representations). As yet, no route to the *Semantic System* has been implemented (Coltheart et al.,

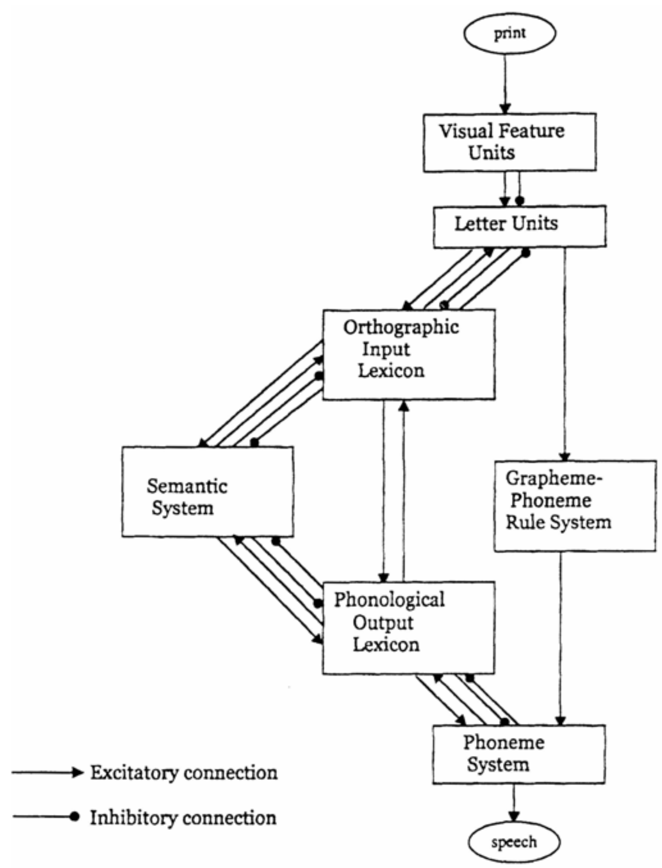

Figure 1. DRC model (Coltheart et al., 2001; p.213)

2001), therefore both routes assume that words are pronounced without access to their meanings.

In the model, it is assumed that regular words are pronounced through either route (*Lexical Nonsemantic* or *GPC routes*), whereas irregular words can only be pronounced through the *Lexical Nonsemantic* route. Low frequency regular words or regular words that have never been encountered before are pronounced through the *GPC* route so that their phonological form is recovered through grapheme-phoneme conversion. Both routes are activated in parallel, but the lexical route can be faster than the *GPC* route, because the GPC route operates serially (each letter is activated one after the other), whereas in the direct route, all letters are activated in parallel.

The second view of the role of phonological and orthographic information during word processing is represented by several models: the classic Seidenberg and McClelland (1989) parallel distributed processing (PDP) model and the revised version from Plaut, McClelland, Seidenberg and Patterson (1996; for a more recent version see also Harm & Seidenberg, 2004,) are two influential instantiations. Only one model will be presented here: the *Bi-Modal Interactive Activation* model (BIAM - Grainger & Ziegler, 2008). This model was mainly developed to account for fast, automatic phonological effects during word recognition (Ferrand & Grainger, 1992, 1993, 1994; Frost, Ahissar, Gotesman & Tayeb, 2003; Perfetti & Bell, 1991; Ziegler et al., 2000, etc). Unlike the DRC model, the BIAM (Grainger & Ziegler, 2008) reflects a two-route hypothesis of word recognition where both orthographic and phonological processing occur in parallel, but most importantly, orthographic and phonological information is automatically activated and necessarily prelexical in the very first moments of word processing for all words - frequent and less frequent, regular and irregular (Ferrand, 2001). In other words, this model is not based on the dichotomization of regular and irregular words, as is the DRC. The BIAM is a silent word reading model (as opposed to a naming model) which is very detailed in the description of early orthographic and phonological processes, but also assumes reading for meaning (contrary to the DRC, where pronunciation of a word can bypass the semantic system). The model is based on research by Grainger and colleagues on early French written word processing by skilled readers (e.g. Ferrand & Grainger, 1992, 1993, 1994, 1996; Grainger & Ferrand, 1994, 1996; Ziegler, et al., 2000). The model is supported by various studies conducted across languages: in English (Lee, Rayner, & Pollastek, 1999; Rayner, Sereno, Lesch, & Pollastek, 1995), Hebrew (Frost & Yogev, 2001; Frost et al., 2003), Dutch (Brysbaert, Van Dyck, & Van De Poel, 1999), and in Chinese (Chen, Allport & Marshall, 1996; Flores

D'Arcais, 1994; Perfetti & Tan, 1998; Perfetti & Zhang, 1991; Perfetti & Zhang, 1995; Weekes, Chen & Lin, 1998).

The main results of this body of research can be summarized as follows: orthographic information processing (for all words) is independent from phonological information processing and, more importantly, follows a different time-course than phonological information processing; orthographic information appears to enter into play slightly earlier than phonological information. Both types of information are activated extremely early during word processing (Grainger & Holcomb, 2008, for a review) and activated at first from subword units. More specifically, the *BIAM* (Grainger & Ferrand, 1994, 1996; Grainger & Holcomb, 2008) posits that separate representations of orthographic and phonological information exert an influence during word processing and that each type of information is subdivided into a prelexical and a lexical level (see Figure 2; for the prelexical/lexical distinction details, see Grainger & Holcomb, 2008). The model accounts for effects of visual and spoken word processing; therefore the entry points are the visual or acoustic analysis of features (*V-features* and *A-features*) as words enter the processing system. These levels will not be discussed further. The various levels are connected with facilitatory connections among levels (represented by lines with arrows) and inhibitory connections within levels (not shown in Figure 2) to represent competition among all activated words from the activation received by the lower levels of processing. According to the BIAM (see Grainger, 2008 for a review), during visual word recognition, prelexical orthographic representations (*O –units*) are operationalized as letters coded for their identity and also for their relative position with respect to one another (e.g. in the word "market", the letter "r" is after the letter "m" and before the letter "k", but not necessarily in third position – as in a slot-based system - so that a prime *MRKT*, for example, would preserve the relative position of letters with respect to one another, but not the prime *MKRT*; see Grainger, Granier, Farioli, Van Assche & van Heuven, 2006). The *O-units* will first be activated (via the *V-features*) and then send activation both to the lexical orthographic level (*O-words*) and the lexical and prelexical phonological levels (*P-units* and *P-words*, respectively)

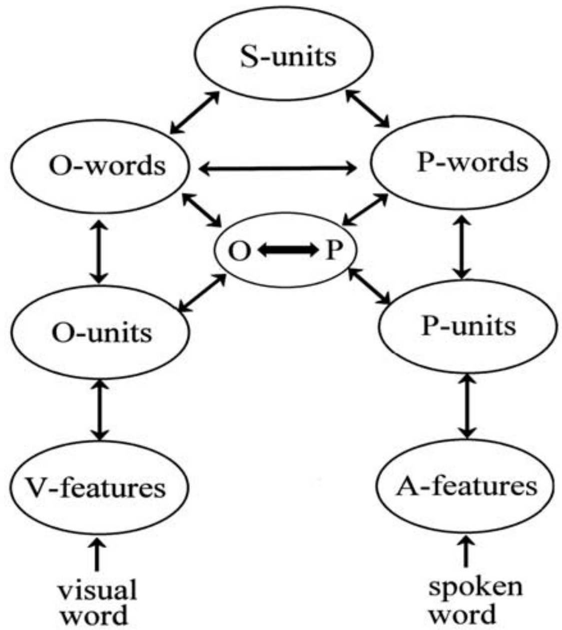

Figure 2. ***Bi-Modal Interactive Activation*** **model (Grainger & Holcomb, 2007; p. 6)**

through the O-P interface. The O-P interface is where sublexical orthographic units are mapped onto corresponding phonological units. The entry into written word processing is therefore through prelexical orthographic representations, but prelexical phonological activation follows shortly after. The lexical phonological level can receive activation from the lexical orthographic level, and also from the O-P interface (or from the prelexical phonological (*P-units*) level in spoken word recognition). The semantic level (*S-units*) is activated from conjoint lexical orthographic and phonological levels. All processing levels feed back activation to the lower levels, as indicated by the double arrows.

It is important in the context of the present work to address methodological issues related to the investigation of early word processing before comparing the DRC and BIAM models. Most studies which provided support for the BIAM have made use of masked priming lexical decision tasks (or eyetracking measures) where prime duration was varied to demonstrate early orthographic and phonological priming effects. In fact, to tap early automatic processes in word processing, two conditions have been suggested as necessary: short stimulus onset asynchronies (SOAs) and masked primes (Ferrand, 2001;

Forster, Mohan, & Hector, 2003). In essence, masked primes and short SOAs are both used to prevent conscious perception of the prime and prevent the prime from being fully processed (Ferrand, 2001; Forster, Mohan, & Hector, 2003). It is assumed that this way only the earlier processes during word recognition are captured. Furthermore, manipulating the prime duration allows a dissociation of different processes as they unfold through time (such as orthographic and phonological codes which have a different time-course during word recognition; Ferrand, 2001). Finally, with this technique, the use of pseudoword primes has also been assumed to tap early prelexical orthographic and phonological processes; a prelexical code derived from a briefly presented pseudoword is said to activate and influence processing of the subsequently presented target (Ferrand, 2001).

Eye movement measures in eyetracking studies are also good indicators of early processes during word recognition. Eyetracking offers the possibility to gather multiple measures on a single word. Perea and Pollatsek (1998) suggested that these measures can be helpful in uncovering the time-course of word processing because they provide sequential information on the processing of words (see also Rayner, 1998). Eyetracking research has also shown that word-level information to the right of the fixation point is used to initiate the processing of a word before it is fixated. This phenomenon is called the *parafoveal preview benefit* (Rayner & Pollatsek, 1987). Parafoveal previews can be thought of as a priming situation (Sereno & Rayner, 1992) and provide an interesting means to investigate early automatic subword processes involved in word recognition.

As mentioned above, there is now considerable evidence that phonological and orthographic codes are activated very early during word recognition and are initially accessed through subword units (letters, syllables, etc; for a review see Ferrand, 2001). Critiques of the DRC model (Coltheart et al., 2001) emphasize that phonological processing is available only for certain words (Booth, Perfetti & MacWhinney, 1999) and that early phonological activation cannot be accounted for by the DRC (see Carreiras & Grainger, 2004). Also, as suggested by Frost (1998), dual-route type models have steered research on word recognition into an obligatory dichotomization: "is phonology addressed or assembled?" (p. 95), whereas he suggests (as does the BIAM model) that "phonology is always partly assembled and always partly lexical" (p. 95). Furthermore, The DRC model has not yet implemented a route to meaning, as the authors acknowledge, therefore the model cannot account for reading comprehension and how access to meaning is achieved (via orthographic and/or phonological representations). Finally, the relative position letter coding implemented in the BIAM is better to explain recent findings showing priming effects for prime/target pairs such as MRKT/market (e.g.: Humphreys, Evett and Quinlan, 1990, Grainger et al., 2006). The DRC model's slot-based letter coding cannot account for such results.

Overall, the models and supporting research presented above suggest an important role of phonological and orthographic codes in expert reading, although the models differ with regard to the relationship, time-course, and representations of orthographic and phonological codes. Despite these differences, knowing that phonological codes are said to be at the center of reading acquisition (and of orthographic representation development), that they are crucially involved and are activated early and automatically during word recognition, one may wonder whether deaf children and adults, who have little or no access to sound, develop and use some form of phonological code in reading. The following section will present a summary of the findings surrounding this question.

1.3 Deaf Readers

Deaf children are faced with a challenge when they learn to read and overall, in the past four decades, research has shown that, as a population, the reading level they attain at the end of high school is not at par with that of their hearing peers. Large scale studies in the United States have shown that the median reading level for high school graduates is equivalent to a 3rd-4th grade reading level (Allen, 1986; CADS, 1991; DiFrancesca, 1972; Gallaudet Research Institute (GRI), 2004; Traxler, 2000; Trybus & Krachmer, 1977). According to the latest survey (GRI, 2004), however, about 5% of deaf high-school graduates had excellent reading comprehension skills that were equal or superior to that of age-matched hearing high-school graduates. Wauters, van Bon & Tellings (2006) also conducted a large scale study (n= 464) in the Netherlands with deaf children (age 6-20 y.o.) and report even more dismal reading performance, with a mean reading level, across the age range, equivalent to that of a first grade hearing child. The highest 25% of the sample was found to read at a third-grade level equivalent. Similar to what is found in the American studies, 4.3% of the sample read at par with age-matched hearing peers.

In the Province of Québec, no such large scale study has been carried out, but Reinwein, Dubuisson and Bastien (2001) have shown that when reading six texts taken from third grade level textbooks, the comprehension score (85%) of 31 deaf adults was equivalent to that of 3rd grade hearing children (83%), compared with hearing adults who performed at ceiling (97%). The adult deaf readers also read more slowly than the 3rd grade hearing children and hearing adult readers. Furthermore, a document presented by the Ministry of Education of Québec (1991) showed that there was a 65% illiteracy rate in deaf adults in the Province, compared to 30% for hearing adults[2]. The results of such studies suggest that in the Province of Quebec, deaf adults also experience important reading difficulties.

The reasons for such reading difficulties are multiple. The following sections will provide an overview of the research on deaf readers (children and adults) and the several factors that can lead to overall low reading skills.

1.3.1 Use of Phonological and Orthographic Codes in Reading

Depending on their degree of hearing loss, deaf individuals have limited or no spoken language input allowing them to use the sounds of language to develop fully specified phonological representations. Several authors qualify deaf individuals' phonological representations as *nonstantard* (Hanson & Fowler,

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[2] A more recent statistic is not available.

1987; Kelly & Barac-Cikoja, 2007) or as *limited abstract* (Olson & Caramazza, 2004), as these representations may be acquired through multiple sources such as the visual channel (through lipreading) or articulatory feedback (through speech production). Considering the nonstandard nature of deaf individuals' phonological representations, the *phonological core deficit* hypothesis (Stanovich, 1986; see Snowling, 1998 and Vellutino, Fletcher, Snowling & Scanlon, 2004 for reviews), suggested as the basis of reading difficulties in dyslexic children, is also the crux of the main hypothesis advanced as the basis of deaf children's difficulty in learning to read (Padden & Hanson, 2000; Perfetti & Sandak, 2000). Furthermore, because in the major models of reading acquisition, orthographic knowledge is said to derive from knowledge of the alphabetic principle (Ehri, 1998; Frith, 1985; Share, 1995), it is unclear how orthographic representations could be developed by young deaf readers and how they contribute to the reading process.

Researchers wanting to investigate the factors involved in successful and poor reading in deaf individuals have looked at whether or not deaf children and adults, who are said to have developed nonstandard phonological representations, use a phonological code (whether they convert print to sound) during reading. One of the main questions is whether the use of a phonological code is related to speech skills (speech and/or lipreading) or to reading level. Two main lines of research on the use of a phonological code during reading can be distinguished: the studies investigating the use of a phonological code in memory and those investigating the use of a phonological code during word recognition. These studies will be presented in the following sections along with the few studies that have directly investigated the role of orthographic information during reading. The participants in all the studies reviewed below have severe to profound hearing loss, therefore degree of hearing loss will not be further mentioned.

With regard to the use of a phonological code in memory, a seminal study was conducted by Conrad (1979), who investigated the use of a speech-based (phonological) code in memory by a large sample (n = 359) of 15 to16 year old deaf students. All of the participants had been orally educated. They performed a serial recall task with lists of five orthographically dissimilar rhyming words (e.g.:

true, *who*, *zoo*, *screw*, *through*) and a control condition of non-rhyming words. The results showed that the better deaf readers were those who used a speech-based code in memory. However, the use of a speech-based code in memory was also related to the degree of hearing loss, level of speech intelligibility and I.Q. Therefore, degree of hearing loss and I.Q. were also highly related to the reading performance of the participants. This study suggested that several factors are interacting when investigating the use of phonological codes in memory by deaf participants and the reading performance of deaf participants.

However, the picture is not as clear as the in-depth study by Conrad (1979) suggests. Several studies including profoundly deaf adult participants who have sign language as a main communication mode (or even as their L1) found evidence for the use of a phonological code in memory. For example, Hanson and colleagues (1982, 1990, 1991) found that deaf signing adults were affected by the phonological similarity of items in serial recall of words or letters (Hanson, 1982; 1990) and showed interference from a phonological code while reading mixed-grapheme tongue-twister (TT) sentences[3] (Hanson, Goodell & Perfetti, 1991). Treiman and Hirsh-Pasek (1983) also found evidence of possible interference from a phonological code in TT sentences. However, the authors interpreted their results as showing that the deaf readers were using a visual code (because of the visual similarity of the letters in their TT sentences – for example: *She sells seashells by the seashore*, p. 52), rather than a phonetic code. This interpretation was suggested because in another experiment, the authors found that in a semantic acceptability judgment task, the performance of deaf readers was not influenced

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[3] For example, *The taxis delivered the tourists directly to the tavern* (Hanson, Goodell & Perfetti, 1991; p.321)

by sentences containing homophones (*He doesn't like to eat meet*; p. 49), contrary to that of hearing readers. In Hanson et al.'s (1991) study with mixed graphemes, however, the effect was more likely phonological than visual because the participants had to perform an articulatory suppression task and the deaf participants' performance was affected by this task (although the effect from articulatory suppression could also simply be due to a more general cognitive overload). Contrary to Conrad's (1979) results, in these studies, the deaf participants had sign language as a L1 (or as a main communication mode), were profoundly deaf and, in one study (Hanson et al., 1991), the deaf participants also had very low levels of speech intelligibility. Still, it was found that in recall tasks they principally used a phonologically-based code in memory. Furthermore, although in Hanson and colleagues' (1990, 1991) and Treiman and Hirsh-Pasek's (1983) studies, the authors commented that the reading level of the deaf participants was quite high, the range of reading levels was quite large (grade 3.3 to 12+). The authors mentioned that the use of a phonological code in short-term memory is "limited to the deaf participants who are the better readers" (Hanson et al., 1991; p. 328). However, in none of these studies was an analysis by reading level performed. Taking the reading level of the participants into consideration could possibly have led to a different (or more nuanced) interpretation of these results.

The studies investigating the use of a phonological code in memory by deaf children also do not provide a clear picture. Hanson, Liberman and Shankweiler (1984) investigated the use of a phonological code in memory in deaf children (age 6.25 to 11.25 y.o.) who communicated through Total

Communication (TC).[4] This study included skilled and less skilled readers (mean reading grade level 2.2 and 1.8, respectively) matched on speech intelligibility. Skilled readers were found to use a phonological code in the serial recall of letters, whereas less skilled readers did not. Because the groups were matched on speech intelligibility, the result could not be attributable to this factor, nor to degree of hearing loss because all the participants had a degree of hearing loss above 80dB. Conrad & Rush (1965) also investigated the serial recall of letters with older deaf children (and young adults – age 13 to 20 y.o.). The deaf participants in this study did not use a phonological code in memory. Furthermore, no evidence was found that deaf participants relied instead on the visual similarity of letters to make their response (reporting *B* for *R*, for example). The authors conclude that the nature of the encoding process in deaf readers is "obscure at present" (Conrad & Rush, 1965; p. 343). MacSweeney, Campbell & Donlan (1996) found that 15 y.o. deaf children educated with TC were affected by concurrent articulatory suppression during serial recall of pictures, suggesting, in this case, the use of a phonological code in memory. However, because hand-tapping also created an interference in memory for hearing and deaf participants, the results need to be taken with caution as a general cognitive overload related to a concurrent task (articulatory suppression or hand-tapping) could be the cause of the interference.

MacSweeney, Campbell and Donlan (1996) and Harris and Moreno (2004) used a serial picture recall task to look at the use of phonological codes in

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[4] TC is an educational approach where communication is made through all the possible means between deaf children and their educators. They may communicate through a combination of oralism and pidgin signing.

memory. The pictures used in the recall task either shared names that were phonologically similar, shared shapes that were visually similar (long, thin objects), shared a similar hand configuration (handshape) in British Sign Language, or shared none of these features. The studies yielded contradictory results. In MacSweeney et al.'s (1996) study, 15 y.o. deaf children appeared to use a phonological code and a visual (imagery) code to recall the pictures presented in this task. However, in Harris and Moreno's (2004) study, the deaf participants (8-14 y.o.) had mixed modes of communication (oral, sign) and the older deaf children were found to use a visual (imagery) code exclusively to recall the pictures, whereas the younger children used both a visual and a phonological code (like the older participants in MacSweeney et al.'s study). However, in Harris and Moreno's study, both chronological and reading-age hearing controls showed an effect of sign similarity on their capacity to recall the pictures, even if they were never exposed to sign language before. Therefore, there may have been another confounding factor influencing the overall results of this study.

Finally, Waters & Doehring (1990) conducted a large-scale study with deaf children (7-20 y.o.) who were orally educated. In a serial recall task with rhyming words and non-rhyming words, all participants showed interference in the recall of phonologically similar words (e.g. *cat*, *bat*, *hat*, etc.), showing use of a phonological code in memory. However, in this task a confound between visual-orthographic and phonological information was present; the authors did not include a condition of orthographically dissimilar rhyming items (such as *blue*, *view*). The effect they found may not be entirely due to shared phonology between the items to be recalled, but could also be due to shared orthography. Interestingly, the authors found no relationship between the use of phonology as a memory code and the reading performance of their participants.

In sum, the studies reviewed above do not converge on a clear conclusion as to whether a phonological code is used in memory by deaf adults and children and whether it is related to speech skills or not. Furthermore, it is unclear whether reading-level truly depends on whether deaf readers use a phonological code in memory or not. Although most studies reviewed above showed evidence for the use of a phonological code in memory, few studies compared the serial recall performance and phonological coding in memory of skilled and less skilled readers. Hanson et al.'s (1984) study found a distinction between skilled and less skilled readers' performance in their use of phonological coding in memory. Only the skilled readers were found to use a phonological code when recalling series of rhyming vs. non-rhyming consonants. In contrast, Waters and Doehring (1990) found no correlation between the reading level of their participants and their use of a phonological code in memory. Waters and Doehring (1990) suggest that there may be two different types of phonological codes: one involved in holding information in memory and one involved in more automatic processes such as word recognition. Indeed, they found that the same deaf participants who showed evidence for phonological coding in memory did not appear to use phonological information when reading words.

With respect to the use of a phonological code during word recognition, several studies used a lexical decision task to investigate whether deaf children showed a regularity effect during word recognition.[5] Mayberry, Chamberlain, Waters and Hwang (2005), Beech and Harris (1997), Waters and Doehring (1990) and Burden and Campbell (1994) found no regularity effects for their young deaf participants, although in some of these studies, control groups of hearing participants did show the effect. In Mayberry et al.'s (2005) study, the regularity effect was absent for signing deaf readers across 1st-8th grade reading levels.

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[5] A regularity effect is found when responses are more accurate (and faster if reaction times are also examined) in the recognition of words that have a regular spelling-sound correspondence rather than irregular, exception or strange spelling-sound correspondences.

Waters and Doehring (1990) tested orally educated deaf children with similar reading levels (3rd-8th grade) and also found no effect of spelling-sound regularity. The regularity effect does not appear to be related to reading level because both studies failed to find the effect across reading levels. Furthermore, the mode of communication of the participants also appears to be unrelated to the results because one study involved signing children and the other involved oralist children. Burden and Campbell's (1994) study also supports this conclusion. Their study involved both signing and oralist children and the results were comparable for both groups; no regularity effect was found. A similar study conducted by Chamberlain (2002) also reports that adult skilled and less skilled deaf readers (reading at post high school and 8th grade reading level, respectively) did not show a regularity effect. Regularity effects as a marker of phonological processing, however, have been criticized because they appear to emerge under specific conditions only (Berent, 1997; Ferrand 2001, for a review). In particular, they are more robust for low-frequency words in naming tasks and can be absent from lexical decision tasks if no strange words are included in the task (Berent, 1997; Ferrand 2001 for a review). In a classic study, Berent (1997) compared two markers of phonological processing at the word level in hearing university-level students: phonological priming and regularity effects. In two lexical decision studies, Berent found very weak or null regularity effects and strong phonological priming effects, suggesting that null regularity effects may not be evidence for the absence of phonological processing in word recognition.

Researchers have also investigated how deaf children and adults process pseudohomophones, the assumption being that if deaf people access the phonological representations of pseudohomophones, the processing of these items will be affected (slowed down and less accurate because of the conflicting phonological representation shared with real words) compared to a control condition. Both Dyer, MacSweeney, Szczerbinski, Green and Campbell (2003) and Transler and Reitsma's (2005) studies with deaf children (aged 12 and 7-13, respectively) showed that young deaf readers are able to derive phonological information from pseudohomophones. However, a study by Beech and Harris

(1997) found the opposite pattern of results with children the same age. Chamberlain (2002) also reported that both skilled and less skilled adult deaf readers were not significantly slower and less accurate in a paired lexical decision task when responding to pseudohomophones[6] (e.g. *hoap*, *joak*) than when responding to non-pseudohomophone foils (*hoak*, *joap*). Because of the finding that skilled deaf readers (all had post high school reading level) did not appear to use phonological information in the tasks they performed, Chamberlain (2002) suggested that "…deaf people recognize words in a qualitatively different manner than hearing people" (p. 222). Finally, Miller (2006) asked young deaf readers (mean reading level: grade 8) to circle "things that human beings eat" (p. 26) in a list of 100 words where 31 pseudohomophone food items were inserted along with 31 real food words. The deaf children performed equally well in circling the food words as hearing controls did, but circled significantly fewer pseudohomophone food items (they had a score of 9/31 versus 28/31 for the hearing children). Miller (2006) suggests that these results do not support the *Self-teaching hypothesis* (Share, 1995), because deaf children had developed effective word recognition (they recognized most of the real food words), but not effective phonological decoding skills (they identified few of the pseudohomophone food items). Finally, Miller (2006) also suggests that for young deaf readers, word processing is based on orthographic knowledge rather than on print-to-sound knowledge.

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[6] The participants had to decide whether two items in a pair are words (TOAD-LOAD) or not (VOAD – DARK). In some of the pairs, the items rhymed with each other, and in other pairs they did not.

Researchers have also looked at different phonological units (rhyme and syllable) and whether these units are processed by deaf children and adults when they read. A study by Dyer et al. (2003) found that young deaf readers (age 12 y.o., with the reading level of 7 y.o.) used rhyme information when asked to point at the pictures of two rhyming objects (*pear-bear*, *light- kite*) in a set of three. Similarly, older deaf readers were also found to use rhyme information when reading words. Indeed, Hanson and Fowler (1987) found that in three separate experiments using paired lexical decision tasks, three different groups of skilled adult deaf readers showed that they relied on rhyme information (*done-none*) to make their judgments even if phonologically dissimilar orthographic foils were included (*bone-gone*) in the task.

Effects showing that deaf children process syllables when reading words have also been found. Daigle and Armand (2007) investigated how three groups of deaf children and adolescents (age 10-12, 13-15, 16-19 y.o.) divided into groups of skilled and less skilled readers processed the syllable structure of nonwords in a probability judgment task. Daigle and Armand (2007) found that only the skilled readers of the older groups (13-15 and 16-19 y.o.) processed syllables when reading nonwords. The performance of the participants on the probability judgement task did not correlate with their speech skills. In contrast, in a similar task, Transler et al. (2001) found that only deaf children (age 9-13 y.o.) with good speech skills were sensitive to the syllabic structure of words. Interestingly, the same authors (Transler, Leybeart & Gombert, 1999) also found evidence that deaf children (age 7-12 y.o.) were sensitive to the syllable structure of words in a study in which the children had to copy multi-syllabic words and nonwords from a blackboard that was placed behind them. The children had to completely twist their bodies to look at the words to copy. The deaf children copied words according to their syllabic structure (that is they copied a syllable each time they turned to look at a word), however the errors that the deaf children made were phonologically-based only 9% of the time (compared to the hearing controls who made phonological errors 43% of the time). No correlation was found between experimental measures and speech skills. The authors suggest that syllable processing may be orthographically-based. Olson and Nickerson (2001) report similar evidence. Deaf adults, who used ASL as a main communication mode and had a relatively low reading level (they were "reading at the level of 12 year-olds"; p. 428) were also influenced by the syllabic structure of the words. In this study, the participants' performance in an illusory conjunction task[7] did not correlate with speech measures (speech intelligibility and speech comprehension ability), nor with the participant's reading level. This suggests that knowledge of syllabic structure in their deaf participants may have been driven by orthographic knowledge. Olson and Caramazza (2004) investigated spelling errors in adult deaf participants. Their results also suggest that deaf individuals have orthographically-based representations of words. Spelling errors by deaf participants were phonologically <u>im</u>plausible 80% of the time, relative to spelling errors by the hearing participants, which were phonologically plausible 80% of the time. Speech skills did not correlate with syllabic complexity or grapheme-phoneme regularity. The authors suggest that "orthographic information by itself or in combination with limited abstract phonological information is sufficient for syllabic principles to apply at this time" (p. 414).

Paire-Ficout (1998) conducted a series of studies in French with orally educated, deaf adults using the ASMP (Semantic priming mediated by phonology)

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[7] In this type of task, participants have to report the colour of a letter (L) in words presented in two colours where the colour change boundary (here in bold) is consistent with syllable boundary (e.g.: **SIL***VER*) or inconsistent with syllable boundary (**SI***LVER*).

paradigm[8]. An important feature of this study is that the duration of the primes was varied across experiments with the same materials, thus providing time-course information of her participants' use of phonological information in word recognition. In three separate studies, prime durations were varied (50, 100, 150 ms)[9]. The hearing controls showed that the phonological representations activated by the semantically related homophonic primes (MAIRE "*mayor",* instead of MER "*sea"*) were facilitating the recognition of the targets (OCEAN "*ocean"*) at all prime durations (50, 100 and 150 ms), whereas the same effect appeared later for the deaf participants (at 100 and 150 ms only). With 50 ms prime durations (or 100 ms SOA), the deaf subjects did not appear to have retrieved the phonological representations of the semantically related homophonic primes that would subsequently affect the processing of the targets. The author acknowledged that some of the homophones used as primes (CHANT "*song"* priming PRÉ "*field",* instead of CHAMP "*field"*) shared more orthographic information with the real semantically related word (CHAMP) than others. She found that for those pairs, the effect of orthography appeared earlier than for the pairs that shared less

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[8] In this type of task, participants have to make a lexical decision on a French word (OCEAN "*ocean"*) primed by a semantically related homophonic prime (MAIRE "*mayor"*) instead of the proper semantically related prime (MER "*sea"*). This condition was contrasted with homophonic words that were not semantically related to the target. A condition with unrelated primes and targets was also included.

[9] The primes were followed by a pattern mask (######) presented for 50 ms, therefore yielding Stimulus Onset Asynchronies (SOAs) of 100, 150 and 200 ms between the onset of the primes and the onset of the targets.

orthographic information. This result suggests that for hearing, and especially for deaf readers, it is important to consider effects of orthographic information along with the time-course of orthographic and phonological processing. Furthermore, phonological information followed a different time-course for the hearing and deaf participants. In the deaf participants, phonological code activation appeared delayed relative to that of hearing participants. It is unclear however, for hearing and deaf participants, whether the phonological code activated was post-lexical or not. The phonological priming effects could have been caused by the fact that primes were words and that the SOAs were quite long (100 ms and more) allowing enough time for conscious processing of the prime and post-lexical phonological code retrieval before the target appeared on the screen.

A study likely to have tapped automatic word processing is that of Leybeart and Alegria (1993). A Stroop task was administered with colour words and colour pseudohomophones. The deaf participants (aged 10-15 y.o.), like the hearing controls, showed interference from colour words. Furthermore, suggesting rapid conversion into a phonological code, the deaf participants also showed interference from color pseudohomophones (French pseudohomophone *vaire* instead of *vert* – *green* in English). The reading level of the participants, however, was not reported in this study.

Few studies have specifically investigated how orthographic information is processed during reading by deaf readers. In fact, studies on reading and deafness often focus on the use of phonological coding in reading by deaf adults or children and discuss the role of orthography as an alternative coding means when no effects of phonology are found (Beech & Harris, 1997; Burden & Campbell, 1994; Miller, 2004, 2006; Transler, Gombert & Leybeart, 2001). One study investigated the use of orthographic knowledge specifically (and not in a spelling task). Daigle, Armand, Demont and Gombert (submitted) looked at the implicit learning of visual-orthographic knowledge in deaf children (age 10-18 y.o.). Specifically, Daigle et al. looked at whether deaf children were sensitive to the orthographic legality of double consonants and double vowels within pseudowords and whether the children accepted the pseudowords as legal[10] if double consonant frequency was varied (*tt* vs. *ff*), if the legality of the double consonants was varied (possible vs. impossible double consonants – *ff* vs. *vv*), or if the position of the double consonants was varied (word medial vs. word final position – *daffim* vs. *dafimm*). Daigle et al. showed that their participants were sensitive to orthographic legality in pseudowords although to a lesser degree than hearing controls. Interestingly, the authors suggest that orthographic knowledge is learned implicitly via exposure to text. One limitation of this study, however, is that the task used does not allow determination of whether orthographic information is used during word processing.

In sum, the studies on the use of a phonological code during word recognition are inconclusive as to whether such a code is used by deaf readers. It is also unclear whether the use of such a code is related to reading level or to speech skills, as this varies considerably across studies. The use of orthographic codes during word recognition, on the other hand, has not been extensively researched and, as mentioned earlier, several studies draw conclusions about the use of an orthographic code when no effects of phonological codes have been

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[10] The children performed a similarity judgment task with pseudowords and were asked *Which item looks more like a real word?* They were presented pairs of pseudowords (*ubitto*-*ubiffo*). The children were readers of French.

found during word recognition, despite the fact that the use of an orthographic code was not directly investigated.

1.3.2 Other Factors Affecting Reading Achievement

Although the present dissertation principally focuses on word recognition processes, it is important to present the research on the use of phonological codes in a broader context, because the difficulties deaf people experience in reading have also been linked to factors other than their ability to represent and use phonological information in reading. Beyond the fact that degree of hearing loss is an important factor in the ability to achieve good reading skills (Conrad, 1979), early research in the 1960-70's reported by King and Quigley (1985, see also Paul, 1998, for reviews) has shown that young deaf readers have less spoken vocabulary depth and breadth than hearing readers. Results on the vocabulary subtest of the *Stanford Achievement Test* are generally lower compared to hearing readers, in contrast to other subtests (such as mathematical skills – King & Quigley, 1985). Traxler (2000), for example, has shown that in a large sample of deaf children (over 4000 participants) aged 8-18 y.o., 80% of the participants had a knowledge of English vocabulary which was below that determined as basic vocabulary knowledge. This lack of vocabulary breadth is generally observed from a young age. Yoshinaga-Itano (1994) found that deaf children aged 3-4 y.o. had a productive vocabulary (signed or oral) of 300 words, whereas older children (5-6 y.o.) had vocabularies of around 500 words. Comparatively, two year old hearing children have a mean productive vocabulary of 300 words (Boyssons-Bardies, 1999). Deaf children have also been found to have problems with words with multiple meanings as well as abstract words compared to their hearing peers (Marschark, 2001). Finally, it has been shown that there is a strong link between vocabulary knowledge and reading comprehension in deaf readers (Kelly, 1996; LaSasso & Davey, 1987).

Syntactic skills have also been investigated as the source of reading difficulties in deaf readers. Deaf individuals have been shown to have difficulties with complex syntactic structures (Kelly, 1993, 1996, 1998; Kelly & Barac-Cikoja, 2007 for a review; Quigley & King, 1980). More specifically, in the case of syntactic knowledge, it has been found that deaf readers have difficulty with sentences in the passive voice and also with relative clauses (Quigley, Wilbur, Power, Montanelli & Steinkamp, 1976). Kelly (2003) found that skilled deaf readers and less skilled deaf readers could be distinguished on their comprehension of relative clauses, skilled readers being less impaired than less skilled readers. Both groups of readers, however, performed equally in the comprehension of less complex sentences containing the same vocabulary items as in the complex sentences.

Syntactic knowledge is also closely linked with the ability to learn more vocabulary during reading. As suggested by Paul (2003; p. 100), "difficulty with understanding syntax curtails […] the use of context cues to derive meanings of important words". The opposite relationship is also true, as despite having good vocabulary skills, difficulties in understanding complex syntactic structures may also impede reading comprehension in deaf individuals (Kelly, 2003; Paul, 2003). In fact, the complex relationship between syntax and vocabulary was investigated by Kelly (1996). Regression analyses showed that a large part of the variance in reading comprehension in deaf adolescents could be explained by the interaction of vocabulary knowledge and syntax. Therefore both types of knowledge appear to be intertwined and important for better reading skills.

Finally, Kelly (2003; see also Kelly & Barac-Cikoja, 2007) adds that automaticity (or speed) is also a determinant factor in the ability of deaf readers to reach adequate reading comprehension. Kelly (2003) found that two groups of skilled and less skilled deaf adult readers could be distinguished on processing automaticity and that this factor was linked to their reading comprehension skills. This finding is in line with research showing that slow processing can create a bottleneck of information which can then block higher-level processes during reading (Laberge & Samuel, 1974; Stanovich, 1980).

As seen above, different aspects of language competence in English (vocabulary knowledge, phonological skills, syntactic knowledge, etc.) lead to good reading skills in deaf adults. However, it has been argued that language competence in sign language is also related to good reading skills in deaf individuals (Chamberlain & Mayberry, 2008; Goldin-Meadow & Mayberry, 2001; Padden & Ramsey, 2000). Chamberlain and Mayberry (2008), for example, found that better syntactic skills and narrative skills in American Sign Language (ASL) were predictive of better reading skills in deaf adults who used sign as a primary mode of communication. Better reading skills in deaf individuals have also been associated with the ability to inflect ASL verbs (Padden & Ramsey, 2000), comprehension of ASL classifiers and ASL stories (Strong & Prinz, 2000), and comprehension of ASL and fingerspelling (Padden & Ramsey, 2000). These studies suggest that knowing a language, whether signed or spoken, is an important factor in skilled reading.

The relationship between language skills (signed or spoken) is not as straightforward as described above. Deaf children, especially deaf children of hearing parents, are a very specific population in that first language acquisition is often delayed relative to what is found in the hearing population. In fact, "exposure to language from birth is not the norm for deaf children" (Morford & Mayberry, 2000; p.112). Going into detail is beyond the scope of the present dissertation (see Mayberry, 2007 for details), however it has been shown that the delay in exposure to a language is an important factor in the inability to achieve adequate skills in the first language (Mayberry, 1993; Boudreault & Mayberry, 2006; Mayberry & Eichen, 1991; Mayberry & Fischer, 1989; Newport, 1990) as well as in a second language (Mayberry, 2007, for a review; Mayberry & Lock, 2003).

Overall, in light of the *Simple View* of reading (Hoover & Gough, 1990), it is clear that when learning to read, deaf children have many hurdles to overcome. They lack the necessary auditory input to develop fully specified phonological representations and may not be able to use phonological representations effectively during reading acquisition. The development of orthographic representations seems to be so closely related to the ability to convert print-to-sound (Ehri, 1998; Frith, 1985; Share, 1995), that it may also be impaired in deaf readers. Furthermore, because the spoken language surrounding them needs to be learnt through rehabilitative intervention (instead of in a more natural context), deaf individuals may have lower language competence (lower spoken and signed vocabulary, comprehension of fewer syntactic structures, etc.), a factor which also interacts with the age of exposure to a first language. Despite all these hurdles, some severely or profoundly deaf individuals reach expert reading levels. It is unclear from the research presented above whether this is related to their use of a phonological code or not.

1.3.3 Visual Processing Abilities

The sensory deprivation of deaf people has led to much research on how this may affect brain plasticity and other sensory modalities. Specifically, much research has been done on visual processing in deaf people (Bavelier et al., 2006, for a review). It appears from this line of research that deaf people do not differ from hearing people in sensory measures such as brightness discrimination, contrast sensitivity, motion detection or motion velocity (see Bavelier, et al. 2006). On the other hand, deaf people have been shown to have enhanced visual processing abilities for stimulus onset, motion processing, orienting and reorienting, and processing of peripheral distractors, but only when the stimuli are presented in the periphery under conditions of attention[11] (Bavelier et al. 2006, for a review). Bosworth and Dobkins (2002) and Proksch and Bavelier (2002) have come to the conclusion that better visual processing skills to the attended peripheral region is related to sensory deprivation and not to use of sign language by comparing deaf native signers, hearing native signers and hearing non-signers. The present work will be the first to verify, with the use of eye movement measures, if enhanced visual skills for attended stimuli in the periphery somehow

[11] The participants need to have been instructed to direct their attention – but not their gaze – to the periphery.

influences the reading process. In order to better understand how eye movements are used to inform reading research, the following sections will first present information on basic notions related to eye movements and reading, along with three of the most current eye movement control models.

1.4 Eye Movements and Reading – Basic Characteristics

When studying word-level processes within connected text, some constraints from the visual system need to be taken into account. When studying words in isolation (such as in lexical decision tasks), words are generally presented centrally, within the center of the visual field. However, the visual field is divided into three parts, which has bearings on reading connected text. The central 2^{o} of the visual field is called the fovea and has the greatest acuity. The parafoveal region extends five degrees on either side of the foveal region and the peripheral region is beyond the parafoveal region. Visual acuity decreases more and more away from the fovea into the parafoveal and peripheral regions (Rayner, 1998). When reading connected text, the eyes do not move fluidly across the lines of text. In order for words to be within the region with the highest visual acuity (the fovea), the eyes jump along the lines of text, so that words can be placed in the center of the visual field for better processing. For skilled readers, the eyes pause on words (fixations) generally for 200-300 ms (Rayner, 1998, for a review). The jumps (saccades) are generally quite short (7-9 letter spaces) and last 25-60 ms (Rayner, 1998). During the saccades, the eyes travel at such high velocity that perception is suppressed because visual information is blurred (Rayner, 1998). Not all words are fixated in the text. On average, 15% percent of content words are skipped, whereas 65% of function words are skipped (Rayner, 1998). Shorter words are also skipped more often than longer words (Rayner, 1998). Finally, 10-15% of the saccades are regressions in the text or within the word just read (Rayner, 1998). For skilled and less skilled readers, eye movement characteristics have been shown to be an extremely sensitive measure of reading skills (Rayner, 1986; 1998; Chace, Rayner & Well, 2005). In beginning readers, fixation times become shorter and the number of fixations and regressions into the text diminishes as reading improves across grade levels (Rayner, 1986). Less skilled readers and dyslexic readers, when compared to better readers, make longer fixations, more fixations and more regressions into the text (Rayner, 1998 for a review). Subtle differences in reading skill can be distinguished using eye movement measures and even within a university-level population, eye movement measures are sensitive to reading skill (Ashby, Rayner & Clifton 2005; Jared, Levy & Rayner, 1999).

Whereas visual acuity clearly constrains eye movement behaviour (fixations and saccades), one question that dominated early research on eye movements was related to how and if text within regions of lesser visual acuity was processed, and if so, what types of information were extracted from the regions away from the fovea. McConkie and Rayner (1975) found that beyond the foveal region, information was extracted and used in the reading process in a region termed the *perceptual span*. The perceptual span extends 3-4 letter spaces to the left of the fixation point and 14-15 letters spaces to the right of the fixation point. Within the perceptual span, low-level information (such as word length, word boundaries and letter information such as ascenders and descenders) is used to guide the eyes throughout the page (Rayner, 1998). There is a smaller region within the perceptual span called the *word identification span* (Rayner, Well, Pollatsek & Bertera, 1982). It extends 3-4 letters to the left of the fixation point, but only 6-8 letters to the right of the fixation point. In this smaller region, useful information is extracted solely for word identification purposes. Orthographic and phonological information are extracted from the word identification span (Pollatsek, Lesch, Morris & Rayner, 1992), but not semantic information (Rayner, Balota, & Pollatsek, 1986).

The findings overviewed in this section have led to the development of eye movement models for reading. Three of these models are presented in the next section.

1.5 Eye Movement Control Models

Models that have been developed in the eye movement field of research have mainly aimed to represent and replicate how the eyes move across the page (hence the name *eye movement control* models rather than *word recognition* or *reading* models). In these models, there is a specific focus on how attention is distributed and allotted across the page while reading and how this may affect reading behaviour and word processing. The most relevant eye movement control models for the present work are the E-Z Reader (Reichle, Pollatsek & Rayner, 2006; Reichle, Rayner & Pollatsek, 2003), the SWIFT model (Engbert, Longtin & Kliegl, 2002; Engbert, Nuthmann, Richter & Kliegl, 2005; Richter, Engbert & Kliegl, 2006) and the Glenmore model (Reilly & Radach, 2003, 2006). The main critique against eye movement control models (see Grainger, 2003; Huestegge, Grainger & Radach, 2003) is that although many of these models argue that the cognitive processes involved in word reading are the "engine" that drives the eye movements in reading, word processing itself is not very well specified in these models. Rather, the main point of contention between the models presented here is whether words are processed serially or in parallel (more than one word at a time). The E-Z Reader assumes that words are processed serially, whereas the SWIFT and the Glenmore assume that multiple words are processed in parallel. This issue however is beyond the scope of the present work. The E-Z Reader is the model that is currently the most advanced; therefore it will be presented in greater detail. However, all three models will be presented as one accounts better for the results of the first and third studies presented here, whereas the other two account better for the second study in the present dissertation.

1.5.1 The Word Recognition Component of Eye Movement Control Models

The E-Z Reader model (Reichle et al., 2003, 2006) endeavours to explain the interplay between visual processing, word processing and attention allocation. In this model, words are said to be processed in two stages. The authors, however, have recently declared themselves "agnostic" as to the exact specification of these two stages, which have been given the generic names of *L1* and *L2* (Reichle et al., 2003). This two-stage view of word recognition has been highly criticized (see the *Open Peer Commentary* section in Reichle et al., 2003) and in a later paper, the authors (Reichle et al. 2006) suggest three ways, which they say are not mutually exclusive, in which the L1 and L2 stages may be conceptualized. First, they suggest that different levels of information (orthographic, phonological and semantic) unfold in time, consistent with a time-course view of word recognition (Ferrand & Grainger, 1994; Ziegler et al., 2000). They suggest that L1 could be a familiarity check based on form information (orthographic and/or phonological information), whereas L2 could be based on access to meaning, which comes later on. Second, they propose that the L1 and L2 distinction is based on the recognition/access distinction. Recognition is said to be faster than retrieval (Atkinson & Juola, 1973, 1974; cited in Reichle et al., 2006) and so L1 would entail the rapid recognition of a word, whereas L2 would correspond to the moment "specific information about a word (e.g. its meaning) is retrieved from memory" (Reichle et al., 2006; p. 7). Finally, they suggest that L1 and L2 may be a reflection of lexical access (L1- i.e. meaning is available) and post-lexical integration (L2). Importantly, in this model, the two lexical processing stages, L1 and L2, have a specific function within the model. The end of the first phase, L1, cues the oculomotor system to prepare to saccade to the next word, whereas the end of the second phase, L2, is the signal for attention to be shifted to the next word. More information on this particular aspect of the model will be presented in the next section.

The word recognition component in the SWIFT model (Engbert et al., 2005) is somewhat unspecified relative to the E-Z Reader and will not be detailed here. The Glenmore model (Reilly & Radach, 2003, 2006), on the other hand, is the model which best integrates research on single word recognition and eye movement control (see also Huestegge et al., 2003). The authors have integrated McClelland & Rumelhart's (1981) *Interactive Activation* model (IA) in the architecture of the Glenmore (the way it has been integrated into the model will not be detailed here). This architecture allows for continuous and parallel processing of words as opposed to two-stage lexical processing. In the Glenmore model, as in the IA model, word processing begins with visual input units which are linked to letter units which then send activation to word units. The word units feed back information (top-down activation) to the letter units and, as in all models based on the IA, there are also inhibitory connections within the word-level units. Contrary to the original IA, however, Glenmore takes into account the specific properties of the visual field. The model includes 30 visual input units connected to 30 letter units and postulates that the center of fixation is at unit 11 (at the visual and letter input units level). On either side of unit 11, activation of the other units decreases more and more as they are further away from the central unit. This architecture accounts for visual and lexical effects in parafoveal vision where information away from the center of fixation is less salient (or activated). As Reilly & Radach (2006; p. 41) explain, "the activation levels of high-frequency words rise more rapidly than lower frequency words, but this is also a function of the activity in the letter units, which in turn is a function of the eccentricity of the letters in the visual field. Consequently, visually eccentric high frequency words will be more rapidly identified than their low frequency counterparts."

One problem with the Glenmore model is that although an effort is made to integrate models of word recognition and eye movement control, the word recognition component (modeled after the IA model of McClelland & Rumelhart (1981), does not take into account the recent developments in research on single word recognition that has led to modification of the original IA model. As was shown in the section on models of single word recognition, the two models presented were also based on the IA model of McClelland & Rumelhart (1981), however they have evolved and include separate orthographic and phonological routes, which is not the case in the Glenmore model. Despite this weakness, the Glenmore is the model that has best taken into account current theories of single word recognition.

1.5.2 Distribution of Attention in Eye Movement Control Models

The way attention is distributed during word reading is at the basis of a major contention on eye movement control modelling where the debate focuses, as mentioned earlier, on whether words within a sentence are processed serially or in parallel (more than one word at a time). The subject of attention distribution is extremely vast and will not be addressed in detail here, but some information on distribution of attention in relation to visual and word-level processing during sentence reading is necessary to interpret the findings of the second study (Chapter 3) in the present dissertation.

In the E-Z Reader model (Reichle et al., 2003, 2006), attention is said to be in the form of an attentional "spotlight"[12] (i.e. it is not spread across the current

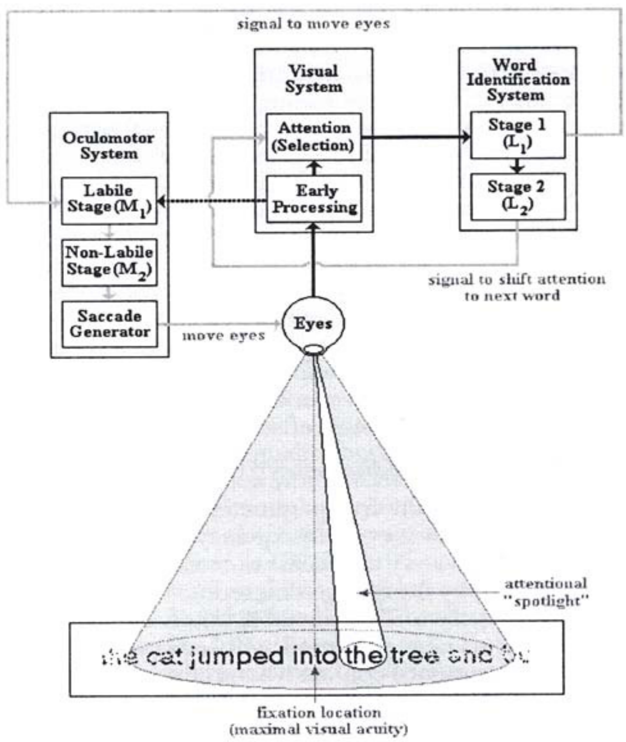

Figure 4. ***E-Z Reader*** **model (Reichle et al., 2003; p. 451)**

line of text but focused only on small sections of the line of text – see Figure 4, for an illustration of the model) which moves from word-to-word across the

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[12] This term is based on research by Posner (1980; cited in Reichle et al., 2003; p. 450)

sentences as reading progresses. The allocation of attention (i.e. where the attentional spotlight focuses next) is highly related to the stages of word processing, as mentioned earlier. While a word is still in parafoveal vision, L1 begins and when it ends a saccade is prepared to the next word. When this word is fixated, L2 begins and attention is on this word. At the end of the L2 stage, the attentional spotlight moves to the next word although the eyes stay on the current word, and so on. The proposed role of attention with regard to word processing constrains the regions where word processing can occur and where low-level visual processing (word length information, spaces between words) can occur. In other words, while words are attended to while still in parafoveal vision or while fixated, only this word is being processed. Because attention is highly focused on the currently processed word, as the word "spotlight" conveys, lower-level visual processing of information across the line of text, and beyond the region attended to is said to be preattentive.

In the SWIFT (Engbert et al, 2002, 2005; Richter et al., 2006) and Glenmore models (Reilly & Radach, 2003, 2006), on the other hand, it is postulated that lexical processing occurs in parallel within an attentional gradient. In other word, attention allocation occurs in parallel over an attentional window containing multiple words. Visual processing (word lengths) also happens in parallel across the entire attentional window with increasing lexical activity leading to the selection of a target for a saccade. This is opposite to the E-Z Reader model where attention is highly focused.

1.6 The Present Investigation

Several weaknesses in previous research on the use of orthographic and phonological codes during word recognition by deaf readers motivated the present research. First, few studies have used tasks that permit determination of whether a phonological code is unequivocally used during word recognition. In fact, the majority of studies that have investigated whether deaf individuals use a phonological code during word recognition employed tasks that do not tap automatic, early effects of phonological processes (Chamberlain, 2002; Daigle & Armand, 2007; Dyer et al., 2003; Hanson & Fowler, 1987; Mayberry et al., 2005; Transler et al., 2001; Waters & Doehring, 1990, etc.) In large part, the tasks used in the research presented above involve some form of decision process (*Is this a word or not?* in lexical decision tasks, or *Do these letter strings rhyme?* in rhyme judgement tasks, etc.). The reaction times in such tasks are generally longer than the time actually required to process a word (around 250 ms, Rayner, 1998) because they also involve secondary processes necessary to generate a response (decision between two possible answers). Therefore, in such tasks, because a decision on the test materials is required, it is unclear whether phonological codes are accessed during word processing or later on, during task-related decision-making (see Frost, 1998 for a discussion of tasks used in investigations of phonological codes during word recognition). In contrast, as mentioned in the section on *Expert Readers*, lexical decision tasks combined with a masked priming procedure (Ferrand, 2001; Forster, Mohan, & Hector, 2003) and eye-tracking measures (Sereno & Rayner, 1992; Rayner, 1998) may be more suited to tap the earliest processes involved during on-line word processing. The present research makes use of such tasks in order to investigate how word recognition unfolds in severely to profoundly deaf adult readers.

Second, the deaf population is highly heterogeneous and this may also account for the discrepant results found in the literature with regard to their use of phonological information in memory and word recognition tasks. Many factors other than limited access to the phonological code of the societal oral language may be involved, such as age, reading level (Chamberlain, 2002; Daigle &

Armand, 2007; Mayberry et al., 2005), degree of hearing loss (Conrad, 1979), incomplete knowledge of the language that is read (Goldin-Meadow & Mayberry, 2001), age of exposure to a first language (Mayberry, 2007; Padden & Ramsey, 2000), and signing skills (Chamberlain & Mayberry, 2000). It is difficult to control for all these possible confounding factors within one study because every one of these factors has several degrees of complexity along a continuum and the performance of every deaf person reflects a combination of all of these varying degrees of complexity. Every effort was made in the present work to control as many factors as possible to form fairly homogeneous groups of deaf adults. More details are provided in the *Methods* section of each study.

Third, few studies have investigated the unique role of orthographic information during word recognition. Furthermore, in several studies, there may be a confound between the effects of phonological and orthographic information because in alphabetical writting systems, both types of information are closely intertwined. As mentioned earlier, orthographic information has been found to play an independent role in early word recognition (e.g. Ferrand & Grainger, 1994) and, to our knowledge, no study with deaf readers has investigated this issue. One of the primary goals of the present research is, therefore, to dissociate the influence of orthographic and phonological information in early word recognition. This is the first study to investigate this question.

Fourth, special attention will be devoted to a shortcoming in the research on deaf readers underlined on several occasions earlier in the text: the lack of control of the participants' reading level. The effects of orthographic and phonological information use during word recognition in deaf readers will therefore be investigated in relation to their reading level.

Finally, it is unclear whether enhanced visual processing skills in deaf individuals transfer to the reading task. This issue will be addressed in the present dissertation through the observation of eye movements in deaf readers. The present work will be the first, to our knowledge, to provide an in-depth portrait of deaf readers' eye movement characteristics.

In the upcoming chapters, the three studies that were conducted for this thesis will be described. The first study (Chapter 2), inspired by earlier work by Ferrand & Grainger (1992, 1993, 1994; see also Ziegler et al., 2000), investigated the use of orthographic and phonological information during word processing with a masked primed lexical decision task in order to tap the earliest moments of word recognition in deaf readers. The sample of deaf readers was separated in two groups, skilled and less skilled readers, to determine whether orthographic and phonological code activation during word processing varied according to reading skill. Finally, prime duration was also varied and two prime durations were used to verify how orthographic and phonological codes unfold during word processing and whether they follow a different time-course.

The second study (Chapter 3) was an essential bridge between the first and third studies. In this study, the basic eye movement characteristics of the same group of skilled and less skilled deaf readers involved in studies one and three was investigated. It was necessary to determine these characteristics in order to better understand the results of study three. One of the main goals of the second study was to see whether deaf readers made used of their enhanced visual skills in the periphery while reading connected text.

Finally, the third study (Chapter 4) was similar to the first study in many ways in that it investigated the use of orthographic and phonological codes with the same group of skilled and less skilled deaf readers. In the third study, however, instead of being seen in isolation, target words were embedded within sentences and the eye movements of the participants were recorded while they read the sentences. More specifically, based on Pollatsek et al. (1992), the use of orthographic and phonological codes in parafoveal vision was investigated and, again, their effects were observed as a function of the reading level of the participants.

Preface to Chapter 2

When they reach adulthood, many deaf individuals read at levels that are much below those of their hearing peers (Allen, 1986; CADS, 1991; DiFrancesca, 1972; Gallaudet Research Institute, 2004; Reinwein, Dubuisson & Bastien, 2001; Traxler, 2000; Trybus & Krachmer, 1977). A small proportion of these young deaf adults, however, do reach expert reading levels (Gallaudet Research Institute, 2004). Presently, the factors that lead to poor (or good) reading skills in deaf individuals remain unclear. One obvious factor may be that they cannot adequately build the sound-based representations (Goldin-Meadow & Mayberry, 2001; Kelly & Barac-Cikoja, 2007) which have been found to have a crucial role in reading development (Ehri, 1998; Frith, 1985) and in skilled reading (Frost, 1998). Much research has investigated the use of sound-based (phonological) coding during reading (Chamberlain, 2002; Daigle & Armand, 2007; Dyer et al., 2003; Hanson and colleagues, 1987, 1991; Harris and colleagues, 1998, 2004, 2006; Mayberry, Chamberlain, Waters & Hwang, 2005; Paire-Ficout, 1998; Waters & Doehring, 1990) and there remains debate as to whether or not deaf readers do use a phonological code when reading. Additionally, it is not clear whether use of a phonological code is related to better reading skills as few studies have actually considered reading level as an experimental variable. Finally, when phonological processing effects are found, it is unclear whether or not they can also be attributable to orthographic information processing as well, since orthography and phonology are tightly woven in alphabetical writing systems.

The goal of the first study was to further current knowledge on how deaf individuals use phonological codes during French word processing. However, it was important to investigate the unique contributions of orthographic and phonological codes to word recognition since phonological effects found in earlier studies of deaf readers could be due at least in part to a confound with orthographic effects. Additionally, the reading level of the participants was taken into account in order to determine whether phonological or orthographic codes play a determining role in skilled reading in deaf individuals. A masked primed lexical decision task was used to address these questions. Based on previous research by Ferrand and Grainger (1994), the amount of orthographic and phonological overlap between primes and targets was manipulated. This permitted the dissociation of orthographic and phonological effects during early word processing. Finally, in order to determine how orthographic and phonological codes unfold in time during word processing, prime durations were varied across trials.

Chapter Two

Unmasking the use of orthographic and phonological information by skilled and less skilled deaf readers of French

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2.1 Abstract

Deaf people often achieve low levels of reading skills. Much research in the deaf population has investigated their use of phonological information in word recognition in order to explain their low reading achievement. Given the confound between orthographic and phonological effects in word recognition, the use of these two types of cues during word processing was investigated. A masked primed lexical decision task was used where the prime/target orthographic and phonological overlap was manipulated allowing for the dissociation of both types of effects. To investigate the time-course of orthographic and phonological information during word recognition, two prime durations were used: 40 and 60 milliseconds. Skilled and less skilled deaf readers participated in the study along with skilled hearing readers. Our results replicate previous findings with skilled hearing readers: orthographic and phonological information use during word recognition is rapid, dissociated, and follows a different time-course (Ziegler et al., 2000). Interestingly, similar results were found for skilled and less skilled deaf readers, indicating that the basis of difficulties in deaf readers may not stem from the encoding processes they use during word recognition.

Keywords: deaf readers, orthographic code, phonological code, word recognition, reading level.

2.2 Introduction

In expert hearing readers, several types of information have been found to help in the recognition of individual words. Specifically, there is growing evidence that phonological and orthographic cues are involved in the very first moments of word recognition (Ferrand & Grainger, 1992, 1994; Grainger & Ferrand, 1996; Perfetti & Bell, 1991; Ziegler et al., 2000). Indeed, it has been shown that phonological information of briefly presented primes facilitates the recognition of targets in masked primed lexical decision tasks (e.g. Ferrand & Grainger, 1992, 1993, 1994; Frost, Ahissar, Gotesman & Tayeb, 2003; Perfetti & Bell, 1991; Rastle & Brysbaert, 2006; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). In alphabetical languages such as English or French, there is a very close mapping between orthographic and phonological information. However, several studies have also shown that orthographic information plays an independent role from that of phonological information in early word recognition in monolingual (Ferrand & Grainger, 1992, 1994; Ziegler et al., 2000) and bilingual readers (Brysbaert, Van Dyck & Van de Poel, 1999; Van Wijnendaele & Brysbaert, 2002).

To isolate orthographic from phonological effects in early word recognition, studies employing a masked priming procedure have determined that the length of presentation of primes is an important factor. These studies show that orthographic and phonological information follow a different time-course and that orthographic effects emerge and decay earlier than do phonological effects (Ferrand & Grainger, 1992, 1993, 1994; Grainger & Ferrand, 1996; Ziegler et al., 2000; Lee, Rayner & Pollatsek, 1999). Orthographic effects appear to be strongest when primes are presented for 25-55 ms, whereas phonological effects emerge with primes of 40 ms and are strongest with 60-80 ms prime durations (Ferrand & Grainger, 1993; Grainger & Holcomb, 2008, for a review).

The goal of the present study is to further investigate the use of phonological information in word recognition by severely to profoundly deaf adults of different reading levels (skilled and less skilled readers). Over the past 40 years, researchers investigating the reading abilities of deaf people have consistently reported that, for many of them, reading performance reaches only a third or fourth grade level (Allen, 1986; CADS, 1991; DiFrancesca, 1972; Gallaudet Research Institute, 2004; Traxler, 2000; Trybus & Krachmer, 1977).[13] The deaf population is highly heterogeneous and the explanation as to why a large number of deaf people do not become good readers is complex. Some deaf individuals, however, do reach expert reading skills and, at present, it is still unclear why they become excellent readers and others do not. Many factors, alone or combined, may thwart young deaf readers' ability to become expert readers, such as degree of hearing loss (Conrad, 1979), degree of knowledge of the language that is read (Goldin-Meadow & Mayberry, 2001), late exposure to a first language (Mayberry, 2007; Padden & Ramsey, 2000), and degree of knowledge of sign language (Chamberlain & Mayberry, 2008; Strong & Prinz, 2000). Another reason invoked for such low median reading skills is that deaf people have "reduced access to the phonological code" (Goldin-Meadow & Mayberry, 2001; p. 222). Phonological representations in deaf readers are not necessarily sound-based (although they can be in part depending on the degree of hearing loss). They have been said to be *nonstandard* (Hanson & Fowler, 1987; Kelly & Barac-Cikoja, 2007) as phonological representations are acquired through multiple channels: the visual channel through lip reading, through articulatory feedback when speech is produced, and also through residual hearing, for some

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[13] Such wide scale surveys of deaf readers' skills do not exist for the Province of Québec, however the range of reading levels of the participants in the present study (1st grade to post secondary reading levels in deaf adults – see *Participants* section) indicates that adult deaf readers in Québec also experience, sometimes severe, reading difficulties.

deaf individuals, especially if they wear hearing aids (Kelly & Barac-Cikoja, 2007; p. 255). Considering the important role of phonological information in word processing (Ferrand & Grainger, 1992, 1994; Grainger & Ferrand, 1996; Perfetti & Bell, 1991; Ziegler et al., 2000), and the nonstandard nature of the phonological representations developed by deaf individuals, much research on deaf readers has focused on their use of phonological information in word reading. However, despite extensive research on this issue in the past decades, there is conflicting evidence as to whether deaf people (children and adults) use a phonological code in reading words (Chamberlain, 2002; Daigle & Armand, 2007; Dyer et al., 2003; Hanson and colleagues, 1987, 1991; Harris and colleagues, 1998, 2004, 2006; Mayberry, Chamberlain, Waters & Hwang, 2005; Paire-Ficout, 1998; Waters & Doehring, 1990). One of the striking contradictions in the literature is that, in some studies, deaf people who have been educated orally do not appear to use phonology in word processing (e.g. Burden & Campbell, 1994; Waters & Doehring, 1990), whereas deaf individuals who have a sign language as their main communication mode have been shown in some studies to use phonology in word processing (Daigle & Armand, 2007; Kelly, 2003; Transler, Gombert & Leybaert, 2001; Transler & Reitsma, 2005).

There are several problems that should be highlighted in the research on the use of a phonological code by deaf readers. First, in the majority of studies on word recognition, the tasks used do not tap automatic word processing (Beech & Harris, 1997; Burden & Campbell, 1994; Chamberlain, 2002; Daigle & Armand, 2007; Dyer et al., 2003; Hanson & Fowler, 1987; Hanson, Goodell & Perfetti, 1991; Harris & Moreno, 2004; Mayberry et al., 2005; Merrills, Underwood & Wood, 1994; Transler & Reitsma, 2005; Transler et al., 2001; Treiman & Hirsh-Pasek, 1983; Waters & Doehring, 1990). Indeed, most of the tasks used involve some form of decision process (*Is this a word or not?* in simple lexical decision tasks, or *Do these letter strings rhyme?* in rhyme judgment tasks, etc.), for which the use of phonological information may be a secondary process used to respond to the task instead of being automatically involved during word processing (Forster, 1998). In contrast, lexical decision tasks combined with a masked priming procedure are believed to better tap processes involved during on-line word processing because they promote the unconscious processing of the primes, which in turn influence the processing of the targets that are presented shortly after (Ferrand, 2001; Forster, Mohan, & Hector, 2003).

Second, and more importantly, in several studies investigating the use of phonology in word recognition by deaf readers, there is a potential confound between the effects of phonological and orthographic information. One simple example of a confound between the involvement of orthographic and phonological information would be to ask if the words *cat* and *hat* rhyme. The decision could be made on the basis of the phonological information (both words share 2/3 phonemes) or on the basis of orthographic information (both words share 2/3 letters). Investigating the spelling-sound regularity effect also involves a confound between the effects of phonological and orthographic information. Share (1995) argues that irregular words are not only processed through a whole-word route (i.e., without grapheme-phoneme correspondence operations) and that words should not be dichotomized into regular or irregular categories. Words, according to Share (1995), are never entirely irregular and are usually only irregular because of the vowel they contain. For example, the word *flood* (from Hagilliassis, Pratt & Johnston, 2006; p. 239) contains four phonemes, three of which (/f/, /l/, /d/) can be assembled through regular grapheme-phoneme conversion. This suggests that even for irregular words, sublexical orthographic and phonological processing (grapheme-phoneme conversion) is also at work during processing.

Because of the tight mapping between orthography and phonology in alphabetical writing systems, it is crucial to ensure that both types of codes are investigated so as to not wrongly attribute, especially in the case of deaf readers, experimental effects to the unique influence of a phonological code when the effects could also be partly attributable to an orthographic code. In order to address the above-mentioned problematic issues, the present investigation used the masked priming procedure combined with a lexical decision task in order to better assess the early, automatic involvement of orthographic and phonological information in word processing by severely to profoundly deaf readers. Furthermore, the time-course of orthographic and phonological information processing was taken into account through the use of two prime durations: 40 and 60 milliseconds. These two prime durations were chosen to tap both orthographic and phonological effects at their most effective priming capacity (Ferrand, 2001; Grainger, Kiyonaga, & Holcomb, 2006).

The present investigation is the first to try to dissociate the roles of orthographic and phonological information in early word recognition by signing deaf readers while controlling for reading level, degree of hearing loss, and mode of communication (here, sign language). Deaf participants were placed in two groups (skilled or less skilled readers) according to their scores on a reading test. Previous research with hearing readers (Chace, Rayner & Well, 2005; Unsworth & Pexman, 2003) investigating the use of phonological information during word recognition by skilled and less skilled adult readers has shown that less skilled readers do not seem to use phonological information as efficiently as skilled readers do. In Chamberlain (2002), there was no evidence that skilled or less skilled adult deaf readers were using phonological information during word recognition. In the present study, the pattern of results for the deaf readers is hard to predict as several results are possible and no prior studies have addressed the same issues. A potential confound between orthographic and phonological effects in previous research in deaf adults and children would predict that the effects attributed to phonological information in word processing are solely due to orthographic information. In this case, it can be predicted that skilled and less skilled deaf readers would not show any effects of phonological priming, but only effects of orthographic priming, in line with Mayberry et al. (2005), Waters and Doehring (1990) and Chamberlain's (2002) results, whereas hearing skilled readers should show both orthographic and phonological priming effects (at least with a 60 ms prime duration for phonological priming effects). No phonological priming for the deaf readers in the present study would have to be interpreted with caution however, because only two prime durations are used. Indeed, if with a 60 ms prime duration, no phonological effects were found for deaf readers – the duration at which they normally are present for hearing readers (e.g. Ziegler et al., 2000) - it could mean that phonological effects may emerge later for deaf readers than for hearing readers. Alternatively, it could also be the case, in line with Chace et al. (2005) and Unsworth and Pexman (2003), that only the skilled deaf and hearing readers use phonological information during word processing. Finally, some studies with deaf children have shown that they use phonological information during word processing (Daigle & Armand, 2007; Dyer et al., 2003; Leybaert & Alegria, 1993; Merrills et al., 1994; Transler & Reitsma, 2005; Transler et al., 2001). Because children can be considered to be less skilled readers (readers who have not reached optimal reading skills), it is possible that all participants, but particularly less skilled deaf readers, will make use of phonological codes during word processing, above and beyond orthographic codes.

2.3 Methods

2.3.1 Participants

Thirty-one adults from Montreal's Quebec Sign Language (LSQ) Deaf community were recruited as participants. All participants were severely to profoundly deaf, had prelingual deafness, used LSQ as their main communication mode, had learned it prior to the age of 13 and had used it for more than 10 years. Because of the various types of educational programs that have been offered to deaf children over the past 40 years in Quebec (Dubuisson & Daigle, 1998), it was not possible to control for the type of education the deaf participants received (see also Chamberlain & Mayberry, 2008). The sample of deaf individuals, however, was homogenous with respect to degree of hearing loss, onset of deafness, main communication mode (sign language) used from childhood. The deaf participants' ages ranged between 20 and 55 years with a mean education level of 15.3 years (SD = 3.3 years). The data from one deaf participant were removed from the analyses as the task was not understood.

A group of sixteen hearing adults served as a control group and were included to ensure that orthographic and phonological priming results found in the literature were replicated. All hearing participants had French as their first language, with medium to high levels of English proficiency (according to self-report) and had not been in contact with a third language. They were between 20 and 49 years of age and had a mean education level of 17 years (SD = 2.3). All hearing participants scored at the highest level of the reading test (>12th grade).

All participants had normal or corrected-to-normal vision and received financial compensation for their participation. The research protocol was approved by McGill University Faculty of Medicine's Institutional Review Board and informed consent was obtained from all the participants.

2.3.2 Background Measures

2.3.2.1 Hearing Status

Twenty-three participants had severe to profound deafness (71 to 95 dB in the better ear) as reported by an audiologist. Seven participants verbally confirmed that they had a severe to profound hearing loss. A deaf research assistant who knew and recruited the deaf participants also verified and confirmed that they fit the inclusion criteria.

2.3.2.2 Speech Use and Comprehension

Deaf participants provided information on their speech use and comprehension by means of a self-report scale. The questionnaire was a French adaptation of a questionnaire devised by Mayberry and colleagues for the assessment of speech use by deaf participants (Chamberlain & Mayberry, 2008). Deaf participants rated their comprehension and use of oral language on a seven-point scale in different daily contexts (within the family, at school, with friends, at work, etc.) at different stages in their lives (school age, teens and adulthood).

2.3.2.3 Reading Level Measure

Prior to performing the experimental task, the participants completed the *Test de rendement du français* (TRF - Sarrazin, 1996), a standardized test normed for readers of French in Canada. The test was timed and consisted of short paragraphs followed by multiple-choice questions. For each participant, the number of correct questions on the reading test was counted and provided a score which was then matched on a standardized scale to a grade equivalent.

2.3.3 Reading Group Assignment for the Deaf Participants

The deaf participants were separated into two groups: skilled (n =14) and less skilled (n =16) readers, according to their results on the reading test. The reading levels of the 30 deaf participants ranged from 1^{st} grade level to >12^{th} grade (post-secondary level – the highest level of the test). The two groups were divided with a median split. The less skilled readers' reading levels ranged between 1^{st} and 6.4^{th} grade level (M = 4.8, SD = 1.6), whereas the skilled readers' reading levels ranged between 7.8^{th} to >12^{th} grade level (M = 9.7, SD = 1.5). Three deaf participants in this group read at the post-secondary level. A one-way ANOVA comparing the reading levels of the skilled hearing (SKH), the skilled deaf (SKD) and the less skilled deaf (LSKD) reader groups resulted in a significant main effect of group ($F(2, 44) = 144.53$, $p = 0.0001$). A Scheffé's *post hoc* test showed that the mean reading level of the three groups all differed from one another (all ps < .0001). Additionally, the mean educational level of the three groups (SKH: M = 17, SD = 2.3; SKD: M = 16.5, SD = 2.7; LSKD: M = 14.2, SD = 3.6) was also compared with a one-way ANOVA. A main effect of group was found ($F(2, 44) = 4.21$, $p = 0.02$). Scheffé's *post hoc* test revealed that only the LSKD and the SKH groups differed on educational level ($p = .03$). The mean number of years of education of the LSKD group, however, was still at post-secondary levels.

2.3.4 Stimuli

The stimuli were adapted from Grainger and Ferrand's (1996) stimulus set. The original set contained 30 target 4-letter words. French target words that were homographs or cognates with English words (e.g. *main*, *vent*, *zinc*, *vain*, etc) were replaced as cross-lingual priming has been found to influence the use of phonological information during word recognition (Brysbaert et al., 1999; Van Wijnendaele et al., 2002). Five-letter words were added to help generate enough strictly French items. The final set of stimuli was composed of 40 target 4-5 letter words. The word targets were preceded by pseudoword primes and the prime/target relationship was varied in four ways: (1) O+P+,[14] the orthographically similar pseudohomophone condition (mert – MÈRE); (2) O–P+, the orthographically dissimilar pseudohomophone condition (mair – MÈRE); (3) O–P–, the orthographically dissimilar nonhomophonic condition (mune – MÈRE); and (4) an unrelated condition in which the primes were orthographically and phonologically unrelated to the targets (siul - MÈRE). These conditions were adapted from Ferrand and Grainger's Experiment 2b (1994), however, the unrelated prime/target condition was added as an additional baseline (see the Appendix for a list of the target words and pseudoword primes). These four conditions allow the investigation of the unique contribution of orthographic and phonological information in French word processing. Orthographic processing is measured by comparing the O+P+ condition with the O–P+. In these two conditions, there is 100% phonological overlap[15] between the primes and targets

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[14] *O* for *orthographic information* and *P* for *phonological information*. The "+" sign indicates that the prime/target pairs share a high percentage of orthographic or phonological information, and the "–" sign indicates that the prime/target pairs share a lower percentage of either type of information.

[15] Phonological overlap was calculated as the number of phonemes shared between a prime and a target.

across all prime/target pairs, but the orthographic overlap[16] between primes and targets is varied. There is an average of 75% orthographic overlap across all prime/target pairs in the O+P+ condition, but only 46% orthographic overlap between prime/target pairs in the O–P+ condition. By comparing these two conditions, phonological overlap is therefore kept constant and orthographic overlap is modulated (see Table 1). The difference between the two conditions gives a measure of the priming that is attributable to the orthographic processing of words.

[Insert Table 1 about here]

Similarly, phonological processing is measured by comparing the O–P+ condition with the O–P– condition. Between these two conditions, orthographic overlap between primes and targets is kept constant (48% and 45% orthographic overlap, respectively), whereas phonological overlap is modulated (100% and 21% phonological overlap, respectively). The word targets have a mean frequency of 113 occurrences per million (range: 2 to 1289/million). The number of orthographic and phonological neighbours for the targets is 7 and 41 on average, respectively.

Because the task was lexical decision, nonword targets were also added to the task. Thirty-seven nonword prime/nonword target pairs were included as fillers. The target nonwords were 4-5 letters long and, as in the original study

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[16] Orthographic overlap was calculated as the number of letters shared between a prime and a target. The letters did not have to be in the exact same position within the prime they were within the target, but they had to respect the relative position of letters within the target (Humphreys, Evett & Quinlan, 1990; Grainger, Granier, Farioli, Van Assche & van Heuven, 2006).

(Grainger & Ferrand,1996), nonword prime conditions, matching the four experimental conditions were also created: (1) O+P+ (keit – KAÎT); (2) O–P+ (kets – KAÎT); (3) O–P– (kaum – KAÎT); and (4) an Unrelated prime (jode - KAÎT). Finally, 148 nonword/word pairs and 160 nonword/nonword pairs were also included as unrelated prime/target fillers to reduce predictability. The filler target words were matched in number of letters and frequency with the experimental target words.

2.3.5 Design

In order to reduce subject and item variability, the factors of prime type (O+P+, O–P+, O–P–, Unrelated) and prime duration (40 ms, 60 ms) were treated as within-subject variables. Each participant saw each target repeatedly (see Frost et al., 2003, for a similar design), once at each of the eight possible combinations of prime type (n = 4) and prime duration (n = 2). Participants were tested twice at a 10-15 day interval and in the first testing session were tested with one of the prime duration conditions (40 ms or 60 ms) and with the alternate prime duration condition (60 ms or 40 ms) in the second session. This type of design is particularly attractive when testing special populations as it may be difficult to form large samples so that target presentation can be counterbalanced across the participants instead of repeated.

Four lists were created with 10 experimental targets in each prime type condition in each list. One hundred and fourteen fillers were also included in each of the four lists. To avoid order of presentation effects for the targets within each prime duration condition, the four lists were presented in four different orders. Each participant received the eight possible combinations of list (n = 4) and prime duration (n = 2) in a different order. The task was presented in four blocks of 154 prime/target pairs. Each block was separated by a brief pause. The task was completed in about 40 minutes.

To reduce the repetition effect resulting from target recurrence, in each testing session the participants took part in a practice session prior to the masked primed lexical decision task (Frost et al., 2003). They first performed a simple lexical decision task in which they were presented with the experimental items twice. Furthermore, the same words had been seen twice each in the same testing session in an eyetracking experiment[17] that preceded the lexical decision task. The assumption is that the repetition effect resulting from seeing each target more than once will reach asymptote during practice trials and reduce the repetition effect in the experimental task because the targets will already have been seen repeatedly (see Frost et al., 2003 for more details).

2.3.6 Procedure and Apparatus

Participants were seated in a quiet and dimly lit room in front of a computer screen. They performed a forward-masked primed lexical decision task and were presented with the following sequence of events on a computer screen: (1) a pattern mask for 500 ms (e.g. #######), (2) a pseudoword prime for 40 or 60 ms (e.g. mert), and (3) a word or pseudoword target for 500 msec (e.g. MÈRE or KAÎT). When presented with a word, the participants responded YES by pressing a button on a button-box with the index finger of their dominant hand. When presented with a pseudoword, participants responded NO by pressing a button with their non-dominant hand. Participants were encouraged to respond as rapidly and as accurately as possible. Eighteen training items were presented to the participants prior to the beginning of the task. All the task instructions were given to the deaf participants in LSQ by a deaf research assistant.

The presentation of the items and the measurement of the participants' reaction times and accuracy of response was controlled by the DMDX software (Forster & Forster, 2003) running on a Pentium 4 PC. The experimental items were presented in isolation in light blue *Courier New* font on a black background.

[17] The results of the simple lexical decision and the eyetracking tasks will not be reported here.

The monitor was a 22-inch iiyama CRT display with a refresh rate of 150 Hz to control variation in the timing of presentation of the stimuli.

2.4 Results

Reaction times (RTs) exceeding 1000-msec were removed from the data set (resulting in 2.53% of the data being rejected). Only RTs for correct responses to the word stimuli were analyzed. Furthermore, the mean error rate across all conditions was low ($M = 2.91$, $SD = 2.61$). First a repeated-measures ANOVA on RTs was performed with prime duration, list (to control for the order of presentation of the targets), and prime type as within-subject variables and group as the between-subjects variable. The main effect of list was not significant, ($F(3, 129) = 1.45$, $p = 0.23$), therefore this factor was removed from further analyses. More importantly, the non-significant list x prime type interaction ($F(9, 387) = 1.31$, $p = 0.23$), indicated that the fact that targets were repeated did not conceal the prime type effects.

A second repeated-measures ANOVA, by both subjects (F_1) and items (F_2), was conducted (without the list factor) with prime duration and prime type as within-subject variables and group as a between-subject variable. Table 2 gives the mean correct RTs along with the mean number of errors for each priming condition for each subject group.

[Insert Table 2 about here]

A main effect of group was found ($F_1(2, 43) = 3.84$, $p = .03$; $F_2(2, 624) = 369.30$, $p = .0001$), along with a main effect of prime duration ($F_1(1, 43) = 6.87$, $p = .012$; $F_2(1, 312) = 17.50$, $p = .0001$), and a main effect of prime type ($F_1(3, 129) = 29.28$, $p = .0001$; $F_2(3, 312) = 7.40$, $p = .0001$). A group x duration interaction was significant in the item analysis only ($F_1(2, 43) = 0.61$, $p = .55$; $F_2(2, 624) = 5.90$, $p = .003$). More importantly, a prime duration x prime type interaction was found, but was significant in the subject analysis only, ($F_1(3, 129) = 3.68$, $p = .014$; $F_2(3, 312) = 0.60$, $p = .59$). None of the other interactions reached significance (all *p*s > .05).

Because the three groups had unequal n's, Scheffé's *post hoc* test was used to investigate the significant main effect of group. The *post hoc* test for group revealed that skilled hearing readers (*M* = 560 ms) were significantly faster than the less skilled deaf readers (*M* = 624 ms, *p* = .03), but not than the skilled deaf readers (*M* = 597 ms, *p* = .32). The skilled deaf readers and the less skilled deaf readers did not significantly differ from each other either (*p* = .53).

To better assess the effects among the four priming conditions, and to determine whether the participant groups showed different patterns of orthographic and/or phonological priming, separate ANOVAs were conducted for each prime duration. At a 40 ms prime duration, the analysis yielded a significant main effect of group (by items only - $F_1(2, 43) = 2.75$, $p = .07$; $F_2(2, 312) = 154.96$, $p = .0001$). There was also a significant main effect of prime type ($F_1(3, 129) = 14.10$, $p = .0001$; $F_2(3, 156) = 2.82$, $p = .04$). The prime type x group interaction was not significant ($F_1(6, 129) = 0.41$, $p = .87$; $F_2(6, 312) = 0.66$, $p = .68$). Scheffé's *post hoc* test for the main effect of prime type showed that there was a significant difference between the O+P+ (*M* = 577 ms) and O-P+ conditions (587 ms; *p* = .02) indicating that there was an effect of orthographic facilitation at a 40 ms prime duration. However, the difference between the O-P+ (*M* = 587 ms) and O-P- conditions (*M*= 586 ms) was not significant (*p* = .98) indicating that at this prime duration there was no effect of phonological priming.

At a 60 ms prime duration, the analysis yielded a significant main effect of group ($F_1(2, 43) = 4.58$, $p = .01$; $F_2(2, 312) = 217.39$, $p = .0001$), along with a significant main effect of prime type ($F_1(3, 129) = 22.29$, $p = .0001$; $F_2(3, 156) = 5.10$, $p = .002$). The prime type x group interaction was not significant ($F_1(6, 129) = 0.98$, $p = .44$; $F_2(6, 312) = 0.96$, $p = .45$). Again, Scheffé's *post hoc* test for the main effect of prime type revealed that orthographic priming was present at a 60 ms prime duration (O+P+, *M* = 587 ms; O-P+, *M* = 597 ms; *p* = .002). At this prime duration, the effect of phonological priming was also significant (O-P+, *M* = 597 ms; O-P-, *M* = 607 ms; *p* = .003).

[Insert Figure 1 about here]

To illustrate the results of the *post hoc* tests at both prime durations, Figure 1 shows the net orthographic and phonological priming effects (i.e.

difference between raw RTs in the O+P+ and O-P+, and in the O-P+ and O-P- conditions, respectively).

A repeated-measures ANOVA on the error data with prime duration and prime type as within-subject variables and with group as a between-subject variable produced no significant results.

2.4.1 Additional Analyses

We conducted regression analyses to verify whether the orthographic and phonological priming effects were related to reading level (as measured by the TRF; Sarrazin, 1996). The skilled hearing readers all performed at the highest reading level and could not be entered into a regression analysis, therefore only the skilled and less skilled deaf readers were included in the analysis. A self-evaluation reading level score collected for all the deaf participants in the *Speech Use and Comprehension* questionnaire was also entered as a predictor. Participants rated their own reading skill on a scale from 0 (null) to 7 (excellent). The ratings ranged from 2 to 7. Finally, a measure of speech comprehension was also entered as a predictor into the regression analyses. This measure was based on self-report. The participants answered on a scale of 0 to 7 how well they understand speech (lip reading) (1) at school/work, (2) with family, (3) with friends, (4) in shops/restaurants and, (5) with strangers. A mean was computed from the response to each of these 5 questions and was entered as a predictor (range from 1 to 5.25) in the regression analysis. Interestingly, the self-rated reading level and speech comprehension variables were not correlated, $r = .15$, $p = .43$ (df = 28).

Multiple regression analyses were not run because of the small sample size. Instead, separate linear regression analyses were run with net orthographic and phonological priming effects at each prime duration as dependent variables with self-rated reading level, normed test reading level (TRF; Sarrazin, 1996), and self-rated speech comprehension as predictors for all deaf readers. At the 40 ms prime duration, there were marginally significant regressions between net orthographic priming and self-rated reading level ($r^2 = .13$, $p = .06$) and net phonological priming and self-rated speech comprehension ($r^2 = .10$, $p = .09$). No other regression results approached significance, as Table 3 shows.

[Insert Table 3 about here]

2.5 Discussion

The purpose of the present experiment was to investigate the use of orthographic and phonological information during early word processing by skilled and less skilled deaf readers whose primary communication mode is sign language. The findings of the present study show that in the 40 ms prime duration condition, orthographic information shared between primes and targets had a facilitating effect on target recognition, whereas phonological information had not yet entered into play. In the 60 ms prime duration condition, however, orthographic and phonological information shared between primes and targets was facilitative. The results of the present study support a time-course hypothesis of orthographic and phonological information processing, where orthographic information is activated slightly earlier than phonological information in the very early moments of visual word recognition (Ferrand & Grainger, 1993; 1994; Grainger et al., 2006; Grainger & Holcomb, 2008 for a review; Ziegler et al., 2000).

Interestingly, this overall pattern of orthographic and phonological activation was found across groups, as shown by the lack of prime type x group interactions at both prime durations. Although this could be due to limited power, the fact that the deaf readers' reading level was not a significant predictor of their use of phonological or orthographic codes during early word recognition reinforces this conclusion. Despite the possible confound between orthographic and phonological information in prior research on deaf readers, our results show that both groups of deaf readers use orthographic information during word processing, even in the very early moments of word processing. Consistent with our findings, several studies on word recognition in deaf children and adults have suggested that these readers do use an orthographic code (Burden & Campbell, 1994; Chamberlain, 2002; Daigle, Armand, Demont & Gombert, submitted; Harris & Moreno, 2004; Miller, 2006, 2007). Just as importantly, the present results show that signing severely to profoundly deaf skilled and less skilled readers also access phonological information during word recognition (Daigle & Armand, 2007; Kelly, 2003; Transler, Gombert & Leybaert, 2001; Transler & Reitsma, 2005). The present study is the first to clearly dissociate the involvement of both orthographic and phonological codes in early word recognition in deaf readers. Our results show that deaf readers, regardless of their reading skills, do activate both types of information quickly and early, and in the same manner as skilled hearing readers, arguing against the claim that deaf readers "recognize words in a qualitatively different way from hearing readers" (Chamberlain, 2002; p. 222) at least when it comes to the use of orthographic and phonological codes in on-line word recognition.

These results also speak to the fact that the use of orthographic and phonological processing in word recognition in deaf readers should not be viewed as though they operate separately and independently from one another. Several studies that found no evidence for the involvement of phonological information during word processing by deaf readers interpret the result to mean that orthographic information must be used instead but without having investigated orthographic information processing per se (Miller, 2006, 2007). The present results suggest that the involvement of orthographic and phonological information in word processing by deaf readers should be viewed as interactive processes wherein one may be more involved than the other at certain moments during word recognition (Ferrand, 2001; Grainger & Ferrand, 1994; Grainger et al., 2006).

As mentioned earlier, much emphasis has been placed on whether or not deaf readers use phonological information during word recognition (see Musselman, 2000; Perfetti & Sandak, 2000 for reviews) in order to find an explanation for the generally low reading skills in this population. However, in the literature on deaf readers, results are mixed. There are several differences across studies which may explain the inconsistencies in the results: the lack of consideration of the participants' reading level, the tasks used, variation in degree of hearing loss, and the mode of communication of the participants (oral-based or sign-based). Despite mixed results in the literature, however, several authors have suggested that the use of phonological information in reading is principally found in older, better deaf readers (Daigle & Armand, 2007; Hanson & Fowler, 1987; Perfetti & Sandak, 2000). The present results argue against such a conclusion in light of the absence of differences between the participant groups with regards to the early activation of phonological information. This is also supported by the lack of a reading level effect when this variable was entered as a predictor of orthographic or phonological priming in a regression analysis for the skilled and less skilled deaf readers (see also Chamberlain, 2002; Leybaert & Alegria, 1993; Waters & Doehring, 1990). In the literature on deaf readers, very few studies have controlled for reading level. Therefore the link between the use of phonological codes and reading level is not clear. Deaf adult readers of various reading skills in the present study do show evidence for the use of phonological codes in early word recognition. Because the participants in this study were adults, what remains to be addressed is whether these codes, for deaf readers, were developed through reading practice or are the basis of reading acquisition (Goldin-Meadow & Mayberry, 2001; Musselman, 2000). Overall our results refocus the common conclusion in the literature: the use of phonological codes by deaf readers is found in adult deaf readers who sign and not exclusively in better readers.

Beyond the use of phonological and orthographic codes in early word recognition by adult deaf readers, one striking observation in this study is the combination of the following findings: (1) the groups did not differ in terms of basic processes involved in early word recognition; (2) there was no relationship between effects of phonological or orthographic processing and reading level for the skilled and less skilled deaf readers; (3) the groups differed in speed of processing; and (4) there was no group effect in the error data. These findings all strongly point to the interpretation that deaf readers' low comprehension levels are not based in the encoding processes (phonological or orthographic) they use during word recognition per se, but rather in other higher-level processes which may affect word recognition automaticity (Kelly 2003; see also Kelly & Barac-Cikoja, 2007). Cutting and Scarborough (2006) have shown that part of the variance in reading comprehension, above and beyond word recognition/decoding and language comprehension skills, could be explained by reading speed in a sample of hearing readers in grades 1 through 11. The reading speed difference of our participant groups was also observed in a study investigating the basic eye movement characteristics of these readers during sentence reading (Bélanger, Mayberry & Baum, submitted-b; Chapter 3). The skilled hearing readers read 341 words per minute (wpm) whereas the skilled deaf readers and the less skilled deaf readers read 281 and 211 wpm, respectively. Recall that the skilled deaf readers, even if labelled as skilled, are not reading level matched with the skilled hearing readers. Both groups of skilled readers are reading at a 9.7th grade (deaf) and post-secondary level (hearing). However, a subgroup of the skilled deaf readers matched to the skilled hearing readers' in reading test performance was still reading more slowly (313 wpm) than the skilled hearing readers.

The different reading and decision speeds across our groups of readers may be attributed to several interrelated factors. Low automaticity in deaf readers may be attributed to reduced reading practice as proposed by Kelly (2003), who suggests that the link between practice and automaticity can be seen in frequency effects in print (frequent words are read faster). It may also be that deaf readers should be considered as readers of a second language (Mahshie, 1995). It has been shown that hearing fluent L2 speakers reading in their second language are slower (by 100 WPM) than hearing monolingual readers (see Fraser, 2004 for a review). Both hearing L2 and deaf readers read in a language for which they have (sometimes temporarily) incomplete representations.

In this perspective, slower reading and low comprehension may stem from low general language competence (Chamberlain & Mayberry, 2008; Goldin-Meadow & Mayberry, 2001; Paul, 2003; Waters & Doehring, 1990). Spoken language skills have been found to account for variance in reading comprehension and word recognition in hearing readers from the 2nd grade to the 10th grade (Catts, Fey, Zhang & Tomblin, 1999; Cutting & Scarborough, 2006). As can be expected, spoken language development is challenging for deaf children with severe to profound hearing loss (see Kelly & Barac-Cikoja, 2007) and requires much overt training. Some deaf children may even be expected to learn to read when entering school without a good mastery of the language they are supposed to read (Marschark, 1993). However the language basis of reading skill does not appear to be solely based in spoken language skills and has also been linked to sign language mastery. Chamberlain and Mayberry (2008) provide evidence for a relationship between sign language proficiency and reading ability (see also Hermans, Knoors, Ormel & Verhoeven, 2008; Hoffmeister, 2000; Strong & Prinz, 1997). As Chamberlain and Mayberry (2008) suggest, "the low median reading achievement reported for the deaf student population is probably linked to incomplete language acquisition, signed or spoken" (p. 383). Although our results do not address this particular question, they certainly point to the fact that reading difficulties in adult deaf readers are not based in the encoding processes they use during word processing.

Taken together, these results for hearing readers and deaf readers of various reading skills are in line with the *Bi-modal Interactive Activation* model (BIAM - Grainger & Ferrand, 1994; Grainger, Diependaele, Spinelli, Ferrand & Farioli, 2003). This model of word recognition posits that separate representations of orthographic and phonological information exert an influence during word processing and that each type of information is subdivided into a prelexical and a lexical level. According to the BIAM, during word recognition, prelexical orthographic representations (letters coded for their identity and relative position) will first be activated and then send activation both to the lexical orthographic level and the orthographic-phonological interface. The lexical phonological level can receive activation from the lexical orthographic level and also from the orthographic-phonological interface. The different time-course of orthographic and phonological information is therefore accounted for by the fact that the entry point into the word processor is purely orthographic and that activation then spreads to phonological levels of information. The combination of short prime durations and the use of pseudoword primes in the present experiment enabled prelexical representations from the pseudoword primes to be activated (Ferrand, 2001) and influence the processing of the closely following target word for all readers in the present study. Therefore, the present results are consistent with the very first stages of word processing in the *Bi-modal Interactive Activation* model.

In sum, the findings of the present investigation show that, like hearing readers, deaf readers of a wide range of reading skills show orthographic information processing during word recognition, which is independent and follows a different time-course from phonological information. Our results also suggest that reading difficulties in deaf adults may not be linked to word encoding processes per se, at least in the first moments of word recognition, but rather to processing automaticity, which itself may be based on language competence (signed or spoken) and on exposure to print.

2.6 Acknowledgements

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Table 1.

Percentage of orthographic and phonological overlap between primes and targets in each experimental condition

	Shared letters (%)	Shared phonemes (%)
O+P+	76%	100%
O–P+	48%	100%
O–P–	45%	21%
Unrelated	0%	0%

Table 2.

Mean correct reaction times and errors with standard deviations for the four prime type conditions at each prime duration and for each group.

Prime Type	Prime Duration – 40 milliseconds							
	O+P+		O-P+		O-P-		Unrelated	
	Rt[a] (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)
SKH[b]	549.09	1.88	555.57	1.88	556.27	2.38	567.68	2.25
	(54.22)	(1.63)	(53.01)	(2.25)	(48.00)	(1.63)	(44.75)	(2.02)
SKD	576.27	2.50	586.26	2.29	589.04	2.93	598.05	3.00
	(78.06)	(1.65)	(71.70)	(1.64)	(74.03)	(2.23)	(69.73)	(2.29)
LSKD	606.89	3.69	619.18	3.06	612.90	3.81	624.59	3.75
	(87.37)	(3.46)	(83.20)	(3.11)	(86.82)	(3.08)	(94.14)	(3.02)

Prime Type	Prime Duration – 60 milliseconds							
	O+P+		O-P+		O-P-		Unrelated	
	Rt (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)	*Rt* (*SD*)	*Error* (*SD*)
SKH	551.88	1.81	558.21	2.75	572.83	2.25	569.43	2.50
	(63.49)	(2.10)	(45.09)	(2.27)	(55.20)	(1.84)	(54.89)	(2.16)
SKD	592.02	3.21	604.26	2.71	613.99	3.21	618.39	2.36
	(72.94)	(2.55)	(79.47)	(1.54)	(68.10)	(2.75)	(69.01)	(1.60)
LSKD	616.93	3.63	629.76	3.44	636.11	4.00	650.46	4.50
	(74.44)	(3.50)	(72.11)	(3.76)	(75.31)	(3.58)	(73.85)	(3.48)

[a] Reactions times are in milliseconds.

[b] SKH = Skilled hearing readers, SKD = Skilled deaf readers, LSKD = Less skilled deaf readers

Table 3.

Regression results for net priming effects and measures of reading and speech comprehension.

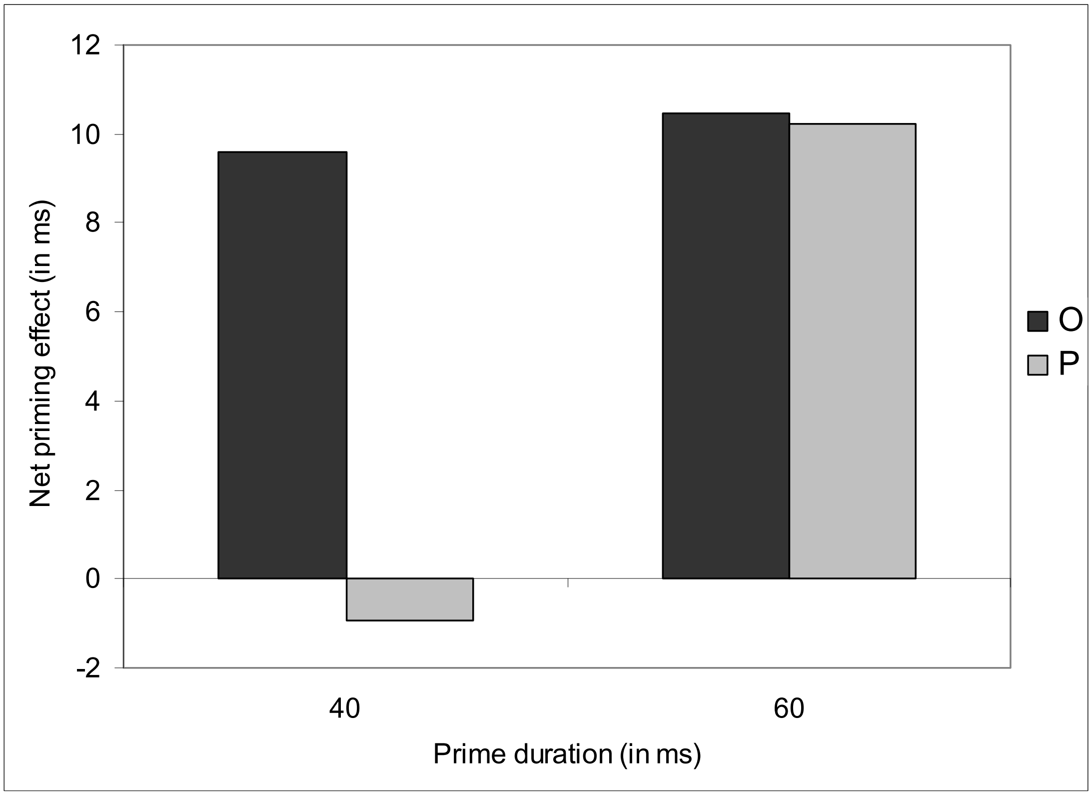
	Priming Effect			
	Orthographic		Phonological	
Prime Duration	R^2	p^a	R^2	p^a
40 msec				
Self-rated reading level	.13	.06	.04	.32
TRF[b]	.03	.36	.08	.14
Self-rated speech comprehension	.01	.58	.10	.09
60 Msec				
Reading Self-Rating	.004	.76	.009	.64
TRF	.01	.57	.003	.77
Speech Comp Self-Rating	.01	.60	.05	.25

[a] df = 1,27

[b] Test de rendement du français (Sarrazin, 1996)

Figure 1.

Net orthographic and phonological effects at 40 and 60 ms prime durations.



Preface to Chapter 3

Research with hearing readers has shown that eye movement measures are extremely sensitive to reading level variations (Rayner, 1986). Better readers make fewer and shorter fixations, for example, and have wider perceptual and word identification spans (Rayner, 1998). Specifically, less skilled readers have been said to devote such attention to the processing of difficult foveated words that they may not use information available in their parafovea (Rayner, 1998; Henderson & Ferreira, 1990). The main goal of the second study (Chapter 3) was to determine the basic eye movement characteristics of skilled and less skilled deaf readers. Additionally, it was important to determine the size of the participants' perceptual and word identification spans in order to see whether or not they use the information available in their parafovea while reading (goal of the third study – Chapter 4). A secondary goal of the present study was to determine whether, while reading, deaf individuals benefit somehow from previously reported enhanced attention allocation to the periphery during visual processing (Bavelier, Dye & Hauser, 2006).

To investigate these questions, participants read single-line sentences while their eye movements were recorded. The same participants as in the first study participated in this study: skilled hearing, skilled deaf and less skilled deaf readers. A window of visible text followed the participants' eyes as they moved along the lines of text and beyond that window, information was blocked as letters were replaced by Xs. The size of the windows was manipulated so that participants had decreasing levels of available textual information in their parafoveal vision in each condition. These conditions were compared to a baseline unmasked condition. Several typical eye movement measures were gathered, namely: mean fixation duration, mean forward saccade length, words read per minute, etc. From these measures, the size of the perceptual and word identification spans was calculated. All the measures were analysed as a function of the reading level of the participants.

Chapter 3

Casting an eye on skilled and less skilled deaf readers: Eye movement patterns during sentence reading

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3.1 Abstract

Eye movements are a very sensitive measure of reading skill (Rayner, 1986), yet the eye movement characteristics of deaf readers have not been fully investigated. In the visual processing domain, deaf readers have been shown to be better at allocating attention to the periphery. One of the aims of the present investigation was to examine whether their enhanced visual processing in the periphery might translate into how deaf readers process written information beyond the fixation point. Skilled and less skilled deaf readers participated in the study, along with skilled hearing readers. Results mainly replicate what has been shown in previous literature on eye movement and reading skills, despite having groups of readers who not only differ in terms of reading level, but also in terms of hearing status. Crucially, the results show that skilled deaf readers appear to have a wider perceptual span than skilled hearing readers matched on reading comprehension level, suggesting that the size of the perceptual span in deaf readers is not only determined by reading skill but also by auditory deprivation.

Keywords: Deaf readers, eye movements, reading skill, perceptual span, visual processing in the periphery.

3.2 Introduction

The way readers move their eyes across the page reflects their skill level. Skilled readers have been shown to fixate words for 200-300 ms on average and to make brief saccades lasting 25-60 ms (see Rayner, 1998, for a review). These readers fixate the majority of words, but some words are skipped (Rayner, 1998). Furthermore, 10-15% of the saccades are backward saccades (regressions) in the text or in the word just read (Rayner, 1998). Crucially, it has been found that general eye movement characteristics differ between skilled readers and beginning readers or dyslexic readers (Rayner, 1986, 1998; Chace, Rayner & Well, 2005). Beginning readers make more fixations, shorter saccades and more regressions than skilled readers (McConkie, Zola, Grimes, Kerr, Bryant & Wolff, 1991; Rayner, 1986). Less skilled readers and dyslexic readers also show this pattern (Rayner, 1998). However, eye movement measures can distinguish more subtle differences in reading skill also, as shown in studies investigating college-level skilled and less skilled readers (Ashby, Rayner & Clifton, 2005; Jared, Levy & Rayner, 1999).

An important factor to take into account when studying eye movements in reading research is that the visual field is divided into three parts (foveal, parafoveal and peripheral regions) and that visual acuity decreases gradually in the parafoveal and peripheral regions (Rayner, 1998). This has led researchers to investigate how much information is available in the parafoveal and peripheral regions and whether this information is useful during reading. McConkie and Rayner (1975) determined that, in addition to the word(s) seen in the foveal region during reading, information from up to 14-15 letter spaces to the right of the fixation point is used to guide the eyes during reading (mainly word length and word-boundaries and some letter information such as ascenders and descenders). This region is called the *perceptual span*. However, the perceptual span is asymmetrical and only information 3-4 letters to the left is available (McConkie & Rayner, 1976; Underwood & McConkie, 1985; see also Rayner 1998 for more details). Furthermore, it was found that a smaller region (3-4 letters to the left of the fixation point, but only 6-8 letters to the right of the fixation point) provides useful information (mainly orthographic and phonological codes) to initiate word recognition before a word is fixated. This region is called the *word identification span* (Rayner, Well, Pollatsek & Bertera, 1982). It has been shown that beginning readers have smaller word identification and perceptual spans than skilled readers (Rayner, 1986). This is also the case for dyslexic readers (Rayner, Murphy, Henderson & Pollatsek, 1989).

Deaf readers' eye movement characteristics in reading have not, to our knowledge, been fully examined yet. Kelly (1995) has investigated the reading speed of skilled and less skilled adolescent deaf readers by using a moving window on a computer screen to display text. The less skilled readers read at a 5th grade level, whereas the skilled readers read at a post-secondary level (12th grade or beyond). Word display was self-paced, with only one word appearing at a time and all other words masked. Kelly (1995) found that skilled deaf readers spent less time viewing each word (325 ms) than less skilled readers (551 ms), a result that is consistent with the literature on hearing readers with a range of reading levels. Similar results were reported in Kelly (2003), where less skilled and skilled deaf readers (reading at a 5th grade level and at college level, respectively) also read whole sentences. Although informative, the moving window technique as used by Kelly (1995, 2003) has limitations. Word reading times are likely to be inflated due to the fact that readers have no access to the information in the word identification and perceptual spans; the reading times therefore reflect a reading-level effect, but do not reveal the full nature of eye movement characteristics in skilled and less skilled deaf readers.

When it comes to eye movement characteristics, deaf readers can potentially differ from other skilled and less skilled readers not only on the basis of reading-level, but also in terms of general visual cognition. Their altered sensory experience has been shown to selectively enhance their visual perception in certain parts of the visual field in certain conditions (Bavelier, Dye & Hauser, 2006 for a review). It has been suggested that deaf people have enhanced visual perceptual abilities, especially in the peripheral region (Finney & Dobkins, 2001 for a review). However, Bavelier et al. (2006) suggest that deaf people have enhanced visual attention to the periphery, as compared with hearing people, who have better visual attention to the central visual field. These conclusions are based on low-level visual perception of motion, orientation or brightness discrimination/detection (Bavelier et al., 2006). To our knowledge no study has investigated how parafoveal processing of written information operates in deaf people and whether there is also enhanced perception in this area during reading.

The goal of the present investigation was to determine the basic eye movement characteristics of skilled hearing and deaf readers along with those of less skilled deaf readers. The eye-contingent moving window paradigm (McConkie & Rayner, 1975) was used, a technique where a moving window is controlled by eye movements rather than by a button press (as in Kelly, 1995). Thus, in this type of experiment, the window moves with the eyes along the line of text. Around the fixation point, text is displayed normally (see Figure 1 for an example), but beyond the window of normal text, words are replaced by a mask (Xs or scrambled letters). The size of the window is manipulated to provide increasing levels of information in the parafovea and periphery. Information in the parafoveal and peripheral regions may therefore be unavailable to be processed. The assumption is that if the window in which text is viewed normally is wide enough, reading will not be disrupted.

[Insert Figure 1 about here]

More specifically, we were interested in how skilled deaf readers, less skilled deaf readers and skilled hearing readers compared in terms of reading speed (words read per minute or wpm)[18], percentage of full line reading speed[19], number of forward fixations per sentence, length of forward fixations, length of forward saccades, and number of regressions. We expected a reading-level effect in these measures. However, we were also interested in finding out whether the perceptual and word identification spans also varied as a function of reading level for the deaf readers (as it does for beginning readers at different reading-levels; Rayner, 1986) and whether the enhanced visual/attentional processing abilities of deaf people for information in the periphery would also be detectable in how they use information in their parafoveal vision while reading sentences.

3.3 Experiment 1

The first experiment was devised to examine the basic eye movement characteristics of skilled and less skilled deaf readers. A group of skilled hearing readers was also included in the study to serve as a point of comparison with existing data in the literature. With the moving window paradigm, four window sizes were created to assess deaf reader's eye movement characteristics. The different window sizes used were based on a study by Rayner (1986 – Experiment 1). Because the perceptual span is asymmetric to the right, and the size of the span from the left varies only minimally (it extends 3-4 characters to the left; Rayner 1998, for a review), only the right side of the window sizes was manipulated (contrary to Rayner, 1986). The baseline condition was the presentation of full-length, unmasked sentences. In the four masked conditions, the window size to the left was always 4 characters in length and the window size to the right was

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[18] According to Rayner (1986, p. 217) reading rate (expressed in wpm) is "the most sensitive and meaningful dependent variable."

[19] This variable is the reading speed in each of the masked sentences conditions relative to the unmasked condition where reading should be unimpeded.

varied with 2, 6, 10 and 14 visible letters (see Table 1). The mask consisted of a series of Xs and the spaces between words were filled.

[Insert Table 1 about here]

3.3.1 Methods

3.3.1.1 Participants

Thirty-one adults from Montreal's Quebec Sign Language (LSQ) Deaf community were recruited as participants in a series of studies on reading. All participants were severely to profoundly deaf (hearing loss of 71dB or more in the better ear), prelingually deaf, used LSQ as their main communication mode, had learned it prior to the age of 13 and had used it for more than 10 years. It was not possible to control for the type of education the deaf participants received (see also Chamberlain & Mayberry, 2008) because of the various types of educational programs that have been offered to deaf children in Quebec in the past decades (Dubuisson and Daigle, 1998). The sample was otherwise closely matched with respect to degree and onset of deafness and daily use of a natural sign language as a primary language from childhood. The deaf participants were aged between 20 and 55 years (*M* = 35 years). Only 25 participants were included in this part of the study as the glasses or contact lenses of six deaf participants were not compatible with the eyetracking equipment. Three more deaf participants were excluded from the study: two were excluded because they did not understand the task and one was excluded because of a lower than chance score on the comprehension questions included in the task to ensure participants read for meaning.

Sixteen skilled hearing readers served as a control group. They were all native speakers of French and were aged 20 to 49 years (*M* = 32 years). They had a mean education level of 17 years (*SD* = 2.4). The eye glasses of one participant were not compatible with the eyetracking equipment; therefore this participant did not complete this part of the study.

All participants had normal or corrected-to-normal vision and received financial compensation for their participation. The research protocol was approved by McGill University Faculty of Medicine's Institutional Review Board. All participants gave their informed consent before they took part in the study.

3.3.1.2 Reading Level Measure

All participants completed the *Test de rendement du français* (TRF - Sarrazin, 1996) before performing the experimental task. This reading comprehension test is standardized and normed for French readers in Canada. The number of correct questions on the reading test provided a score which was then matched on a standardized scale to a grade equivalent. All the hearing participants scored at the highest level of a reading test (>12th grade or post-secondary reading level).

3.3.1.2.1 Reading Group Assignment for the Deaf Participants

Two groups of deaf readers (skilled deaf readers and less skilled deaf readers) were created based on their results on the reading test. Deaf participants' reading levels ranged from 3rd grade level to >12th grade (post-secondary level – the highest level of the test). The two groups were created by dividing the reading levels of the deaf participants with a median split. The LSKD group (n=11) read at grade levels ranging between 3rd and 5.7th grade level (M = 5, SD = 0.8). The SKD group (n=11) read at levels ranging between 7.8th to >12th grade level (M = 9.9, SD = 1.7). Three of them read at a post-secondary level. A one-way ANOVA comparing the three groups of readers (skilled hearing, skilled deaf and less skilled deaf readers; SKH, SKD and LSKD, respectively) on mean reading level yielded a main effect of group ($F(2, 34) = 162.74$, $p = 0.0001$). A Scheffé *post hoc* test indicated that the three groups differed from one another (all ps < .00003). The mean education level of the three groups was also compared via a one-way ANOVA (SKH: M = 17, SD = 2.4; SKD: M = 16, SD = 2.2; LSKD: M = 15, SD = 3). The main effect of group was not significant ($F(2, 34) = 1.59$, p = 0.22).

Because overall the SKD readers were not matched to the SKH readers on reading level, in order to assess the effects of deafness rather than the effects of reading-level on eye movement measures, we regrouped the deaf readers and reanalysed the data with this alternative classification. To this end, a subset of the

SKD readers (n = 5) were matched on reading level with the SKH readers (SKD: *M* = 11.5, *SD* = 0.8; SKH: *M* = 12). The LSKD group was thus increased (n = 17) and the groups' mean reading level increased to 6.3th grade accordingly (*SD* = 1.9).

3.3.1.3 Stimuli

Ninety sentences containing 7 to 16 words were created to serve as experimental material (see Table 2 for examples). There were 15 practice sentences (3 per window condition) and 15 test sentences per window size condition. The sentences had a mean length of 11 words (*SD* = 0.84) and had a mean word length of 4.33 letters/word (*SD* = 0.13). All the conditions were matched on these variables and also on mean print word frequency per sentence (*M* = 5538/million; *SD* = 135) as determined by the *Lexique* database (New & Pallier, 2001). The practice sentences were also matched to the experimental sentences on these variables. All the sentences had a simple structure in order to avoid reading difficulties that could be brought on by complex syntax for the deaf readers (Kelly, 1998).

[Insert Table 2 about here]

To ensure that all participants (from the weakest to the best readers) would understand the reading materials, all the words used in the sentences were compared to words in *NOVLEX* (Lambert & Chesnet, 2001), a database of words taken from school books for 8-9 year old children. The overall mean frequency of all the words used for the experimental sentences in the present experiment (*M* = 2131 occurrences/million) was much higher than the overall mean frequency for all the words in the database (*M* = 92 occurrences/million). To ensure that the words used to compose the experimental sentences were frequent words, they were also entered into *VocabProfile* (Cobb, 2006), a web-based tool breaking down lists of words according to their frequency in French written texts. The output is a percentage of words in four categories: the 1000, 2000 and 3000 most frequent words in French along with the "off-list" words. Eighty-three percent of the words used to compose sentences in the present experiment were in the 1000-most-frequent-words-in-French category, 4.79 % of the words were in the top

2000 category, 1.1% were in the top 3000 category and 10.69% were in the off-list category. The majority of the "off-list" words were proper names, which had not been removed from the word lists when entered in *VocabProfile*. The use of *NOVLEX* and *VocabProfile* confirmed that the words used in the present experiment would most likely be accessible to all the participants.

As in Rayner (1986), the 15 sentences for each condition were presented in a block. Three lists were created where block order was varied to avoid practice effects within the experiment. The lists were counterbalanced across the subjects.

Fifteen yes/no comprehension questions were interspersed among the experimental sentences to ensure that the participants were reading for meaning.

3.3.1.4 Apparatus and Procedure

The sentences were presented using *Eye Track 0.7.7* software developed for the eyetracking lab at University of Massachusetts Amherst (Stracuzzi & Kinsey, 2006). Sentences were presented in white 11pt *Courier New* font on a black background to avoid eye fatigue. The display was a 22-inch iiyama CRT monitor with a refresh rate of 150 Hz. The participants sat 85 cm away from the monitor and 1^{o} of visual angle comprised 4.09 letters. All sentences were displayed on a single line and were a maximum of 75 characters long (including spaces).

The eye movements were gathered with an *EyeLink1000* eye tracker (*SR Research*). The *Eyelink1000* is an infrared video-based system gathering a sample of the eye position every millisecond with a 0.15^{o} mean accuracy. The computer on which the experimental sentences were presented and the data acquisition computer were interfaced with an Ethernet connection ensuring fast communication between the computers and a 1.8 ms delay (plus up to 6.7 ms to refresh the display) for a display change to occur following eye movements. The changes between letters and Xs as the mask followed the eyes and moved along the sentences were not perceived by the readers as they occurred during saccades. During saccadic eye movements, perception is drastically suppressed because of the speed at which the eyes travel (Rayner, 1998), therefore the windows of visible text appeared to smoothly follow the eye movements of the readers. Eye movements were recorded from the right eye, however viewing was binocular.

The testing session started with the completion of the reading test, followed by the eyetracking experiment. For the experimental task, the participants sat comfortably in front of the computer display and rested their chin and forehead on the tower-mounted eyetracker. Participants were told that most of the sentences would be masked by a series of Xs and that they should try to read the sentences normally, forgetting about the Xs. Participants were also asked to try to read the sentences once only, and to reread the sentences only if they had not understood them the first time. All the task instructions were given to the deaf participants in LSQ by a deaf research assistant.

The participants performed a 5-point calibration procedure. Then they read the 15 practice sentences, starting with the unmasked sentences and then reading the sentences with decreasing window sizes to ensure habituation when reading with smaller windows. After the fifteen practice sentences, the experiment started. After each experimental sentence was read, the participants pressed a button on a button box to signal they were finished reading the sentence. Yes/no questions appeared randomly after some of the experimental trials and participants had to respond by pressing one of two buttons on the button box. A drift correction point was presented between each sentence. If at any point in the experiment, the calibration had become imprecise, participants were recalibrated by performing a 5-point calibration procedure again.

3.3.1.5 Data Analyses

Before the data were analyzed statistically, each sentence for each participant was examined in order to exclude trials if necessary. Trials were excluded if there was a track loss or if the sentence was reread. In a few cases, the eye movements were extremely erratic (due to equipment malfunction on certain trials). These trials were also removed. Overall, for the three groups of readers, 6%, 11% and 19% of the trials were rejected (for the SKH, SKD and LSKD readers, respectively). The results for the comprehension questions were 97%, 92% and 81% for the SKH, SKD and LSKD readers.

Following Rayner (1986), the wpm variable was calculated as the mean number of words per sentence/mean total time taken to read the sentence for each window size and for each participant group. The percentage of full line reading was calculated as the wpm in each window size condition (WS-2, WS-6, WS-10 and WS-14) divided by the wpm in the full length condition (WS-FL) for each subject.

3.3.2 Results

Separate analyses, by subjects (F_1) and items (F_2), were performed for the following dependent variables: wpm, percentage of full line reading speed, number of forward fixations per sentence, mean length of forward fixations, mean length of forward saccades, and number of regressions. Repeated-measures ANOVAs were performed for each dependent variable with group (SKH, SKD and LSKD) as a between-subject variable and window size (2, 6, 10, 14[20] and full length) as a within-subject variable.

For the wpm variable, there was a main effect of group ($F_1(2, 34) = 13.42$, $p = .0001$; $F_2(2, 140) = 484.96$, $p = .0001$) and window size ($F_1(4, 136) = 60.86$, $p = .0001$; $F_2(4, 70) = 47.54$, $p = .0001$). The group x window size interaction was significant in the items analysis only, ($F_1(8, 136) = 1.12$, $p = .35$; $F_2(8, 140) = 4.37$, $p = .0001$). Figure 2 shows the wpm results.

[Insert Figure 2 about here]

Because the three groups had unequal n's, Scheffé's *post hoc* tests were used to investigate the significant main effects. The *post hoc* test for group revealed that the SKH readers ($M = 293$ wpm) read significantly faster than the

[20] The numbers refer to the number of character spaces visible to the right of fixation.

SKD readers (*M* = 221 wpm, *p* = .01) and the LSKD readers (*M* = 184 wpm, *p* = .0001). The SKD readers and the LSKD readers did not differ significantly from each other (p = .10). The *post hoc* for window size revealed that there were differences between the WS-2 and WS-6 conditions (*M* = 150 wpm and 217 wpm, respectively; *p* = .0001), and the WS-6 and WS-10 conditions (*M* = 276 wpm, *p* = .0001), but not between WS-10 and WS-14 (*M* = 266 wpm, *p* = .89) or between WS-14 and WS-FL (*M* = 284, *p* = .95). This suggests that maximum reading speed was attained in the WS-10 condition and that larger windows (WS-14) did not impede the reading process. The group x window size interaction in the items analysis only reflected the fact that for the LSKD readers, conditions WS-2 and WS-6, and conditions WS-6 and WS-10 did not differ significantly (*p*s = .54 and .42, respectively), whereas these conditions differed significantly for the SKD and SKH readers ($p < .05$). For the three groups of readers however, the differences between conditions WS-10 and WS-14 were not significant and neither were the differences between WS-14 and WS-FL ($p > .05$). These results could suggest that the LSKD readers reached their maximum reading performance earlier than the SKD and SKH readers however, for the LSKD group, conditions WS-2 and WS-10 also differed significantly (*p* = 00001; as can be clearly seen in Figure 2). This indicates that like the other two groups, the LSKD readers reached maximum reading performance when they had 10 characters to the right of fixation. Overall, the *post hoc* results for window size sum up the effects and show that the three reader groups reached their maximum reading speed in the WS-10 condition and that larger window sizes did not interfere with reading by blocking out information in the perceptual span.

The analysis of the percentage of full line reading speed for the 4 window size conditions[21] yielded a main effect of group (items analysis only - $F_1(2, 34) = 1.11$, $p = .34$; $F_2(2, 112) = 7.19$, $p = .001$) and window size ($F_1(3, 102) = 106.65$, $p = .0001$; $F_2(3, 56) = 41.92$, $p = .0001$). The group x window size interaction was not significant ($F_1(6, 102) = 0.37$, $p = .89$; $F_2(6, 1120) = 0.29$, $p = .94$). Although the group effect was only significant in the items analysis, the numerical difference in the group means attracted our attention. Indeed, it appears that the SKD readers had a lower percentage of full reading speed in all the window size conditions relative to the LSKD and SKH readers. Figure 3 shows the group means at each window size condition.

[Insert Figure 3 about here]

Scheffé's *post hoc* tests replicated the results found for the wpm variable in the window size condition. A significant difference was found between the WS-2 and WS-6 conditions (M = 55% and 79%, respectively; $p = .0001$) and between WS-6 and WS-10 conditions (M = 99%, $p = .0001$), but not between WS-10 and WS-14 conditions (M = 94%, $p = .38$).

For the number of forward fixations, mean forward fixation duration (in milliseconds), forward saccade length (in number of character positions), and number of regressive fixations measures, the main effects of groups and window size were significant in the subjects and items analyses. The group x window size interaction was only significant (or marginally significant) in the items analyses

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[21] Recall that the full length unmasked condition (WS-FL) is used in the calculation of this measure, therefore the window size condition in this analysis only has four levels.

for number of forward fixations, mean forward fixation duration, and forward saccade length. See Table 3 for a summary of the ANOVA results.

[Insert Table 3 about here]

Scheffé's *post hoc* tests for the group effects revealed that for the number of forward fixations measure, the LSKD and SKD groups did not differ from each other (M = 10.8 and 10.2, respectively; p = .40), but both groups of deaf readers differed from the SKH (M = 8.47, p = .003 and p = .03, for LSKD and SKD, respectively), indicating that the SKH group made significantly fewer fixations than the two deaf reader groups at all window size conditions. *Post hoc* analysis for mean forward fixation duration yielded a similar pattern of results. Again, the LSKD and SKD were not significantly different (M = 307 ms and 280 ms, respectively; p = .10). The SKH readers (M = 250 ms) were significantly different from the SKD and the LSKD readers (p = .01 and p = .0001, respectively). For the forward saccade length measure, *post hoc* tests revealed that only the SKH and the LSKD readers differed significantly from each other (M = 7 and 5.8, respectively; p = .01), but the SKD (M = 6.4) and LSKD did not (p = .38), nor did the SKH and SKD readers (p = .28). This result indicates that the length of forward saccadic movement for the SKH was longer than for the LSKD readers in all window conditions. Finally, for the number of regressive fixations, none of the differences between groups was significant, although the SKH readers (M = 1.40) made fewer regressions into the text; the difference between the SKH, and the SKD or LSKD readers (M = 1.97 and 1.95, respectively) exhibited a trend toward significance (p = .09 and p = .10, respectively). This difference was numerically, and marginally significant, suggesting that SKH readers may be regressing into the text less than both groups of deaf readers. Figure 2 shows the results for the number of forward fixations and mean forward fixation duration variables.

Scheffé's *post hoc* tests for the window size main effects yielded similar patterns for the number of forward fixations and forward saccade length where the effect of window size ceased to interfere at a window size showing 10 character spaces to the right of fixation or more ($p < .03$ between WS-10 and WS-14, and between WS-14 and WS-FL conditions for both variables). On the other hand, *post hoc* tests for mean forward fixation duration revealed that only the difference between WS-2 and all the other conditions was significant (all *p*s < .0001). The other window size conditions did not differ from one another (*p*s > .05). This result suggests that when readers had six letters or more available to the right of fixation, they had enough information to process the fixated word at a normal speed. This is an indication of the size of the word identification span. For the number of regressive fixations measure, the *post hoc* results revealed that the four masked sentence conditions did not differ from each other (all *p*s > .05), but they all differed from the unmasked full-length control condition (all *p*s < .0001). This result is not surprising, since in the four masked conditions, only four character spaces to the left of the fixation were unmasked, potentially restricting regressions into an earlier portion of the sentences, in contrast with the unmasked full-length control condition where participants had access to the full sentence to the left of fixation, allowing them to saccade back into the text more easily.

As a final analysis, an estimated of the word identification span of the three groups of participants was calculated. The size of the word identification span was calculated for each subject by dividing the mean number of words per sentence by the mean number of fixations in the full-length, unmasked condition (see Rayner, 1986). The values were entered in a one-way ANOVA with group as a between-subjects variable. There was a main effect of group ($F(2, 33) = 3.68$, $p = .04$; see Table 4 for group means). Scheffé's *post hoc* tests revealed that the word identification span of the SKH readers was larger than that of LSKD readers ($p = .04$). No other differences reached significance although, again, the means paralleled reading level.

[Insert Table 4 about here]

3.3.2.1 Additional Analyses

As mentioned above, the groups of skilled hearing and skilled deaf readers were not matched on reading level. The inclusion of the skilled hearing reader group, even if unmatched to the skilled deaf reader group, was an attempt to reproduce eye movement effects found in the literature for adult readers. However, the differences found across the three reader groups in the analyses just presented could simply be attributed to a reading-level effect. To investigate the potential effects of deafness and increased visual perception/attention in the periphery (see Bavelier et al., 2006) and whether it affects reading is some way, the deaf participants were regrouped so that the skilled hearing readers and skilled deaf readers were as closely matched as possible. The top five readers in our sample formed the skilled deaf reader group and the other deaf readers were placed in the less skilled deaf readers group. We will label the prior set of analyses and the present one the *Full group* and *SKH-SKD matched* analyses for clarity.

Although five participants makes a very small sample, we felt justified to look at such a small sample as Rayner (1986) and Rayner et al.'s (1981) classic studies investigating the perceptual span of beginning or adult readers had 6 participants/group. With the new grouping of participants, the same analyses as in the above section were performed, but mainly, we were interested in the wpm, the word identification span, and in the percentage of full line reading speed variables.

The analysis for the wpm variable yielded a main effect of group ($F_1(2, 34) = 12.37$, $p = .0001$; $F_2(2, 140) = 274.24$, $p = .0001$) and window size ($F_1(4, 136) = 52.23$, $p = .0001$; $F_2(4, 70) = 46.09$, $p = .0001$). Again, the interaction was significant (items analysis only - $F_1(8, 136) = 1.29$, $p = .25$; $F_2(8, 140) = 3.39$, $p = .001$). The interaction in the items analysis reproduced the exact same pattern as the interaction in the analysis for the full group and did not affect the main effect of window size, therefore it will not be discussed further.

Scheffé's *post hoc* tests for the main effect of group showed that the LSKD readers differed significantly (i.e. read more slowly) from the SKH readers (M = 195 wpm and 293 wpm, respectively; $p = .0001$), but the SKD readers (M = 227 wpm) did not differ from the LSKD readers ($p = .52$). The difference between the SKH and SKD readers was only marginally significant ($p = .09$). As in the full group analysis, the *post hoc* tests for window size yielded similar results and again the three groups of readers reached full reading speed when 10 character spaces were uncovered to the right of the fixation.

Similarly to the results for the full group analysis, the analysis for percentage of full line reading speed yielded a main effect of group (items analysis only - $F_1(2, 34) = 1.55$, $p = .23$; $F_2(2, 112) = 12.46$, $p = .0001$) and window size ($F_1(3, 102) = 78.15$, $p = .0001$; $F_2(3, 56) = 35.60$, $p = .0001$). The group x window size interaction was not significant ($F_1(6, 102) = 0.45$, $p = .85$; $F_2(6, 112) = 0.23$, $p = .96$). The *post hoc* test for the window size variable replicated the *post hoc* in the full group analysis. Maximum reading speed was reached with a window size of 10 characters visible to the right of fixation. Again, the SKD readers reached lower percentage of reading speed at all window conditions relative to the other two groups of readers. Figure 3 shows the differences in means between the three groups of readers at each window size.

The analyses for the other four variables, number of forward fixation, mean forward fixation duration, forward saccade length and number of regressive fixations, replicated the full group results, except for a few differences in the *post hoc* tests for the group variable. See Table 5 for a summary of the ANOVA results.

[Insert Table 5 about here]

Scheffé's *post hoc* tests for two variables yielded different results than what was found in the full group analyses. The *post hoc* tests for the group variable for number of forward fixations revealed that the LSKD made significantly more fixations than the SKH readers ($M = 10.8$ and 8.47, respectively; $p = .0007$), but the SKD group ($M = 9.43$) did not differ significantly from the SKH or the LSKD readers (*p*s > .05). The same pattern of results was true for the mean forward fixation duration; only the LSKD readers differed significantly (i.e. made longer fixations) from the SKH readers ($M = 296$ ms and 250 ms, respectively; $p = .0005$). The SKD readers ($M = 281$ ms) did not differ significantly from the SKH or the LSKD readers ($p = .13$ and .62, respectively).

Finally, an estimate of the word identification span was calculated for each subject and a one-way ANOVA yielded a main effect of group ($F(2, 33) = 4.37$, $p = .02$; see Table 4 for group means). Scheffé's *post hoc* revealed that the word identification span of the SKH readers was again larger than that of LSKD readers

(p = .03), but the other means did not differ significantly. In this case, the word identification span for the SKH and SKD readers was equivalent (M = 1.23 and 1.21, respectively).

3.3.3 Discussion

The pattern of data in Experiment 1, in the full group analyses, generally reproduced reading level effects on eye movements as shown by Rayner (1986), who investigated the eye movement characteristics of young readers in 2^{nd}, 4^{th} and 6^{th} grade relative to adult readers. Rayner (1986) found that less experienced readers made more fixations, shorter saccades, more regressions into the text and had smaller perceptual and word identification spans than skilled adult readers. The size of the word identification span of his participants also paralleled reading level and was smaller for the less experienced readers, indicating that less skilled readers focus their attention on the foveated words and may not benefit as much from preview of words in their parafoveal vision. Overall, in the present study, the better readers read faster (see also Kelly, 1995, 2003; for skilled and less skilled deaf readers), made fewer fixations, shorter fixations and had a wider word identification span than the less skilled readers (Rayner, 1986; see also Chace et al., 2005). Although the differences between the SKD and the LSKD readers were not always significant in the *post hoc* tests, they were generally different in magnitude and the means paralleled reading level. Because there was more variation within the groups of deaf readers – recall that the reading level of each group spanned 3 to 4 grade levels - and the samples were small, the differences between the SKD and the LSKD readers may have been obscured.

The perturbing effect from smaller windows on reading was also evident and very robust for all the measures examined. The blocked information on the right of fixation prevented normal reading behaviour. As window sizes increased, reading speed increased, number of forward fixations and mean forward fixation duration decreased, and forward saccade length and number of regressive fixations increased (Rayner, 1986; Rayner et al., 1981, 1982). This was mainly true for the two smaller window sizes, WS-2 and WS-6. As in Rayner (1986), reading speed reached asymptote with larger windows, indicating that the information blocked on the right of fixation no longer impeded information processing in parafoveal vision. In the present experiment, normal reading speed appears to have been reached with a window exposing 10 character positions to the right of fixation. This result is not consistent with what is found in the literature. We will return to this issue in the *General Discussion*.

Although for the wpm measure window size interacted with reading level in Rayner's (1986) investigation, this was not the case in the present experiment[22]. The interaction in Rayner's results reflected the fact that 2nd and 4th graders had a smaller perceptual span than 6th graders and adult readers, indicating that maximal perceptual span width is reached around the 6th grade. The less skilled readers in our study read at 5th grade level and therefore, if the size of perceptual span is based on reading level, their perceptual span may have already reached its maximal extension to the right of fixation. Alternatively, it may be that because all of our participants are adult readers, extensive exposure to print[23] may also explain why, despite large reading level differences, all three reader groups appeared to reach their maximum reading speed when at least 10 character spaces were unmasked on the right of fixation. This was also supported by the results for the number of forward fixations measures.

Because the results with the full group analyses did not permit us to verify whether deafness per se (rather than reading level) has an effect on eye movements during reading (especially when it comes to the size of the perceptual span), the subject groups were re-formed so that SKD and SKH readers were

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[22] Recall that the interaction did not really change the conclusions related to the main effect of window size.

[23] Adults presumably have had more exposure to print than 6th grade children.

matched as closely as possible on reading level. These analyses yielded similar results to the full group analyses. The main difference between the full group and SKH-SKD matched analyses is that, in the latter set of analyses, SKD readers did not differ from the SKH readers on the number of forward fixation and mean forward fixations duration variables, whereas in the full group analyses, SKD readers made more forward fixations and fixation duration was longer than the SKH readers. Furthermore, interestingly, both groups of skilled readers, when matched on reading level, had identical word identification spans.

To conclude, the results for the percentage of full line reading speed analyses for the full group and the SKH-SKD matched analyses attracted our attention. As can be seen in Figure 3, in both graphs, the SKD readers did not reach 100% reading speed in any of the conditions (especially for the larger windows), whereas the LSKD and SKH readers did reach 95% to 100% reading speed in the two larger window sizes, when 10 or 14 characters were available to the right of fixation. This pattern of results holds in the full group and in the SKH-SKD matched analyses. In the latter analysis, the SKD reader group appears to be even further from reaching full reading speed at the larger window sizes. Although the perceptual span appears to extend 10 character positions to the right of fixation for all groups, the pattern of results in the full line reading speed analyses suggests that the SKD readers may not have reached full reading speed at any window size. In other words, unlike the SKH and LSKD readers, their reading may have been disrupted by the masked information even when they had 10-14 visible characters to the right of fixation. This suggests that SKD readers have a wider perceptual span than that of SKH readers. Experiment 2 was designed to investigate this pattern of results in more depth.

3.4 Experiment 2

Five deaf and five hearing participants who had participated in Experiment 1 were retested; however, the conditions in which they read sentences were changed. Three window sizes were kept from the previous study, WS-10, WS-14, and WS-FL (used as a baseline condition), but wider windows to the right of fixation were added: WS-18 and WS-22 where 18 and 22 characters were visible in parafoveal vision to the right of fixation. The size of the window to the left of fixation was kept constant with 4 letters visible as in the previous study (see Table 1).

3.4.1 Methods

3.4.1.1 Participants

The five hearing participants were randomly chosen from the original sample of hearing readers. All read at a post-secondary level (> 12^{th} grade). The five deaf readers were the five best readers in the original sample. Their reading level ranged between 10.1 to >12th grade (mean = 11.5^{th} grade). The two groups were matched on education level (*M* = 17 years for both groups) and on reading level as closely as possible.

3.4.1.2 Stimuli

Ninety new French sentences were created by using the same criteria and variables as the sentences in the previous experiment. The new sentences were also matched to the characteristics of the sentences in the previous experiment.

3.4.1.3 Apparatus, Procedure and Design

The procedure and design were the same as in the previous experiment. The apparatus was also the same, however the display was changed to a 21-inch *ViewSonic* CRT monitor and placed 71 cm from the participants' eyes. The number of characters per 1^{o} of visual angle could not be replicated exactly but was matched as closely as possible to that of Experiment 1. The sentences were presented in white 10pt *Courier New* font on a black background and 1^{o} of visual angle comprised 4.15 letters.

3.4.1.4 Data Analyses

The data were examined as in Experiment 1 for trial exclusion due to track loss, erratic eye movement (due to equipment malfunction on certain trials), or if a sentence was reread. On this basis, 3% of the data were rejected for the SKH readers and 6% for the SKD readers. Both groups had an 89% success rate on answering the comprehension questions presented throughout the reading task.

3.4.2 Results

As in Experiment 1, separate repeated-measures analyses were performed for wpm, percentage of full line reading speed, number of forward fixations, mean forward fixation duration, forward saccade length and number of regressive fixations with group as the between-subject variable and window size as a within-subject variable.

For the wpm variable, the analysis yielded a main effect of group (in the items analysis only - $F_1(1, 8) = 0.32$, $p = .59$; $F_2(1, 70) = 49.95$, $p = .0001$) indicating that the SKD group ($M = 351$) read more slowly than the SKH readers ($M = 389$). There was also a main effect of window size ($F_1(4, 32) = 3.25$, $p = .02$; $F_2(4, 70) = 5.03$, $p = .001$). The group x window size interaction was not significant ($F_1(4, 32) = 0.83$, $p = .52$; $F_2(4, 70) = 1.65$, $p = .17$).

A Newman-Keuls *post hoc* test for the window size variable revealed that the full length condition was significantly different than the smallest window size ($M = 342$ and 400 wpm, respectively; $p = .04$). Other comparisons between the different conditions were not significant (ps > .05). This result replicates the wpm results for Experiment 1 in that full reading speed appears to have been reached at the smallest window size condition, WS-10.

The analysis for the percentage of full line reading speed measure yielded a main effect of group (in the items analysis - $F_1(1, 8) = 0.69$, $p = .43$; $F_2(1, 56) = 15.54$, $p = .0002$), indicating that overall, the SKD readers reached a lower percentage of full line reading speed ($M = 86\%$) than the SKH readers did ($M = 94\%$). Although the effect was only significant in the items analysis, the pattern was found for 3/5 participants. The analysis also yielded a nearly significant effect of window size (in the subjects analysis - $F_1(3, 24) = 2.96$, $p = .053$; $F_2(3, 56) = 1.21$, $p = .31$), however, as in the wpm analysis, the only significant difference, as revealed by a Newman-Keuls *post hoc* test, was between the smallest window size (WS-10; *M* = 85%) and the largest window size (WS-22; *M* = 95%, *p* = .03). The interaction was not significant ($F_1(3, 24) = 0.18$, $p = .91$; $F_2(3, 56) = 0.61$, $p = 0.61$). Figure 4 shows the results for this measure.

[Insert Figure 4 about here]

Few results reached significance in the subject analyses for the number of forward fixations, mean forward fixation duration, forward fixation length, and number of regressive fixations variables. For brevity, the repeated-measures ANOVA results are reported in Table 6.

[Insert Table 6 about here]

Overall, the results for number of forward fixations suggest that for larger windows, the participants made fewer fixations. Interestingly, there was a marginal group x window size interaction in the subject analysis, which was also highly significant in the items analysis (see Figure 5). In the WS-10 condition (the smallest window), SKD readers made more fixations than SKH readers (*M* = 7.73 and 7.26, respectively), whereas in the WS-FL condition, SKD readers made fewer fixations than the SKH readers (*M* = 6.11 and 6.67, respectively).

[Insert Figure 5 about here]

The results for the mean forward fixation duration suggest that SKH readers spent less time fixating a word (238ms) than SKD readers (258 ms). The results for the forward saccade length measure suggest that SKD readers make longer saccades overall than SKH readers (*M* = 8.50 and 8.18, respectively; see Figure 6). Finally, the results for the number of regressive fixations did not yield great differences between the groups or window sizes. The main effect of group was not significant, however, it is interesting to note that numerically, the SKD readers made more regressions into the text than the SKH readers (*M* = 1.62 and 1.31, respectively).

[Insert Figure 6 about here]

3.4.3 Discussion

The goal of the present experiment was to compare skilled deaf and skilled hearing readers matched on reading level and investigate differences and similarities in their eye movements during reading. Specifically, the results in Experiment 1 suggested that skilled deaf readers had a wider perceptual span than skilled hearing readers, and the present experiment was intended to confirm the evidence for this observation.

The results of the present experiment revealed several differences between skilled deaf and hearing readers matched on reading level. The deaf readers were slower than the hearing readers. This was shown in the number of words per minute they processed relative to the hearing readers and in the mean forward fixation duration. Furthermore, although this difference was not significant, the deaf readers tended to make more regressions into the text than the hearing readers. The fact that the deaf readers were slower than the hearing readers can be explained by several factors. First, although in the present study deaf people were compared to hearing people reading in their first language, it has been suggested that deaf readers be considered as readers of a second language (Mahshie, 1995). Hearing fluent L2 speakers reading in their second language have been shown to read more slowly (by 100 wpm) than hearing monolingual readers (see Fraser, 2004 for a review). Therefore for hearing L2 and deaf readers, in spite of good comprehension skills in their second language, it may be that they read more slowly because they have had less exposure to their L2 than their L1. Second, our sample of deaf readers read at levels ranging from 10th grade to >12th grade (but 3/5 participants read at >12th grade), whereas all five hearing participants read at >12th grade. It may be that despite our best effort to match the deaf and hearing readers, eye movement measures are sensitive enough to pick up slight differences in reading levels. Previous research with college-level students has shown that there was enough of a reading level difference among these students to create differences in eye movement behaviour (Ashby et al., 2005; Chace et al., 2005; Jared et al., 1999).

Interestingly, the combination of three results in the present experiment suggests that deaf readers differ from hearing readers and that these differences may be due to some characteristics brought on by their deafness rather than by reading-level or the fact that they read in a language that can be considered as their L2: 1) as in Experiment 1, the SKD readers did not seem to reach full reading speed when the text was masked, even if they had 10, 14, 18 or 22 visible character spaces to the right of fixation; 2) there was a group x window size interaction in the number of forward fixations, indicating that when the sentences were masked, SKD readers made more fixations than the SKH readers, but in the unmasked full-length sentence the pattern was reversed and SKD readers made fewer fixations than the SKH readers; 3) overall, SKD readers made longer forward saccades than SKH readers. These results suggest, as was also suggested in Experiment 1, that skilled deaf readers have a larger perceptual span than the skilled hearing readers. Indeed, the percentage of full line reading speed results suggest that the reading behaviour of the skilled deaf readers is disrupted even when the larger windows are presented to them. These results are discussed in more depth below.

3.5 General Discussion

The present studies are the first studies to thoroughly investigate eye movement characteristics of adult deaf readers with varying reading levels. The eye movements of a group of adult skilled hearing readers were also observed and served as a baseline to compare with the existing results in the literature on eye movements. Interestingly, despite having three groups of readers who not only differ on reading level, but also in hearing status, several findings in the present experiments are consistent with what has been shown in previous literature on eye movements. Experiment 1 showed that reading level affects several eye movement measures in adult readers of various reading levels (irrespective of hearing status), as it does in beginning readers of various reading levels (Rayner, 1986), in college-level readers of various reading levels (Ashby et al, 2005; Jared et al, 1999) and also in skilled and less skilled adult deaf readers (Kelly, 1995, 2003, for reading rate). Indeed, the present results showed that reading speed, forward saccade length, and word identification span increased with reading level, whereas mean forward fixation duration, number of forward fixations and number of regressive fixations decreased with reading level. An even more striking result showed that the size of the word identification span of SKD and SKH readers became equivalent after the two groups were reading-level matched. Furthermore, the LSKD readers' span was smaller than that of the other two groups of readers. The word identification span is clearly determined by reading level, as was also shown in previous research (Rayner, 1986), again, irrespective of hearing status.

The finding that the LSKD readers' estimated word identification span was 0.95 suggests that they need a little more than one fixation to identify a word (as opposed to the SKD and SKH readers who need less than one fixation to identify a word as shown by their respective word identification spans of 1.11 and 1.23). A smaller word identification span for the LSKD readers would suggest that they may have more trouble processing the foveated words. They may have to devote so many resources to process the foveated word that they would not benefit from orthographic and phonological information available in their parafoveal vision to start processing words before they are fixated. Therefore, although LSKD readers are similar to SKH readers in the size of the span of effective vision (the perceptual span), they may differ qualitatively from skilled readers in that they may not benefit from word/letter information in their parafoveal vision. The difference in the estimated word identification span size however was not that large between the groups so it remains to be seen whether or not the LSKD readers would benefit from word-level information in the parafovea or not. The fact that in Experiment 1, the first fixation duration measure reached asymptote for the three groups of readers with a window size revealing only 6 letters to the right of fixation may be a better indicator of the word identification span. Because they had sufficient word-level information available in the WS-6 (and with larger windows), word processing could be normally initiated from information available in the parafovea and proceed normally. This was reflected by the first fixation duration which did not differ between WS-6 and WS-FL (or between WS-10 and WS-FL and WS-14 and WS-FL). This result suggests that in fact the three groups of readers may not differ in their capacity to use orthographic and phonological information available in the parafovea.

Another way in which deaf readers appear to differ qualitatively from hearing readers is in the number of regressions into the text. In Experiment 1, in the full group analysis for the number of regressive fixations, the SKD readers differed marginally from the SKH in the number of regressive fixations they made, but they made the same number of regressive fixations as the LSKD readers despite being more competent readers. However, an even more remarkable result (although the difference was not statistically significant) is that when matched to the SKH readers on reading level, the SKD readers still made numerically more regressions into the text than the SKH readers. In other words, this result suggests that even when they have high comprehension levels, deaf readers appear to be more cautious readers and return back into the text more often than skilled hearing readers.

Experiment 1 also reproduced the effects related to masked information in the parafoveal region to the right of fixation (Rayner, 1975, 1986; Rayner et al., 1981, 1982). In other words, when information is blocked in the parafoveal region to the right of the fixation point, reading is impeded and cannot proceed normally because of a lack of information (mainly word length and word-boundary information) to clearly guide the eyes through the text. The window size affected all the eye movement measures investigated. Indeed, reading rate and forward saccade length were decreased with the smaller windows, whereas the number and mean length of forward fixations increased. With larger windows however, in Experiment 1 with windows of 10 and 14 characters to the right of fixation, enough information was available to guide the eyes and reading could proceed normally.

The results for the size of the perceptual span were not, however, in line with what is generally reported in the literature for alphabetical writing systems (Rayner, 1998). The perceptual span, in Experiment 1, appeared to extend only up to 10 characters to the right of fixation. Rayner (1986), for example, found that for 6^{th} grade readers and adults, the perceptual span extended up to about 14-15 characters to the right of fixation. Rayner et al. (1981, 1982) found similar results for adult readers. In these studies, readers viewed 3 characters per 1^{o} of visual angle. In an earlier study with adult readers (Rayner, 1975), it was found that the perceptual span only extended up to 12 character positions to the right of fixation instead of 14-15 characters to the right of fixations. This may be related to methodological differences. In Rayner's (1975) study, 4 characters subtended 1^{o} of visual angle, similar to our study (Experiment 1), where 4.09 characters subtended 1° of visual angle. This may explain why the perceptual span of our participants was slightly smaller than what is typically reported in the literature (see Rayner, 1998, for a review). In our experiment, as in Rayner (1975), there was more information to process within the foveal region. A parallel can be drawn with research investigating the perceptual span of Japanese readers. Osaka (1992), for example, found that for kanji or kana characters (which pack more visual and linguistic information than single letters in the roman alphabet), the perceptual span extended 5-7 character spaces to the right of fixation, which is smaller than the perceptual span for English readers.

At several points in the present paper, it was suggested that the perceptual span appears to extend 10 character positions to the right of fixation, that is, it seems that beyond 10 character positions to the right of fixation, no letter or word boundary information was picked up by our participants. In fact, some results suggest that this may not be quite the case, for the SKD readers at least. Although the wpm analyses do not support this assumption, in the percentage of full line reading speed analysis in Experiment 1, the SKD readers appeared to never reach full reading speed at any of the masked window conditions, whether they had 10 or 14 characters visible to the right of fixation. Experiment 2 employed wider windows to extend the results of Experiment 1 and found similar results. There was a group effect, indicating that the SKD readers, when matched on reading level with the SKH readers, read significantly more slowly, as measured by the percentage of full reading speed variable, than the SKH readers in any of the window size conditions. In fact, even with 22 letters visible to the right of fixation, SKD readers read on average at 89% of their full reading speed in the unmasked condition. As mentioned earlier, two more results strengthen the hypothesis that skilled deaf readers have a wider perceptual span than do skilled hearing readers: in Experiment 2, the group x window size interaction in the number of forward fixations showed that when the sentences were masked, SKD readers made more fixations than the SKH readers, but in the unmasked full length sentences, the SKD readers made fewer fixations than the SKH readers. Furthermore, the SKD readers made longer forward saccades than SKH readers, suggesting that they grasp more information in their perceptual span, allowing guiding of the eyes further into the text. The fact that SKD readers have a wider span might also explain why they are slower readers than SKH readers because in each fixation they have more information to process. However, as mentioned earlier, deaf readers may be considered as L2 readers (Mahshie, 1995), therefore their slower reading rate and longer fixation durations may also be explained by this factor or by a combination of both factors.

The observation that skilled deaf readers have a wider perceptual span is not altogether surprising. Deaf people who communicate principally through sign language do rely, after all, on parafoveal and peripheral information to process sign language as they generally fixate their interlocutor's face and the hand movements are perceived in the parafovea and periphery, up to 7° on either side of fixation (Bosworth, Wright, Bartlett, Corina, & Dobkins, 2000; cited in Bosworth and Dobkins, 2002; see also Siple, 1978). Furthermore, deaf people, whether they communicate using sign language or not, must rely exclusively on visual cues (as opposed to auditory and visual cues) to monitor ongoing and upcoming events/activity in their surroundings; therefore they may rely more on peripheral cues to compensate for the lack of auditory cues (to detect a person entering a room, upcoming traffic, etc).

Much research has investigated the visual functions of deaf people (Bosworth & Dobkins, 2002; Finney & Dobkins, 2001; Loke & Song, 1991; Neville & Lawson, 1987a, 1987b, 1987c; Parasnis, 1992; Parasnis & Samar, 1985; Proksch & Bavelier, 2002, Sladen, Tharper, Ashmead, Grantham & Chun, 2005; see also Bavelier et al., 2006 for a review) and the central question is: "Do deaf individuals see better?" (from Bavelier et al., 2006). The consensus appears to be that deaf individuals do not differ from hearing individuals on general low-level visual perception (brightness discrimination, contrast sensitivity or motion direction). Rather deaf individuals appear to be better than hearing individuals in distributing their attention across the visual field and in processing low-visual information they are attending to, especially in the periphery (Bosworth & Dobkins, 2002; Proksch & Bavelier, 2002; Sladen et al., 2005; Bavelier et al., 2006). These results were found for profoundly deaf people who learned sign before the age of 5. It was therefore asked whether the ability to attend to low-level visual information beyond central vision was a function of the ability to process a language through the visual channel or a function of auditory deprivation per se. Proksch and Bavelier (2002) and Bosworth and Dobkins (2002) compared profoundly deaf signers exposed to sign language from birth (up to the age of 5), hearing signers born to deaf parents who had also been exposed to sign language from birth and hearing non-signers on attention-based visual processing tasks. They found that the deaf signers distinguished themselves from both the hearing signers and hearing non-signers, suggesting that enhanced ability to attend to visual stimuli in the periphery is due to auditory deprivation rather than to signing skills. Although this hypothesis was not tested directly in the present experiments, previous research suggests that the present finding that skilled deaf readers who communicate principally through sign language have a wider perceptual span than skilled hearing readers is a result of auditory deprivation rather than a result of their exposure to sign language.

The findings that the skilled deaf readers in the present experiments have a wider perceptual span than skilled hearing readers and the idea that this effect might be related to the fact that deaf individuals are better at deploying attention to the periphery does not link up perfectly with the E-Z Reader model of eye movement control during reading (Reichle, Rayner & Pollatsek, 2003). The size and orientation of the perceptual span (which is asymmetric to one side) have been said to be attention-based because they vary according to several factors such as reading-level, text difficulty, properties of the writing system (letters versus characters), and reading direction (see Rayner, 1998 for a review). However, within the E-Z Reader model (Reichle et al., 2003), processing of low-level visual information (such as word-boundaries) within the perceptual span is said to be pre-attentive. Within the model, words are said to be processed as objects. For the letter features within parafoveal vision to be visually integrated into a perceptual whole, or an object, attention must be allocated to the word/object. In the E-Z Reader model, attention allocation is said to be sequential and allocated to the upcoming word in parafoveal vision only,[24] one word at a time. Visual processing taking place within the rest of the effective field of vision (the perceptual span), beyond the word which is attended to, is thus considered pre-attentive (Reichle et al., 2003; 2006).

This early, pre-attentive visual processing stage is said to be important for two reasons: it provides word-boundary information so that saccades to words ahead in the text can be planned by the oculomotor system and it provides information to direct the attentional spotlight on the upcoming word so that it can be processed (Reichle et al., 2003). Reading unspaced text (readingunspacedtext) or texts where the spaces are filled (readingxtextwherexthexspacesarexfilled - with Xs or other patterns), in other words, texts where word boundaries are missing, has been extensively studied (McConkie & Rayner, 1975; Morris, Rayner & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner, Fischer & Pollatsek, 1998). Results show that reading is impeded (slowed down, saccades are shorter, fixations are longer) when there are no spaces in the text to determine word-boundaries further into the perceptual span and guide saccades. These

[24] Based on Posner (1980, cited in Reichle et al., 2003; p. 450), the attention directed to a word is termed the “attention spotlight”.

studies, although different from the present experiments, represent similar situations to what is found in the present experiment beyond the boundaries of the windows (recall the example of the mask in Figure 1 where the word boundaries are not preserved).

In the current study, the widest window extended to 22 character positions to the right of fixation. This brings the right outer boundary of the window to 5.3° degrees beyond the center of the visual field, at the limit between parafoveal and peripheral fields of vision. One hypothesis that may account for SKD readers' performance to be disrupted at all window sizes, even at the widest ones, is that the information in their parafoveal/peripheral vision is anomalous because, beyond the boundary of the window, the text is masked and the spaces between words are not preserved. Because deaf people have been shown to be better able to attend to information in the periphery, it is possible that, although early visual processing is said to be pre-attentive, their attention is triggered by the anomaly (masked word boundaries) in the parafovea/periphery in the masked conditions relative to the unmasked sentences where reading can proceed normally. Alternatively, the present results may simply indicate that the SKD readers can better process low-level visual information in written text beyond the central field, whether their attention is distributed towards the parafovea/periphery or not.

Whether the LSKD readers also have a wider perceptual span than hearing readers matched on reading level remains to be determined. In the present experiment, the LSKD readers did not differ from the SKH readers in the percentage of full line reading speed measure despite the fact that the two groups read at 5th grade and post-secondary level, respectively. Unlike the SKD readers, the LSKD readers were not disrupted by widows showing more than 10 character spaces to the right of fixations. This is consistent with previous research showing that text difficulty can reduce the size of the perceptual span (Rayner, 1986) and with research showing that the size of the span is diminished when the foveated word is difficult to process (Henderson & Ferreira, 1990). Despite the fact that the texts used were composed of easy, high frequency words, it may be that word recognition is less automatized for the less skilled deaf readers (see also Bélanger, Mayberry & Baum, submitted-a; Chapter 2), therefore requiring more resources to process the foveated word and reducing the size of the perceptual span. Thus, even if they are better at attending to information in the parafovea/periphery, deaf people who have reading difficulties may not benefit from this advantage as much as SKD readers. For the SKD readers, word identification is more automatized, making foveated words easier to process and allowing them to process more information further out into the parafovea and periphery. The size of the perceptual span in deaf readers does not therefore appear to be solely determined by auditory deprivation and this factor may be trumped by reading skills. This hypothesis needs to be further investigated, however, with less skilled deaf readers matched on reading level with hearing readers.

Taken together, the present results show that deaf readers, although often studied for their differences from hearing readers, share several similarities with them when it comes to their eye movements during reading. Like hearing readers of varying reading skills, the eye movement characteristics of deaf readers appear to be mainly a function of reading level. Still, deaf readers differed from hearing readers in two ways. First, the skilled deaf readers appeared to be more cautious than the skilled hearing readers, even when matched on comprehension levels, as they regressed more into the text than skilled hearing readers. Second, and more striking, preliminary evidence that deaf readers have a wider perceptual span was found. This finding needs to be put to further tests. Research is necessary to verify whether skilled deaf readers truly have a wider perceptual span or whether they are more distracted by anomalous information (missing word boundaries) in their parafoveal/peripheral filed of vision. However, the present findings suggest that skilled deaf readers have a wider perceptual span. Whether this is verified or not with future research, the present experiments show that, one way or another, skilled signing deaf readers transfer their enhanced visual attention allocation capacity to the reading process. Whether this is also true for less skilled deaf readers remains to be determined. Contrary to hearing readers, the size of the perceptual span in deaf readers appears to be a function of two interacting factors: reading skill and auditory deprivation.

3.6 Acknowledgements

This research was supported by SSHRC (752-2002- 2323 and 831-2002-0100) and FQRSC (83796) Doctoral Fellowships to N. Bélanger, SSHRC grant (410-200401775) to R. Mayberry, and by the Centre for Language, Mind and Brain. The authors extend their gratitude to Marc-André Bernier for invaluable help in participant recruitment and data collection, the deaf and hearing participants, and Dr. Debra Titone for the use of lab equipment.

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Table 1.

Window size conditions for Experiment 1 and 2, with number of character spaces visible on either side of the fixation point.

Window size	Label	Left of Fixation	Fixation	Right of Fixation
7[a]	WS-2*	4	1	2
11	WS-6*	4	1	6
15	WS-10* +	4	1	10
19	WS-14* +	4	1	14
23	WS-18+	4	1	18
27	WS-22+	4	1	22
Full Length (FL)	WS-FL* +	all	1	all

[a] The numbers indicate the total number of unmasked letters including the fixation point.

* Window sizes in Experiment 1

+ Window sizes in Experiment 2

Table 2.

Example of test sentences.

Sentences used in Experiments 1 and 2
Il va nager tous les jeudis avec son meilleur ami.
Je vais aider ma mère à laver les vitres de son appartement.
Mon professeur de français est un homme très drôle.
Plusieurs étudiants sont arrivés en retard ce matin.
Mon amie aimerait beaucoup aller visiter la ville de New-York.
Je vais lire un bon livre après le travail.

Table 3.

Repeated-measures ANOVA results for the measures *number of forward fixations*, *mean forward fixation duration*, *forward saccade length* and *number of regressive fixations*.

	Independent variables								
	Group			Window size			Group x Window size		
Eye movement measures	F	*p*	df	F	*p*	df	F	*p*	df
Subject analysis									
Number of forward fixations	7.46	.002	2,34	107.27	.0001	4,136	1.48	.17	8,136
Mean forward fixation duration	12.74	.0001	2,33	20.23	.0001	4,132	0.53	.83	8,132
Forward saccade length	4.95	.01	2,34	49.38	.0001	4,136	1.06	.40	8,136
Number of regressive fixations	3.45	.04	2,31	5.29	.0006	4,124	0.54	.82	8,124
Items analysis									
Number of forward fixations	331.18	.0001	2,140	56.26	.0001	4,70	7.47	.0001	8,140
Mean forward fixation duration	395.80	.0001	2,140	70.85	.0001	4,70	1.83	.08*	8,140
Forward saccade length	159.79	.0001	2,140	211.23	.0001	4,70	1.90	.10*	8,140
Number of regressive fixations	37.47	.0001	2,140	4.06	.005	4,70	1.05	.40	8,140

* = marginally significant

Table 4.

Word identification span estimates for the three groups of readers when the skilled deaf readers are not reading level matched to the skilled hearing readers and when they are reading level matched to the skilled hearing readers. Results are compared to those of Rayner (1986) for children in the 4th and 6th grade and in adult readers.

	4th Grade	5th Grade	6th Grade	9.9th Grade	12+	12+
Rayner (1986)	0.78	-	0.82	-	-	Adults = 1.08
Present Study	-	LSKD = 0.95	-	SKD = 1.11	-	SKH = 1.23
Present Study **SKD + SKH matched**	-	-	LSKD = 0.97	-	SKD = 1.21	SKH = 1.23

Table 5.

Repeated-measures ANOVA results for the measures *number of forward fixations*, *mean forward fixation duration*, *forward saccade length* and *number of regressive fixations* in the subanalyses in Experiment 1 with skilled deaf readers matched on reading level with skilled hearing readers.

	Independent variables								
	Group			Window size			Group x Window size		
Eye movement measures	F	*p*	df	F	*p*	df	F	*p*	df
Subject analysis									
Number of forward fixations	9.13	.0006	2,34	77.0	.0001	4,136	1.33	.23	8,136
Mean forward fixation duration	9.80	.0004	2,33	16.2	.0001	4,132	0.46	.88	8,132
Forward saccade length	6.23	.005	2,34	39.21	.0001	4,136	0.87	.55	8,136
Number of regressive fixations	3.73	.04	2,31	3.45	.01	4,124	0.79	.61	8,124
Items analysis									
Number of forward fixations	207.66	.0001	2,140	59.59	.0001	4,70	5.86	.0001	8,140
Mean forward fixation duration	203.84	.0001	2,140	59.29	.0001	4,70	2.25	.03	8,140
Forward saccade length	124.34	.0001	2,140	170.37	.0001	4,69	1.74	.09*	8,140
Number of regressive fixations	30.16	.0001	2,138	3.59	.01	4,69	2.59	.01	8,138

* = marginally significant

Table 6.

Repeated-measures ANOVA results for the measures *number of forward fixations*, *mean forward fixation duration*, *forward saccade length* and *number of regressive fixations* in Experiment 2.

	Independent variables								
	Group			Window size			Group x Window size		
Eye movement measures	F	*p*	df	F	*p*	df	F	*p*	df
Subject analysis									
Number of forward fixations	.0006	.98	1,8	9.32	.0001	4,32	1.96	.12*	4,32
Mean forward fixation duration	4.50	.07*	1,8	1.33	.28	4,32	1.18	.34	4,32
Forward saccade length	0.14	.72	1,8	5,93	.001	4,32	1.06	.39	4,32
Number of regressive fixations	2.02	.20	1,6	2.18	.10*	4,24	0.15	.96	4,24
Items analysis									
Number of forward fixations	0.23	.64	1,70	4.65	.002	1,70	7.02	.0001	4,70
Mean forward fixation duration	54.57	.0001	1,70	1.74	.15	1,70	2,26	.07*	4,70
Forward saccade length	17	.0001	1,70	10.42	.0001	1,70	3.21	.02	4,70
Number of regressive fixations	2.20	.14	1,67	2.94	.03	1,67	0.46	.77	4,67

* = marginally significant

Figure 1.

Example of the moving window technique on three consecutive fixations. The asterisk represents the position of the eye. In this example, the window is asymmetrical and shows 5 character positions to the left and 7 character spaces to the right of fixation.

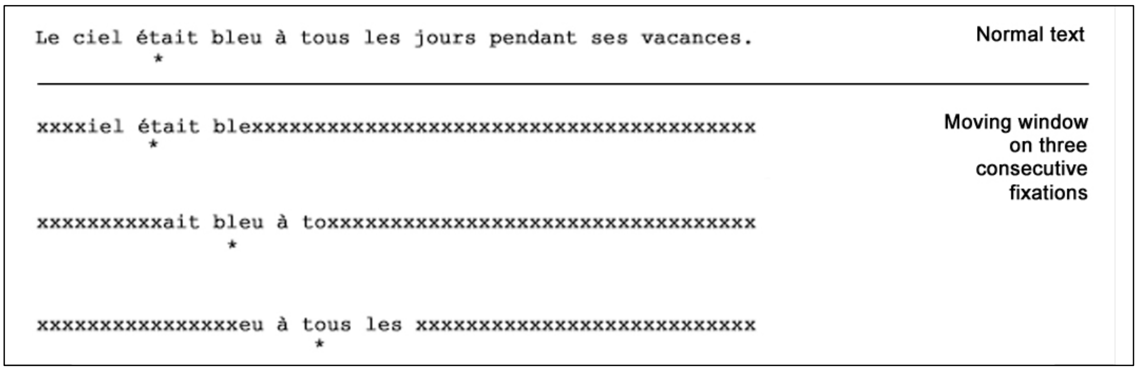


Figure 2.

Words per minute, number of forward fixations and mean forward fixation duration as a function of group and window size.

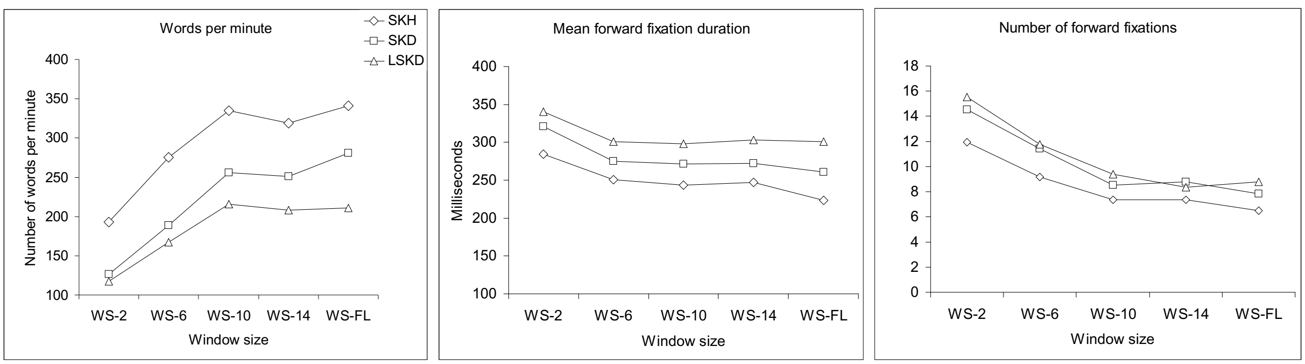


Figure 3.

Percentage of full line reading speed and standard error bars as a function of group and window size for the full group and SKH-SKD matched analyses.

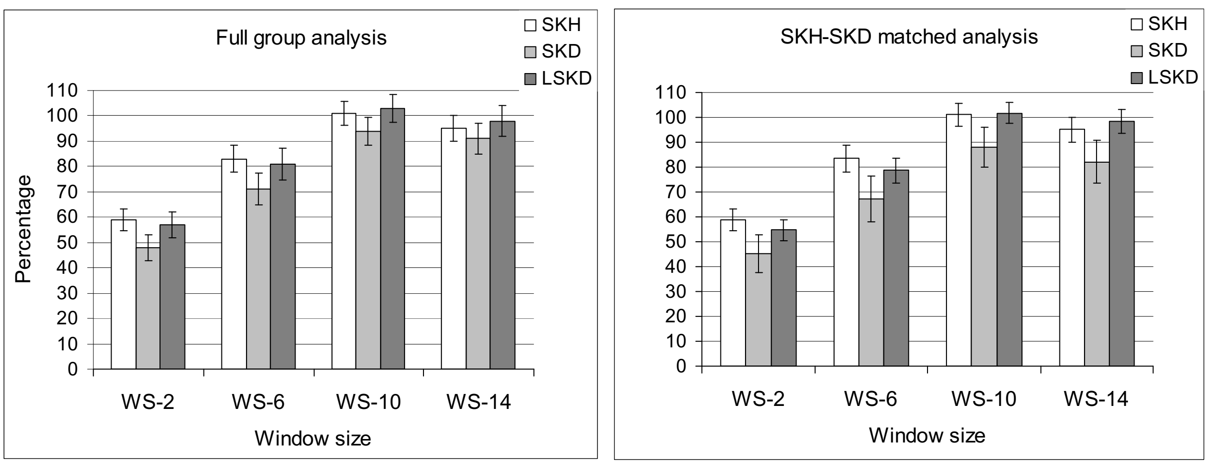


Figure 4.

Percentage of full line reading speed and standard error bars as a function of group and window size for Experiment 2.

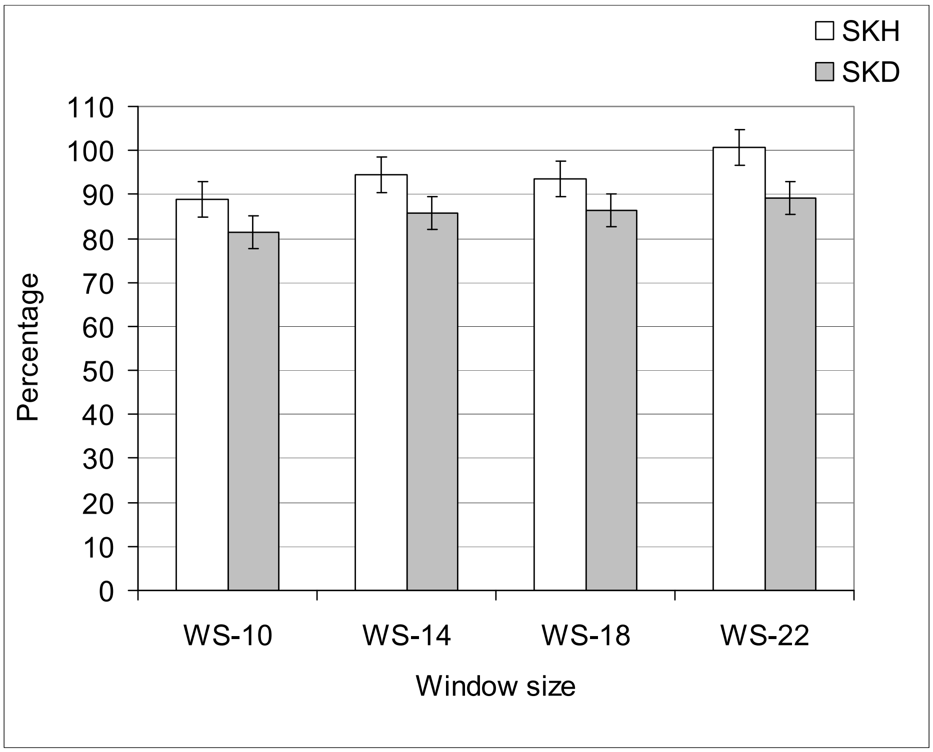


Figure 5.

Group by window size interaction for the number of forward fixation variable for SKD and SKH readers in Experiment 2.

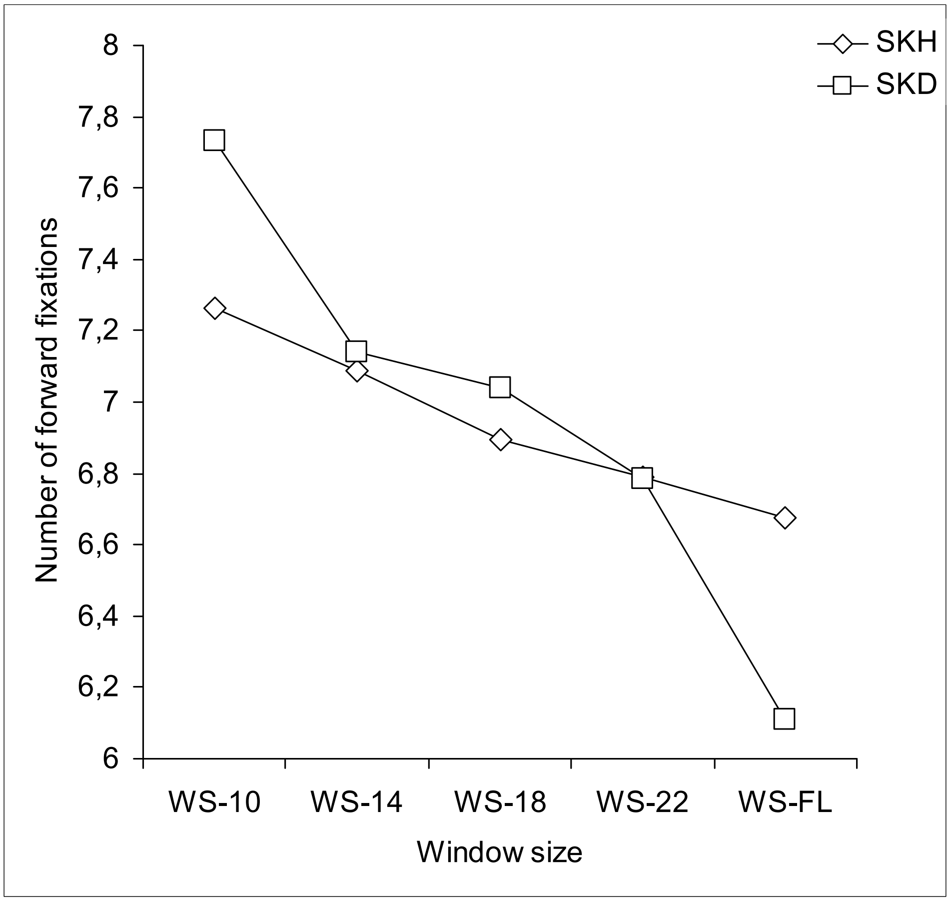
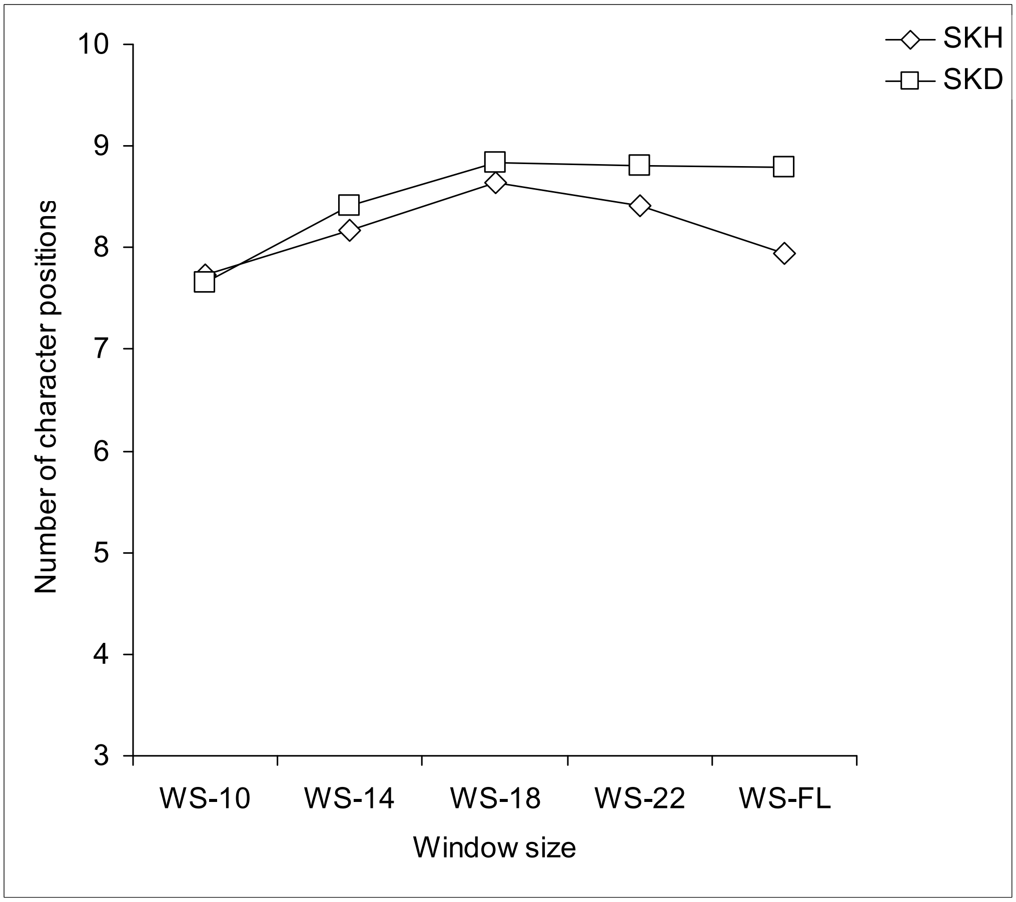


Figure 6.

Mean forward saccade length as a function of window size for the SKD and SKH readers in Experiment 2.



Preface to Chapter 4

The goal of the third study was to extend the findings of the first study and investigate the use of orthographic and phonological codes in early word processing by skilled and less skilled deaf readers of French. Previous research with skilled hearing readers has shown that while they read continuous text, they make use of orthographic and phonological information from words in their parafoveal vision, and use this information to initiate word processing before a word is fixated (Chace, Rayner & Well, 2005; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992).

The third study investigated whether or not skilled and less skilled deaf readers also use orthographic and phonological information from words in their parafovea. To do so, the same participants as in the first two studies - skilled hearing, skilled deaf and less skilled deaf readers - read single-line sentences while their eye movements were recorded. The same target stimuli as in the first study were used. Recall that the orthographic and phonological overlap between target words and pseudoword primes (to be called *previews* here) was manipulated to investigate the unique contribution of the two codes. In the third study, the target words were inserted in neutral sentences. While the participants read, the pseudoword preview was available in their parafoveal vision so that the orthographic and phonological information could be extracted from it. While the eyes moved to the location of the pseudoword preview, the pseudoword preview was replaced by the target word, the reading of which was facilitated (or not) by the orthographic and phonological information gathered from the pseudoword preview. Two classic eye movement measures were gathered for the target words: first fixation duration and gaze duration. These measures tap the earlier processes involve during word processing (Rayner, 1998).

Chapter 4

Use of orthographic and phonological information in early word recognition by skilled and less skilled deaf readers: Focusing on eye movements

Nathalie Bélanger
Rachel I. Mayberry

4.1 Abstract

Few severely to profoundly deaf individuals attain expert reading skills (Gallaudet Research Institute, 2004). Despite the belief that good phonological processing skills during reading are associated with good reading skills in deaf readers (Perfetti & Sandak, 2000), the research conducted on this question over the past decades has not yet provided clear answers as to whether skilled reading and adequate phonological processing during reading are necessarily related. The present experiment investigated skilled and less skilled adult deaf readers' use of a phonological code during early word recognition using eye movement measures. A group of skilled hearing readers was also included as a means of comparison to existing literature. Given the close mapping of orthographic and phonological information in alphabetical languages such as French, the unique contribution of both codes was investigated. Our results show that orthographic information was extracted from parafoveal vision to initiate word processing before a word was fixated. Although significant effects were not found, there were hints of phonological information processing in the parafovea as well. Interestingly, the same pattern of results was found for the three groups of readers (skilled hearing, skilled deaf and less skilled deaf readers), suggesting that reading difficulties in deaf readers may not be a matter of the encoding processes they use during early word processing.

Keywords: deaf readers, orthographic code, phonological code, eye movements, word processing, reading level.

4.2 Introduction

Deaf readers have been the focus of researchers for many years because, as a population, they achieve below standard reading levels. For the past 40 years, large-scale surveys of reading skills in the deaf population in the U.S. have shown that for deaf high school graduates, the median reading level is a third grade level[25] (Allen, 1986; CADS, 1991; DiFrancesca, 1972; Gallaudet Research Institute, 2004; Traxler, 2000; Trybus & Krachmer, 1977). The factors leading to such low reading achievement are multiple and interacting: degree of hearing loss (Conrad, 1979), knowledge of the language that is read (Goldin-Meadow & Mayberry, 2001), late exposure to a first language (Mayberry, 2007; Padden & Ramsey, 2000), degree of proficiency in sign language (Chamberlain & Mayberry, 2008; Strong & Prinz, 2000) and a limited access to the sounds of language (Perfetti & Sandak, 2000). Deaf people with severe to profound hearing loss mainly acquire, access and process a phonological code through the visual channel by lip reading, through articulatory feedback when they produce speech and partly through amplification devices if/when they are worn. As a result, deaf people's phonological representations may be thought of as *nonstandard* (Kelly & Barac-Cikoja, 2007; p. 255). Much research with the deaf population has focused on their use of nonstandard phonological codes in reading (Burden & Campbell, 1994; Chamberlain, 2002; Daigle & Armand, 2007; Dyer, MacSweeney, Szczerbinski, Green & Campbell, 2003); Hanson and colleagues, 1987, 1991;

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[25] Such data are not available in the Province of Québec, however the random sampling of participants in the present study yielded a wide range of reading skills (1st grade to post-secondary level – see *Participants* section), indicating that deaf adults in Quebec are also faced with serious reading difficulties.

Harris and colleagues, 1998, 2004, 2006; Kelly, 2003; Mayberry, Chamberlain, Waters & Hwang, 2005; Paire-Ficout, 1998; Transler, Gombert & Leybaert, 2001; Transler & Reitsma, 2005; Waters & Doehring, 1990) as phonological codes have been shown to play a significant, early role during reading and word recognition in expert hearing readers (Ferrand & Grainger, 1992, 1993, 1994; Frost, Ahissar, Gotesman & Tayeb, 2003; Lee, Rayner & Pollatsek, 1999; Perfetti & Bell, 1991; Pollatsek, Lesch, Morris, & Rayner, 1992; Rastle & Brysbaert, 2006; Ziegler et al., 2000). The results of such research, however, do not lead to clear conclusions about the use of a phonological code by deaf readers. Some research has shown that deaf readers do not appear to use phonological codes during word processing (e.g. Burden & Campbell, 1994; Waters & Doehring, 1990), whereas other studies show that they do use such a code (Bélanger, Mayberry, & Baum, submitted-a: Chapter 2; Daigle & Armand, 2007; Kelly, 2003; Transler, Gombert & Leybaert, 2001; Transler & Reitsma, 2005).

Several issues have not been addressed in the investigation of the extent to which deaf readers use a phonological code. First, it is as important to investigate the reasons why some deaf people fail to become skilled readers as it is to investigate why some deaf readers become expert readers. Surprisingly few studies in the literature on deaf readers have related their findings to well controlled reading level. Despite this lack of control in the literature, it seems to be commonly accepted that the use of phonological information in reading is principally found only in older (children), better deaf readers (Daigle & Armand, 2007; Hanson & Fowler, 1987; Perfetti & Sandak, 2000). Second, and more importantly, a survey of the literature investigating the use of a phonological code in reading by deaf individuals revealed that in many cases, the stimuli hid a potential confound between orthographic and phonological codes.

Research on expert hearing readers has shown that the effect of orthography during word recognition follows a different time-course and is independent from the effect of phonology (Ferrand & Grainger, 1992, 1993, 1994; Grainger & Ferrand, 1996; Grainger & Holcomb, 2008; Ziegler et al., 2000; Lee, Rayner & Pollatsek, 1999). This has been shown for French, English (e.g.:

Ferrand & Grainger, 1992, 1993, 1994; Lee et al., 1999-a), and even for non-alphabetical writing systems such as Chinese (Weekes, Chen & Lin, 1998). The tight mapping between orthography and phonology, particularly in alphabetical writing systems, along with the fact that effects of orthography are independent from those of phonology during word recognition suggest that it is critical that both types of codes be investigated so as to not wrongly attribute, especially in the case of deaf readers, experimental effects to the unique influence of a phonological code when the effects could also be partly attributable to an orthographic code. The dissociation of these effects is especially important to understanding reading processes in deaf individuals whose language experience is primarily through the visual modality.

The goal of the present study was to explore the use of phonological and orthographic codes in order to determine their unique contribution to the word recognition process in severely and profoundly deaf readers who use sign language. Additionally, these effects were measured as a function of the reading level of the participants. Two groups of severely to profoundly deaf signing adult readers were tested: a group of skilled deaf readers and a group of less skilled deaf readers. A group of skilled hearing readers was also included in order to compare the present results to what is found in the literature. In an effort to investigate the reading process as undisturbed as possible, an eyetracking paradigm was used. More specifically, participants' eye movements were observed to investigate the use of orthographic and phonological codes to initiate processing of words while they are in parafoveal vision.

A particularity of the visual system that must be taken into account when investigating eye movements is that the visual field is divided into three parts (foveal, parafoveal and peripheral regions) and that visual acuity decreases gradually from the fovea into the parafovea and periphery (Rayner, 1998). While a word is fixated within a sentence, additional information is available in parafoveal vision. Researchers have investigated what type and how much information is available in the parafoveal and peripheral regions, and how this information influences the reading process. It has been shown that within a region called the perceptual span, useful information (mainly word length, word-boundaries and some letter information such as ascenders and descenders, McConkie & Rayner, 1975) is gathered to guide the eyes during reading. This region extends up to 14-15 letters to the right of the fixation point. Within a smaller region, called the word identification span, word-level information (mainly orthographic and phonological codes) is retrieved and used to initiate word processing prior to a word being fixated (Rayner, Well, Pollatsek & Bertera, 1982). The region extends only 6-8 letters to the right of the fixation point.

Previous research with hearing expert readers has shown that while reading sentences, words in parafoveal vision (words located to the right of the fixated word) act as primes to themselves, and orthographic and phonological information extracted from these prefixated words is used to initiate their processing before they are actually fixated (i.e., information is extracted from words before they are fixated, Chace, Rayner & Well, 2005; Pollatsek et al., 1992). This is referred to as the *parafoveal preview benefit* (Rayner & Pollatsek, 1987). However, it is important to consider that, in general, only partial-word information is available in the parafoveal region. Readers acquire information mainly from the first three letters of a word (Lima, 1987; Lima & Inhoff, 1985; see Rayner, 1998 for a review). This is due to the size of the word identification span. When a word is fixated, usually within the first half of the word, the next word in parafoveal vision is likely to be only partially within the word identification span, especially if the next word is a long word.

Pollatsek et al. (for English - 1992) and Miellet and Sparrow (for French – 2004) investigated the effect of phonological information extracted from a preview word (or prime) when it is in the parafoveal region. To do so, both studies used what is called the *invisible boundary paradigm* (see Figure 1). In this technique, the phonological and orthographic relationship between a preview item and a target word is manipulated. The preview word is inserted in the sentence at the same position as the target. While the eyes fixate the word preceding the preview word, the preview word is in the parafoveal region and is partially processed. The preview word is replaced by the target while the eyes move from the word preceding the target to the target location. An invisible boundary is inserted before the target to trigger the preview-to-target change when the eyes cross it. The change is generally not perceived by the participants, as vision is suppressed during saccades (Rayner, 1998). The present study made use of this technique.

[Insert Figure 1 about here]

In order to measure the effect of phonological information from previews on targets, Pollatsek et al. (1992) manipulated the orthographic and phonological overlap between preview words and target words. All preview and target words were 4-7 letters long. Miellet & Sparrow (2004) used similar conditions but, in their case, the previews were pseudowords. The preview pseudowords and target words were 4-12 letters long. These two studies have shown that preview words (Pollatsek et al., 1992) or pseudowords (Miellet & Sparrow, 2004) sharing phonological or orthographic information with the target words facilitated the processing of the targets. In other words, the phonologically or orthographically related preview items were preprocessed while in the parafovea and this prepocessing of the previews facilitated the processing of the targets when they were subsequently fixated.

Pollatsek et al.'s (1992) study was replicated with hearing skilled and less skilled university-level hearing readers (Chace et al., 2005). Chace et al. (2005) found that skilled readers were using phonological information from the previews to facilitate target processing. The less skilled readers, however, did not show such an effect. Based on Chace et al.'s (2005) results, one might hypothesize that skilled deaf readers in the present study will show effects of phonological previews on target reading but less skilled deaf readers may not. However, the picture is not so clear. Previous research investigating the use of a phonological code in skilled and less skilled signing deaf adult readers (Chamberlain, 2002) and in deaf oralist[26] adults (Nemeth, 1992) showed no effects of phonology in word recognition, whereas a more recent study by Bélanger et al. (submitted-a; Chapter 2) using masked primed lexical decision showed the opposite pattern. Both skilled and less skilled signing deaf adult readers showed early phonological processing during word recognition. In fact, neither group differed from a group of hearing skilled readers in their use of orthographic and phonological codes during word recognition. The skilled and less skilled deaf readers differed only in the speed at which they recognized words, suggesting that the way deaf readers encode words may not be the source of their reading difficulty. Based on the results of Bélanger et al. (submitted-a; Chapter 2), it was expected that in the present study both skilled and less skilled severely to profoundly deaf readers who use sign language would show orthographic and phonological preview benefits. In other words, both groups of readers should use the orthographic and phonological information available in parafoveal vision to initiate word processing before a word is fixated.

4.3 Methods

4.3.1 Participants

Thirty-one deaf adults from Montreal's Deaf community were recruited to participate in the present study. They were all severely to profoundly deaf (hearing loss of 71dB or more in the better ear), prelingually deafened. They all used LSQ (langue des signes québécoise) as their main communication mode, had learned it prior to the age of 13 and had used it for more than 10 years. In the

[26] Deaf individuals communicating mainly through spoken language.

Province of Québec, several types of educational programs for deaf children have coexisted in the past decades (Dubuisson & Daigle, 1998). Therefore it was not possible to form a homogeneous group in terms of the specific type of educational program the participants attended as children with respect to whether sign language was used in the classroom (see also Chamberlain and Mayberry, 2008). However, the sample was homogenous with respect to degree and onset of deafness and daily use of a natural sign language as a primary language from childhood. The deaf participants' ages ranged between 20 and 55 years (M = 36 years). Five participants were excluded from the study because their glasses or contact lenses were not compatible with the testing equipment. In addition, two participants did not perform the task because they did not understand it.

A group of sixteen hearing adults was recruited and served as a control group. All hearing participants were native speakers of French. They were between 20 and 49 years of age (M = 32 years) and had a mean education level of 17 years (SD = 2.3). One hearing participant was excluded from the study because her glasses were not compatible with the testing equipment.

All participants had normal or corrected vision. Informed consent was obtained from all the participants and they received financial compensation for their participation. The research protocol was approved by McGill University Faculty of Medicine's Institutional Review Board.

4.3.2 Background Measures

4.3.2.1 Speech Use and Comprehension

Deaf participants filled out a self-report scale for the assessment of their speech use and comprehension (a French translation of an English scale used by Chamberlain & Mayberry, 2008). They rated their comprehension and use of French oral language on a seven-point scale in different daily contexts (within the family, at school, with friends, at work, etc.) at different stages in their lives (school age, teens and adulthood).

4.3.2.2 Reading Level Measure

Before the experimental task, the participants completed the *Test de rendement du français* (TRF- Sarrazin, 1996), a standardized test normed for readers of French in Canada. The raw score on the reading test was converted using the standardized scale to a grade level reading equivalent. All the hearing participants scored at the highest level of the reading test (>12th grade).

4.3.3 Reading Group Assignment for the Deaf Participants

The 24 deaf participants' reading level ranged from 1st grade level to >12th grade (post-secondary level – the highest level of the test). They were separated into two groups: skilled (n=11) and less skilled (n=13) readers, according to their performance on the reading test. A median split was used to create the two groups. The less skilled readers' reading levels ranged between 1st and 6.4th grade level (M = 4.8, SD = 1.3), whereas the skilled readers' reading levels ranged between 7.8th to >12th grade level (M = 9.9, SD = 1.7). Three deaf participants in this group read at the highest level of the test. A one-way ANOVA with group as the independent variable and reading level as a dependent variable revealed a significant main effect of group ($F(2,36) = 136.53$, $p = .0001$). Scheffé's *post hoc* test for the group effect revealed that the three groups differed from one another in reading level (all ps < .0003). A second one-way ANOVA was performed to compare the groups (SKH, SKD, LSKD) on their level of education. The main effect of group was not significant ($F(2,36) = 2.63$, $p = .09$), indicating that the groups did not differ in terms of numbers of years of education.

4.3.4 Stimuli

In order to assess the use of orthographic and phonological cues in parafoveal vision, pseudoword previews were presented in the parafovea and replaced by target words when fixated, as in Miellet and Sparrow (2004). In the present study, however, the length of the target words was restricted to 4 or 5 letters. The stimuli were adapted from Grainger and Ferrand's (1996) stimulus set which was composed of 30 4-letter target words. Cross-linguistic priming has been found to influence word recognition (Brysbaert et al., 1999; Van

Wijnendaele et al., 2002), therefore the original stimulus set was modified and French target words that were homographs or cognates with English words (e.g. *main*, *vent*, *zinc*, *vain*, etc.) were replaced. [27] Five-letter words were added to help generate enough strictly French items, bringing the final set of stimuli up to 34 target words (see the Appendix for a list of the target words and preview items). Based on Ferrand and Grainger's Experiment 2b (1994), the preview/target relationship was varied in four ways: (1) O+P+,[28] the orthographically similar pseudohomophone condition (mert – MÈRE); (2) O–P+, the orthographically dissimilar pseudohomophone condition (mair – MÈRE); (3) O–P–, the orthographically dissimilar nonhomophonic condition (mune – MÈRE); and (4) an unrelated condition in which the previews were orthographically and phonologically unrelated to the targets (siul - MÈRE). This set of manipulations of the relationship between pseudowords and targets teases apart the effects of orthographic and phonological information in French word processing. The comparison of the O+P+ and the O–P+ conditions gives a measure of orthographic processing. In these two conditions, phonological overlap between the two conditions is kept constant, but orthographic overlap is modulated (see

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[27] Most French-Canadians know some degree of English so the stimuli were changed to avoid a cross-linguistic priming confound in the expected pattern of results.

[28] *O* for *orthographic information* and *P* for *phonological information*. The "+" sign indicates that the preview/target pairs share a high percentage of orthographic or phonological information, and the "–" sign indicates that the preview/target pairs share a low percentage of either type of information.

Table 1) and gives a measure of the preview benefit that is uniquely attributable to the orthographic processing of words.

[Insert Table 1 about here]

To measure phonological processing, the O–P+ and O–P– conditions are compared. Between these conditions, orthographic overlap between previews and targets is kept constant, whereas phonological overlap is modulated, providing a measure of phonological preview benefit.

The word targets have a mean frequency of 120 occurrences per million. The mean number of orthographic and phonological neighbours for the targets is 7 and 40, respectively. In addition to the target words, 136 words were inserted in sentences and served as fillers. The filler target words were matched in number of letters and frequency with the experimental target words.

All the target words were inserted into neutral sentence contexts (see Table 2 for an example). Since each target was preceded by one of four previews (for the preview conditions), four sentences were constructed for each target. To ensure that the 4-5 letter word targets were not skipped, they were always placed mid-sentence and were preceded by a long verb and a short article. Furthermore, in the four sentences for each target, the word following the target was always the same. Twenty practice sentences were also prepared following the same criteria as for the experimental stimuli. In half of the practice sentences, there was a display change and the preview items were pseudowords unrelated to the practice target words.

[Insert Table 2 about here]

The experimental sentences had a mean length of 11 words (*SD* = 0.30) with a mean word length of 4.10 letters (*SD* = 0.06). All conditions were matched on these variables and also on mean print word frequency per sentence (*M* = 6124/million; *SD* = 234), as determined by the *Lexique* database (New & Pallier, 2001). The filler and practice sentences were also matched to the experimental sentences on these variables. All sentences had a simple structure in order to avoid reading difficulties related to complex syntax processing for the deaf readers (Kelly, 1998).

To ensure that the sentences would be understood by all the participants (who read from 1st grade to post-secondary grade level), the mean frequency of all the vocabulary items used to form the sentences was compared to the mean frequency of all the words in the NOVLEX database (Lambert & Chesnet, 2001). NOVLEX is a database of words taken from French school books for 8-9 year old children. The words in the experimental sentences had a mean of 1040 occurrences/million which was much higher than the overall mean frequency for all the words in the database (M = 92 occurrences/million). Finally, to ensure that during the experimental task the participants read for comprehension, yes/no questions were presented after one quarter of the sentences.

4.3.5 Design

In order to reduce subject and item variability, the prime type (O+P+, O–P+, O–P–, Unrelated) factor was treated as a within-subject variable (Frost et al., 2003). Each participant saw each target four times, once at each level of the prime type condition. Recall that the targets were inserted in different sentences. Participants were seen on two occasions at a 10-15 day interval. Two lists of sentences were created and in each list, the participants saw 17 (of 34) target words twice, but in two different conditions. In the second list, the other 17 target words were also seen twice, in the other two prime type conditions. However, to be certain that participants did not specifically identify the target words as targets because they were repeated within a test session, several of the non-target words forming the contexts were also repeated several times within the experiment. In the first testing session, the participants read sentences from the first list and in the second testing session, they received the second list of items. Each list therefore contained 68 experimental sentences. Sixty-eight filler sentences were added to each list so the participants read a total of 136 sentences per testing session. They also read twenty practice sentences, but these were the same in both lists. The order in which the two lists were presented was counterbalanced across participants. Each testing session lasted between 20 and 40 minutes.

4.3.6 Procedure and Apparatus

Eye Track 0.7.7 software developed for the eyetracking lab at the University of Massachusetts Amherst (Stracuzzi & Kinsey, 2006) was used to present the sentences. In order to avoid eye fatigue, all the stimuli were presented in white 11pt *Courier New* font on a black background. The monitor displaying the sentences was a 22-inch iiyama CRT, with a refresh rate of 150 Hz. The monitor was 85 cm away from the participants and 1^{o} of visual angle comprised 4.09 letters. All sentences were a maximum of 70 characters long (including spaces) and were displayed on a single line.

While the participants read the sentences on the display screen, their eye movements were monitored with an SR Research *EyeLink1000* eye tracker, sampling the eye position every millisecond with a 0.15^{o} mean accuracy. Recall that an invisible boundary was inserted before the target to initiate the preview-to-target change when the eyes crossed it (see Figure 1). The boundary was placed before the second to last letter of the word preceding the target. There was 1.8 ms delay (plus up to 6.7 ms to refresh the display monitor) for a display change to occur after the eye crossed the invisible boundary. The changes were not perceived by the readers as they occurred during saccades (which generally last between 25-60 ms; Rayner, 1998). Viewing was binocular, but the eye movements were recorded from the right eye only.

When the participants arrived for the first testing session, they completed the reading test and the first half of the reading experiment. The second half of the reading experiment was completed 10-15 days later. In both testing sessions, participants were told to read the sentences normally and to read for meaning. They were informed that comprehension questions would follow some of the sentences. The task instructions in both testing sessions were given to the deaf participants in LSQ by a deaf research assistant.

For the experimental task, the participants sat comfortably in front of the computer display and rested their chin and forehead on the tower-mounted *Eyelink 1000* eyetracker. Before beginning the experiment, the participants performed a 5-point calibration procedure and read 20 practice sentences. After each experimental sentence was read, during the practice and the experiment, the participants signalled they were finished reading by pressing a button on a button box. Yes/no questions appeared after some of the experimental trials and participants responded by pressing one of two buttons on the button box. A drift correction point was presented between each sentence to ensure the accuracy of data collection throughout the experiment. If the calibration became imprecise, the 5-point calibration procedure was performed again.

4.3.7 Data Analyses

In order to check for trial exclusion, all the sentences were examined. Trials were excluded if (1) the target word was not fixated, (2) the display change occurred after the critical word was fixated, (3) there were hooks,[29] (4) there was a track loss due to a blink just before, on, or just after the experimental word, (5) the display change occurred during a fixation and not during a saccade, or (6) the display change did not occur at all (because of equipment malfunction). Because of the multiple reasons to reject a trial, the percentage of rejected trials was high (46%, 41%, 45% for the SKH, SKD and LSKD, respectively). However, the rate of rejected trails here is similar to that of previous experiments using display changes (Lee et al., 1999-b; Pollatsek et al., 1992; Sereno & Rayner, 1992; Rayner, Juhasz & Brown, 2007; Rayner, Sereno, Lesch & Pollatsek, 1995). About 4% of the data were outliers and were removed from the analyses (fixations

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[29] The eyes sometimes come close enough to the invisible boundary to trigger it, but then slightly regress back so that the display change is initiated but the eyes land at the end of the previous word instead of on the target word. These situations are called "hooks" (Sereno & Rayner, 1992).

shorter than 80 ms or longer than 800 ms). The results for the comprehension questions were 91%, 90% and 82% for the SKH, SKD and LSKD readers.

4.4 Results

The measures that are presented here are standard measures used to report processing at the word level. *First fixation duration* (duration of the first fixation on the target, independent of the total number of fixations) analyses will be presented, followed by the analysis of *Gaze duration* (sum of the duration of all fixations on the target prior to the eyes moving away from it). These measures are contingent on the target having been fixated and not skipped and are considered measures which tap early first pass word processes (see Rayner, Juhasz & Brown, 2007).

Although all targets were seen twice in each session, they were inserted in different sentences. To determine whether there was a repetition effect in spite of differing sentence contexts, repeated-measures ANOVAs were performed for each measure (first fixation and gaze duration) with group (SKH, SKD, LSKD) as a between-subject factor, with preview (O+P+, O-P+, O-P-, Unrelated) as a within-subject factor, but also with target presentation order (target seen 1st or 2nd within a testing session) as a within-subject factor. Separate analyses, by subjects (F_1) and by items (F_2), were performed for each measure. The results of these analyses suggest that there was a repetition effect despite target words being embedded within different sentence contexts and that this influenced the effects related to the preview condition. Based on this interaction, it was therefore decided to examine items seen first separately from items seen second. The results of these analyses, along with more detailed results for the two measures, are described next.

4.4.1 First Fixation Duration

The analysis with the target order effect revealed a main effect of group ($F_1(2, 36) = 18.51$, $p = .0001$; $F_2(2, 256) = 159.71$, $p = .0001$) along with interactions for group x target order ($F_1(1, 36) = 11.56$, $p = .0001$; $F_2(2, 256) = 5.61$, $p = .004$) and target order x preview ($F_1(3, 108) = 3.38$, $p = .02$; $F_2(3, 128) =$

2.36, p = .07). All other effects were non-significant (all ps > .05). The target order x group interaction indicated that, although the SKH and the SKD readers were as fast for items seen first as for items seen second (SKH: M = 253 and 254 ms, p = .99; SKD: M = 278 and 293, p = .10), the LSKD readers were faster for the first items relative to the second items (M = 338 and 322 ms, p = .04). The three-way interaction was not significant ($F_1(6, 108) = 0.32$, p = .92; $F_2(6, 256) = 1.08$, p = .37).

For the items seen for the first time, a main effect of group was found ($F_1(2, 36) = 24.62$, p = .0001; $F_2(2, 128) = 105.48$, p = .0001). The main effect of preview was nearly significant in the subject analysis only ($F_1(3, 108) = 2.49$, p = .06; $F_2(3, 64) = 1.70$, p = .18). Furthermore, the group x preview interaction was not significant ($F_1(6, 108) = 0.79$, p = .58; $F_2(6, 128) = 1.32$, p = .25). A Scheffé's *post hoc* test for the group effect showed that the mean first fixation duration of SKH and SKD readers did not differ significantly (M = 256 ms and 275 ms, respectively; p = .35), whereas the LSKD readers (M = 342 ms) differed from both the SKH (p = .0001) and the SKD readers (p = .0002).

For the items seen for the second time, the same analyses also yielded a significant main effect of group ($F_1(2, 36) = 13.62$, p = .0001; $F_2(2, 128) = 62.74$, p = .0001). The main effect of preview was not significant ($F_1(3, 108) = 2.21$, p = .09; $F_2(3, 64) = 1.03$, p = .38) nor was the group x preview interaction ($F_1(6, 108) = 1.23$, p = .30; $F_2(6, 128) = 1.05$, p = .39).

4.4.2 Gaze Duration

The analyses with group, preview and target order as factors replicated the analyses for the first fixation duration measure and will not be reported here. Importantly, the target order x preview interaction was significant ($F_1(3, 108) = 3.99$, p = .01; $F_2(3, 128) = 3.21$, p = .02).

For the targets seen first, a main effect of group was found ($F_1(2, 36) = 24.27$, p = .0001; $F_2(2, 128) = 118.56$, p = .0001) along with a main effect of preview ($F_1(3, 108) = 3.89$, p = .01; $F_2(3, 64) = 2.77$, p = .05). The group x preview interaction was not significant ($F_1(6, 108) = 0.70$, p = .65; $F_2(6, 128) = 1.53$, p = .17). The means for each group are presented in Table 3.

[Insert Table 3 about here]

Scheffé's *post hoc* test for the group effect revealed that, as for the first fixation duration measure, the SKH and SKD readers did not differ significantly (M = 250 ms and 274 ms, respectively; p = .23), whereas the LSKD readers (M = 338 ms) differed from the SKH (p = .0001) and the SKD readers (p = .0002). To better asses the effects of orthographic and phonological information, planned comparisons were performed. The comparison of the O+P+ and O-P+ conditions yielded a significant main effect of orthographic preview (a 22 ms difference between conditions, $F_1(1, 36) = 8.04$, $p = .007$; $F_2(1, 32) = 8.92$, $p = .005$). However, the main effect of phonological preview was not significant (comparison of the O-P- and O-P+ conditions; 9 ms difference - $F_1(1, 36) = 1.35$, $p = .25$; $F_2(1, 26) = 3.62$, $p = .07$). The net orthographic and phonological effects (the difference between the compared conditions) for each group of readers are shown in Figure 2.

[Insert Figure 2 about here]

For the items seen for the second time, a significant main effect of group was found ($F_1(2, 36) = 15.13$, $p = .0001$; $F_2(2, 128) = 75.12$, $p = .0001$). The main effect of preview was not significant ($F_1(3, 108) = 1.15$, $p = .33$; $F_2(3, 64) = 0.92$, $p = .44$), nor was the group x preview interaction ($F_1(6, 108) = 0.97$, $p = .45$; $F_2(6, 128) = 0.86$, $p = .52$).

4.4.3 Additional Analyses

Because the reading level factor was treated as a categorical variable in the previous analyses, regression analyses were run with reading level treated as a continuous variable. This was especially pertinent in the case of deaf readers as their reading skills spanned a wide range. Because all of the SKH readers performed at ceiling level in the reading test (recall that they all read at post-secondary levels), they were excluded from the following analyses. Multiple regression analyses were not run because of the small sample size. Instead, separate linear regression analyses were run with net orthographic and phonological priming effects as dependent variables, and reading level (TRF - *Test de rendement du français*; Sarrazin, 1996) and self-rated speech comprehension as predictors for all deaf readers to ascertain whether reading level and speech comprehension were predictive of the magnitude of orthographic and phonological preview effects for the gaze duration measure. Regression analyses were also run to determine whether reading level was predicted by speech comprehension levels, and whether mean gaze duration was predicted by reading level.

The speech comprehension measure was based on self-report (see *Background Measures* section). The participants rated, on a scale from 0 to 7, how well they understand speech (lip reading) in five different situations: (1) at school/work, (2) with family, (3) with friends, (4) in shops/restaurants and, (5) with strangers. A mean was computed (range from 1 to 5.25) and was entered as a predictor in the regression analysis. The results of these analyses are reported in Table 4 for brevity.

[Insert Table 4 about here]

The only significant result was that phonological preview could be predicted by self-rated speech comprehension scores ($r^2 = .16$, $p = .05$). Interestingly, however, self-rated speech comprehension scores did not predict reading level ($r^2 = .006$, $p = .72$). Also, consistent with the group effects found in the repeated-measures ANOVAs presented earlier, reading level was highly predictive of mean gaze duration ($r^2 = .44$, $p = .0001$).

Finally, to ensure that previews were processed while in parafoveal vision, launch sites (location of the fixation prior to target fixation measured as the number of character positions) were analyzed. If the location of the fixation prior to the target fixation is too far to the left, then preview items would likely be outside of the word identification span and may therefore not be processed. In a repeated-measures ANOVA with group as a between-subjects factor and preview and target order as within-subject factors, the only significant results were the interactions for target order x preview ($F_1(3, 108) = 7.84$, $p = .0001$; $F_2(3, 128) = 2.00$, $p = .12$) and target order x preview x group ($F_1(3, 108) = 2.20$, $p = .05$; $F_2(6, 256) = 1.47$, $p = .19$); however, these interactions were significant in the subject analyses only. More importantly, the preview effect was not significant (F_1(3,

108) = 0.17, p = .92; F_2(3, 128) = 0.18, p = .91), nor was the preview x group interaction (F_1(6, 108) = 1.34, p = .24; F_2(6, 256) = 0.47, p = .83). The means (and standard deviations – in number of character positions) for the O+P+, O-P+, O-P- and Unrelated conditions were 7.0 (1.1), 7.0 (1.1), 7.0 (1.1), and 6.9 (1.4).

4.5 Discussion

The present study investigated the use of orthographic and phonological information in parafoveal vision as cues to initiate word processing by skilled hearing and deaf readers and less skilled deaf readers. Whether deaf readers use a phonological code during word recognition has not been agreed upon in the literature. Furthermore, it was suggested that phonological and orthographic codes may have been confounded in previous studies with deaf readers. The present study investigated these issues, also taking into account the reading level of the participants to test the widely accepted, but not well supported, assumption that only the better deaf readers use phonological codes in reading (Perfetti & Sandak, 2000).

The present results show that there was a repetition effect for the word targets, despite the fact that each target was presented in a different neutral sentence context where it could not be predicted. This effect interacted with preview effects, thus targets seen first were analyzed separately from targets seen second in the reading task. The results for the first fixation duration measure show that, at least for the items seen first, fixation times of the three groups of readers were highly related to reading level: the better readers fixated the target words for a shorter time and showed a hint of a preview benefit from the pseudowords seen in parafoveal vision, although this did not reach significance. Interestingly, the interaction between group and preview effects was not significant. Similar results were found for the gaze duration measure (again for the items seen first), but in this case the preview effect was significant, indicating that processing of pseudowords while in parafoveal vision influenced target processing when it was fixated. Planned comparison showed that the preview effect due to orthographic processing in the parafovea influenced target word processing, whereas the preview effect due to phonological processing did not. However, the interaction between preview and group was not significant, suggesting that target processing in the three groups was similarly influenced by the preview pseudowords. Regression analyses for the deaf participants showed that, for the gaze duration measure, orthographic or phonological preview effects were not predicted by reading level, but that phonological preview effects increased with better self-rated speech comprehension skills. Importantly, the results for the launch site analysis suggest that overall pseudoword previews were within the word identification span and indicating that phonological and orthographic information from the first letters of the preview pseudowords were available in the parafovea. These results provide two important findings which will be discussed in greater detail below: (1) the exclusive use of orthographic codes in parafoveal vision to initiate word processing; and, in line with the present study's goals, (2) the three groups showed a similar pattern of activation of orthographic information in parafoveal vision, a finding strengthened by the lack of predictive value of reading level with regard to orthographic and phonological processing in parafoveal vision.

The present findings closely replicate the results of Bélanger et al. (submitted-a; Chapter 2) in which the same participants viewed the same target words preceded by the same prime/preview pseudowords in a masked primed lexical decision task. Similar to Bélanger et al.'s (submitted-a; Chapter 2) findings, the present results again show that reading skill influences the speed at which target words are processed (Ashby, Rayner & Clifton, 2005; Bélanger et al., submitted-a, submitted-b: Chapters 2 and 3; Chace et al., 2005, Jared, Levy & Rayner, 1999; Rayner, 1986; Kelly, 1995, 2003). The results show that the relation between mean first fixation duration/mean gaze duration and reading level holds irrespective of hearing status and whether the primary language is signed or spoken. Furthermore, the present findings also demonstrate that for the deaf participants, greater speech comprehension predicts larger phonological priming/previews effects. Importantly, however, reading level is not predictive of phonological preview effects. A notable difference between Bélanger et al. (submitted-a; Chapter 2) and the present study, is that whereas early phonological priming effects were found in Bélanger et al., no such effects were found here. This issue will be addressed below. Finally, in the two studies, all groups were similarly affected by pseudoword previews (or primes).

In the present study, a combination of results (lack of group x preview interaction and lack of predictive value or reading level for the use of phonological and orthographic codes), suggests that in deaf readers, the early encoding process of words does not differ from that of hearing readers and is not related to reading level. Although limited power, due to loss of trials and to the analysis of targets seen first only, may have caused the lack of interaction between reader groups and preview effects, Figure 2 demonstrates clearly that all groups of readers show early effects of orthographic processing in parafoveal vision. In other words, all readers processed targets words similarly, when pseudoword previews in the parafovea shared orthographic information with the targets. The present results provide strong evidence for the use of orthographic codes in parafoveal vision in gaze duration measures. The effects of preview in the first fixation measure for targets seen first were only nearly significant in the analysis by subjects. However, when calculating the difference between the O+P+ and O-P+ conditions for first fixation duration, there was a 19ms effect due to orthographic previews, an effect which was of the same magnitude as the significant effect of orthographic preview found for the gaze duration measure. This suggests that orthographic codes are computed in parafoveal vision and affect the very first measures of fixation on the target words when they are fixated. These results complement the results of Miellet & Sparrow (2004), who also found effects of orthographic previews in their gaze duration analysis. In line with these results, and not surprisingly, research on word recognition in deaf children and adults has found that these readers do make use of an orthographic code (Bélanger et al., submitted-a: Chapter 2, Burden & Campbell, 1994; Chamberlain, 2002; Harris & Moreno, 2004; Miller, 2006, 2007). The present results extend these findings by showing that deaf readers, skilled or less skilled, process orthographic codes extremely early during word processing as they, like hearing readers, extract the orthographic codes even before a word is fixated while it is still in parafoveal vision. More importantly however, expert reading skills in deaf readers do not appear to be determined by the way they encode words. The skilled deaf readers in the present study did not show early word processing patterns that differed from the less skilled deaf readers (see also Bélanger et al., submitted-a; Chapter 2).

The results of the present study do not permit us to draw conclusions about the use of phonological codes by deaf readers as no effects of phonological preview effects were found across the groups of readers, hearing or deaf. Previous research with the same participants using the same stimuli and prime/preview conditions in a masked primed lexical decision task found early phonological priming effects when primes were presented for 60 ms (Bélanger et al., submitted-a; Chapter 2). Therefore, the lack of phonological effects in initial word encoding we find here cannot be due to the stimuli used. It could be argued then that the lack of phonological preview effects in the present study is due to methodological differences and to differential visual processing of the primes/previews. Indeed, in Bélanger et al. (submitted-a; Chapter 2), pseudoword primes and target words were foveated (seen in the center of the visual field), whereas in the present study, pseudoword previews were processed in the parafovea and target words were foveated. However, previous research in French and English investigating phonological previews in parafoveal vision using similar items, conditions and data acquisition methods as the present study found facilitative effects of phonological processing in parafoveal vision in hearing readers (Chace et al., 2005; Miellet & Sparrow, 2004; Pollatsek et al., 1992).

On the basis of a cursory review of the present findings, it could be argued that contrary to Pollatsek et al. (1992), and Miellet and Sparrow (2004), phonological codes are not computed in parafoveal vision; however, a close inspection of individual results prevents such a conclusion. With respect to phonological preview effects in the gaze duration measure (and in the first fixation measure), there was substantial variation across subjects. Only 31% of the participants (the proportion was the same across groups) showed facilitative effects of phonology in parafoveal vision. The remainder of the participants

(69%) showed sometimes quite large (up to 86 ms) inhibitory effects of phonological previews. Overall, the facilitative and inhibitory effects cancelled each other, leading to small, non-significant inhibitory effects on the order of 10 ms. This is not altogether surprising. Rastle & Brysbaert (2006) point out in their meta-analysis of phonological priming effects that these effects were, across the studies reviewed, in the order of 10 ms and that the effect size was small to medium in magnitude. The fact that there was both phonological facilitation and inhibition from phonological previews, even if the effect was not significant, indicates that phonological codes were activated to some degree.

The fact that phonological previews were in large part inhibitory across participants may also partially explain why there appears to be no preview effect at all when looking at the mean gaze duration in the unrelated condition (see Table 3). If phonological previews were in large part inhibitory, then conditions with high phonological overlap (O+P+ and O-P+) may be slowed down relative to those that have no phonological overlap (O-P- and Unrelated conditions) and may therefore be slowed down enough as to be almost equivalent to the effects of unrelated previews. Chace et al. (2005) found that only skilled university-level hearing readers (as opposed to less skilled university-level hearing readers) showed differences between the high overlap preview/target and the unrelated preview/target conditions. They interpreted the effect as showing that less skilled readers were so focused on processing the foveated word that they did not process information in the parafovea. This interpretation cannot explain the present results as there was a large range of reading levels in the present experiment and the presence or lack of an overall priming effect (difference between the O+P+ and Unrelated conditions) was evenly distributed across participants irrespective of reading level.

The only way in which the three groups of readers differed in the present study was in the mean length of time for which words were fixated, which paralleled reading levels as demonstrated by the robust group effects. The better the reader, the less time was spent fixating a word. This is also supported by the regression analyses for the deaf readers where reading level was found to be a strong predictor of gaze duration (see Table 4). These results indicate that the deaf readers, expert or not, differ from hearing readers primarily in the speed at which they read words. This finding suggests that the difference between groups may lie in higher level processes, not in the encoding process per se.

Previous research with skilled and less skilled deaf readers has found that reading speed is highly related to reading level (Bélanger et al., submitted-b: Chapter 3; Kelly, 1995, 2003). Surprisingly, however, when isolating the 5 best deaf readers in the present study (mean reading grade level = 11.5) so that they were matched on reading level with the SKH readers, the overall mean gaze duration of the subgroup of SKD readers was still higher (M = 276 ms, SD = 27 ms) than that of the SKH group (M = 249 ms, SD = 33 ms; see also Bélanger et al., submitted-b for similar results; Chapter 3). Reading speed differences in the deaf readers may be viewed in terms of lower automaticity of word recognition (Kelly 2003; see also Kelly & Barac-Cikoja, 2007). It has been shown that with hearing readers (grades 1 to 11), part of the variance in reading comprehension, above decoding skills and spoken language skills, can be explained by reading speed (Cutting & Scarborough, 2006; Joshi & Aaron, 2000). Skilled and less skilled deaf readers may process words in the same manner as hearing readers. They may just be slower at it, potentially creating a bottleneck of information blocking higher-level processes during reading (Laberge & Samuel, 1974; Stanovich, 1980).

One way to explain the reading speed difference is that, as suggested by Mahshie (1995), deaf readers may better be thought of as second language readers. Hearing readers of a second language also have been found to read slower when compared to a group of monolingual readers, even when fluent in their second language (see Fraser, 2004 for a review). Alternatively, it has been shown that language skills account for variance in reading comprehension and word recognition in hearing readers (2^{nd} grade to 10^{th} grade - Catts, Fey, Zhang & Tomblin, 1999; Cutting & Scarborough, 2006). Therefore, as in hearing readers, the *language basis of reading hypothesis* may be a crucial explanation for reading skill and weaknesses in deaf readers. In the case of deaf readers, however, the language basis of reading skill may not be solely based in spoken language skills. Spoken language development in deaf individuals can be laborious and is generally acquired through much overt training. Deaf children are often faced with the challenge of learning a spoken language that they cannot hear in less than natural conditions and may even be expected to learn to read before they possess a good mastery of the language they are supposed to read (Marschark, 1993; Paul, 2003). However, an increasing body of research with deaf readers suggests that sign language fluency and mastery is also an important factor influencing their reading ability (Chamberlain & Mayberry 2008; Hermans, Knoors, Ormel & Verhoeven, 2008; Hoffmeister, 2000; Strong & Prinz, 1997). Chamberlain and Mayberry (2008) suggest that "the low median reading achievement reported for the deaf student population is probably linked to incomplete language acquisition, signed or spoken" (p. 25). Oral and sign language skills were not measured in the present investigation. We nonetheless suggest that slower reading and low comprehension in deaf readers may both be attributable to low general language competence (Chamberlain & Mayberry, 2008; Goldin-Meadow & Mayberry, 2001; Paul, 2003; Waters & Doehring, 1990; Wauters et al. 2006). Although the findings of the present study do not address this particular question, there was also no evidence that deaf readers, skilled and less skilled, differed in the encoding processes used in early word recognition (see also Bélanger et al., submitted-a; Chapter 2).

A final word is necessary to discuss the repetition effects found in this study. Repetition can be informative as it also reflects natural reading processes. After all, when reading a text, words are often repeated several times. Although target words were inserted in four different neutral contexts (i.e. the target words were not predictable), there was a repetition effect in the present study, and this affected preview benefits. For targets seen for the first time, the overall effects of orthography (22 ms) and phonology (-10 ms) were of small magnitude, indicating that the processing stage of form information is extremely rapid in parafoveal vision. Repetition effects have been suggested to be due either to an episodic memory trace (a prototypical trace) or to modified lexical access processes (modified orthographic representations, for reviews see Bowers, 2000; Ferrand, 2001). The present results cannot distinguish between the two hypotheses. However, Grainger & Jacobs (1999) and Bowers (2000) suggest there is strong evidence for repetition effects to be based on increased activation of the abstract orthographic code after a word has been seen once, leading to a “a change in perceptual sensitivity such that the orthographic system is more efficient in processing repeated words” (Bowers, 2000; p. 94). This interpretation is consistent with the present results where it appears that on second encounter with target words, orthographic and phonological information in parafoveal vision may have been processed so rapidly that it was not detected by the present measures. It is important to note that all the groups in the present study showed these repetition effects, irrespective of hearing status or reading level, suggesting that sensitivity to orthographic form is a primary factor in initial word recognition.

Taken together, the present results do not permit us to definitely determine why some deaf readers become better readers than others. However, the findings do suggest that the way deaf readers encode words are not the likely source of such differences. Instead, the present findings point to lower automaticity of word processing as the basis of reading difficulties in deaf readers. Low automaticity itself may be based on several factors, one of them being language competence in general, whether in signed or spoken language. Like the findings reported in Bélanger et al. (submitted-a; Chapter 2), the current results demonstrate important parallels in the manner in which deaf and hearing readers process text and, more specifically, in the manner in which they process the orthographic and phonological properties of words. Future research should focus on other potential processing mechanisms to ascertain the basis of reading outcome variability in deaf readers.

4.6 Acknowledgements

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Table 1.

Percentage of orthographic and phonological overlap between preview pseudowords and target words in each experimental condition

	Shared letters (%)	Shared phonemes (%)
O+P+	77%	100%
O–P+	45%	100%
O–P–	45%	20%
Unrelated	0%	0%

Table 2.

Example of a target word inserted in four neutral sentence contexts

Condition	Preview	Sentences with target words in bold
O+P+	nore	Mes parents ont une maison dans le **nord** de la ville.
O-P+	naur	Je vais aller marcher dans le **nord** de la ville.
O-P-	nade	Ses enfants vont à l'école dans le **nord** de la ville.
Unrelated	sate	Cet homme aimerait habiter dans le **nord** de la ville.

Table 3.

Mean gaze duration with standard deviations in milliseconds for the four prime type conditions for each group.

Prime Type	O+P+	O-P+	O-P-	Unrelated
SKH	242 (26)	261 (30)	252 (30)	246 (29)
SKD	284 (52)	292 (54)	279 (54)	275 (44)
LSKD	318 (57)	357 (53)	351 (52)	326 (49)
Mean	281 (57)	294 (61)	303 (62)	283 (52)

Table 4.

Regression results for net orthographic and phonological preview effects and measures of reading level (TRF) and speech comprehension, for reading level and speech comprehension, and for mean gaze duration and reading level.

	Orthographic preview		Phonological preview		TRF score		Mean gaze duration	
	R^2	p^a	R^2	p^a	R^2	p^a	R^2	p^a
TRF[b]	.06	.27	.03	.45	-	-	.44	.0001
Speech comprehension[c]	.01	.71	.16	.05	.01	.72	-	-

[a]df = 1,22

[b]Test de rendement du français (Sarrazin, 1996)

[c] Self-rated

Figure 1.

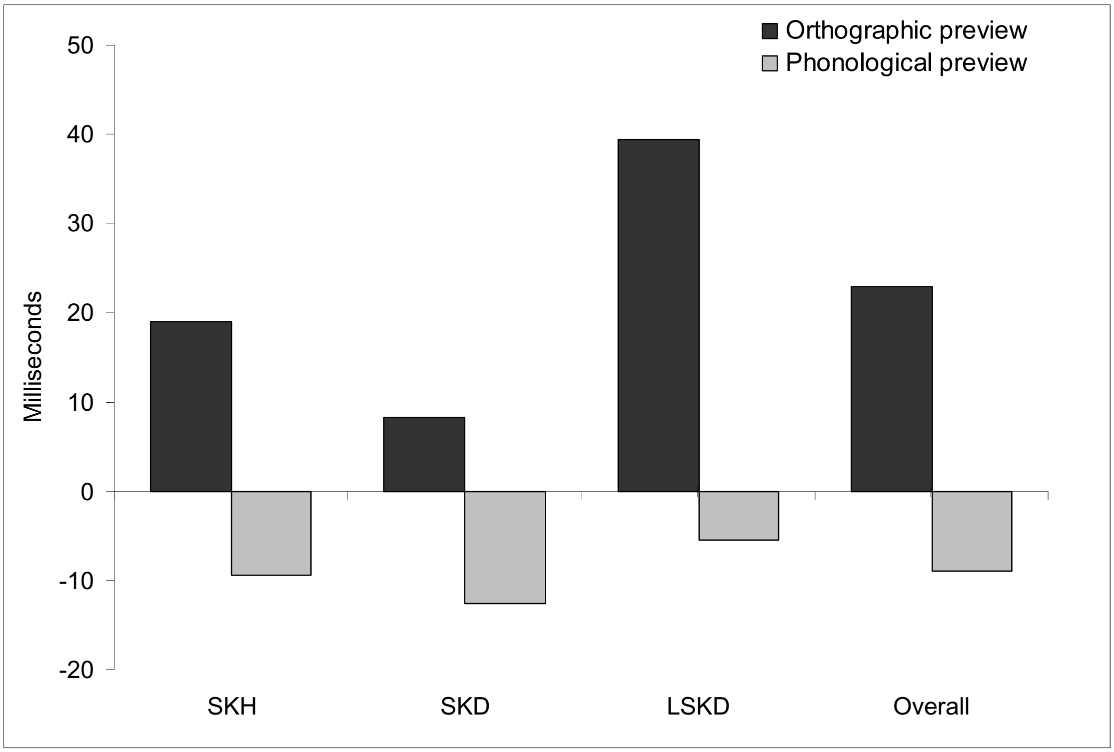
An example of the trajectory of the eyes and the related events in the invisible boundary paradigm[a].

```
    *---*----*------*------*
a)  Je vais aller marcher dans |le nore de la ville.

                                  --*
b)  Je vais aller marcher dans |le nord de la ville.

                                     ----------*
c)  Je vais aller marcher dans |le nord de la ville.
```

[a]The stars represent the location of the eye fixations and the dashed lines represent the saccades. The vertical lines indicate the location of the invisible boundary and it is not seen by the participants. In line *a)*, the word *dans* ($word_5$) is fixated and the pseudoword *nore* ($word_7$) begins to be processed in parafoveal vision. During the saccade from $word_5$ (*dans*) to $word_7$ (*nord* – see line b), the eyes cross the boundary and trigger the display change so that the pseudoword preview *nore* is replaced by the target word *nord*. When the eyes land on $word_7$ (*nord*), the preview word is already changed for the target word (*nord*). After the target word has been fixated, reading continues normally (line c).

Figure 2.

Net orthographic and phonological preview effects for the gaze duration measure for targets seen first for the three groups of readers.



Chapter 5

Discussion

The present dissertation addressed the crucial topic of reading and deafness from several angles. The main objective was to investigate how severely and profoundly deaf adults use orthographic and/or phonological codes as cues during early word processing as a function of reading level. This goal was addressed in the first and third studies with a masked primed lexical decision task (Chapter 2) and with the observation of eye movements (Chapter 4). Specifically, the latter study examined how much orthographic and phonological information was available from parafoveal vision to begin word processing before a word was fixated. A group of expert hearing readers was included in the studies to compare their results to existing findings in the literature. A secondary goal of the present dissertation was to determine the basic eye movement characteristics of the same sample of deaf and hearing readers as in the previous studies and, specifically, to examine whether the reported enhanced visual skills to the attended peripheral region of the visual field in deaf individuals affected their reading behaviour. The second study (Chapter 3) addressed these goals by gathering several eye movement measures using an eye-contingent moving window paradigm (McConkie & Rayner, 1975) and served as a bridge between the first and third studies.

5.1 Summary of the Findings

In the first study (Chapter 2), based on earlier work by Ferrand and Grainger (1993, 1994), the orthographic and phonological overlap between primes and targets was manipulated in order to dissociate the effects of both types of information (yielding four conditions: O+P+, O-P+, O-P-, and Unrelated) with a masked primed lexical decision task. Because orthographic and phonological information have been found to unfold differently across time (Ferrand & Grainger, 1994; Ziegler et al., 2000), two prime durations were used (40 ms and 60 ms) to better tap the timing component of word processing. The participants were skilled hearing readers (reading at post-secondary level), skilled deaf readers (mean reading level 9.7th grade) and less skilled deaf readers (mean reading level 4.8th grade). Previous findings on early orthographic and phonological priming effects were replicated (Ferrand & Grainger, 1994; Zielger et al., 2000). With a 40 ms prime duration, effects of orthographic priming were found, but no effects of phonological priming emerged. With a prime duration of 60 ms, effects of orthographic and phonological priming were found. The most striking finding of this study, however, was that the overall priming effects were not different across the groups of readers; skilled or less skilled, hearing or deaf. Regression analyses confirmed this pattern of results for the deaf readers as phonological and orthographic priming effects were not predicted by reading level. It was also shown that for the deaf readers, self-rated speech comprehension was not related to the magnitude of phonological priming effects. The accuracy scores were very high for all three groups, indicating that the participants had no difficulty recognizing the experimental items. In fact, the only measure on which the three groups of participants differed was in terms of speed of processing: the better readers they were, the faster they responded. It was concluded based on the overall findings that, in the case of deaf readers, the encoding processes, at least in the earliest moments of word recognition, may not be the source of the reading difficulties for this population. It was argued that the difference between skilled and less skilled deaf readers may be related to low automaticity in word recognition as demonstrated by the speed differences between groups. It was further suggested that low word recognition automaticity may be due to low general language competence.

In the second study (Chapter 3), two experiments were conducted. In the first experiment, eye movements were gathered using an eye-contingent moving window paradigm (McConkie & Rayner, 1975) to determine the basic eye movement characteristics of the same groups of readers who took part in Study 1. Several eye movement measures (number of words read per minute (wpm), mean forward fixation duration, number of forward fixations, number of regressive fixations, forward saccade length, size of the word recognition span and percentage of full reading speed) were gathered in four conditions where the window sizes were incrementally smaller and compared to an unmasked baseline condition. Several important results emerged from this study. Overall, Experiment 1 revealed that the eye movement measures collected reproduced the patterns found in the literature for hearing readers (Rayner, 1986; Chace et al., 2005) and were closely tied to the reading level of the participants, irrespective of their hearing status.

More specifically, the main findings of Experiment 1 revealed that, irrespective of hearing status, reading speed and forward saccade length increased with reading level, whereas mean forward fixation duration, number of forward fixations and number of regressive fixations decreased with reading level. The estimated size of the word identification span was also determined by reading level: the hearing skilled readers had a larger span than the deaf skilled readers, who had a larger span than the less skilled deaf readers. Recall that the skilled deaf readers read at an overall lower reading level than the skilled hearing readers, however when the five best deaf readers were matched to the skilled hearing readers on reading level, the size of their word recognition span matched that of hearing readers. Overall, deaf readers differed from hearing readers in two important ways: the number of regressions back into the text and, more importantly, in the size of their perceptual span (for the skilled deaf readers at least). Skilled deaf readers made more regressions into the text than skilled hearing readers. This was true even for the smaller sample of skilled deaf readers matched on reading level with the skilled hearing readers, indicating that they were more cautious readers than skilled hearing readers even if their reading comprehension was good.

The most striking finding was that skilled deaf readers were more affected by blocked text in the parafoveal vision than skilled hearing readers. When looking at the percentage of full reading speed in each window size condition,[30] reading in the group of skilled deaf readers was still impeded even with the largest window available (which uncovered 14 letter spaces to the right of fixation) relative to the baseline unmasked condition. This suggested that blocked information in parafoveal vision, contrary to the skilled hearing readers, was affecting skilled deaf readers' reading behaviour even when text was available up to 14 letter spaces away from the center of fixation. This pattern of results also held when a subgroup of skilled deaf readers matched on reading level to the skilled hearing readers was considered. It was suggested that skilled deaf readers' perceptual span may be wider than that of skilled hearing readers.

To better understand this notable finding, Experiment 2 was set up using the same procedure as in Experiment 1, but larger windows (up to 22 letter spaces to the right of fixation) were included to see how far the skilled deaf readers' perceptual span extended compared to that of skilled hearing readers. In this experiment, only two groups of five skilled deaf and hearing readers matched on reading level were tested. This experiment revealed several findings. First, the deaf readers read fewer words per minute than the skilled hearing readers; they were slower readers, even if their comprehension levels matched that of hearing readers. Second, and most importantly, the skilled deaf readers, again, were impeded in their reading compared to the skilled hearing readers (as measured by the percentage of full reading speed variable), even when a window of visible text

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[30] Recall that this variable is the reading speed in each of the masked conditions relative to the unmasked condition where reading should be unimpeded.

extended out to 22 letter spaces to the right of fixation. This, it was suggested, indicates that the perceptual span of skilled deaf readers extends further out than that of skilled hearing readers, which, in this study, had a perceptual span extending out to about 10 letter spaces to the right of fixation.

The overall conclusion for Experiments 1 and 2 (Study 2; Chapter 3), was that deaf readers are very similar to hearing readers in many ways when it comes to basic eye movement characteristics: these were highly reflective of reading level, irrespective of hearing status. Crucially, a wider perceptual span for skilled deaf readers was interpreted in terms of their reported enhanced visual skills in peripheral vision under conditions of attention. Based on previous vision research findings, it was concluded that the size of the perceptual span in deaf readers must be determined, not only by reading level, but also by sensory compensation which is itself due to auditory deprivation. The less skilled deaf readers, contrary to the skilled deaf readers, did not appear to have a wider than normal perceptual span (Study 2 - Experiment 1), thus it was concluded that reading level trumps the sensory compensation effect in determining the size of the perceptual span in deaf readers.

Finally, in the third study (Chapter 4), the same question as in the first study was examined, but this time eye movement measures were gathered while the participants (the same three groups as in the previous studies) read single-line sentences. The same stimuli were used. Recall that the orthographic and phonological overlap was manipulated between target words and pseudoword primes. The target words in this study were imbedded within neutral sentences rather than presented in isolation. Using an eye-contingent invisible boundary paradigm, the pseudoword primes (or previews) were presented in parafoveal vision and were replaced by the targets after the eyes crossed a specific location (the invisible boundary) in the text. *First fixation duration* and *gaze duration* were analyzed. Because each target was seen twice in each testing session, the first and second viewings of a target word yielded different results, even if they were embedded in different sentences, therefore targets seen first or second were analyzed separately.

For the targets seen first, the results showed that for first fixation duration and gaze duration, reading time of the targets was again highly reflective of reading level (this was also true for targets seen second): better readers read target words faster. A preview benefit effect from pseudoword previews in parafoveal vision was apparent only in the gaze duration measure (although there was also a trend for such an effect in the first fixation duration measure). A further investigation of the preview benefit in gaze duration showed that it was due to orthographic information shared between pseudoword previews and target words, and not to phonological information. It was acknowledged that there were statistical power issues because of the large amount of data loss in the study, but the patterns of preview benefits from orthographic information in the parafovea were remarkably similar across the three groups of readers, replicating the findings of the first study. Although no significant phonological activation was found for first fixation duration and gaze duration, there was some phonological activity created by the preview pseudowords as shown by the predominantly (but non-significant) inhibitory effects of phonological information shared between pseudoword previews and targets. Again this pattern was consistent across the three groups of participants. Based on this observation, it was difficult to argue that there was no phonological processing at all from pseudowords presented in the parafovea. Phonological preview magnitude was related to self-rated speech comprehension scores only, suggesting that the participants who rated themselves as better speech comprehenders had larger effects of phonological previews. However, and more importantly, as in the first study, the magnitude of orthographic and phonological preview effects was not related to reading level in deaf readers. Finally, in the analyses of the targets seen second, it appears that the repetition effect masked the effects of any potential preview benefit from the pseudoword primes as the magnitude of the repetition effect was likely to be larger. The repetition effect was found for the three groups of readers indicating that processes involved in the repetition effect, whether due to an episodic memory trace or to increased activation of the abstract orthographic code (Bowers, 2000; Ferrand, 2001 for reviews), were not different across the groups of readers, again, irrespective of reading level or hearing status. Overall, it was concluded for the third study, as for the first study, that the way deaf readers encode words, at least in the earliest moments of word processing, is not the source of their reading difficulty. Again, the results suggest that low automaticity in word recognition due to potential low language competence may be the source of reading difficulties in deaf readers.

Taken as a whole, the present work finds more similarities than differences between hearing and deaf readers. Not only did deaf readers' basic eye movement characteristics reproduce in large part the patterns found for skilled and less skilled hearing readers, deaf readers, skilled or not, shared with hearing readers word encoding processes very early in word recognition. That is, deaf or hearing readers both encoded words orthographically in the earliest moments of word processing, as shown by the results of Studies 1 and 3. They also used phonological codes in early word processing, as shown by the results of Study 1 (and also indirectly by the results of Study 3). Importantly, consistent with these findings, the reading level for the deaf readers was not predictive of their use of a phonological code during word processing, again in Studies 1 and 3.

There were, however, two important and noticeable differences in the findings summarized above: deaf readers read more slowly than hearing readers (even when matched on reading level) and skilled deaf readers appear to have a much wider perceptual span than skilled hearing readers. The following sections discuss these results in greater depth.

5.2 The Present Findings in a Broader Context

Because of the different nature of Studies 1 and 3 relative to Study 2, their implications, although linked, will be discussed in two separate sections below. First, the use of orthographic and phonological codes by skilled and less skilled deaf readers will be discussed, followed by the implications of Study 2 with regard to the suggested wider perceptual span of skilled deaf readers.

5.2.1 Use of Orthographic and Phonological Codes in Early Word Recognition: Implications

With regard to early orthographic and phonological information processing during word recognition, it is unclear at the moment how it is possible to integrate results for the masked primed lexical decision task (Chapter 2) with the results from the eye movement study (Chapter 4) within one single model. The present work did not intend to test different models and integrate word recognition models with eye movement control models. However it can be said that seeing words in isolation (as in lexical decision tasks) or within sentences (as in eye movement tasks) implicate different processes mainly dictated by the properties of the visual field, principally in terms of visual acuity distribution across the field. Models of word recognition view word processing as different types of information being activated in parallel (BIAM: Grainger et al., 2003; DRC: Coltheart et al., 2001), whereas eye movement control models view word recognition either as a two-stage process (E-Z Reader: Reichle et al., 2003, 2006; SWIFT: Engbert et al., 2002, 2005) or as occurring in parallel (Glenmore: Reilly & Radach, 2003, 2006). The Glenmore is closer to word recognition models than the E-Z Reader and the SWIFT models because a parallel processing interactive activation model (McClelland & Rumelhart, 1981) adapted from single word recognition research was integrated into its architecture. However, the Glenmore does not account for recent developments in word recognition research where separate orthographic and phonological routes are necessary to account for dissociated effects of orthographic and phonological codes (as found in the present study). Thus, Study 1's (Chapter 2) and Study 3's (Chapter 4) results with regard to current models will be addressed separately in this perspective.

The results for the masked primed lexical decision task fit well within the *Bi-modal Interactive Activation Model* (BIAM: Grainger et al., 2003) as argued in the discussion of the first study (Chapter 2). The BIAM posits separate routes for orthographic and phonological representations. In other words, the effects of both types of information are dissociated, as found in the present work (Study 1): orthographic and phonological information uniquely contributed to early word recognition. Furthermore, the BIAM accounts for the different time-course of orthographic and phonological information by proposing an entry point into word processing through prelexical orthographic representations, which then spread to phonological representations shortly after via an orthography-to-phonology interface. Recall that, consistent with previous research on word recognition (Ferrand & Grainger, 1992, 1993, 1994; Ziegler et al., 2000), the present work (Study 1) revealed that orthographic representations were activated with a prime duration of 40 ms, whereas phonological representations were only activated with a slightly longer prime duration (60 ms). Crucially, however, the use of briefly presented pseudoword primes activated prelexical phonological (and orthographic) representations, which then facilitated target processing [31]. This is contrary to what the DRC model (Coltheart et al., 2001) would predict. This model predicts that only less frequent regular words and pseudowords are processed through the GPC route (i.e. the only route where prelexical phonological processing can occur). Although word frequency was not a controlled factor in the present work, recall that the target words covered a large frequency range (2 to 738/million) and that the overall priming effect was consistent across items (as shown by robust effects in the by-items analyses). In other words, the prelexical orthographic and phonological effects were not apparent just for low frequency words, a result which is more consistent with the BIAM model (Grainger et al., 2003) than with the DRC model (Coltheart et al., 2001)

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[31] It must be pointed out here, that the exact nature of the prelexical units used in the present study (graphemes, rhyme, syllables) cannot be determined as this factor was not controlled.

As for the findings of orthographic preview effects in the eye movement study (Chapter 4), it is not possible to interpret them within the framework of the Glenmore model (Reilly & Radach, 2003, 2006), because it posits one single undissociated route for orthographic and phonological preview effects. Although only the orthographic preview benefit effect was significant in this study, there was an indication of phonological activity as pseudoword previews were processed in the parafovea. At present, it is suggested that the results of this study fit better within the E-Z Reader model (Reichle et al., 2003, 2006). It is unclear, however, that word recognition should be viewed as a two-stage process as the model claims. This issue is beyond the scope of the present work and until more research is done on the exact unfolding of word recognition in eye movement control models, the present results fit well with one of the proposed definitions of the L1 and L2 stages in the E-Z Reader model (recall that the authors remained "agnostic" as to the exact nature of these stages). More specifically, the results of Study 3 (Chapter 4) fit well with the proposition that the L1 stage of word recognition is a familiarity check based on form information (orthographic and/or phonological information), whereas the L2 stage is based on access to meaning, which comes later on. Because the preview items in Study 3 were pseudowords, it is likely that only form (orthographic and phonological codes) information was activated while these items were processed in parafoveal vision and that meaning activation was not the cause of the preview effects in the present work.

With regard to the question as to whether or not deaf readers use a phonological code in reading, the fact that deaf participants show evidence for phonological coding (in Study 1 – and some phonological "activity" in Study 3) supports earlier research on word recognition showing phonological effects in deaf readers (Daigle & Armand, 2007; Dyer, et al., 2003; Hanson & Fowler, 1987; Leybeart & Alegria, 1993; Paire-Ficout, 1998; Transler & Reitsma 2005; Transler et al., 2001; Transler et al., 1999). In addition, the fact that pseudowords were used as primes (or previews) suggests that a prelexical code was used to facilitate target reading, indicating, as in previous research (on syllables or rhyme as processing units, for example), that deaf readers do use smaller units of processing during word recognition (Daigle & Armand, 2007; Dyer et al., 2003; Hanson & Fowler, 1987; Olson & Nickerson, 2001; Transler et al., 2001; Transler et al., 1999). The present investigation (Studies 1 and 3) also provide more evidence for the use of an orthographic code by deaf readers (Beech & Harris, 1997; Burden & Campbell, 1994; Miller, 2004, 2006; Transler et al., 2001). Overall, Studies 1 and 3 are the first ones to report early automatic involvement and unique contribution of orthographic and phonological codes in skilled and in less skilled deaf readers. These results are at odds with the commonly accepted, but not well supported, view that phonological codes are only used by the better deaf readers (Daigle & Armand, 2007; Hanson & Fowler, 1987; Perfetti & Sandak, 2000). The present findings cannot determine the exact nature of the phonological codes used by the deaf readers, however. As mentioned repeatedly, it has been suggested that phonological representations in deaf readers are *nonstandard* (Hanson & Fowler, 1987; Kelly & Barac-Cikoja, 2007; Olson & Caramazza, 2004) and are based on a mix of visuo-articulatory, articulo-kinesthetic and acoustic cues (from residual hearing – but this varies according to degree of hearing loss and use of hearing aids), leading to partially (but not necessarily) sound-based, abstract phonological representations. It appears that despite the fact that deaf readers develop *nonstandard* phonological representations (Hanson & Fowler, 1987; Kelly & Barac-Cikoja, 2007; Olson & Caramazza, 2004), the deaf readers in the present studies could use these (multi)specified representations extremely quickly as an entry point into the mental lexicon.

Taken together, the results of the studies conducted for the present dissertation can be interpreted within the *Simple View* of reading (Hoover & Gough, 1990). In the *Simple View* of reading (Hoover & Gough, 1990), two components are said to be involved in reading comprehension: fluent word recognition and language comprehension. Both components are said to have equal importance in explaining optimal reading comprehension. Joshi & Aaron (2000), however, have also suggested that a reading speed component be added to the *Simple View* of reading. The *Simple View* of reading was mainly developed in relation to reading in children and adolescents (Catts, Adolf & Ellis Weismer, 2006; Catts, Fey, Zhang & Tomblin, 1999; Cutting & Scarborough, 2006; Nation & Snowling, 2004), however it has also recently been shown to be relevant to explain reading in adult university-level readers (Kirby & Savage, 2008). Recall that the main difference between the skilled hearing readers, skilled deaf readers and less skilled deaf readers was speed of processing, a result which was consistent across the three studies that were conducted for the present work. In the discussion of Studies 1 and 3, it was suggested that the basis of reading difficulties in deaf readers was not related to the way these readers encode words and that variation in reading speed rather lies in the fact that deaf readers may have low general signed and spoken language competence (see also Goldin-Meadow & Mayberry, 2001; Chamberlain & Mayberry, 2008).

Previous research on the language basis of reading has shown that language comprehension is not only a predictor of efficient reading comprehension (Catts et al., 1999; Cutting & Scarborough, 2006; Nation & Snowling, 2004), but also a predictor of word recognition (Nation & Snowling, 2004). Although this was not tested directly, it is suggested here that the difference in reading speed found across the reader groups could be accounted for by the language comprehension component of the *Simple View* of reading. Deaf children lack the necessary auditory input to develop spoken language without rehabilitative intervention (rather than learning a language from a natural context). This may lead deaf children, especially deaf children of hearing parents who are less likely to be exposed to a signed language from birth, to have developed low general language competence (Chamberlain & Mayberry, 2008), a factor which is also highly modulated by the age of first language acquisition in deaf children (Mayberry, 1993, 2007, for a review; Boudreault & Mayberry, 2006; Mayberry & Eichen, 1991; Mayberry & Fischer, 1989; Mayberry & Lock, 2003; Newport, 1990). The low general language hypothesis for deaf individuals is supported by studies finding that they may have lower spoken and signed vocabulary than hearing age-matched peers (Traxler, 2000; Yoshinaga-Itano, 1994) and weak syntactic comprehension skills in the spoken language (Kelly, 1993, 1996, 1998;

Kelly & Barac-Cikoja, 2007 for a review), but also by studies showing that skills in sign language are an important factor in the development of good reading skills (Chamberlain & Mayberry, 2008; Goldin-Meadow & Mayberry, 2001; Padden & Ramsey, 2000). Because both reading comprehension and word recognition can be influenced by language comprehension skills and language comprehension skills - signed or spoken - are often not optimal in deaf individuals, it is suggested that degree of general language comprehension skills may explain the reading differences found across the different groups of readers in the present studies. This is in line with a *Simple View* of reading (Hoover & Gough, 1990) and the fact that the deaf readers in the present study did not differ on word encoding processes but still differed in reading comprehension ability.

5.2.2 Implications of a Wider Perceptual Span on Reading and Word Recognition

One of the striking findings in the present work is that skilled deaf readers appear to have a larger perceptual span than skilled hearing readers matched on reading level. Their word identification span was also calculated, based on Rayner (1986), by dividing the mean number of words per sentence by the mean number of fixations per sentence. On this measure, the skilled deaf readers did not differ from skilled hearing readers. This measure however is an estimate of the word identification span (see Rayner, 1986) and does not determine precisely how many letters to the right of fixation are used to initiate word processing, but rather suggests the number of fixations taken to identify a word (1.23 in the case of the skilled hearing and deaf readers). It was suggested in the *Discussion* section of the second study (Chapter 3) that the fact that skilled deaf readers have a wider perceptual span may be due to sensory compensation (which is itself due to auditory deprivation), although this was not directly tested. It was also suggested that one of the reasons why skilled deaf readers read more slowly than skilled hearing readers, even when the two groups are matched on reading level is that skilled deaf readers may have more information to process simultaneously in their perceptual span, thus slowing them down.

The eye movement control models introduced earlier make specific prediction with regard to word processing in parafoveal vision. The E-Z Reader model (Reichle et al., 2003, 2006) assumes that one word is processed at a time. The SWIFT (Engbert et al., 2002, 2005) and Glenmore (Reilly & Radach, 2003, 2006) models rather assume that several words are processed in parallel. For example, in the SWIFT model, it is predicted that four words are processed in parallel (Engbert et al., 2002, 2005): the fixated word, one word to its left and two words to its right. Such a prediction would suggest that parafoveal preview benefits could be obtained from the second word away to the right of the fixated word. Only two published studies have investigated this effect (Rayner, Juhasz & Brown, 2007; Angele, Slattery, Yang, Kliegl, & Rayner, 2008). Neither study found that any type of information was extracted from the second word (n+2) away from the fixated word to initiate its (n+2) processing. Angele et al. (2008) however, discuss an unpublished study (Radach, Glover & Vorstius, 2007; cited in Angele et al., 2008) where information was extracted from word(n+2) when the fixated word(n) was a very short word. This leaves open the debate between the models as to whether there is more than one word treated in parallel during sentence reading. Related to the present experiment however, it also opens the door to the possibility that deaf readers may process more than one word at a time as well. As mentioned earlier, the word identification span, as calculated in Study 2 (Chapter 3) is only an estimate and is not specific enough to determine whether skilled deaf readers processed more than one word at a time or not. Besides the evidence that skilled deaf readers seem to have a larger perceptual span, it was shown in Experiment 2 (of Study 2) that in the unmasked sentence reading condition, they made overall fewer fixations and longer forward saccades than skilled hearing readers. Although the differences were not significant between skilled deaf and hearing readers, they were different in absolute magnitude, suggesting that skilled deaf readers may have extracted more visual information in their perceptual span, but also potentially more word-level (orthographic and phonological) information from a wider word identification span, allowing them to process more than one word at a time and slowing their reading speed. This is a potentially important finding that requires further investigation.

5.3 Limitations and Future Directions

Though there are some limitations, the several strengths of the present work should be highlighted. The present studies are the first to investigate the early processes involved during word recognition in deaf readers. Most previous work with deaf readers has examined the use of phonological codes in memory or has used word processing tasks that left room for strategic use of phonological codes. A masked primed lexical decision task with brief prime durations and eye movement measures both combined with pseudoword primes/previews ensured that the earliest moments of word processing were tapped and that other extra-verbal strategic processes did not taint the results. The present work was also the first study to investigate the eye movement characteristics of deaf readers and to examine whether there was any effect from their reported enhanced visual skills in the attended peripheral region while they read. An important finding resulted from this research: skilled deaf readers do seem to have a wider perceptual span than hearing readers, suggesting that they process low-level visual information differently while reading, but also implying that skilled deaf readers may process information from more than one word at a time. This is an important question which needs further investigation. The most important design feature of the present work, however, is that skilled and less skilled deaf readers were included in all studies so that their reading processes could be compared to one another. This was crucial so that the widely held belief that only skilled deaf readers use a phonological code in reading could be tested. The present findings show that this is not the case and that all deaf readers, skilled and less skilled, did use a phonological (and an orthographic) code to initiate word processing. Additionally, although deaf readers are said to have developed nonstandard phonological representations, these representations were still efficient enough to initiate word processing even in the less skilled deaf readers.

There are certainly some limitations of the present studies. The most important shortcoming is related to the limited statistical power of Studies 1 and 3. This limitation of power was due to several factors, some of which were beyond the investigator’s control. In Study 1 and 3, limited power was mainly due to small sample size. As mentioned earlier however, the population of deaf people is highly heterogeneous in terms of age of acquisition of a first language, main mode of communication (oral or signed), degree of hearing loss, type of schooling received (oralist or including some sign language), and age at which deafness occurred (at birth or later, more importantly, prelingually or not). It was thought that it was important to try to control as many of these factors as possible, with the added consequence that samples may be small. Because the Montreal LSQ Deaf community is small, participants were difficult to recruit, especially when trying to control factors such as age of LSQ acquisition, number of years of LSQ usage, degree of hearing loss and age of hearing loss (prelingual in this case). In Study 3, there was also a large amount of data loss due to the experimental technique used, which as mentioned previously, is not unusual for this type of technique (Lee et al., 1999-b; Pollatsek et al., 1992; Sereno & Rayner, 1992; Rayner, Juhasz & Brown, 2007; Rayner, Sereno, Lesch & Pollatsek, 1995). Importantly, however, despite limited power, the patterns of results in Studies 1 and 3 were remarkably similar across groups and were confirmed for the deaf readers through regression analyses. The consistency of these results is likely due to the strict participant controls that were used here; that is, participants all used LSQ for 10 years or more, and were severely to profoundly deaf from birth. Thus, the careful experimental controls, and the similarity of findings with divergent experimental methods offset the power limitations of the study. Nonetheless, more research is required to replicate the results found in the present work as this would solidify the proposed conclusions.

A second limitation is related to the age of L1 acquisition of the deaf participants in the present studies and their proficiency in French and LSQ, which were not controlled. Throughout the present dissertation, the effects of such variables have been alluded to as they have been found to have profound effects on language processing and reading outcomes (Chamberlain & Mayberry, 2008; Golding-Meadow & Mayberry, 2001; Mayberry, 2002, 2007). Had these variables been controlled, they could have been entered into the regression analyses that were performed in Studies 1 and 3 and provided additional information.

Finally, a third limitation that should be mentioned is the absence of a less skilled hearing readers control group. Knowing that most likely the sample of deaf readers would most likely include deaf adults with very low reading levels (recall that some of the deaf participants read at 1st, 3rd or 4th grade levels only), it was reasoned that it would be extremely difficult to find hearing adults with such low reading skills who could be age-matched and educational-level matched to the less skilled deaf readers (for example, one deaf participant read at 1st grade level but had 15 years of education). Another possibility would have been to match the less skilled deaf readers to hearing children matched on reading level, but again this was not implemented, as children and adults likely differ on several variables, one of them being the degree of reading practice and exposure to print. It was therefore decided that the less skilled deaf readers would not be matched in reading level to a control group but would be compared to the skilled deaf readers and also skilled hearing readers (who were mainly included to serve as a baseline and replicate existing results found in the literature.) The absence of a control group for the less skilled deaf readers leaves open the question as to whether or not they have a wider perceptual span than hearing readers matched on reading level. It does not appear that this is the case, however, as the less skilled deaf readers' estimated perceptual span was equivalent to that of the skilled hearing readers, but also similar in size to what was found in previous research with 6th grade children (Rayner, 1986). More research would be needed to resolve this issue, perhaps by comparing less skilled deaf readers to adult beginning readers of a second language, for example.

5.4 Conclusion

The main conclusion to retain from the present work is that there were more similarities than differences between hearing and deaf readers in the studies that were conducted for the present dissertation. They used orthographic and phonological codes in a similar manner during early word processing and their eye movement characteristics (fixation duration, size of word identification span, etc.) were highly determined by their reading level rather than by their hearing status. One notable effect of hearing status, however, was that skilled deaf readers were found to have a wider perceptual span than skilled hearing readers matched on reading level. This may have an influence on word processing as it was suggested that deaf readers may process information from more than one word at a time. Finally, it was suggested that the underlying cause of reading difficulties was not the encoding processes used by deaf readers during word recognition per se, but rather general language competence, which may affect reading comprehension and word processing.

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Appendix

Stimuli common to Studies 1 and 3

TARGETS*	O+P+	O-P+	O-P-	Unrelated
AISE	aize	èzze	oube	toul
BAIN	baim	bint	baun	dour
BANC	bant	bemp	bour	moir
BELGE	belje	bailj	banne	daune
BORD	bore	baur	boin	clat
CERF	cers	sair	neul	nise
CHAUD	shaud	sheau	phape	herfe
CHOSE	choze	shauz	vhimp	vram
CRAIE	crais	krèts	grice	geuf
DAIM	dain	dint	dams	lenf
ENCRE	enkre	amkre	chlèr	paxpe
FAIM	fain	fint	foum	neur
FAUX	faud	fots	foig	seil
FILS	fiss	phys	caks	ceme
GREC	grek	graik	gleum	doir
HAUT	haux	hôts	heit	reil
MAUX	maut	meau	muxe	sede
MÈRE	mert	mair	mune	siul
NEIGE	neije	naije	noine	crops
NORD	nore	naur	nade	sate
PAUSE	pauze	pozze	peife	noilk
PIÈGE	pieje	piaij	plare	daque
PLAIE	plais	plets	paufe	chage
POCHE	poshe	paush	paune	juine
PORC	pord	paur	pacs	tabe
SAIN	saim	sint	sanf	nour
SINGE	sinje	seinj	saune	duate
SOIE	sois	swas	sruc	vure
TAIE	taix	tèts	taum	goul
TAUX	taud	tots	treg	dile
TEMPS	temts	tands	trige	ruilf
THYM	thyn	tein	trid	peul

VEAU	vhau	vots	vlon	clon
VERT	verd	vair	vons	doin

Stimuli only in Study 1

TARGETS[1]	O+P+	O-P+	O-P-	Unrelated
BERGE	berje	bairj	blote	clond
FAIT	faie	fets	folt	sule
FLOT	flos	flau	fouk	dien
NAIN	naim	nint	nine	fule
NERF	nert	nair	nilf	couar
TORT	tors	taur	tite	bind

*The target words were presented in capital letters in Study 1 only.

Ethics Approval Certificate

McGill

Faculty of Medicine
3655 Promenade Sir William Osler
Montreal, QC H3G 1Y6

Faculté de médecine
3655, Promenade Sir William Osler
Montréal, QC, H3G 1Y6

Fax/Télécopieur: (514) 398-3595

June 10, 2008

Dr. Shari Baum
School of Communication Sciences and Disorders
Beatty Hall
1266 Pine Avenue West
Montreal Quebec H3G 1A8

RE: IRB Reference Number A06-B22-06A

Dear Dr. Baum,

We are writing in response to your request for continuing review for the study **A06-B22-06A** entitled "The Use of Phonological and Orthographic Information during Word Processing and Memory Tasks by Hearing and Deaf People".

The progress report was reviewed and we are pleased to inform you that full Board re-approval for the study was provided on **June 9, 2008,** valid until **June 8, 2009**. The certification of annual review has been enclosed.

We ask that you take note of the investigator's responsibility to assure that the current protocol and consent document are deposited on an annual basis with the Research Ethics Board of each hospital where patient enrolment or data collection is conducted.

Should any modification or unanticipated development occur prior to the next review, please advise the IRB promptly.

Sincerely,

Roberta Palmour, PhD
Co-Chair
Institutional Review Board

cc: A06-B22-06A

McGill Faculty of Medicine
Institutional Review Board

- Continuing Review Form -

DATE OF I.R.B. APPROVAL
JUN 09 2008
Faculty of Medicine
McGill University

Principal Investigator: Shari R. Baum   Department/Institution: SCSD

IRB Review Number A06-B22-06A   Study Number (*if any*):   Review Interval: Annual

Title of Research Proposal: The use of phonological and orthographic information during word recognition and short-term memory tasks by hearing and deaf people.

INTERIM REPORT (PLEASE CHECK OR SPECIFY)

Current Status of Study: Active Study ☒ On Hold ☐ Closed to Enrolment ☐

Interim Analysis ☐ Final Analysis ☐ Study Not Activated ☐**

**If the study has not become active at McGill, please enclose correspondence to explain or provide explanation:

McGill hospital(s) where study is being conducted and has received acceptance of local Research Ethics Board(s) (*if applicable*): N/A

Douglas: ☐ JGH: ☐ MUHC/MCH (Mtl Children's): ☐MUHC/MCI (Mtl Chest Ins).: ☐ MUHC/MGH: ☐

MUHC/MNH-MNI: ☐ MUHC/RVH: ☐ Shriners Hospital ☐ SMH: ☐ Other: ☐

McGill hospital(s) where study is being conducted and has NOT received acceptance of local Research Ethics Board(s) (*if applicable*): N/A

In the case of a clinical trial, has the lead sponsor registered the study in the WHO Clinical Trials Registry http://isrctn.com/ Yes ☐ No ☐ or the NIH Clinical Trials Registry http://www.clinical trials.gov ? Yes ☐ No ☐ N/A

If study sponsorship or financial support has changed, please provide correspondence to explain; enclosed: N/A

Total number of subjects to be enrolled in the study: 50 Number of subjects to be enrolled at McGill sites: 50

Number of subjects enrolled by McGill PI to date: 47 Number of subjects enrolled by McGill PI since the last review: 19

Have any of these subjects withdrawn from the study, and if yes, how many? Yes ☐ No ☒

Has the study been revised since the last review? Yes ☐ No ☒

Has the consent form been revised since the last review? Yes ☐ No ☒ Date of current consent form 08 JANUARY 2007

Have the study and consent form revisions been submitted and approved by the IRB? Yes ☐ No ☐

Are there any new data since the last review that could influence a subject's willingness to provide continuing consent?: No

Have there been any Serious Adverse Experiences (SAEs)?: Yes ☐ No ☒

Have all Serious Adverse Experiences (SAEs) and Safety Reports relevant to the study been reported to the IRB?: Yes ☐ No ☐ N/A

SIGNATURES:

Principal Investigator: Shari R Baum   Date: 27 May 08

IRB Chair: Roberta Palmour   Date: June 9, 2008