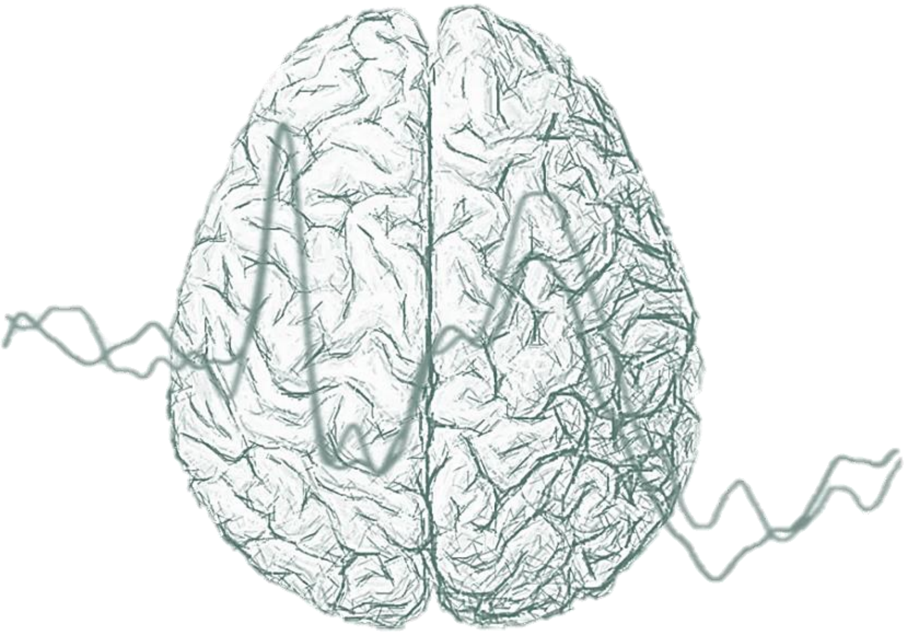
Phonological and orthographic processes in Spanish deaf skilled readers



Doctoral dissertation by:

Noemi Fariña Díaz

Supervised by:

Prof. Manuel Carreiras and Dr. Jon Andoni Duñabeitia

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Doctoral dissertation by:

Noemi Fariña Díaz

To obtain the grade of doctor by the University of La Laguna

Director:
Prof. Manuel Carreiras

Co-director:
Dr. Jon Andoni Duñabeitia

Academic tutor from ULL:
Dr. Moisés Betancort

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BCBL. Basque Center on Cognition, Brain and Language
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Mila esker…

> “Si no te equivocas de vez en cuando,
> es que no lo intentas.”
>
> **Woody Allen**

Durante tres años y medio esta frase ha estado colgada en mi escritorio, como un lema que me ha acompañado en este proceso de aprendizaje, frustración y evolución, porque fueron muchas las veces que me equivoqué, pero nadie podrá decir nunca que no lo intenté una y otra vez.

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"No temas, yo te ayudo"
Isaías 41:13

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Resumen amplio en castellano

Aprender a leer es probablemente uno de los hitos más importantes de nuestra vida. La lectura nos da múltiples oportunidades y su aprendizaje hace que cambie nuestro cerebro (Carreiras et al., 2009). La mayoría de personas oyentes con un desarrollo típico y una adecuada trayectoria académica adquieren la lectura tras un período de instrucción y aprendizaje. A pesar de esto, algunos niños tienen dificultades de aprendizaje que no consiguen adquirir un buen nivel de lectoescritura. Así mismo, existen otras poblaciones, como las personas sordas, que a pesar de no tener ningún problema de aprendizaje, se encuentran con dificultades para conseguir una buena lectura acorde con sus compañeros oyentes (Conras, 1970; Traxler, 2000). Según Marschark (1997), sólo un 10% de los adultos sordos consiguen ser buenos lectores.

Un alto porcentaje de personas sordas hacen el esfuerzo de aprender a leer con el obtejivo de conseguir un buen nivel lector, pero no está claro por qué algunas personas lo consiguen y otras no. Varios autores han sugerido que la ausencia de audición y la limitación al acceso de la fonología son la causa principal de las dificultades lectoras en la población sorda (Hanson & Fowler, 1987; Perfetti & Sandak, 2000). Aún así, hay diferencias de opiniones en cuanto a que el entrenamiento explícito de la conciencia fonológica, por ejemplo, ayude a las personas sordas a conseguir un nivel de lectura competente (Campbell & Wright, 1988; Izzo, 2002; Nielsen & Luetke-Stahlman, 2002). Un meta-análisis realizado por Mayberry, Del Giudice y Lieberman (2011) analizó la relación que hay entre la decodificación fonológica y la conciencia de la fonología con la habilidad lectora en personas sordas, concluyendo que la conciencia fonológica predice solamente un 11% de la varianza sobre habilidad lectora. En cambio, la habilidad lingüística (capacidad de comprender y producir el lenguaje, ya sea orla o signado), independientemente de que la lengua dominante sea oral o signada, predecía más del 35%. Según los estudios previos (Fernández-Viader & Pertusa, 1995; Wilcox; 1994), lo más importante para los estudiantes sordos es estar inmersos en un entorno lingüístico adecuado a sus necesidades perceptivas, para asegurar un buen aprendizaje, especialmente de la lengua escrita. Existe una alta correlación entre la habilidad lectora y el uso de la lengua de signos en la población sorda (Izzo, 2002; McQuarrie & Abbott. 2013; Morford, Wilkinson, Villwock, Piñar & Kroll, 2011; Novogrodsky, Caldwell-Harris, Fish & Hoffmeister, 2014; Padden & Ramsey, 1998; Prinz & Strong, 1998), mostrando una activación del léxico de signos a la hora de acceder al significado durante la lectura.

La mayoría de las investigaciones previas sobre lectura y sordera se han centrado en las dificultades que tienen los lectores sordos en relación con el procesamiento fonológico (Colin, Magnan, Ecalle & Leybaert, 2007; Kelly & Barac-Cikoja, 2007). Existen evidencias sobre el uso de la fonología en personas sordas durante tareas meta-fonológicas o en tareas donde la conciencia fonológica es requerida explícitamente (Aparicio, Gounot, Demont & Metz-Lutz, 2007; Campbell & Wright, 1988; Dyer, MacSweeney, Szczerbinski, Green & Campbell, 2003; Transler, Leybaert, & Gombert, 1999; Waters & Doehring, 1990). Aun así, nuestro interés se focaliza en tareas en las que la conciencia fonológica no se requiera de manera explícita, con el fin de conocer si existe una activación de la codificación fonológica durante una tarea de lectura. Algunos estudios no han encontrado evidencias sobre dicha activación fonológica, o por ejemplo, la existencia de un beneficio previo de la fonología a través de la información parafoveal durante la lectura (Bélanger, Baum, & Mayberry; 2012; Bélanger, Mayberry, & Rayner, 2013).

Cabe destacar que la mayoría de los estudios sobre la lectura en personas sordas se han hecho en inglés, una lengua cuya ortografía es opaca, y la ausencia de activación fonológica durante el reconocimiento visual de palabras en lenguas con este tipo de ortografía podría deberse a la relación irregular que existe entre los grafemas y fonemas. Pero, ¿qué ocurre con una lengua con ortografía transparente, como es el español, donde la correspondencia grafema-fonema es bastante regular? Un gran número de trabajos han demostrado que la base del reconocimiento visual descansa en la representación y mediación fonológica, dependiendo del grado de transparencia de la lengua en la que se lee (Ehri, 1986; Frith, 1985; Harm & Seidenberg, 2004; Share, 1995). Según Frost y Katz (1992), el procesamiento fonológico es imprescindible durante el reconocimiento visual de palabras en lenguas con ortografías transparentes. Además, otros autores (Carreiras et al, 2009; Pollatsek et al., 2005) muestran que el acceso a la codificación fonológica durante la lectura en una lengua con ortografía transparente, como el español, es automático. Existen muy pocos estudios sobre personas sordas y lectura en español. La mayoría se han centrado en perspectivas educativas, por lo que la investigación desde el punto de vista de la neurociencia cognitiva sobre la lectura en español con personas sordas es bastante limitada.

Por lo tanto, la investigación de cómo los lectores sordos llevan a cabo el reconocimiento de la palabra visual en una ortografía transparente es fundamental para comprender mejor la contribución real de los procesos fonológicos a la lectura en esta población. Los estudios que conforman esta tesis se centran en buenos lectores sordos del español, un idioma con una ortografía transparente. Una de las fortalezas de este estudios es la selección de la muestra, ya que los participantes sordos son lectores expertos con un alto nivel de lectura, equivalente a los lectores oyentes de su mismo rango de edad. Nuestro interés se centra en conocer qué procesos se activan durante la lectura en estos lectores sordos altamente cualificados y cómo difieren de los lectores oyentes. Nos interesa saber cómo es posible que una persona alcance un alto nivel de lectura a pesar de la pérdida auditiva, sin acceso a la información auditiva del lenguaje oral. Por lo que, el objetivo de este proyecto es investigar el papel de los procesos fonológicos y ortográficos de los buenos lectores sordos y oyentes, y así descubrir si ambos grupos muestran patrones similares o diferentes respecto a estos procesos.

La sección experimental se divide en tres partes y contiene descripciones de varios experimentos, mostrando los resultados correspondientes a las respuestas conductuales y respuestas neurofisiológicas que se registraron en cada uno de ellos. Las técnicas conductuales nos proporcionan información directa sobre el tiempo que tardan los participantes en ejecutar la respuesta y los errores que comenten en estas tareas. Así mismo, los potenciales relacionados con eventos (ERP, de sus siglas en inglés) (Rugg & Coles, 1995) obtenidos mediante electroencefalografía (EEG) nos proporcionan una medida de alta precisión del curso temporal de la respuesta neural. Esto nos permite saber cuándo ocurren los procesos y subprocesos que intervienen en las tareas que se desarrollan en cada experimento. Los experimentos expuestos a lo largo de esta tesis utilizan esta técnica y por medio de algunos componentes de interés (N100, N250 y N400), dependiendo del tipo de tarea y paradigma que se realiza, determinamos los procesos.

En el **Experimento 1** se estudia la codificación fonológica durante el reconocimiento visual de palabras utilizando dos tareas. En el Experimento 1a se lleva a cabo una tarea de decisión léxica, en la que los participantes debían decidir si la cadena de letras presentada en la pantalla correspondía a una palabra real del español o a una pseudopalabra. El experimento incluía dos tipos de pseudopalabras: pseudohomófonos (pseudopalabras que suenan como palabras reales, p.e. "javón", de la palabra "jabón") y pseudopalabras control (p.e. "jacón"). Los resultados conductuales mostraron un efecto de pseudohomonofía, que interfería en la decisión de los lectores oyentes, produciendo más errores con los pseudohomófonos que con las pseudopalabras control. Esta diferencia en cuanto al porcentaje de errores entre ambas condiciones de pseudopalabras en los lectores oyentes replica los resultados encontrados en estudios previos realizados en lenguas con ortografías opacas (Briesemeister et al., 2009; Ferrand & Grainger, 1994; Ziegler et al., 2001). Existe una interferencia de la información fonológica durante el reconocimiento visual de palabras y acceso al léxico. En cambio, en el grupo de los sordos lectores no hubo diferencias entre pseudohomófonos y pseudopalabras control en cuanto al porcentaje de errores, sugiriendo que este grupo no activa los códigos fonológicos durante la lectura de palabras. Los resultados de los ERP revelaron un efecto de lexicalidad en la ventana temporal de 350-550ms, mostrando una N400 de mayor amplitud en las pseudopalabras que en las palabras. Además, los oyentes mostraron una diferencia entre las ondas correspondientes a la condición de pseudohomóhonos y pseudopalabras control, con mayor negatividad en esta última condición; diferencia que no se encontró en los lectores sordos. Los oyentes mostraron una reducida N400 para los pseudohomóhonos, acercándose a las ondas de las palabras reales. Estos resultados coinciden con los conductuales, proporcionando evidencias sobre la codificación fonológica de este tipo de pseudopalabras para los oyentes. De acuerdo con estos resultados y con los estudios anteriores (Briesemeister et al., 2009; Kramer & Donchin, 1987), los oyentes procesan los pseudohomófonos como palabras reales, disminuyendo su negatividad alrededor de los 400ms, mientras que en los sordos no está presente este efecto. El Experimento 1b consta de una tarea de categorización semántica go/no go con una técnica de *priming* enmascarado, usando pseudohomófonos y pseudopalabras control como primes. En este experimento sólo se recogieron datos electrofisiológicos, los cuales mostraron una interacción entre tipo de prime y grupo en la ventana 150-350ms. Los oyentes mostraron una diferencia de N250 entre los targets precedidos por pseudohomófonos y pseudopalabras control. Este resultado replica el que se ha encontrado en estudios anteriores (Duñabeitia et al., 2009; Holcomb & Grainger, 2006), sugiriendo que los lectores oyentes no sólo activan los códigos fonológicos a nivel léxico, sino también a nivel subléxico. Los lectores sordos no mostraron diferencias entre las condiciones. La ausencia del efecto N250 en los sordos refleja que, al igual que en el experimento anterior, los lectores sordos no activan la codificación fonológica durante la lectura de palabras.

En el **Experimento 2** se investigan las diferencias y similitudes entre los lectores sordos y oyentes en cuanto a los procesos ortográficos, utilizando las mismas tareas que en el Experimento 1. El Experimento 2a consiste en una tarea de decisión léxica. Las condiciones de pseudopalabras eran dos: pseudopalabras con transposición de letras (p.e. “mecidina”, de la palabra “medicina”) y pseudopalabras con sustitución de letras (p.e. “mesifina”). Los resultados conductuales mostraron un efecto de transposición de letras en ambos grupos, con mayores tiempos de reacción y número de errores en la condición de pseudopalabras con letras transpuestas que en la condición de sustitución de letras. Este efecto ha sido investigado por varios autores (Perea & Fraga, 2006; Perea & Lupker, 2004; Perea & Carreiras, 2006) y está considerado como uno de los efectos más robusto sobre el procesamiento ortográfico. Esto supone que tanto los sordos como los oyentes son sensibles a las manipulaciones ortográficas durante el reconocimiento visual de palabras, activando los códigos ortográficos para acceder al léxico. Los resultados de ERP mostraron que las pseudopalabras con letras transpuestas provocaban una menor negatividad que las pseudopalabras con sustitución de letras, asemejándose a las palabras. Estos resultados son consistentes tanto con lo encontrado en las respuestas conductuales como con los estudios previos (Carreiras et al., 2007; Kramer & Donchin, 1987; Vergara-Martínez et al., 2013). El Experimento 2b, basado en el Experimento 1b, se trata de una tarea de categorización semántica go/no go mediante *priming* enmascarado, pero las condiciones de pseudopalabras del Experimento 2a como primes. A pesar de los resultados encontrados en la literatura previa, en este experimento no se encontró ningún resultado significativo en cuanto a los análisis de ERP. Aunque los gráficos muestran diferencias entre condiciones, y concretamente en los oyentes, en consonancia con estudios previos, estadísticamente no se han encontrado resultados significativos. Tal vez se deba a una falta de potencia en el efecto debido a un bajo número de sujetos o de items por condición.

Para lograr un reconocimiento visual de palabras de manera eficiente son necesarios dos pasos claves: la codificación de la identidad de las letras y de su posición (Carreiras, Duñabeitia, et al. 2009; Carreiras, Gillon-Dowens, et al. 2009; Duñabeitia & Carreiras, 2001; Perea et al., 2013). Estos procesos previos al reconocimiento de la palabra se basan en mecanismos ortográficos (Carreiras, Quiñones, Hernández-Cabrera and Duñabeitia, 2015). Los lectores expertos son capaces de distinguir entre palabras muy similares, reconociendo sus letras independientemente del tipo de fuente, tamaño o caja (mayúsculas vs. minúscula) (Chauncey, Holcomb, & Grainger, 2008; Petit, Midgley, Holcomb, Grainger, 2006). Además, la percepción de la localización de cada letra es esencial para llevar a cabo una lectura correcta (Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2012). Por esta razón, se llevó a cabo el **Experimento 3**, donde se estudia más detalladamente los subprocesos ortográficos centrados en la codificación de las letras, utilizando tres tareas de correspondencia perceptual explícitas basadas en tareas de *same-different*, donde los participantes deben decidir si dos cadenas de letras sin significado (ej. FTRP) son iguales o diferentes. A través de estas tareas estudiamos en qué se asemejan y difieren los buenos lectores sordos y oyentes en cuanto a la percepción de las letras. El primero, se centra en el estudio de la codificación de la posición de letras (Experimento 3a), comprobando el efecto inhibitorio de transposición de letras. Los siguientes experimentos se enfoncaron a la codificación de la identidad de las letras, estudiando sus dos vertientes: la similitud visual (Experimento 3b) y la identidad abstracta mediante cambio de cajas (Experimento 3c). Según algunos estudios (Bowers & Michita, 1998), la fonología juega un papel importante para la identificación abstracta de las letras. Otros autores (Bigsby, 1978; Coltheart, 1981) defienden que no hay implicación de fonología durante la codificación de la identidad de las letras. Polk et al. (2009) no descarta el papel de la fonología, pero siendo necesaria únicamente en las etapas de desarrollo y creación de la identidad abstracta de los caracteres, argumentando que a los lectores adultos no les hace falta acceder a ella para su identificación. Los resultados conductuales del Experimento 3a muestran un efecto de transposición de letras en ambos grupos, en la misma línea que el Experimento 2a de decisión léxica. Los tiempos de reacción y porcentajes de errores fueron mayores para los pares de estímulos con letras traspuestas que para aquellos que tenían letras reemplazadas. En cuanto a los análisis de ERP, encontramos una ventana significativa (450-650ms), mostrando diferencias entre condiciones, con mayores amplitudes negativas para los targets precedidos por referencias con letras traspuestas. En el Experimento 3b se muestra un efecto simple en los resultados conductuales, con mayores tiempos de latencia y número de errores para los pares que compartían letras muy similares, en comparación con aquellos pares que no compartían similitud visual. Este efecto está presente en ambos grupos. Se obtuvieron dos ventanas de interés en los resultados de ERP, con diferencias entre condiciones. Primero, la ventana 100-200ms, muestra una mayor negatividad para los targets precedidos por letras no similares. En una ventana posterior, 450-650ms, encontramos también una diferencia entre ambas condiciones pero en el sentido inverso, con mayores amplitudes negativas para los targets cuyas referencias compartían caracteres altamente similares. Los efectos de ambas ventanas están presentes tanto en sordos como en oyentes. Finalmente, en el Experimento 3c encontramos que ambos gurpos tardaron más tiempo y cometieron más errores en los pares que comparten la misma identidad pero distinta caja, en comparación con aquellas referencias y targets que tenían la misma caja. Además, los sordos son más certeros y rápidos que los oyentes, coincidiendo con los experimentos de decisión léxica. El análisis de la ventana 400-550ms muestra un efecto de caja (mayúsculas vs. minúsculas), con mayor negatividad para la condición de pares de estímulos con distinta caja. Estos resultados muestras que ambos grupos son sensibles a las manipulaciones de posición e identidad de las letras (ya sea en cuanto a similitud visual como a cambio de cajas). Todo ello sugiere que no existen diferencias entre sordos y oyentes buenos lectores respecto a los subprocesos subyacentes a la codificación de la ortografía. Las similitudes mostradas entre ambos grupos en estas tres tareas de coincidencia perceptiva cuestiona la hipótesis de Bowers y Michita (1998), ya que si existiera una implicación fonológica, se hubieran esperado diferencias entre sordos y oyentes, especialmente en el Experimento 3c.

En resumen, los buenos lectores sordos no activan la fonología durante el reconocimiento visual de palabras, pero son sensibles a las manipulaciones ortográficas, mostrando similitudes con los lectores oyentes en lo que se refiere a procesos y subprocesos ortográficos. ¿Es posible que los lectores sordos obtengan un alto nivel de lectura sin acceso a la fonología? Según nuestros resultados, la respuesta es sí. Mientras que los lectores oyentes muestran una sensibilidad a las manipulaciones fonológicas y ortográficas (lo que implica la utilización de la conciencia fonológica y ortográfica para el acceso léxico durante la lectura de palabras), los lectores sordos sólo muestran sensibilidad a las tareas manipuladas ortográficamente. Es posible que la ausencia de mediación fonológica haga a esta población más propensa a estrategias alternativas. Los buenos lectores sordos son capaces de reconocer una palabra sin la activación de la fonología, codificándola tal vez como una imagen visual basada en las características ortográficas y accediendo al significado de la palabra impresa a través de una estrategia visual-ortográfica.

Para concluir, la presente tesis muestra diferencias y similitudes entre personas sordas y oyentes con un buen nivel de lectura. En particular, los hallazgos sugieren que, a diferencia de los lectores oyentes, la activación fonológica no es necesaria para los lectores sordos al leer palabras en una lengua con una ortografía transparente, como es el español. Los lectores sordos y oyentes son sensibles a las manipulaciones ortográficas, mostrando la importancia de que a través de la conciencia ortográfica es posible lograr un nivel de lectura competente, sin necesidad de codificación fonológica. Tras nuestros hallazgos, se pone en duda que la codificación fonológica sea necesaria para el reconocimiento exitoso de palabras de forma visual, tal y como dice la literatura previa (Carreiras et al, 2009; Ehri, 1986; Frith, 1985; Frost y Katz, 1992; Harm & Seidenberg, 2004; Pollatsek et al., 2005; Share, 1995). El caso especial de lectores sordos con un alto nivel de lectura demuestra que el reconocimiento de palabras puede depender de otros procesos, como el procesamiento visual-ortográfico o la decodificación de la palabra escrita a través de unidades sub-léxicas de la lengua de signos (Petitto et al., 2006). Asimismo, es importante seguir investigando los procesos que apoyan la adquisición de un alto nivel de alfabetización por parte de los lectores sordos y que suponen opciones alternativas a los modelos clásicos sobre el reconocimiento visual de palabras.

1. GENERAL INTRODUCTION

Learning to read is probably one of the most important milestones in our lives. Acquiring this ability opens up a host of opportunities and also brings about changes in our brains (Carreiras et al., 2009). Hearing children with typical development and academic progress acquire reading after an appropriate amount of instruction. This process is easier in languages with a transparent orthography, such as Spanish, in which there is a regular correspondence between letters and phonemes. However, children with learning disabilities and most deaf children do not achieve fluent reading. Most deaf people do not reach proficient levels of reading with respect to their hearing peers (Conrad, 1979; Traxler, 2000). Only 10% of deaf adults become skilled readers (Marschark, 1997).

These levels of illiteracy in the deaf population limit their access to information and curtail their rights as citizens in today's society in which the written word is essential (Allen 1986; Chamberlain & Mayberry 2000). In addition, reading is a key to academic achievement, so the reading difficulties of deaf children represent a serious problem for accessing formal education and future job opportunities. Therefore, it is important to investigate how the deaf population can become proficient readers and thus enjoy equal opportunities.

Various authors have suggested that the lack of audition and access to phonology are the main underlying causes of these reading difficulties in the deaf (Hanson & Fowler, 1987; Perfetti & Sandak, 2000). While deaf people make a great effort to learn to read, it is not known why some are successful but others are not. Additionally, it is unclear whether explicit training in phonological awareness helps deaf individuals to achieve high reading proficiency (Campbell & Wright, 1988; Izzo, 2002; Nielsen & Luetke-Stahlman, 2002).

Most research on deaf readers has been conducted in languages with an opaque orthography and most of these studies do not show the activation of phonological coding in visual word processing. The result is not altogether surprising since phonological coding may not be central to reading an opaque orthography. In contrast, languages with transparent orthographies show greater support for phonological processes in visual word recognition (Frost & Katz, 1992). In fact, accessing phonological codes seems to be required when reading in Spanish (Carreiras, Perea, Vergara & Pollatsek, 2009; Pollatsek, Perea & Carreiras, 2005). Therefore, investigating how deaf skilled readers carry out visual word recognition in a transparent orthography can provide insight into the real contribution of phonological processes to reading in this population.

Despite years of research on reading in deaf people, we still do not know many issues that could help to mitigate the reading problem in the deaf: Why do some deaf people become skilled readers but others do not? What are the brain mechanisms that enable reading in deaf skilled readers? What similarities and differences are there between deaf and hearing skilled readers?

Most of the past studies focused on understanding whether the poverty of phonological processes in deaf individuals could account for their failure (Colin, Magnan, Ecalle, & Leybaert, 2007; Kelly & Barac-Cikoja, 2007). For this reason, we adopt a very different perspective: we focus attention on understanding how deaf skilled readers in a transparent orthography such as Spanish manage to read. This thesis examines phonological and orthographic processes in adult deaf skilled readers. In the first section, we will discuss the most important issues related to reading processes and deafness. Section 1.1 briefly describes the education of deaf people in relation to literacy acquisition, the reading difficulties of deaf people, and the most relevant previous research on reading and deafness. Section 1.2 discusses visual word recognition, and underlying processes such as letter identity and position coding, as well as the role of phonological and orthographic coding during reading. Section 1.3 describes the research tools and methods used for the development of this thesis project, including the behavioral techniques used and the main components of Event-Related Potentials (ERP). The general objectives of the thesis are described in section 1.4. Section 2 is the experimental section, which is divided in three experiments and is organized by the reading processes that were investigated: phonological processes (Experiments 1a and 1b), orthographic processes (Experiments 2a and 2b), and orthographic subprocesses (Experiments 3a, 3b and 3c. The discussion of each experiment begins with a brief introduction, followed by a description of the methods and results, and a brief discussion of the main findings. The general discussion and conclusions are described in the section 3, which includes an exposition of a summary of findings (section 3.1). Also, it explains the main insights into reading processes in deaf skilled readers (section 3.2), what implications our results have in relation to the models of visual word recognition (section 3.3) and the limitations of this thesis (section 3.4). Finally, applications and future directions are described in the section 3.5.

1.1. Reading and deafness

The majority of deaf people do not reach competent levels of reading with respect to hearing readers (Conrad, 1979; Traxler, 2000) and almost 90% of deaf adults are less-skilled readers or even illiterate (Marschark, 1997). To understand the reasons for this heterogeneity in reading levels in the deaf population, it is necessary to briefly explain the history of the education of deaf students and its methodological foundation. In addition, we describe the main reading difficulties of deaf people, highight favorable conditions that can facilitate their reading acquisition, and review the most relevant existing research on reading processes in deaf individuals.

1.1.1. Education and literacy of deaf people

Throughout the history of deaf education, the goal has been to integrate deaf people into hearing society through a focused approach of reading and writing (Plann, 1997). From the founding of the first schools for the deaf in the eighteenth century and for a long period thereafter, the educational methodology with deaf students was based on the manual alphabet and gestures or signs, and it was assumed that sign language was the more natural form of communication between deaf people (Gascón & Storch de Gracia, 2004). The creation of these specialized schools led to the formal education of deaf children and offered the opportunity to learn the written form of the spoken language.

At the International Congress of Educators of the Deaf, held in Milan in 1880, it was resolved that aim of the education of deaf people was to teach them to speak, since the prevalent thinking at the time held that this was the best way for deaf individuals to integrate into society. This focus on the spoken language placed emphasis on the acquisition of reading and writing skills but also entailed the exclusion of sign language and the manual alphabet since these gestural methods were thought to have negative effects on the development of spoken language. This congress effectively imposed oralist education, focused on the teaching of spoken language exclusively, and prohibited the use of any gestural or manual system in deaf schools. Although the United States and a few European countries opposed this decision, Spain was one of the countries that adopted the oralist philosophy in schools.

This *oralist or monolingual approach*, which included the rejection and prohibition of sign language, was more prevalent in the past than it is now, and only in recent times have educational policies started to change. Until only a few years ago, children's hands were tied to stop them from signing in class, in much the same way that minority spoken languages were stigmatized in the classroom. Although some schools still maintain a monolingual approach aimed at oralization, most methodologies of this type also incorporate the use of different support systems such as sign language, manually coded speech systems (i.e., using signs with the syntactic structure of the spoken language) or cued speech to support lip-reading. This evolution in educational practice has come about for two main reasons: on the one hand, shortcomings of the oralist approach, and, on the other, growing interest in the benefit of using sign language.

On the first count, mounting evidence revealed that monolingual education obtained unsatisfactory results in relation to academic achievement (Berent, 1996; Bochner & Albertini, 1988). More damningly, deaf students educated in an oralist methodology only partially acquire competence in the spoken language (Fischer 1998; Morford & Mayberry 2002). Despite the adoption of oralist methodologies, the teaching of reading and writing was not very successful. Deaf students ended up performing tasks of imitation and repetition that were meaningless and did not adequately develop their skills in reading and writing (Lynas, 2005; Svarthlom, 1984).

Secondly, in the second half of the 20th century, the use of gestural and sign systems in education began to make a comeback. The publication of "*Sign Language structure: an outline of the visual communication system of the American deaf*" (Stokoe, 1960) demonstrated that sign languages have linguistic structure, comparable to that of spoken languages, and thus brought sign languages within the domain of linguistic study. This launched research on sign languages that began to spread to other countries and served to change attitudes towards sign languages in the academic, social and educational spheres. Importantly for educational practice, it was recognized that early learning and use of sign language favored the linguistic and cognitive development of deaf people (Stokoe, 1978). At the same time, the decision to reintroduce the use of sign languages in educational methods was motivated by the evidence that the oralist method was simply not successful.

The growing realization that sign language was a rich linguistic system and could be beneficial for the cognitive development of deaf children gave rise to the *bilingual approach*. This methodology adopts the use of sign language as the natural language of deaf people and as the main language in the educational system with deaf children. At the same time, this model defends the teaching of spoken and written language as a complement to the educational development of deaf people. The objective of bilingual education is for deaf students to have complete access to the school curriculum and the social integration of deaf children in the hearing community (Pust, 2005). The methodology is based on the belief that competence in sign language provides a solid grounding for the acquisition of any other language, including written language (Svarthlon, 1994).

1.1.2. Reading difficulties for deaf individuals

Most deaf people never achieve good reading and lag behind their hearing peers (Conrad, 1979; Traxler, 2000; Walker & Rickards, 1993). According to one study, only 10% of deaf adults become skilled readers (Marschark, 1997). One of the main difficulties that deaf students have when they learn to read or write is a lack of linguistic knowledge and especially of spoken language, and insufficient general knowledge about the world (Albertini & Schley, 2003; Chamberlain & Mayberry, 2000; Conrad, 1979; Paul, Marschark & Spencer, 2003). At the lexical level, deaf people have problems decoding words but better knowledge of the meaning of the words is associated with better scores in reading comprehension levels (Paul, Marschark, & Spencer, 2003).

At the sublexical level, various authors have suggested that deaf people do not seem to access phonology because they cannot hear. Most previous research on reading and deafness has focused on the difficulties of deaf readers in relation to phonological processing (Colin, Magnan, Ecalle & Leybaert, 2007; Kelly & Barac-Cikoja, 2007). This seems to be the main underlying cause of their reading difficulties and the reason for the high proportion of deaf people who are not skilled readers (Hanson & Fowler, 1987; Perfetti & Sandak, 2000). If this is the case, then a possible solution could be to remediate shortcomings in phonological representations in order to improve reading skills. However, it is unclear whether explicit training in phonological awareness helps deaf individuals achieve reading proficiency (Campbell & Wright, 1988; Izzo, 2002; Nielsen & Luetke-Stahlman, 2002).

Aside from the contribution that phonological competence plays in reading ability, other factors may be critical to reading proficiency outcomes. Learning to read is based on two important features: decoding skills and good communication with strong verbal comprehension, whatever the linguistic system used (Dayan, Kakade, & Montague, 2000; Jackson & McClelland, 1979; Palmer, MacLeod, Hunt, & Davidson, 1985; Perfetti, 2007; Perfetti & Sandak, 2000). This latter observation is relevant because general language skills may be more relevant than phonological awareness of the specific written language. Deaf and hearing children reach the same milestones during the early stages of literacy acquisition and development (Mayer, 2007), and it is insufficient knowledge of language, regardless of whether spoken or written language is used, that influences the progress with the written language in deaf children (Bellés & Teberosky,1989). Indeed, a meta-analysis of 57 studies of reading outcomes in deaf adults and children revealed that language ability (measured in terms of sign or spoken comprehension and vocabulary production) accounted for 35% of the variance in reading ability, while phonological awareness of speech accounted for 11% of the variance (Mayberry, Del Giudice, & Lieberman, 2011).

The importance of general language ability raises the relevance of sign language ability for reading skills. Competence in sign language of deaf students may be a fundamental factor for better understanding and written production (Wilson, 1994), and various studies have observed a positive correlation between reading and the use of sign language (Izzo, 2002; Padden & Ramsey, 1998; Prinz & Strong 1998). Perfetti and Sandak (2000) suggest that the achievement of reading in deaf readers is based on a good knowledge of a sign system, not only on competence in spoken language. Treiman and

Hirsh-Pasek (1983) found that deaf people access sign language during silent reading, not through phonological coding, accessing the lexicon of signs primarily to recover the meaning of the written word.

The evidence points toward sign language competence as having a beneficial effect on reading skill. This may be due to improved general knowledge of the world and also the linguistic foundations from a well acquired language that may aid in dealing with written language. However, the question of the role of phonology remains, and the next section reviews research that has addressed this issue.

1.1.3. Relevant reading research for the deaf

The lines of research on deafness and reading have focused mainly on two themes: the role of sign language during reading in deaf, and the difficulties of deaf readers in relation to phonological processing.

Studies focusing on sign language and deaf readers have shown that sign language has a strong influence in the performance of deaf people during reading tasks (Izzo, 2002; McQuarrie & Abbott. 2013; Novogrodsky, Caldwell-Harris, Fish & Hoffmeister, 2014; Padden & Ramsey, 1998; Prinz & Strong, 1998). Morford, Wilkinson, Villwock, Piñar and Kroll (2011) carried out a study that demonstrated that deaf individuals activated American Sign Language (ASL) when reading English words, even though sign language was not required in the task. The study has been replicated for German Sign Language and German (Kubus, Villwock, Morford, & Rathmann, 2015), and for hearing bimodal bilinguals in ASL and English (Morford, Kroll, Piñar, & Wilkinson, 2014) and in Spanish Sign Language and Spanish (Villameriel, Dias, Costello, & Carreiras, 2016).

Turning to phonological processing, many studies have highlighted the importance of phonological coding and phonological awareness for reading skills in deaf individuals (Hanson & Fowler, 1987; Perfetti & Sandak, 2000). Most studies that investigate the role of phonology in the deaf population do so through meta-phonological tasks and/or phonological awareness tasks and those require explicit phonological judgments (Aparicio, Gounot, Demont & Metz-Lutz, 2007; Campbell & Wright, 1988; Dyer, MacSweeney, Szczerbinski, Green & Campbell, 2003; Transler, Leybaert, & Gombert, 1999; Waters & Doehring, 1990). In addition, many of these studies focus on deaf children who are still in the development phase of reading. This present study, in contrast, investigates the role of phonology by means of more implicit reading tasks, such as lexical decision between words and nonwords, and focuses on adult deaf readers. Studies that use this type of paradigm have shown evidence for phonological coding in visual word recognition in deaf readers of Dutch (Transler & Reitsma, 2005); however, the population studied was children. In contrast, the few other studies that have looked at reading in deaf adults have reported no evidence for the use of phonological coding during word reading. For example, Bélanger, Baum and Mayberry (2012) concluded that skilled deaf readers of French might activate visual, orthographic and semantic codes during reading, but not phonological codes. Furthermore, Bélanger, Mayberry and Rayner (2013) investigated the phonological and orthographic preview benefit in parafovea in English readers. The authors manipulated whether, when reading sentences, the word processed in the parafovea corresponded to a homophone of or an orthographically similar word to the target word. The target word only appeared once the eye gaze landed on it. The results showed that skilled hearing readers, skilled deaf readers and less-skilled deaf readers benefited from orthographic coding in parafoveal vision, with shorter fixations for target words previewed as an orthographically similar word in the parafovea. In contrast, only the hearing group benefited from phonological coding, suggesting that homophones seen in the parafovea were recognized and that phonological information influenced the subsequent reading time. This benefit and processing of phonological information during parafoveal viewing was not present in the deaf group.

In summary, the education of the deaf population has been marked by the variability of teaching methodologies, many of which have resulted in academic delays. These methodologies have made many deaf people essentially illiterate. In spite of this, the teaching method has changed to a bilingual approach, supported by different studies that found positive effects of immersion in sign language on reading and writing acquisition, and underline the importance of language acquisition for deaf people (whether spoken or signed). In relation to the relevant research on deafness and reading, most studies have focused on the relationship between sign language and written word recognition. These studies have found positive correlations between sign language proficiency and reading skills, and have shown that deaf and hearing users of sign language activate signs when reading words. Other authors have studied the role of phonology in deaf readers, with a wide variety of experimental paradigms and mixed results. In particular, some studies did not find evidence of phonological activation when deaf individuals read words or sentences. Even so, it should be noted that the majority of these studies have been carried out in languages such as French or English, whose orthographies are opaque and different from Spanish, which is a language with a transparent orthography, which may be more conducive to phonological coding during reading.

1.2. Visual word recognition

An essential part of the reading process is the identification of individual words within the text. This process consists of transforming a series of graphic symbols into sounds or meanings. One of the major objectives of research in psycholinguistics has been to discover how adults are able to read single words (Grainger & Holcomb, 2010).

In contrast to the acquisition of a spoken (or signed) language, reading requires explicit learning and instruction. Although for most people reading is an automatic task, it involves a complex series of cognitive processes: when we recognize words, various stages are required, from the visual identification of the graphemes, and the recognition of linguistic symbols, to accessing the meaning of the associated concept.

The following sections describe different processes involved in visual word recognition, such as letter identity and position coding, and the role of phonological and orthographic processes in relation to orthographic depth. In addition, this section includes a description of the main theoretical models of visual word recognition.

1.2.1. Letter coding and orthographic processes

The first stages of reading a word are concerned with recognizing and identifying the individual letters. When we read, our eyes make fixations on different words. During these fixations, the brain receives visual information from the eyes, detects the visual features and begins collecting information. The duration of fixations depends on the characteristics of the word. For example, long words produce longer fixations as compared to short words (Rayner, 1977; Just & Carpenter, 1980). Nevertheless, the duration of fixations does not depend on the extraction of visual information, but on higher-level processes, such as lexical or semantic processing. The time required to extract the visual information from the graphic features is only 50 milliseconds (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

After extracting the visual information in the initial milliseconds of each fixation, the brain begins to identify the letters. Current evidence supports recognition models based on the features of each letter (Dehaene, Cohen, Sigman, & Vinckier, 2005; Pelli, Burns, Farell, & Moore-Page, 2006) and theoretical models (described in section 1.2.3 below) suggest that word recognition, in turn, is based on the analysis of letters.

Identifying letters is complicated by the fact that the same letter can be written in different ways (e.g. b, 𝔹, b, **B**, *b*, etc.). Nevertheless, the different letter forms maintain some common features. Therefore, one of the key steps for achieving efficient visual word recognition is abstract letter identity coding. Readers are able to recognize words regardless of the type of font, size or case that the letters appear in because they develop abstract letter units that enable the identification of each letter. Furthermore, they must be able to distinguish between words that are very similar (e.g. *car-cat*). For this reason, letter identity is an important subprocess for efficient visual word recognition. Grainger and Ziegler (2011) suggest that the main task in learning to read is to associate letter identities with sounds. Through these associations, readers make connections between the known phonological representations and printed words. In the same line, Bowers and Michita (1998) conclude that phonology plays an essential role in the development and learning of abstract letter identity (ALI), to establish an abstract representation of letters, regardless of their visual appearance (font, size, case, etc.). Similarly, Posner (1978) concludes that the association of "A" and "a" with the same entity depends on a *name code*, which is equivalent to a phonetic code. Conversely, other authors, such as Bigsby (1988), found no evidence that ALI computation depends on phonology. A case study with a patient with impaired production and discrimination of phonemes concluded that despite impaired phonological codification, the patient was able to identify the letters with different cases (Coltheart, 1981). According to Besner, Coltheart and Davelaar (1984), the level of letter identity representation is neither visual nor phonological, but abstract, associating particular physical forms with the same common name. Polk et al. (2009) reconcile these conflicting points of view: phonology may be important for the *development* of ALI (Bowers & Michita or Posner), but it does not continue to play a role in skilled readers (in line with Bigsby and Coltheart).

In addition to the coding of abstract letter identity, recognizing the location of letters within a word is also essential. This information is very important for alphabetic languages, such as Spanish, in which there are a large numbers of anagrams (Peressotti & Grainger, 1999). We can distinguish words with the same letters but with different letter positions, for example *cosa/saco/ocas/caos"* ("thing"/"sack"/"geese"/"chaos"). There are authors who have studied if the letter position coding (through the transposed-letter effects) may be based in a phonological component, as well as abstract letter identity coding. Perea and Lupker (2004) suggested that these effects of transposition might have a phonological mediation. In contrast, Perea and Carreiras (2006) concluded that transposed-letter effects are orthographic, not phonological. In relation to this, Grainger and Ziegler (2011) describe two types of orthographic coding after visual feature analysis of letters: coarse-grained and fine-grained code. The fine-grained orthographic code assumes a more detailed analysis of letter processing. The authors suggest that readers can access meaning through phonological representations thanks to this fine-grainer code. To carry out this, it is necessary to encode different letters identities in precise order. The authors base this hypothesis on studies such as they one carried out by Acha and Perea (2010), in which transposed-letter primes based on a pseudohomophone do not generate priming effects, while transposed-letter primes based on a real word or pseudohomophones primes without letter transposition do generate the effects. This means that the altered order of pseudohomophones hampers fine-grained orthographic processes, and hence does not prompt activation of phonological representations.

In section 1.2.3 below, we describe two main theoretical models of visual word recognition. Nonetheless, in this section we want to draw attention to models that try to explain these subprocesses of letter identity and, particularly, letter position. The interactive activation (IA) model (McClelland & Rumelhart, 1981) establishes different levels for letter recognition: feature detectors, letter detectors and word detectors (shown in the bottom, middle and top levels, respectively, of figure 1). This model suggests that position is coded as if the word were a string, in which letter identification and letter position detectors are processed in parallel. For example, in the word "BEST", the B is in position 1, E position 2, and so on. Each position has associated with it a single identification of the letter. This model is very useful for the recognition of anagrams in alphabetic languages, but from a representational point of view it is uneconomical. Moreover, this model does not explain the tolerance of readers for letter strings with transposed characters, since they can read words whose letter order is altered (e.g. “Aoccrding to a rscheerch at Cmabrige Uinervisty…”).

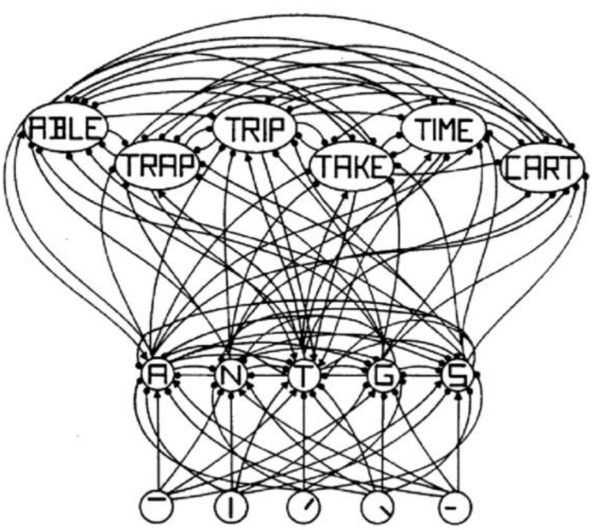


Figure 1. *Interactive activation (IA) model of letter recognition (McClelland & Rumelhart, 1981)*

Open-bigram models (Grainger & Van Heuven, 2003; SERIOL model by Whitney, 2001) assume that readers encode the relative position of letters by activating pairs of letters, named “open bigrams” (e.g. the word “BEST” has the contiguous bigrams BE, ES, ST, and the noncontiguous bigrams BS, BT, ET). The position of the letters is determined by the bigrams activated. The activation of the different contiguous and noncontiguous bigrams would explain the tolerance of the skilled readers to be able to read words with transposed letters without difficulty. According to Perea and Lupker (2004), Frankish and Barnes (2008) showed larger priming effects for adjacent transposed-letter primes with low bigram frequency (e.g. pucnh-PUNCH) than for high bigram frequency (e.g. panit-PAINT). They concluded that the same manipulation (transposition of two adjacent letters) show different effect depending on frequency of the open-bigrams, suggesting that phonological processing intervenes in the transposed-letter effect, at least with adjacent letters. This study is in line with Frankish and Turner

(2006), who found that transposed-letter nonwords like “SOTRM” (from the base word “storm”) were harder to reject in a lexical decision task than “STROM”. Their conclusion is that phonology is activated when transposed-letter nonwords contain conventional orthographic patterns, when they have orthographic regularity letter strings and when they are pronounceable.

Finally, the Overlap model (Gómez, Ratcliff, & Perea, 2008) is presented as an alternative to the IA model. According to this model, the position of the letters activates certain "noise". This means that the exact location of a letter is not the point, but the position is assumed by the distribution over space. A letter not only activates its actual position within the word, but also activates neighboring positions. For example, in the word "BEST", E is in position 2, but could also occupy position 1 and 3. Thus, this model would also explain the effect of tolerance for letter transposition in adult readers.

In summary, the role of phonological knowledge in abstract letter identity and letter position coding is not clear. The basis of efficient visual word recognition is analysis of the letter (Pelli et al., 2006), and during reading and letter coding phonology may play an important role. In section 1.1.3, we cited some studies which concluded that deaf readers do not activate phonology during reading. For this reason, it would be interesting to study, not only the role of phonology during word reading, but during letter processing. Given the assumption that deaf readers do not activate phonology during visual word recognition, we would expect differences between deaf and hearing people in the coding of abstract letter identity and letter position, two orthographic subprocesses which could have a phonological locus.

Also, the mechanism of letter position coding varies across different visual word recognition models. Notwithstanding, it is important to note that these orthographic processes are essential in achieving efficient visual word recognition.

1.2.2. Phonological processes

A mechanism of grapheme-phoneme conversion is responsible for assigning a phonemic sound to each letter. The phonemes are assembled to retrieve the phonological representation of the word from a specific store of our memory, the phonological lexicon. Once the phonological form of the word has been generated, it is necessary to access the auditory lexicon, in order to identify the acoustic image of the word. Subsequently, the semantic system is accessed to retrieve the meaning of the word that has been read.

Some studies (Doctor & Coltheart, 1980; Frith, 1985; Reitsma, 1984; Share, 1995) have shown that phonological processes are the first to develop in children and particularly in transparent orthographies, such as Spanish (Valle-Arroyo, 1989). In addition, in the initial stages of reading acquisition, phonological processes play an essential role because they contribute to the creation of the ultimate orthographic representations (Alegría, 1985).

Phonological decoding has been the central focus of reading instruction, especially in languages with transparent orthography. Previous studies have demonstrated that the presence of phonological mediation in tasks of word-processing is a necessary step to lexical access (Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; Frost, 1998; Van Orden, Johnston & Hale, 1988). These studies conclude that the basis of visual word recognition rests on the phonological representation, rather than on the orthographic representation. However, this seems to depend on the degree of transparency of the language in which reading occurs (e.g., languages with a transparent orthography such as Spanish vs. languages with an opaque orthography such as English; Ehri, 1986; Frith, 1985; Harm & Seidenberg, 2004; Share, 1995). Frost and Katz (1992) hypothesized that transparent orthographies are more easily able to support a word recognition process that involves phonological coding. In contrast, in opaque orthographies, readers can process printed words by relying on alternative strategies (e.g., on the visual-orthographic structure). Crucially, it has been shown that phonological codes are automatically accessed during reading in Spanish, a language with a transparent orthography (e.g., Carreiras, Perea, Vergara-Martínez & Pollatsek, 2009; Pollatsek, Perea & Carreiras, 2005), suggesting that efficient phonological processing may be an obligatory step for word identification in transparent languages.

Orthographic and phonological processes provide the framework for most theoretical models of visual word recognition. For this reason, the next section discusses some of the main theoretical models on visual word recognition, and the role of phonological and orthographic representations according in these models.

1.2.3. Models of visual word recognition

The access to meaning from the printed word has been examined by numerous experiments based on lexical decision tasks (described in section 1.3.1.1), which provide insight into how a person is able to recognize written words and rejecting meaningless linguistic stimuli, such as non-words. The results of these experiments constitute a body of evidence demonstrating that certain characteristics of words influence how they are recognized and read. For example, a variable that influences the recognition of words is lexical frequency: high-frequency words are recognized faster than low-frequency words

(Rubenstein, Garfield, & Millikan, 1970). Another such property is the orthographic neighborhood of a word, which refers to the number of new words that can be created by changing one letter of that word (Coltheart, Davelaar, Jonasson, & Besner, 1977). For example, in Spanish, *pato*, *peso*, *palo* and *vaso* ("duck", "weight", "stick" and "glass") are orthographic neighbors of "paso" ("step") because these words differ from the critical word only in a letter. Orthographic neighborhood is relevant to word reading because the identification of a given word gets harder the more orthographic neighbors it has. Other characteristics that influence visual word recognition are age of acquisition, familiarity, imagability and word length.

In the 1970s and 1980s, several models of visual word recognition were designed (Logogen model by Morton, 1969; Serial search model by Forster, 1976; Cohort model by Marslen-Wilson, 1989; etc.), but there are two notable models: the Dual Route Cascaded (DRC) model and the Parallel Distributed Processing (PDP) model. In the context of understanding how deaf people are able to recognize visual words and access the lexicon, these two models address the issue of the degree of involvement of phonological and orthographic processes during reading. In this sense, these theoretical models provide frameworks that allow us to identify the possible processes and routes that deaf readers could avail of. Each of the models is described in the following sections.

1.2.3.1. *Dual Route Cascaded (DRC) model*

The basic premise of the DRC model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) is that there are two possible routes to access the lexicon and the meaning of a word: the lexical route, based on the visual-orthographic properties of the word, and the sublexical route, based on the phonological structure (see figure 2).

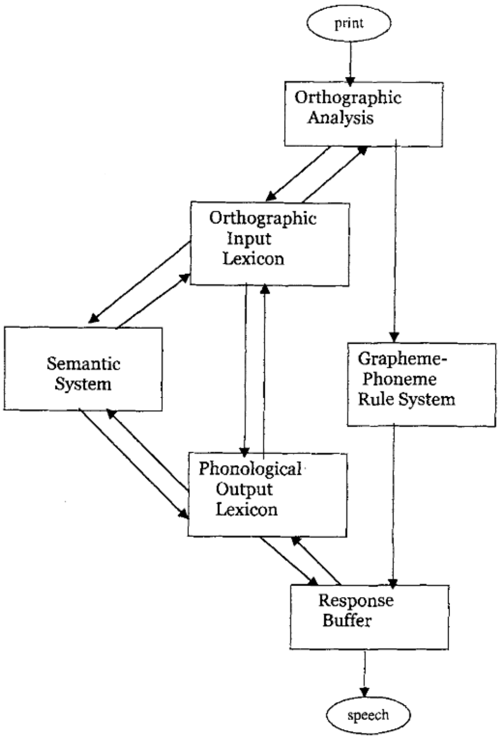


Figure 2. *Basic architecture of the DRC model of visual word recognition (Coltheart et al., 2001)*

The lexical or orthographic route implies that the recognition of the words is visual, without any phonological mediation; this route is used when reading very high-frequency words but cannot be employed for new or unknown words. For these words, the sublexical or phonological route would be used by applying the grapheme-phoneme conversion rules and accessing the meaning from the phonological image of the word. According to this model, skilled readers should read the words through both routes. During the learning process, they rely more on the sublexical route, but when a word is already known, the lexical pathway is predominant (Coltheart et al., 2001).

1.2.3.2. *Parallel distributed processing (PDP) model*

The PDP or "triangle" model (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989) is an alternative to the DRC model (see figure 3). It differs in that the grapheme-phoneme conversion rules are not required. In this model, the phonological representations constitute a property of the system, and phonological activation is an intrinsic process of word recognition. It consists of sets of units that form orthographic, phonological and semantic codes. Orthographic representations are assigned phonological representations in a single route model, establishing connections. That is, it uses distributed representations instead of a schema.

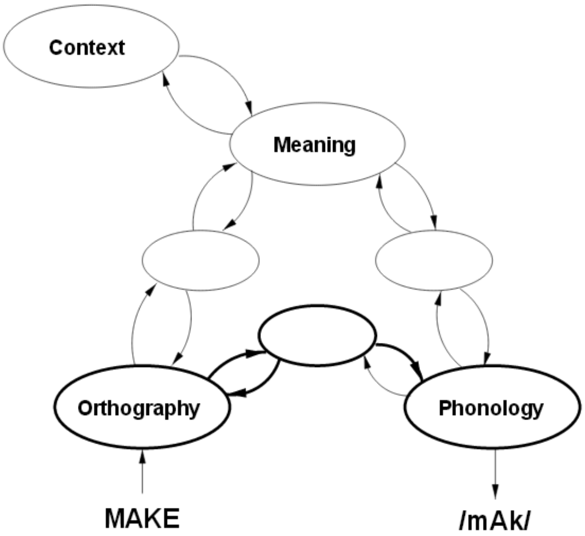


Figure 3. *The PDP or "triangle" model of visual word recognition (Seidenberg & McClelland, 1989)*

This model suggests that a single mechanism in parallel is enough to access semantics and lexicon. The processing of information, both lexical and semantic, depends on the interaction of a large number of simple codes that allow activation through the connections. The relationships between these codes are constituted by the force or weights that are assigned to the connections between units. Such connections may vary based on the exposure to new words. The same input (a string of letters) produces two outputs: one pattern of phonological units, and another of orthographic units. With the parallel activation of both outputs, the route that gives the first available response is selected.

The aim of this project is to discover how deaf people recognize visual words in Spanish. In characterizing this process, we will examine how well these theoretical models, which give an important role to phonological representation and coding, can be applied to deaf readers. To this end, we will use different behavioral techniques and also measure participants' electrophysiological activity in each experiment. In the next section, we explain each of these research methods.

1.3. Research tools and methods

In this section we describe the behavioral methods and the event-related potential (ERP) technique that have been used in this thesis project. For the former, two main tasks served to collect behavioral responses through reaction times and error rates.

1.3.1. Behavioral methods

1.3.1.1. *Lexical decision task*

The lexical decision task is the most widely used means to investigate the processes involved in visual word recognition and lexical access (Paap, McDonald, Schvaneveldt, & Noel, 1987). The task has been used in different populations, from children to adults (Ehri & Wilce, 1983; Perfetti & Hogaboam, 1975). The task consists of deciding if a string of letters is a real word or a nonword. In order to make this decision, the participant must access the mental lexicon and the semantic representation associated with the word. Usually, this type of task is performed on a computer, and the participant responds by pressing one of two different keys to indicate whether the stimulus is a word or a nonword (as such, the response is motor and non-verbal). The latency time from when the stimulus is presented until the participant responds, known as the reaction time, reflects the time taken by the participant to access the mental lexicon. By varying the type of stimulus presented and measuring the associated reaction time, it is possible to obtain an indication of the amount of cognitive processing that is required for visual stimulus recognition. For example, the lexicality effect is a classic effect in lexical decision tasks: recognizing real words involves shorter reaction times than identifying nonwords (Forster & Chambers, 1973). Other factors that effect visual word recognition include lexical frequency (Rubenstein, Garfield, & Millikan, 1970) and orthographic neighborhood (Grainger & Seguí, 1990), both of which were described above in section 1.2.3, Models of visual word recognition. Manipulating properties of the stimuli, such as those mentioned above, allows us to investigate the processes involved in the lexicon and meaning access of words and nonwords. In addition to reaction times, lexical decision tasks also record the number of errors committed by the participant, and this provides another indication of how the stimulus properties influence access to the lexicon.

1.3.1.2. *Same-different judgment task*

Same-different tasks have been used mainly for perceptual matching processes. A typical task consists of the presentation of two physically identical stimuli (*same*) or of two stimuli that differ in some feature (*different*). As in the lexical decision task, this type of task requires a non-verbal motor response: the participant must press one of two different keys to indicate whether the pairs of stimuli are "*same*" or "*different*". Usually, the response time for "*same*" pairs is lower than for "*different*" (Bamber, 1969; Keuss, 1977; Krueger, 1973b; Nickerson, 1965; Pachella & Miller, 1976; Proctor, 1981). The classic task of same-different (Ratcliff, 1981) has been exploited to investigate the abstract letter identity and letter position coding in an explicit perceptual matching task with strings of letters without lexical meaning (Duñabeitia, Orihuela, & Carreiras, 2014), but also with symbols or digits (Duñabeitia, Dimitropoulou, Grainger, Hernández, & Carreiras, 2011; García-Orza, Perea, & Muñoz, 2010; Massol, Duñabeitia, Carreiras, &

Grainger, 2013). Reaction times and errors are measured with this type of task in order assess the processes that play a role in the judgment of same or different elements.

1.3.2. Event-related potential (ERP)

The behavioral techniques described above do not provide direct information on the temporal development of the processes involved in visual word recognition. In contrast, Event-Related Potentials (ERP) (Rugg & Coles, 1995), obtained using electroencephalography (EEG), provide a high precision measure of the time course of the neural response. In our case, this allows us to know when the processes and subprocesses that intervene in the access to the lexicon or the judgment of the same-different pair occur.

Language processing involves physiological and anatomical activity, generating patterns of biological activity that can be recorded by electrodes placed on the scalp. ERPs are a reflection of this activity associated with specific events or tasks, such as the presentation of words and nonwords or other types of linguistic stimuli. After collecting electrophysiological data, specific segments can be extracted and averaged to obtain a wave for a specific time window that is related to a specific process. By taking into account the type of task and systematic variations in the stimuli, a series of components can be identified that are modulated by the experimental manipulation (Donchin, 1979; Coles, Graton, & Fabiani, 1990). Analyzing the latency of these components reveals the temporal course of the different cognitive processes involved, although a given time window may reflect more than one process (Kutas & Van Petten, 1994). Additionally, the distribution of an effect across the the electrodes on the skull can give information about the topography that these processes share.

The experiments in the thesis that use this technique identify several components of interest, depending on the type of task and paradigm employed. These components are described below.

1.3.2.1. *N100 component*

The N100 component is associated with discrimination that occurs at a location that is being attended to (Duñabeitia, et al., 2012; Vogel & Luck, 2000). This component is found when participants are required to discriminate among stimuli, and is not present in single-stimuli tasks (Mangun & Hillyard, 1991). In a same-different task, greater negativity appeared at around 100ms for word pairs that differ due to character replacements, compared to pairs that differ because of character transpositions (Duñabeitia et al., 2012). They concluded that character replacements might require greater attention demands than pairs including character transpositions. Perhaps is because the judgment between pairs with replaced-letters requires greater perceptive requirement, and therefore also a greater attentional demands are needed (Mangun & Hillyard, 1991). This component is distributed mostly over the frontal-central region of the scalp (Spitz, Emerson, & Pedley, 1986).

1.3.2.2. *N250 component*

The N250 reflects sublexical processing (Holcomb & Grainger, 2006). The N250 component is modified in amplitude when there is phonological overlap between a prime and target (Grainger & Holcomb, 2009). With a masked priming paradigm, when targets were preceded by nonwords similar to real words (like pseudohomophones or transposed-letter nonwords primes), this gave rise to changes in the amplitudes in the 250-350ms time window, reflecting phonological and orthographic sublexical processes in this epoch (Carreiras, Duñabeitia, & Molinaro, 2009; Carreiras, Gillon-Dowens, Vergara, & Perea, 2009; Carreiras, Perea, Vergara, & Pollatsek, 2009; Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009; Grainger, Kiyonaga, & Holcomb, 2006). The N250 has an extended distribution across the scalp and is larger in the anterior regions of the left hemisphere (Grainger & Holcomb, 2009).

1.3.2.3. *N400 component*

The N400 component has been associated with semantic processing in written word recognition and with semantic incongruence (Kutas & Hillyard, 1980; Kutas & Van Petten, 1988). The N400 appears in different languages (Friederic, 1996), with visual and auditory stimuli. During single word reading, nonwords elicited greater negative amplitude around 400ms compared with words (Holcomb, 1993). The phonological or orthographic characteristics of the stimuli can influence the ERP components in lexical decision tasks, such as reducing amplitude negativity around 400ms (Kramer & Donchin, 1987). Although the presence of the N400 effect with nonwords is well established, nonwords that are very similar to real words (such as pseudohomophones or transposed-letter nonwords) reduce the N400 effect (Carreiras, Perea, Vergara, & Pollatsek, 2009; Carreiras, Vergara, & Perea, 2007; Holcomb & Neville, 1990; Vergara-Martínez, Perea, Gómez & Swaab, 2013; Vergara-Martínez, Perea, Marín & Carreiras, 2010). Usually, the N400 component has been associated with semantic processing. However, this component can also be elicited when there is incongruity between non-linguistic stimuli which have no meaning (Gallagher et al., 2014). The topography of the N400 shows greater amplitudes in posterior and centroparietal regions (Kutas, Van Petten, & Besson, 1988).

1.4. General objectives of the project

As mentioned in the general introduction (section 1), much research on deaf readers has been conducted in languages with an opaque orthography and most of these studies do not show activation of phonological coding in visual word processing. As pointed out in the section 1.2.2, several works have claimed to show that the basis of visual word recognition rests on phonological representation, depending on the degree of transparency of the language in which reading occurs (Ehri, 1986; Frith, 1985; Harm & Seidenberg, 2004; Share, 1995). According to Frost and Katz (1992), phonological processes are required in transparent orthographies for visual word recognition. In addition, others authors (Carreiras et al., 2009; Pollatsek et al., 2005) showed that accessing phonological encoding when reading a transparent language like Spanish is automatic. This suggests that phonological processing is an obligatory step for word identification in transparent languages.

There are very few studies on deaf people and reading in Spanish. Most have focused on educational perspectives, and research on reading in Spanish (a language with transparent orthography) by deaf individuals from the point of view of cognitive neuroscience is limited. The studies that make up this thesis project focus on deaf skilled readers of Spanish. Although much previous work on deaf readers has been limited to children in the process of developing their language skills (see section 1.1.2 and 1.1.3), this study looks at skilled adult readers. These are individuals who have overcome the difficulties of learning to read and we are interested in finding out how they have managed this by examining what mechanisms underlie their reading skills. The aim of this project is to investigate the role of phonological and orthographic processes of deaf and hearing skilled readers of Spanish, and to discover whether both groups show similar or different patterns in this respect.

The experimental section is divided into three parts and contains descriptions of several experiments, including behavioral responses and electrophysiological activity.

Experiment 1 investigates phonological processes using two tasks. Experiment 1a involves a lexical decision task with two types of nonwords: pseudohomophones (nonwords that sound like real words) and control nonwords. Experiment 1b involves a go/no go semantic categorization task with a masked priming technique, using nonwords as primes. Through this experiment we want to verify what role phonology plays during visual word recognition in deaf readers and to assess the differences and similarities in the reliance on phonological processes during word reading between deaf and hearing readers with similar reading proficiency levels.

Experiment 2 focuses on the role of orthographic processes, using the same tasks as in Experiment 1. Experiment 2a, a lexical decision task, involves two types of nonwords: transposed-letter nonwords and replaced-letter nonwords. Experiment 2b explores the same manipulation with a masked priming go/no go semantic categorization task. The goal of this experiment is to investigate whether deaf and hearing skilled readers respond similarly or differently to orthographic manipulations, such as the transposition of letters, during visual word recognition.

Experiment 3 investigates orthographic sub-processes in more detail using three explicit perceptual matching tasks based on a same-different judgment. We study two key steps for orthographic processing: letter position coding (Experiment 3a) and letter identity coding, focusing on visual similarity (Experiment 3b) and abstract identity by changing cases (Experiment 3c). As suggested by Pelli et al. (2006), word recognition is based on the analysis of letters. Therefore, in order to further investigate the differences and similarities in orthographic processing between deaf and hearing skilled readers, we assessed the perceptual processing of letter position and identity (in relation to visual similarity and abstract identity).

2. EXPERIMENTAL SECTION

2.1. EXPERIMENT 1: Phonological processes

The aim of this first experiment is to investigate the involvement of phonological processes during visual word recognition in deaf skilled readers using a lexical decision task and measuring behavioral responses and electrophysiological activity, and to compare the use of phonological processes by deaf and hearing readers. It is important to note that the deaf participants in the experiments reported here are skilled readers with high reading levels compared to the majority of the deaf population and that their reading level is comparable to that of hearing readers of the same age. We are interested in the underlying processes in visual word recognition by deaf high-skilled readers and these may differ from hearing readers. We are also interested in obtaining a better understanding of how someone can achieve a high reading level despite hearing loss and without being able to access auditory information in the spoken language.

Experiment 1a tested phonological processing in a lexical decision task with two types of nonwords: pseudohomophones (nonwords that sound like real words) and control nonwords. In behavioral measures, the pseudohomophone effect is one of the strongest indicators of phonological processing in visual word recognition (Briesemeister, Hofmann, Tamm, Kuchinke, Braun & Jacobs, 2009; Ferrand & Grainger, 1994; Rubenstein, Lewis, & Rubenstein, 1971; Ziegler, Jacobs & Klüppel, 2001), as indicated by slower reaction times and/or more errors for pseudohomophones than control nonwords. In electrophysiological measures, the N400 component has been associated with semantic processing in written word recognition and semantic incongruence. Prior studies have shown larger negative amplitude around 400ms when hearing individuals read nonwords compared to words (Holcomb, 1993). Briesemeister et al. (2009) showed that nonwords that were similar to real words (like pseudohomophones) were associated with reduced N400 amplitude compared to nonwords that were not similar to real words (see also, Holcomb & Neville, 1990; Vergara-Martínez, Perea, Gómez & Swaab, 2013). Also, Newman and Connolly (2004) concluded that the absence of a N400 effect for pseudohomophones suggests that phonological access facilitates semantic integration during visual word recognition. Therefore, for the hearing control group we expect to replicate the same results that have already been found in previous experiments (increase of the N400 amplitude for nonwords and decrease of N400 for pseudohomophones). If the deaf skilled readers also rely on phonological information during lexical access, then we expect the same pattern of results as for hearing readers. However, if deaf skilled readers are not sensitive to phonological codes, then they should not show reduced N400 amplitude for pseudohomophones, and instead should show the electrophysiological response for pseudohomophones as for other nonwords.

In Experiment 1b we tested the role of phonological processing with a go/no go semantic categorization task using masked priming. Several masked priming studies have found early phonological effects in visual word recognition. For example, Grainger, Kiyonaga and Holcomb (2006) found a N250 component when words were preceded by pseudohomophones primes. This component reflects sublexical processing, in contrast to the N400 component, which is sensitive to lexical processing and semantic representation (Holcomb & Grainger, 2006).

If deaf skilled readers activate phonological codes, then they should perform like hearing readers and show longer reaction times and/or higher error rates for pseudohomophones than control nonwords. Also, they should show reduced amplitude around 400ms for pseudohomophones and real words compared to control nonwords in Experiment 1a. In addition, in Experiment 1b they should show a N250 component for words preceded by pseudohomophones primes compared to control nonword primes. In contrast, if they do not activate phonological codes, then they should not show any differences between pseudohomophones and control nonwords in either experiment.

In summary, these two experiments investigate whether deaf skilled readers activate phonological codes to the same extent as hearing readers during visual word recognition, and to what extent phonological mediation is necessary for skilled reading in a language with a transparent orthography.

2.1.1. Experiment 1a: Lexical decision task

2.1.1.1. Method

2.1.1.1.1. Participants

Twenty skilled adult Spanish severely (70-90 dB) to profoundly (>90 dB) readers (14 females; mean age=33.10 years; SD=7.44; range=23-45 years old) participated in the study. All participants lost the audition before they were 3 years old (i.e., prelingual deafness). Also, all of them learned Spanish Sign Language before 10 years old and used it as main language for communication. In addition, most of them learned to read at an early age, mostly at school, except two who learned after 16 years old. Fifteen hearing Spanish readers (9 females; mean age=29.40 years; SD=5.86; range=20-44 years old) were also included as a control group. All participants completed the ECL-2 reading assessment Test (De la Cruz, 1999) to assess their reading comprehension level. This test is a standardized reading test, which evaluates different types of texts and aspects of reading comprehension: knowledge of the meaning of words, synonyms, antonyms, understanding the meaning of sentences and the ability to integrate information into a text. The test consisted of five short paragraphs followed by multiple-choice questions, 27 in total. It does not require a reading aloud task to get the raw score and percentil (which would have been problematic for the deaf group). Only participants who scored at least at the 75th centile (more than 17 correct answers) on the test were included in the study and considered relatively skilled readers, and there was no significant difference in raw scores between the two groups (deaf: mean=22.20, SD=3.32, range=18-27; hearing: mean=24.07, SD=2.89, range=17-27; p=.079). All the participants also completed the Spanish version of LexTALE (Izura, Cuetos, & Brysbaert, 2014), a lexical decision test consisting of 60 real words and 30 nonwords that provides a good estimate of language knowledge (e.g., de Bruin, Carreiras, & Duñabeitia, 2017; Lemhöfer & Broersma, 2012). The final scores (in percentages) showed that both groups completed the test accurately, demonstrating a high level of Spanish vocabulary knowledge (deaf: mean=90.96, SD=12.93; hearing: mean=94.58, SD=5.93; p=.240). As a non-verbal intelligence test, the Raven Progressive Matrices test (Raven, Raven & Court, 1998) was administered to all participants, which measures general cognitive ability and involves identifying the item that is missing from a series of figures. The basic version of the test, the Standard Progressive Matrices (SPM), consists of five series of 12 items, each of increasing complexity, requiring progressively greater cognitive capacity to encode and analyze information. This test is standardized by age, and percentile scores can be obtained for different age groups. We excluded participants with notably low percentile scores (≤ 25). There was no significant difference in percentile scores between the two groups (deaf: mean=84.15, SD=9.74; hearing: mean=86.40, SD=9.88; p>.250).

2.1.1.1.2. Materials

For word trials, 80 Spanish words between four and six letters long were selected (mean log word frequency in the EsPal database (Duchon, Perea, Sebastián-Gallés, Martí & Carreiras, 2013): 3.57, range: 3.01-3.87; mean number of letters: 5). For nonword trials, 80 Spanish base words between four and six letters long with a similar frequency to the first set were also selected (mean log word frequency: 3.96, range: 2.61-4.65; mean number of letters: 5.29). These words were then used to create (1) pseudohomophones by replacing one letter by another letter that corresponded to the same phoneme (e.g., the pseudohomophone *javón* created from the base word *jabón*, 'soap'), and (2) control nonwords in which one letter was replaced by another letter that corresponded to a different sound (e.g., the nonword *jacón* created from the same base word). Two lists were constructed such that each base word used to generate the nonwords appeared once in each list, either as a pseudohomophone or as a control nonword. Participants were randomly assigned to the two lists. In total, each participant completed 160 trials: 80 trials with words and 80 trials with nonwords (40 pseudohomophones and 40 control nonwords).

2.1.1.1.3. Procedure

The experiment was run individually in a room with no acoustic or visual distractions. Presentation® software (Version 0.70, www.neurobs.com) was used for stimulus presentation and recording of response times and accuracy. Each trial began with the presentation of a centered fixation cross (+) for 500ms followed by a blank screen for 200ms and presentation of the stimulus word in lowercase font (45-pt. Courier New) for 1500ms or until the participant responded (see Figure 4). Participants were instructed to press one of two buttons on the keyboard ('M' and 'Z') to indicate whether the letter string was a word or nonword. Participants were instructed to respond as quickly and accurately as possible. The order of presentation of the stimuli was randomized for each participant and the two response buttons were counterbalanced for word and nonword responses. Each participant completed eight practice trials prior to starting the experiment.

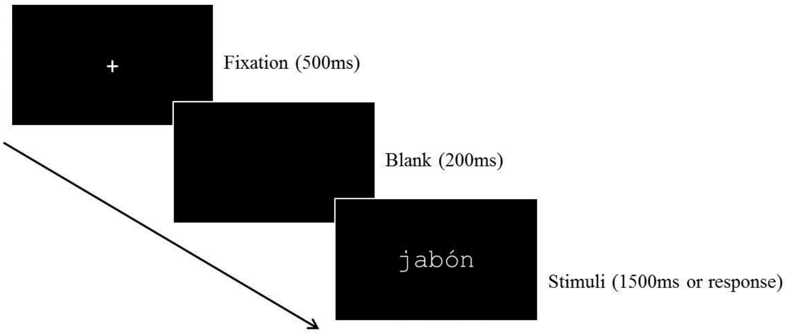


Figure 4. *Sequence of an experimental trial in Experiment 1a*

2.1.1.1.4. Behavioral analysis

Mean error percentages and response latencies for deaf and hearing readers are presented in Table 1 and Figure 6. Trials with incorrect responses (6.03% of the trials) were excluded from RT analysis. RTs above or below 2.5 standard deviations from the mean for each condition per participant were also excluded from the analysis of the response latencies (0.14% of the data). ANOVAs were conducted on error percentages and response latencies to analyze the lexicality effect following a 2 (Group: deaf, hearing) x 2 (Lexicality: word, nonword) design. Also, we conducted ANOVAs on error percentages and response latencies to analyze the differences between critical conditions following a 2 (Group: hearing, deaf) x 2 (Type of Nonword: pseudohomophone, control nonword) design.

2.1.1.1.5. EEG recording and analysis

The EEG was recorded with a 32-channel BrainAmp system (Brain Products GmbH) at a 500 Hz sampling rate. Scalp voltages were collected from 27 Ag/AgCl electrodes were placed in an EasyCap recording cap. The right mastoid was used as reference. An additional electrode at FCz served as ground, and 4 electrodes (2 on the orbital ridge below and 2 on the lateral junctions of both eyes) recorded the electro-oculogram (EOG). Impedance was kept below 5KΩ for mastoid and scalp electrodes, and below 10KΩ for EOG electrodes. The EEG signal was analyzed using Brain Vision Analyzer 2.0. EEG was filtered with a bandpass filter (Butterworth Zero Phase Filter, 1–20 Hz, 24 dB/octave). Epochs of the EEG corresponding to 800ms after target string presentation in the trials were averaged and analyzed. Baseline correction was performed using the average EEG activity in the 200ms preceding the onset of the target stimuli as a reference signal value. We removed the epochs with incorrect responses in all trials. The epochs were free of ocular or muscular artifacts, after performing an independent component analysis (ICA) and an artifact rejection process to average (96.09% of the data). We selected nine electrodes for repeated-measures ANOVA analyses, creating the factors Anterior-Posterior (frontal, central, parietal) and Hemisphere (right hemisphere, midline, left hemisphere). The frontal electrodes that we selected were F3 (left), Fz (midline) and F4 (right). The central electrodes were C3 (left), Cz (midline) and C4 (right), and the parietal electrodes were P3 (left), Pz (midline) and P4 (right). In addition to these factors, the main variables of interest and factors in the ANOVAs were Group (deaf, hearing), Lexicality (word, nonword) and Type of Nonword (pseudohomophone, control nonword). We selected one critical ERP time-window for analysis, based on previous literature and visual inspection: 350-550 post-stimuli onset.

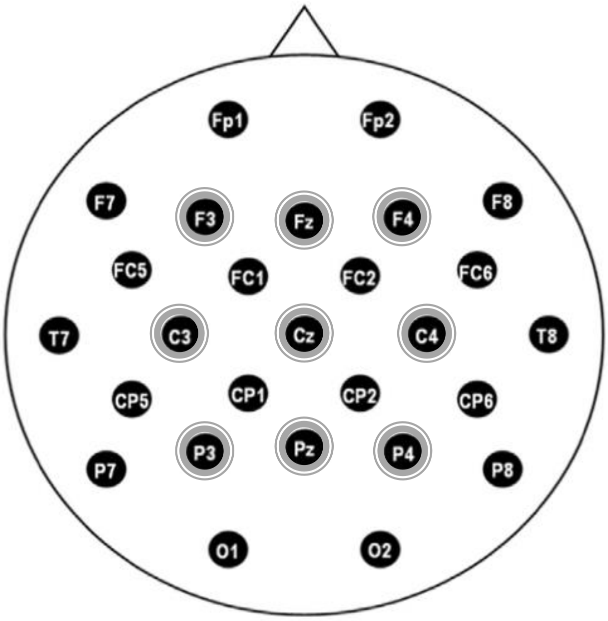


Figure 5. *Schematic representation of the electrode positions in an EasyCap recording cap. The electrodes in grey correspond to electrodes used in the electrophysiological analysis in all experiments.*

2.1.1.2. Results

2.1.1.2.1. Behavioral measures

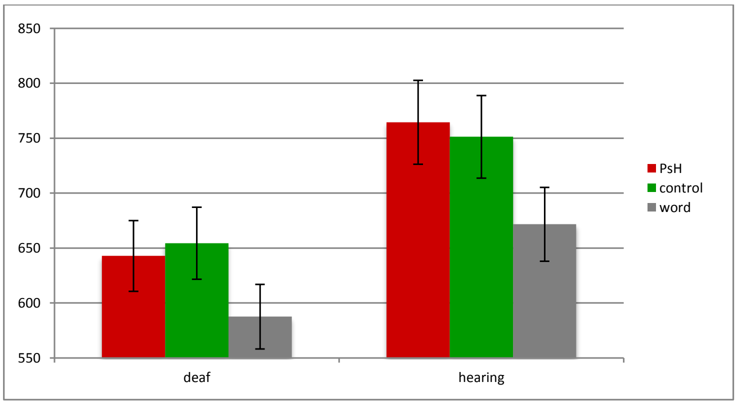
*Words vs. Nonwords***.** In the analysis of response latencies, the lexicality effect was significant [$F_1(1,36)=56.83$, $p<.001$, $\eta^2=0.594$; $F_2(1,78)=0.02$, $p<.001$, $\eta^2=0.657$], showing that participants were faster in words than nonwords. Also, there was a difference between Group [$F_1(1,36)=7.15$, $p=.011$, $\eta^2=0.161$; $F_2(1,78)=428.87$, $p<.001$, $\eta^2=0.846$], where deaf readers responded significantly faster than hearing readers (640ms vs. 726ms). The analysis of error percentages showed a main effect of lexicality [$F_1(1,36)=3.56$, $p<.001$, $\eta^2=0.227$; $F_2(1,78)=10.81$, $p=.002$, $\eta^2=0.121$]. The main effect of Group [$F_1(1,36)=9.19$, $p=.004$, $\eta^2=0.190$; $F_2(1,78)=26.13$, $p<.001$, $\eta^2=0.266$] was significant. Also, the interaction between these factors was significant [$F_1(1,36)=9.18$, $p<.001$, $\eta^2=0.227$; $F_2(1,78)=16.09$, $p<.001$, $\eta^2=0.171$], showing a difference between words and nonwords in hearing (4.50% vs. 10.82%; $t_1(19)=4.04$, $p<.001$; $t_2(79)=4.34$, $p<.001$) but not in deaf (4.06% vs. 4.75%; $t_1(19)= 0.68$, $p>.250$; $t_2(79)=0.58$, $p>.250$).

Pseudohomophones vs. Control nonwords. The analysis of response latencies yielded a main effect of Group, demonstrating faster responses for deaf than hearing readers (661ms vs. 758ms; $F_1(1,36)=6.88$, $p=.013$, $\eta^2=0.157$; $F_2(1,78)=257.93$, $p<.001$, $\eta^2=0.766$). The main effect of Type of nonword was not significant [$F_1(1,36)=0.81$, $p>.250$, $\eta^2=0.02$; $F_2(1,78)=0.02$, $p>.250$, $\eta^2=0.000$]. The interaction between the two factors was not significant either [$F_1(1,36)=4.02$, $p=.052$, $\eta^2=0.098$; $F_2(1,78)=2.47$, $p=.120$, $\eta^2=0.030$], but the pattern follows the direction we expected, at least by subjects. For this reason, we have done the analysis separately for each group, showing differences in the reaction times in hearing [$t_1(19)=2.10$; $p=.049$], with higher latency in pseudohomophones than control nonwords. This difference was not significant for deaf

[$t_1(19)=0.74$; $p>.250$]. The analysis of error percentages yielded a main effect of Group [$F_1(1,36)=12.00$, $p=.001$, $\eta^2=0.240$; $F_2(1,78)=33.18$, $p<.001$, $\eta^2=0.295$] showing that deaf readers were more accurate than hearing readers (4.75% vs. 10.81%). The main effect of Type of nonword was also significant [$F_1(1,36)=25.38$, $p<.001$, $\eta^2=0.311$; $F_2(1,78)=19.37$, $p<.001$, $\eta^2=0.194$]. More importantly, the interaction between the two factors was significant [$F_1(1,36)=19.22$, $p<.001$, $\eta^2=0.236$; $F_2(1,78)=26.83$, $p<.001$, $\eta^2=0.252$], showing that hearing readers made more errors when responding to the pseudohomophones than to the control nonwords (17.00% vs. 4.63%; $t_1(19)=5.49$, $p<.001$; $t_2(79)=5.47$, $p<.001$), while deaf readers showed no difference between the two conditions (5.25% vs. 4.25%; $t_1(19)=0.79$, $p>.250$; $t_2(79)=0.60$, $p>.250$).

Table 1. Mean response latencies and error percentages for words, pseudohomophones and control nonwords for the deaf and hearing skilled readers in Experiment 1a.

	DEAF			**HEARING**		
	Reaction Time		*% Errors*	*Reaction Time*		*% Errors*
	Mean	SD	Mean	Mean	SD	Mean
Words (*novio*)	597	64	4.06%	660	93	4.50%
Pseudohomophones (*nobio*)	656	99	5.25%	773	162	17.00%
Control nonwords (*notio*)	666	82	4.25%	744	121	4.63%



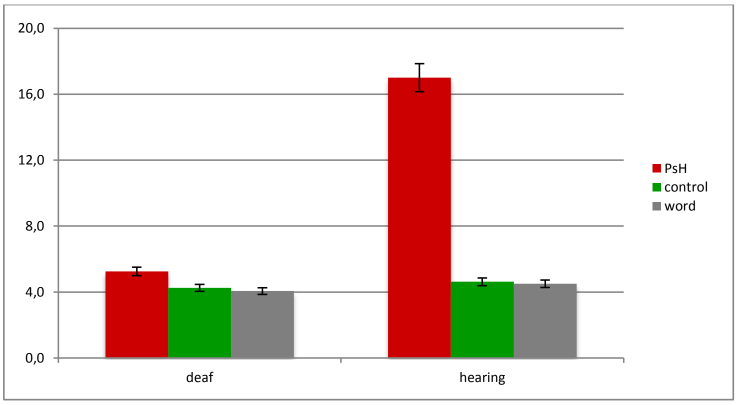


Figure 6. *Mean response latencies and error percentages for deaf and hearing in the Experiment 1a. Error bars represent 95% confidence intervals.*

2.1.1.2.2. Electrophysiological measures

<u>350-550ms epoch:</u>

Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=61.94, p<.001, η^2=0.604], reflecting that nonwords elicited larger negativities than words. Group effect was not significant [p>.250] and the interaction between these factors was not significant either [F(1,38)=2.61, p=.114, η^2=0.026]. Regarding topographical factors the interactions between lexicality and anterior-posterior regions was significant

[F(2,76)=4.04, p=.022, η^2=0.092], showing differences between words and nonwords in frontal [t(39)=6.68; p<.001], central [t(39)=7.57; p<.001] and parietal region [t(39)=6.95; p<.001].

Pseudohomophones vs. Control nonwords. The main effect of Type of nonword was significant [F(1,38)=12.69, p=.001, η^2=0.241], showing that in this time-window control nonwords elicited larger negativities than pseudohomophones. Group effect was not significant [p>.250]. The interaction between these two factors was not significant either [F(1,38)=1.98, p=.167, η^2=0.038]. Although the interaction was not significant, following the graphs, we decided to do the analysis of each group separately. The main effect of Type of nonword was significant in hearing [F(1,19)=25.37, p<.001, η^2=0.572] but not in deaf [F(1,19)=1.53, p=.231, η^2=0.075]. Regarding topographical factors, the interaction between Type of nonword and hemisphere was significant [F(2,76)=3.65, p=.030, η^2=0.088], showing differences in between words and nonwords in left hemisphere [t(39)=2.81; p=.006], middle [t(39)=3.60; p<.001] and right hemisphere [t(39)=3.90; p<.001].

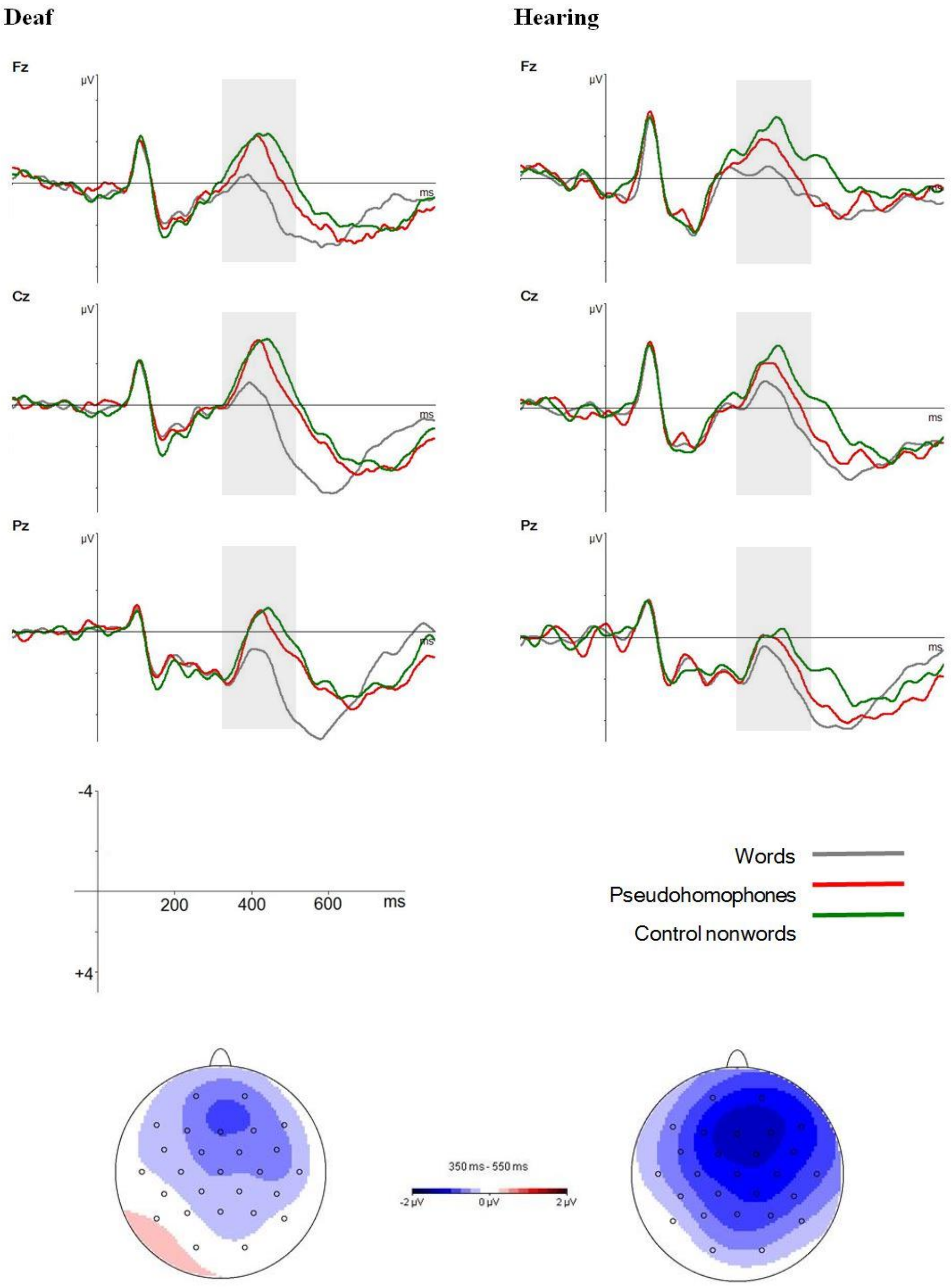


Figure 7. *Grand-averaged ERPs in Experiment 1a for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the word, pseudohomophone and control nonword conditions. Bottom: The N400 component in its corresponding time window (350-550ms) in topographical maps (created by subtracting the observed voltage for control nonwords minus pseudohomophones).*

Lack of power may have contributed to the non-significant interaction between Type of nonword and Group, because the number of trials got reduced when excluding error responses. Therefore, we also performed the same analyses including all trials.

350-550ms epoch (errors included):

Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=41.40, p<.001, η^2=0.512], reflecting that nonwords elicited larger negativities than words. Group effect was not significant [p>.250]. The interaction between these factors was significant [F(1,38)=47.40, p<.001, η^2=0.512], showing a greater effect in the deaf [F(1,19)=32.86, p<.001, η^2=0.634] than the hearing [F(1,19)=14.54, p=.001, η^2=0.434].

Pseudohomophones vs. Control nonwords. The main effect of Type of nonword was not significant [F(1,38)=2.94, p=.095, η^2=0.065] and Group effect was not significant either [p>.250]. However, the interaction between these two factors was significant, when we included the error responses [F(1,38)=4.19, p=.048, η^2=0.093], showing a significant difference between conditions in the hearing [F(1,19)=10.91, p=.004, η^2=0.365], with a reduced negativity for pseudohomophones compared with control nonwords. In contrast, this effect was not present in the deaf [F(1,19)=0.41, p=.842, η^2=0.002].

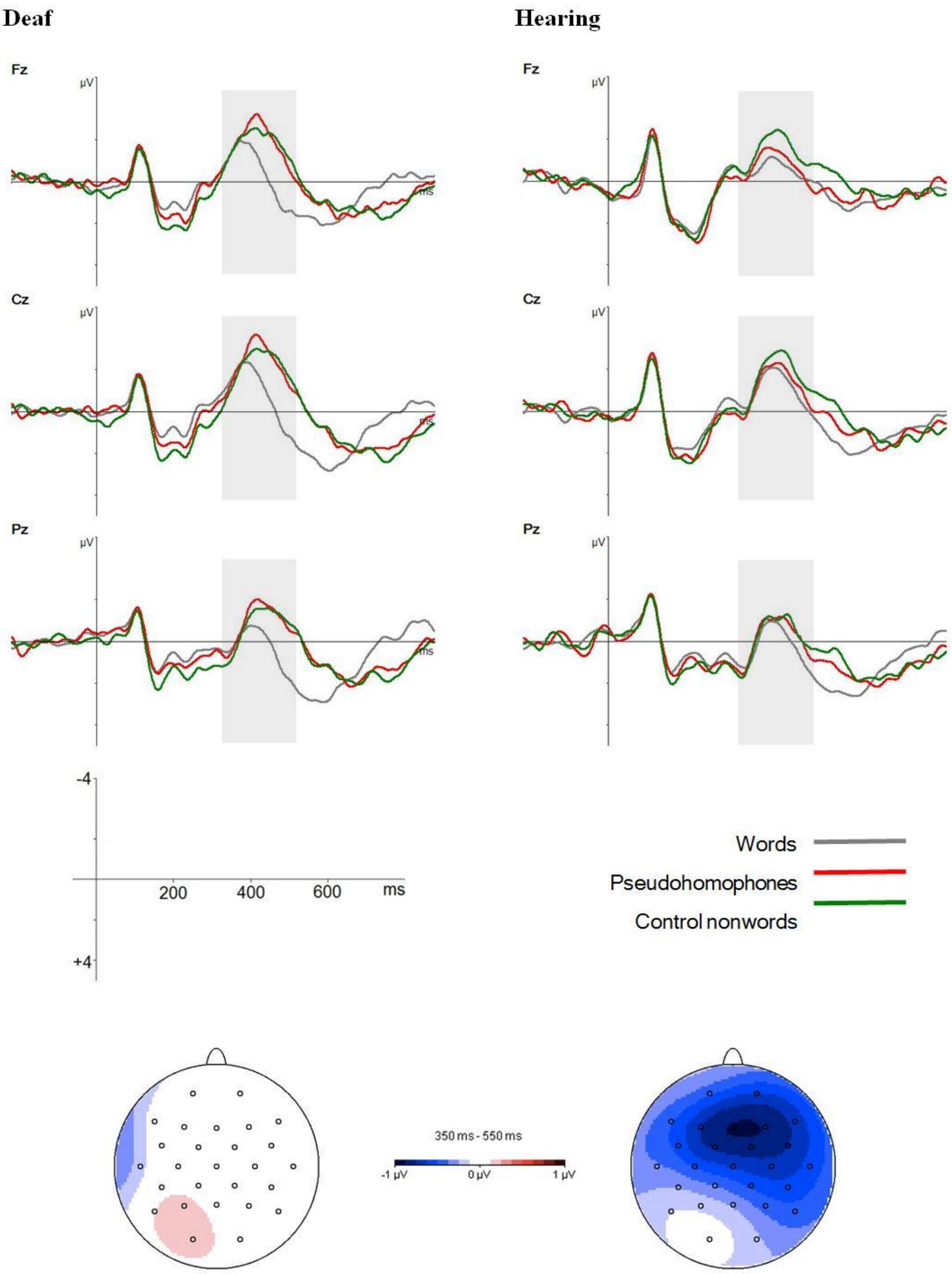


__Figure 8.__ Grand-averaged ERPs in Experiment 1a (errors included) for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the word, pseudohomophone and control nonword conditions. Bottom: The N400 component in its corresponding time window (350-550ms) in topographical maps (created by subtracting the observed voltage for control nonwords minus pseudohomophones).

2.1.2. Experiment 1b: Masked priming paradigm

Holcomb and Grainger (2006) argued that the N250 component might reflect sublexical processing. In particular, Grainger and Holcomb (2009) showed that phonological overlap across primes and targets yielded an N250 effect. In addition, Grainger, Kiyonaga, et al. (2006) showed that pseudohomophone primes were associated with changes in the amplitude at the 250-350ms time window, reflecting phonological sublexical processing. Here we will investigate phonological sublexical processes in deaf skilled readers using a similar masked priming procedure in a go/no-go semantic categorization task with pseudohomophones.

2.1.2.1. Method

2.1.2.1.1. Participants

The participants were the same as in the Experiment 1a.

2.1.2.1.2. Materials

The experimental targets were 80 Spanish words (4-6 letters long) were selected from EsPal database (Duchon et al., 2013) (mean log word frequency: 3.96, range: 2.61-4.65; mean number of letters: 5.29). The targets were preceded by nonword primes that were (1) pseudohomophones (40 trials), which were created by replacing one letter of the target word by another letter that corresponded to the same phoneme (e.g., the pseudohomophone *nobio* created from the base word *novio*, 'boyfriend'), and (2) control nonwords (40 trials), in which one letter of the target was replaced by another letter that corresponded to a different sound (e.g., the nonword *notio* created from the same target word). Two lists were constructed such that each target word used to generate the nonwords appeared once in each list, either as a pseudohomophone or as a control nonword.

We selected 80 Spanish words (4-6 letters long) for control targets (mean log word frequency: 3.57, range: 3.01-3.87; mean number of letters: 5) preceded by prime words that were identical to the target. In addition, we selected an additional 20 Spanish words (4-6 letters long) corresponding to animal names (mean log word frequency: 3.49, range: 2.26-4-50; mean number of letters: 4.50) preceded by another word with the same number of letters (mean log word frequency: 3.16, range: 2.51-3.50; mean number of letters: 4.50). The 20 names of animal were presented twice, once as target and onces as primes (followed by unrelated word targets) to control for prime visibility.

Participants were randomly assigned to the two lists. In total, each participant completed 200 trials: 80 trials with prime word-control target word pairs, 80 trials with experimental prime nonword-target word pairs (40 pseudohomophones and 40 control nonwords), 20 trials with prime word-animal target word pairs (trials for go/no-go task), and 20 trials with animal prime-filler target word pairs.

2.1.2.1.3. Procedure

The experiment was run individually in a room with no acoustic or visual distractions. Presentation® software (Version 0.70, www.neurobs.com) was used for stimulus presentation and recording of response times and accuracy. Each trial began with the presentation of a forward mask consisting of a row of hash marks (######) for 500ms (the hash marks' number depended of the prime's length), followed by the prime, which was presented in lowercase (25-pt. Courier New) and remained on the screen for 50ms. The prime was followed immediately by the target stimulus in lowercase too. The targets remained on the screen for 1500ms or until response (if the target was an animal name) (see Figure 9). Participants were instructed to press one button on the keyboard (space bar) only when the word on the screen was an animal name. Participants were instructed to respond as quickly and accurately as possible. The order of presentation of the stimuli was randomized for each participant.

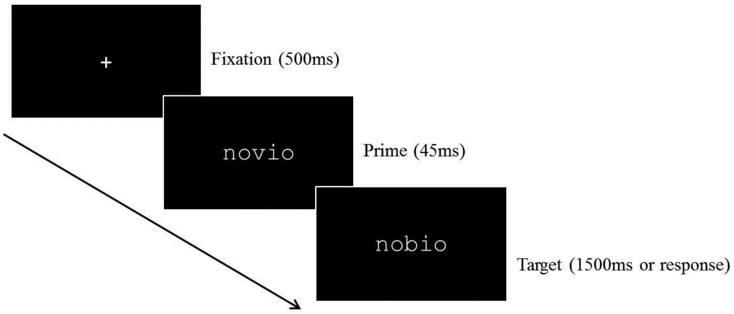


Figure 9. *Sequence of an experimental trial in Experiment 1b*

2.1.2.1.4. EEG recording and analysis

The EEG recording and analysis was the same as in Experiment 1a. The artifact - free epochs to average were 87.47% of the data. The variables of interest and main factors in the ANOVA were Group (deaf, hearing) and Type of Nonword (pseudohomophone, control nonword). We selected one critical ERP time-window for analysis, based on previous literature and visual inspection: 200-325ms post-target onset.

2.1.2.2. Results

2.1.2.2.1. Electrophysiological measures

200-325ms post-target:

The main effect of Type of nonword was significant [F(1,38)=6.69, p=.014, ŋ^2=0.135], showing that in this time-window, targets preceded by control nonwords elicited larger negativities than pseudohomophones. Group effect was not significant [p>.250]. But the interaction between these two factors was significant [F(1,38)=4.88, p=.0.33, ŋ^2=0.099], reflecting that control nonwords elicited a larger negative amplitude than pseudohomophones in the hearing [F(1,19)=9.50, p=.006, ŋ^2=0.333] but not in the deaf [F(1,19)=0.09, p>.250, ŋ^2=0.005]. There were no interactions with topographical factors [ps>.250].

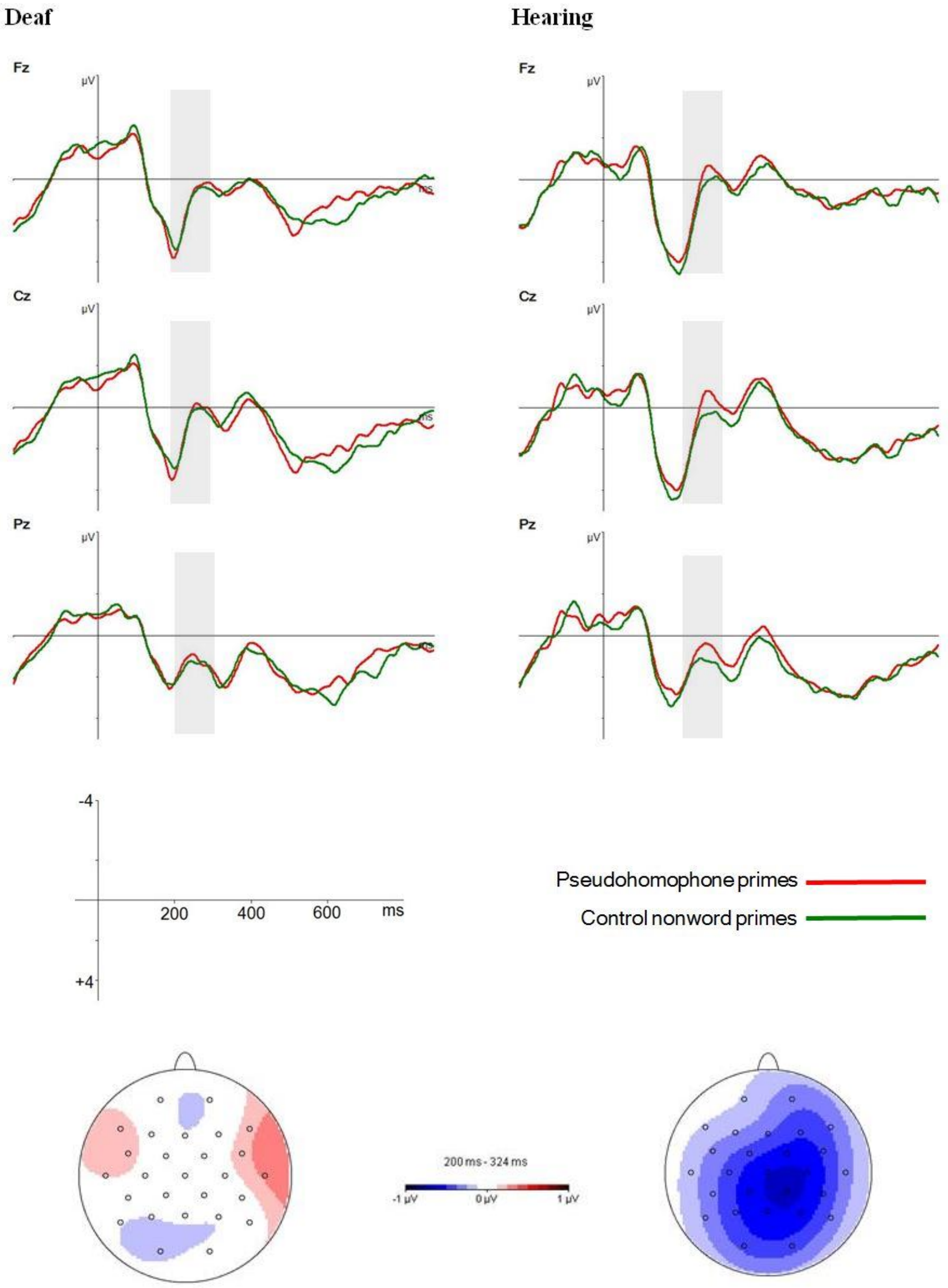


Figure 10. *Grand-averaged ERPs in Experiment 1b for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the pseudohomophone primes and control nonword primes. Bottom: The N250 component in its corresponding time window (150-325ms) in topographical maps (created by subtracting the observed voltage for pseudohomophone references minus control nonword references).*

2.1.3. Discussion of Experiment 1:

The results of Experiment 1a showed a lexicality effect for both groups in the behavioral responses and ERP results. However, only the hearing readers showed a pseudohomophone effect. Specifically, behaviorally the hearing group showed a higher percentage of errors when rejecting pseudohomophones compared to control nonwords and a trend in the same direction in their reaction times. Thus, hearing readers experienced greater difficulty rejecting nonwords that sounded like real words (Briesemeister et al., 2009), suggesting that they experienced interference of phonological information during lexical access. Importantly, for skilled deaf readers, error percentages for pseudohomophones were similar to those for control nonwords, suggesting that they did not activate phonological codes. Since the deaf readers in the current study are proficient readers, these results challenge the idea that deaf individuals need to access phonology in reading tasks to be competent readers (Perfetti & Sandak, 2000).

A somewhat surprising finding in Experiment 1a was that deaf readers responded significantly faster than hearing readers across conditions. Faster reaction times in word reading tasks for deaf than hearing readers have been previously reported (Brown & Brewer, 1996; Hanson & Fowler, 1987; Morford, Occhino-Kehoe, Piñar, Wilkinson & Kroll, 2015). In addition, several studies have found faster responses for deaf than hearing participants on other visual tasks, such as non-linguistic perceptual threshold tasks (Nava, Bottari, Zampini & Pavani, 2008) or simple detection and lateralization tasks (Colmenero, Catena, Fuentes & Ramos, 2004; Lore & Song, 1991; Reynolds, 1993). This finding will be discussed in more detail in the General Discussion (section 3).

As for the ERP results in Experiment 1a, the reduced negativity around 400ms for pseudohomophones in hearing readers replicates the findings of Briesemeister et al.

(2009), indicating that they activate phonological codes during lexical access. However, skilled deaf readers did not show a reduced negativity for pseudohomophones, providing further evidence that they do not activate phonological codes during visual word recognition.

The results of Experiment 1b showed a larger N250 amplitude in hearing readers for words with pseudohomophone primes compared to words preceded by control nonword primes, indicating phonological sublexical processing (Grainger, Kiyonaga & Holcomb, 2006; Holcomb & Grainger, 2006). Consistent with the results of Experiment 1a, deaf readers did not show a similar difference between pseudohomophone primes and control nonword primes in the N250 component.

Taken together, the two experiments revealed critical differences between deaf and hearing skilled readers in their reliance on phonological processes in visual word recognition. In contrast to hearing readers, deaf readers do not activate phonological codes when reading words in a transparent language. Although automatic phonological coding may usually be the default mechanism for reading in transparent orthographies (Carreiras et. al, 2009; Pollatsek et al., 2005), it seems that is not obligatory for successful visual word recognition.

2.2. EXPERIMENT 2: Orthographic processes

The results of Experiment 1a and 1b showed a different role for phonological processes during word reading in deaf and hearing skilled readers. The next question we asked was whether orthographic processes during visual word recognition also differ between deaf and hearing readers. To that end, we used the same type of tasks as in the first two experiments (lexical decision task and go/no go semantic categorization task with masked priming) to measure behavioral responses and electrophysiological activity in relation to an orthographic manipulation.

Specifically, Experiment 2a investigated orthographic processing using a lexical decision task with two types of nonwords: transposed-letter nonwords (TL) and replaced-letter nonwords (RL). The transposed-letter effect reflects slower reaction times and/or more errors for TL nonwords than RL nonwords, and is a robust indicator of orthographic processing (Perea & Fraga; 2006; Perea & Lupker, 2004; Perea & Carreiras, 2006). In electrophysiological studies, TL nonwords are associated with a smaller N400 amplitude than RL nonwords (Carreiras, Vergara, & Perea, 2007; Vergara-Martínez, Perea, Gómez, & Swaab, 2013).

To test the time course of orthographic processing during visual word recognition by deaf and hearing readers, Experiment 2b used a masked priming go/no go semantic categorization task with TL and RL nonwords. Previous studies with hearing readers have found differences between TL and RL primes in the N250 component (Duñabeitia, Molinaro, Laka, Estévez, & Carreiras, 2009; Grainger, Kiyonaga & Holcomb, 2006; Holcomb & Grainger, 2006). Therefore, if hearing and deaf skilled readers activate orthographic codes during visual word recognition, then TL prime effects in the N250 component should be the same for both groups. In contrast, if the modulation of the N250 effect interacts with group (deaf vs. hearing), then this would suggest that orthographic processes also differ between deaf and hearing readers.

In summary, if deaf readers activate orthographic codes during word reading, then in Experiment 1a they should show longer reaction times and/or higher error rates for transposed-letter nonwords than replaced-letter nonwords, and a smaller negativity for transposed-letter words than replaced-letter nonwords around 400ms. In Experiment 2b, if deaf readers activate orthographic codes, then words that are preceded by transposed-letter primes should trigger a N250 effect compared to replaced-letter primes.

2.2.1. Experiment 2a: Lexical decision task

2.2.1.1. Method

2.2.1.1.1. Participants

The participants were the same as in Experiment 1.

2.2.1.1.2. Materials

For the word trials, 80 Spanish words between eight and ten letters long were selected (mean log word frequency: 3.88, range: 3.45-4.48; mean number of letters: 8.73; Duchon et al., 2013). For the nonword trials, 80 Spanish base words between eight and ten letters long with a similar frequency to the first set were also selected (mean log word frequency: 3.91, range: 2.97-5.12; mean number of letters: 8.74). These base words were then used to create (1) transposed-letter (TL) nonwords, in which the position of two non-adjacent consonants was swapped (e.g., *mecidina* from the base word *medicina*, ‘medicine’), and (2) replaced-letter (RL) nonwords in which the two critical consonants were substituted by others with a similar physical shape as in the transposed-letter nonword (e.g., *mesifina*). Two lists of materials were constructed so that each base word appeared only once in each list, either as a TL nonword or as a RL nonword. Participants were randomly assigned to the two lists. In total, each participant completed 160 trials: 80 trials with words and 80 trials with nonwords (40 transposed-letter nonwords and 40 replaced-letter nonwords).

2.2.1.1.3. Procedure

The procedure was the same as in Experiment 1a.

2.2.1.1.4. Behavioral analysis

Mean error percentages and response latencies for deaf and hearing readers are presented in Table 2 and Figure 11. Trials with incorrect responses (7.00% of the trials) were excluded from RT analysis. RTs above or below 2.5 standard deviations from the mean for each condition per participant were also excluded from the analysis of the response latencies (0.65% of the data). ANOVAs were conducted on error percentages and response latencies to analyze the lexicality effect following a 2 (Group: deaf, hearing) x 2 (Lexicality: word, nonword) design. Also, we conducted ANOVAs on error percentages and response latencies to analyze the differences between critical conditions following a 2 (Group: hearing, deaf) x 2 (Type of Nonword: transposed-letter nonword, replaced-letter nonword) design.

2.2.1.1.5. EEG recording and analysis

The EEG recording and analysis was the same as in Experiment 1. The artifact - free epochs to average totaled 95.94% of the data. The main variables of interest and factors in the ANOVAs were Group (deaf, hearing), Lexicality (word, nonword) and Type of Nonword (transposed-letter, replaced-letter). We selected two critical ERP time-windows for analysis, based on previous literature and visual inspection: 300-425ms and 450-600ms post-stimuli onset.

2.2.1.2. Results

2.2.1.2.1. Behavioral measures

Words vs. Nonwords. The analysis of response latencies showed that the main effect of lexicality was significant [$F_1(1,36)=567.38$, $p<.001$, $\eta^2=0.604$; $F_2(1,78)=237.04$, $p<.001$, $\eta^2=0.741$], showing that participants were faster in words than nonwords. The effect of Group was also significant [$F_1(1,36)=11.56$, $p=.002$, $\eta^2=0.234$; $F_2(1,78)=937.54$, $p<.001$, $\eta^2=0.922$], where deaf readers responded significantly faster than hearing readers (680ms vs. 808ms). The analysis of error percentages showed a main effect of lexicality [$F_1(1,36)=73.87$, $p<.001$, $\eta^2=0.661$; $F_2(1,78)=115.55$, $p<.001$, $\eta^2=0.596$]. The main effect of Group is only significant by items, not by subjects [$F_1(1,36)=1.51$, $p=.227$, $\eta^2=0.040$; $F_2(1,78)=7.52$, $p=.008$, $\eta^2=0.086$]. The interaction between these factors was significant only by items [$F_1(1,36)=1.72$, $p=.198$, $\eta^2=0.015$; $F_2(1,78)=6.77$, $p=.011$, $\eta^2=0.074$].

Transposed-letter nonwords vs. Replaced-letter nonwords. The analysis of response latencies yielded a main effect of Group, indicating that deaf skilled readers responded faster than hearing readers (706ms vs. 842ms; $F_1(1, 36)=10.84$, $p=.002$, $\eta^2=0.222$; $F_2(1,78)=322.60$, $p<.001$, $\eta^2=0.805$). A main effect of Type of nonword was also found [$F_1(1,36)=132.46$, $p<.001$, $\eta^2=0.780$; $F_2(1,78)=150.83$, $p<.001$, $\eta^2=0.659$], showing faster responses for replaced-letter nonwords than transposed-letter nonwords (711ms vs. 836ms). The interaction between the two factors was not significant [$F_1(1,36)=0.40$, $p>.250$, $\eta^2=0.002$; $F_2(1,78)=1.40$, $p=.239$, $\eta^2=0.014$]. The analysis of error percentages yielded a main effect of Type of nonword [$F_1(1,36)=82.38$, $p<.001$, $\eta^2=0.679$; $F_2(1,78)=93.93$, $p<.001$, $\eta^2=0.546$], indicating that participants made more errors in the transposed-letter condition than in the replaced-letter condition (21.06% vs. 2.75%). The main effect of Group was not significant by subjects, only by items [$F_1(1,36)=1.74$, $p=.194$, $\eta^2=0.006$; $F_2(1,78)=8.49$, $p=.005$, $\eta^2=0.093$]. The interaction between the two factors was not significant either [$F_1(1,36)=0.78$, $p>.250$, $\eta^2=0.006$; $F_2(1,78)=2.70$, $p=.104$, $\eta^2=0.033$].

Table 2. Mean response latencies and error percentages for words, transposed-letter and replaced-letter nonwords for deaf and hearing skilled readers in Experiment 2a.

	DEAF			**HEARING**		
	Reaction Time		*% Errors*	*Reaction Time*		*% Errors*
	Mean	SD	Mean	Mean	SD	Mean
Words (*medicina*)	628	52	2.06%	739	146	2.13%
TL nonwords (*medicina*)	765	93	18.75%	908	182	23.38%
RL nonwords (*mesifina*)	647	65	2.00%	776	162	3.50%

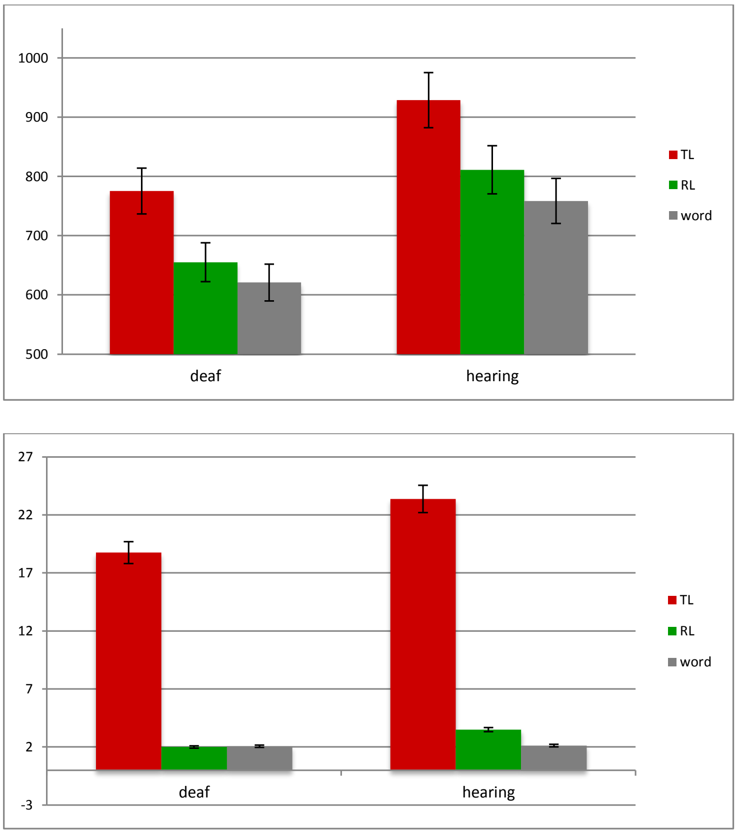


Figure 11. *Means response latencies and error percentages for deaf and hearing in the Experiment 2a. Error bars represent 95% confidence intervals.*

2.2.1.2.2. Electrophysiological measures

300-425ms epoch:

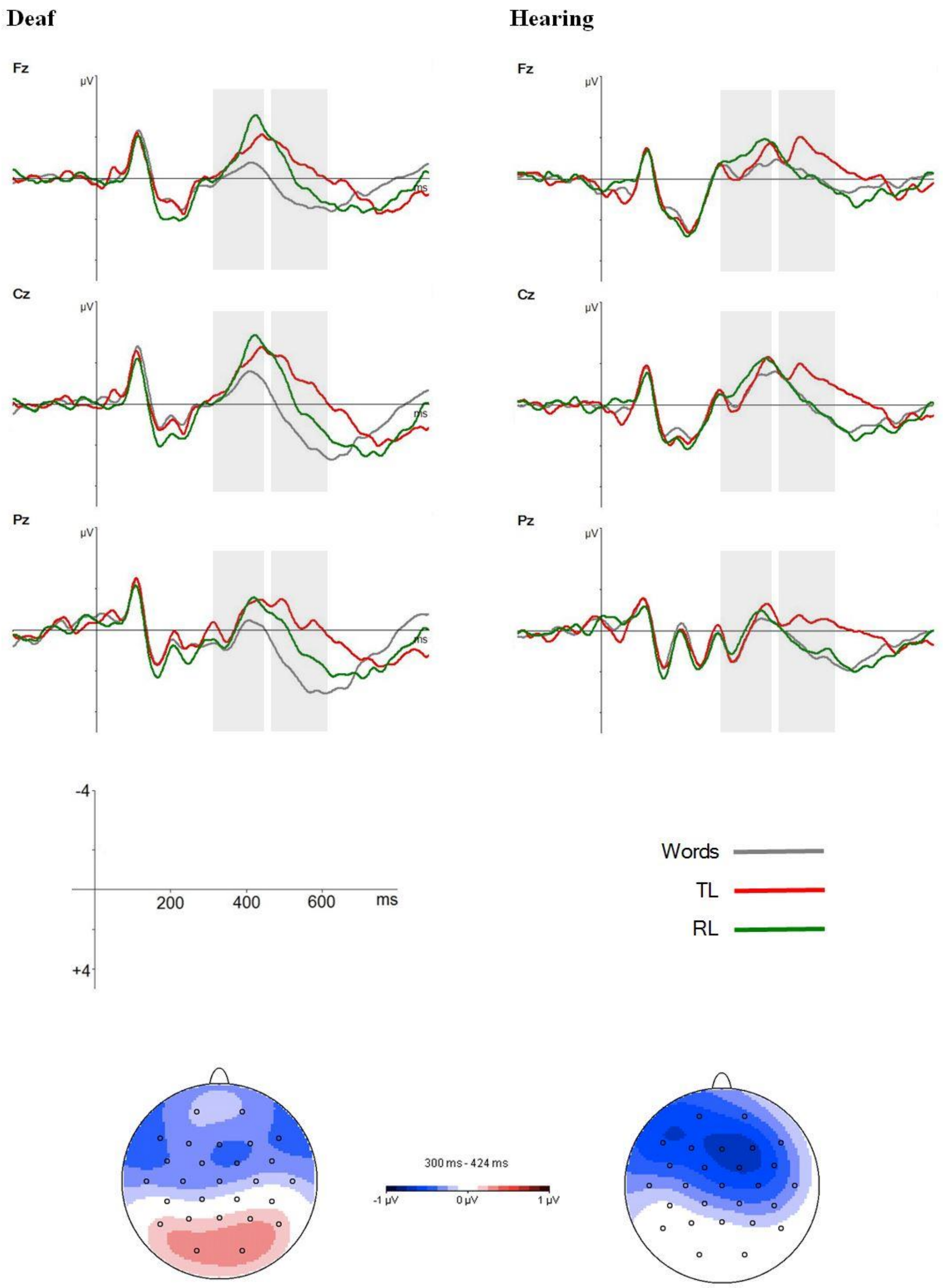
Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=9.38, p=.004, ŋ^{2}=0.192], reflecting that nonwords elicited larger negativities than words. Group effect was not significant [p>.250]. The interaction between these factors was not significant either [F(1,38)=1.58, p=.216, ŋ^{2}=0.032]. Regarding topographical factors, the interaction between lexicality and anterior-posterior regions was significant [F(2,76)=8.71, p=.013, ŋ^{2}=0.186], showing differences between words and nonwords in frontal [t(39)=3.73; p<.001], central [t(39)=2.70; p=.010] and parietal region [t(39)=2.29; p=.027], suggesting a greater effect in the frontal region.

Transposed-letter nonwords vs. Replaced-letter nonwords. The main effect of Type of nonword was significant [F(1,38)=5.47, p=.025, ŋ^{2}=0.125], showing a larger negativities for replaced-letter than transposed-letter nonword. Group effect was not significant [F(1,38)=1.03, p>.250, ŋ^{2}=0.026]. The interaction between these two factors was not significant either [p>.250]. Regarding topographical factors, the interaction between Type of nonword and anterior-posterior regions was significant [F(2,76)=15.05, p<.001, ŋ^{2}=0.283], showing differences between transposed-letter and replaced-letter nonwords in frontal [t(39)=3.73; p<.001] and central region [t(39)=2.57; p=.014], but not in parietal region [p<.250].

450-600ms epoch:

Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=43.93, p<.001, ŋ^{2}=0.501], reflecting that nonwords elicited larger negativities than words. Group effect was also significant [F(1,38)=5.03, p=.031, ŋ^{2}=0.117]. The interaction between these factors was significant [F(1,38)=5.76, p=.021, ŋ^{2}=0.066], showing a greater effect in deaf [F(1,19)=32.64, p<.001, ŋ^2=0.632] than hearing [F(1,19)=11.89, p=.003, ŋ^2=0.385]. Regarding topographical factors, the interaction between lexicality and anterior-posterior regions was significant [F(2,76)=14.98, p<.001, ŋ^2=0.265], showing differences between words and nonwords in frontal [t(39)=3.97; p<.001], central [t(39)=6.18; p<.001] and parietal regions [t(39)=7.76; p<.001], suggesting the effect increases from anterior to posterior sites (Figure 12).

Transposed-letter nonwords vs. Replaced-letter nonwords. The main effect of Type of nonword was significant [F(1,38)=53.23, p<.001, ŋ^2=0.583], showing a larger negativity for transposed-letter nonwords compared with replaced-letter. Group effect was not significant [F(1,38)=1.64, p=.207, ŋ^2=0.042]. The interaction between these two factors was not significant either [p>.250]. Regarding topographical factors, the interaction between Type of nonword and anterior-posterior regions was significant [F(2,76)=3.85, p=.025, ŋ^2=0.087], showing differences between transposed-letter and replaced-letter nonwords in frontal [t(39)=6.93; p<.001], central [t(39)=6.88; p<.001] and parietal region [t(39)=7.14; p<.001.


Deaf
Hearing
Fz
Cz
Pz
µV
ms
-4
+4
200
400
600
ms
Words
TL
RL
300 ms - 424 ms
-1 µV
0 µV
1 µV

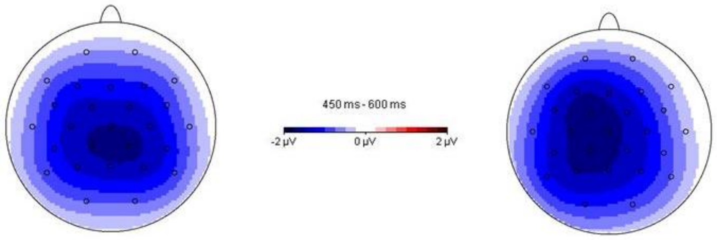


Figure 12. *Grand-averaged ERPs in Experiment 2a for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the word, transposed-letter nonword and replaced-letter nonword conditions. Bottom: The N400 component in two time windows (300-425ms and 450-600ms) in topographical maps (300-425ms: created by subtracting the observed voltage for replaced-letter nonwords minus transposed-letter nonwords; 450-600ms: created by subtracting the observed voltage for transposed-letter nonwords minus replaced-letter nonwords).*

As in Experiment 1a, the same analyses were performed including trials with errors.

<u>350-425ms epoch (errors included):</u>

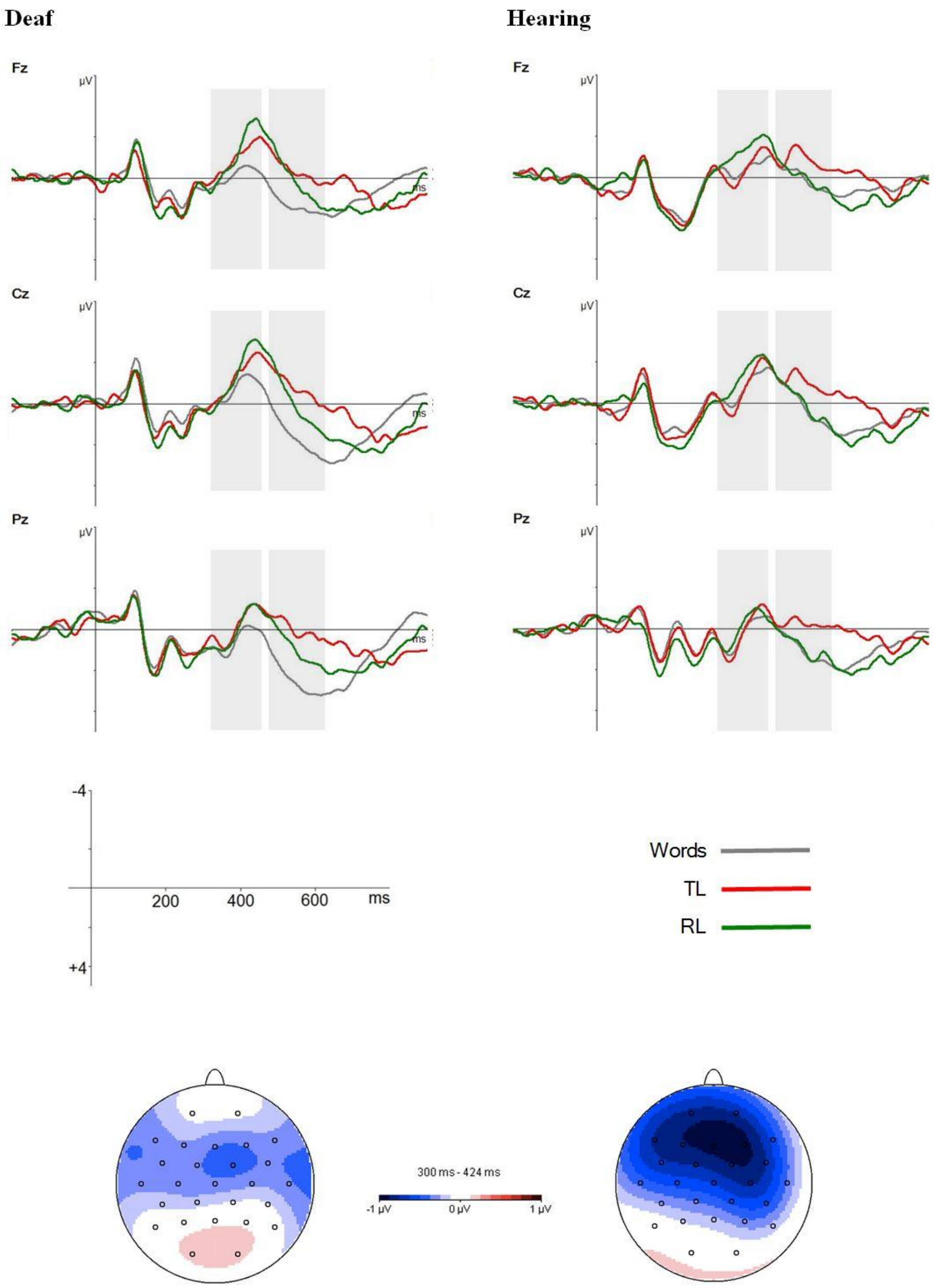
Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=10.33, $p<.001$, $\eta^2=0.202$], where nonwords elicited larger negativities than words. Group effect was not significant [$p>.250$]. The interaction between these factors was not significant either [F(1,38)=2.78, $p=.103$, $\eta^2=0.054$].

Transposed-letter nonwords vs. Replaced-letter nonwords. The main effect of Type of nonword was significant [F(1,38)=31.81, $p<.001$, $\eta^2=0.451$], showing a larger negativity for replaced-letter than transposed-letter nonwords. Group effect was not significant [$p>.250$] and the interaction between these two factors was not significant either [$p>.250$].

<u>450-600ms epoch (errors included):</u>

Words vs. Nonwords. The main effect of lexicality was significant [F(1,38)=44.88, $p<.001$, $\eta^2=0.496$], reflecting that nonwords elicited larger negativities than words in this epoch. Group effect was also significant [F(1,38)=5.29, $p=.027$, $\eta^2=0.122$]. The interaction between these factors was significant [F(1,38)=7.66, p=.009, η^2=0.085], showing a greater effect in deaf [F(1,19)=40.50, p<.001, η^2=0.681] than hearing [F(1,19)=8.64, p=.008, η^2=0.313].

Transposed-letter nonwords vs. Replaced-letter nonwords. The main effect of Type of nonword was significant [F(1,38)=32.53, p<.001, η^2=0.461], showing a larger negativity for transposed-letter nonwords compared with replaced-letter. Group effect was not significant [F(1,38)=1.49, p=.229, η^2=0.038]. The interaction between these two factors was not significant either [p>.250].


Deaf
Hearing
Fz
Cz
Pz
µV
ms
-4
200
400
600
ms
+4
Words
TL
RL
300 ms - 424 ms
-1 µV
0 µV
1 µV

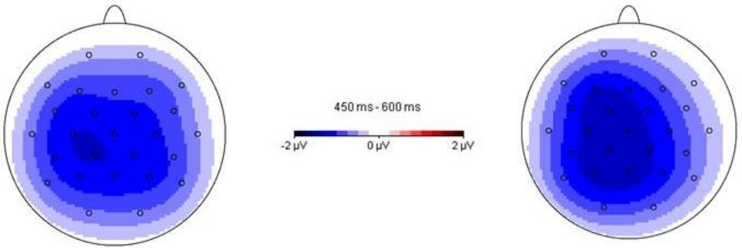


Figure 13. *Grand-averaged ERPs in Experiment 2a (errors included) for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the word, transposed-letter nonword and replaced-letter nonword conditions. Bottom: The N400 component in two time windows (300-425ms and 450-600ms) in topographical maps (300-425ms: created by subtracting the observed voltage for replaced-letter nonwords minus transposed-letter nonwords; 450-600ms: created by subtracting the observed voltage for transposed-letter nonwords minus replaced-letter nonwords).*

2.2.2. Experiment 2b: Masked priming paradigm

According to Grainger and Holcomb (2009), the N250 component is not only sensitive to phonological overlap between prime and target words, but also orthographic overlap. Indeed, Duñabeitia, Molinaro, et al. (2009) found a smaller N250 amplitude for transposed-letter nonword primes than replaced-letter nonword primes in Spanish hearing readers. Thus, if deaf Spanish readers are also sensitive to orthographic sublexical processes during visual word recognition, then we expect to obtain a modulation of the N250 component in both groups.

2.2.2.1. Method

2.2.2.1.1. Participants

The participants were the same as in Experiment 1 and 2a.

2.2.2.1.2. Materials

The experimental targets were 80 Spanish words (8-10 letters long) were selected (mean log word frequency: 3.91, range: 2.97-5.12; mean number of letters: 8.74; Duchon et al., 2013). The targets were preceded by nonword primes that were (1) transposed-letter (TL) nonwords (40 trials), in which the position of two non-adjacent consonants was swapped (e.g., *tefélono* created from the target word *teléfono*, 'telephone'), or (2) replaced-letter (RL) nonwords (40 trials), in which the two critical consonants were substituted by other consonants with a similar physical shape as in the transposed-letter nonword (e.g., *tehélono* created from the same target word). Two lists were constructed such that each target word used to generate the nonwords appeared once in each list, either as TL nonwords or as RL nonwords.

We selected 80 Spanish words (8-10 letters long) for control targets (mean log word frequency: 3.88, range: 3.45-4.48; mean number of letters: 8.73) preceded by prime words that were same word as the target. In addition, we selected 20 additional Spanish words (8-10 letters long) corresponding to animal names (mean log word frequency: 2.68, range: 1.97-3.66; mean number of letters: 8.80) preceded by another word with the same number of letters as the target (mean log word frequency: 2.56, range: 2.00-2.99; mean number of letters: 8.80). As in Experiment 1b, filler trials were created by presenting prime words as targets, preceded by the animal names as primes, in order to control prime visibility and to ensure that participants had not consciously seen the animal primes.

Participants were randomly assigned to the two trial lists. In total, each participant completed 200 trials: 80 trials with prime word-control target word pairs, 80 trials with prime experimental nonword - target word pairs (40 TL nonwords and 40 RL nonwords), 20 trials with prime word-animal target word pairs, and 20 trials with animal prime-filler target word pairs.

2.2.2.1.3. Procedure

The procedure was the same as in Experiment 1b.

2.2.2.1.4. EEG recording and analysis

The EEG recording and analysis was the same as in Experiment 1a. The artifact - free epochs totaled 85.66% of the data. The main variables of interest and factors in the ANOVAs were Group (deaf, hearing) and Type of Nonword (TL nonword, RL nonword). We selected one critical ERP time-window for analysis, based on previous literature and visual inspection: 200-325ms post-target onset.

2.2.2.2. Results

2.2.2.2.1. Electrophysiological measures

<u>200-325ms post-target:</u>

The main effect of Type of nonword was not significant [F(1,38)=0.01, p>.250, η^2=0.000] and Group effect was not significant either [p>.250]. The interaction between these two factors was not significant [F(1,38)=0.40, p>.250, η^2=0.011]. There were not interactions with topographical factors [ps>.250].

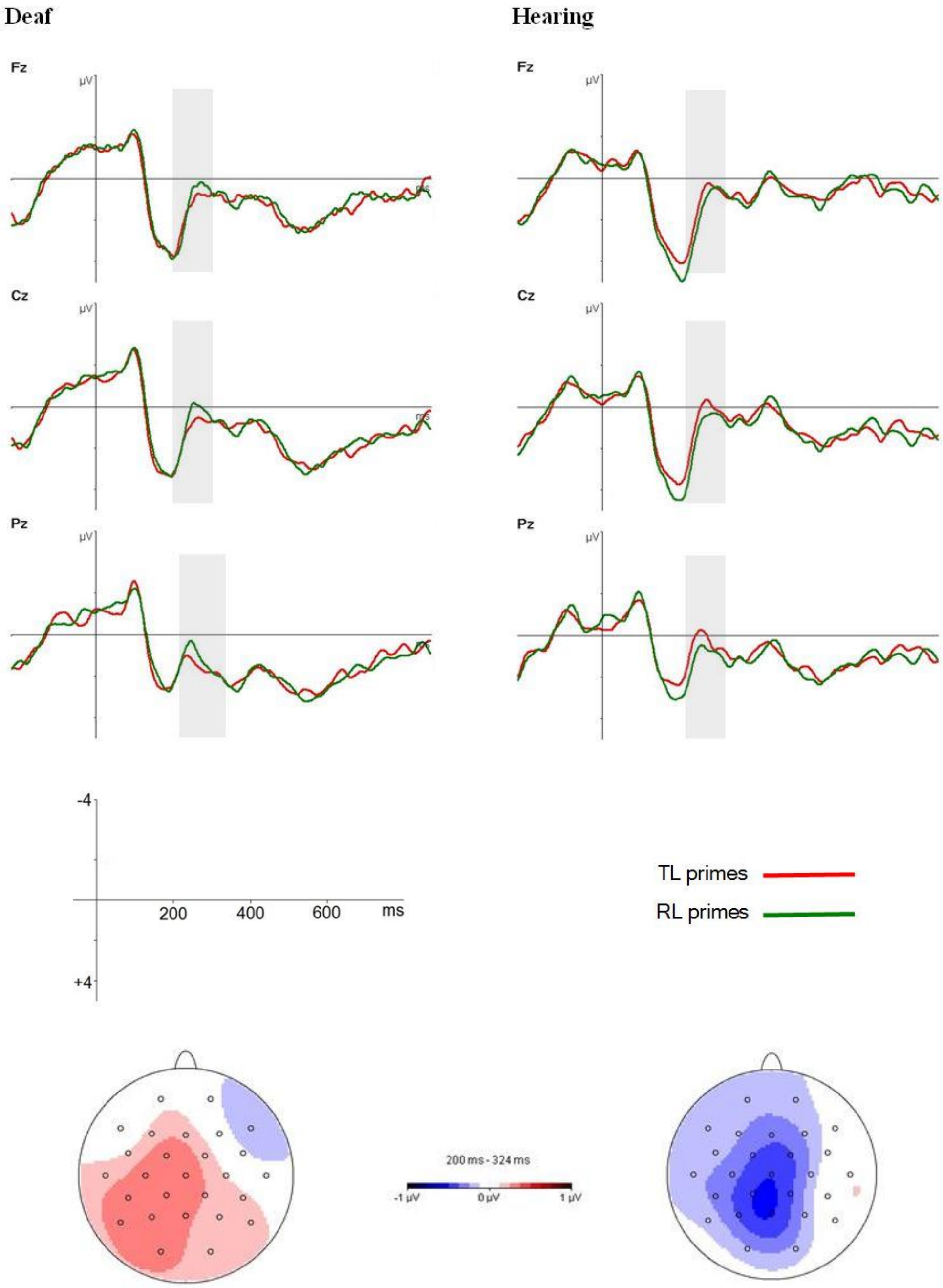


Figure 14. *Grand-averaged ERPs in Experiment 2b for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the transposed-letter primes and replaced-letter primes. Bottom: The N250 component in its corresponding time window (200-400ms) in topographical maps (created by subtracting the observed voltage for transposed-letter nonwords minus replaced-letter nonwords).*

2.2.3. Discussion of Experiment 2:

Experiment 2a showed a lexicality effect for both groups in the behavioral task and in the ERP results, as in Experiment 1a. Furthermore, both deaf and hearing skilled readers were slower and less accurate in rejecting transposed-letter nonwords compared to replaced-letter nonwords, replicating the classic transposed-letter effect in hearing readers in a lexical decision task (Chambers, 1979; O'Connor & Forster, 1981), and extending this effect to skilled deaf readers. Previous studies have suggested that the transposed-letter effect reflects orthographic processing (Perea & Carreiras, 2006). The current results therefore demonstrate that deaf and hearing skilled readers do not differ in their use of orthographic processes during visual word recognition.

In addition, transposed-letter nonwords were associated with reduced amplitude relative to replaced-letter nonwords in the first time window of the N400 epoch for both groups. The electrophysiological response diverged in the opposite direction (reduced negativity for replaced letter as compared to transposed letter nonwords) in a later time window. This reversal of the transposed-letter effect in later time-windows was also reported by Carreiras et al. (2007), and may arise because transposed-letter nonwords trigger more lexical activity and competition than replaced-letter nonwords, following the idea of an activation-verification model, which predicts greater lexical activation for orthographic regular nonword (such as transposed-letter nonwords) over irregular nonwords (Paap, Newsome, McDonald, & Schvaneveldt, 1982).

In Experiment 2b we expected to replicate the results of Duñabeitia, Molinaro, Laka, Estévez and Carreiras (2009) and Grainger, Kiyonaga and Holcomb (2006) for the N250 component, which reflects orthographic sublexical processing. Specifically, these studies found a smaller N250 amplitude for transposed-letter primes than replaced-letter primes. In the current study we did not found differences statistically significant. For the hearing readers, the visual trend is in line with previous studies that found larger negative amplitude for transposed-letter primes than replaced-letter primes. A lack of power in terms of subjects and items per condition may have contributed to the absence of significant effects in this experiment.

In summary, the findings of these two experiments suggest important similarities between deaf and hearing skilled readers in the orthographic processes underlying word reading, even though deaf readers do not activate phonological codes. In addition, similar to Experiment 1a, deaf readers overall again recognized words and non-words faster and more accurately than hearing readers.

2.3. EXPERIMENT 3: Orthographic subprocesses

Experiments 1 and 2 showed differences and similarities between deaf and hearing skilled readers in the visual recognition of the words of a language with a transparent orthography, such as Spanish. Only hearing readers activated phonological codes during word reading, while the two groups did not differ in orthographic processing. To further investigate orthographic sub-processes in deaf and hearing skilled readers, in Experiment 3 participants completed several explicit perceptual matching tasks (same-different judgment tasks), in which we manipulated position and identity of letters in strings without lexical meaning (e.g., FRTL).

In order to achieve efficient visual word recognition there are two key steps: letter identity and letter position coding (Carreiras, Duñabeitia, et al. 2009; Carreiras, Gillon-Dowens, et al. 2009; Duñabeitia & Carreiras, 2001; Perea et al., 2013). According to Carreiras, Quiñones, Hernández-Cabrera and Duñabeitia (2015), identity and position coding are based on perceptual mechanisms adapted for orthographic processing. Skilled readers are able to distinguish highly similar words by recognizing letters in different fonts, sizes and case (Chauncey, Holcomb, & Grainger, 2008; Petit, Midgley, Holcomb, Grainger, 2006). Also, the encoding of the location of each letter is essential to distinguish between stimuli with orthographic overlap (*read-dear*) (Duñabeitia, et al., 2012). Therefore, the experiments in this chapter investigate the similarities and differences between deaf and hearing skilled readers in letter perception.

Specifically, participants completed three same-different judgment tasks. In these tasks, pairs of four-consonant strings were presented to the participants, who had to indicate whether the two letter strings were identical or different. In the first experiment, we investigated letter position coding through trans-posed letter effects (Experiment 3a). Based on previous studies (Carreiras, et al., 2015; Duñabeitia, et al., 2012), we expected that targets preceded by transposed-letter references would yield longer reaction times and higher error rates compared to targets preceded by replaced-letter references. In Experiments 3b and 3c, we focused on two different aspects of letter identity: visual similarity (Experiment 3b) and abstract identity (Experiment 3c). In Experiment 3b, the two internal letters of the target and preceding letter strings were physically either similar or non-similar characters. Participants were presented with pairs in which the two internal letters were replaced. We expected longer reaction times and more errors for similar pairs versus non-similar pairs. In Experiment 3c, the target preceding letter strings consisted of the same letters, but differed in whether they were presented in the same case or not. We expected longer reaction times and more errors for stimulus pairs presented in different case.

Because the deaf and hearing readers showed similar transposed-letter effects in Experiment 2a, we also did not expect a group difference in letter position coding in Experiment 3a. In contrast, if phonology plays an important role in letter identity coding (Bowers & Michita, 1998), then we expect differences between deaf and hearing readers in Experiments 3b and 3c, in line with the results of Experiments 1a and 2a, which showed that deaf readers do not activate phonological codes during word reading. Specifically, only the hearing readers should show longer reaction times for word pairs with visually similar characters or different case. If no group difference is observed in these experiments, then this suggests that phonological knowledge does not play an essential role in letter identity coding in adult readers (Bigsby, 1988; Coltheart, 1981). Finally, if the overall faster reaction times in word reading tasks for deaf readers reflect enhanced early perceptual processes, then we expect a similar overall reaction time advantage for deaf readers in simple perceptual matching tasks that do not rely on lexical access.

Regarding ERP effects, Duñabeitia et al. (2012) showed that the N100, N200 and P300 components were sensitive to the transposition effect using a same-different judgment task. Therefore, we expect to find the same components in the three experiments, at least in Experiment 3a, which had the same manipulation of Duñabeitia et al. (2012). In addition, if faster overall reaction times in word reading tasks for deaf readers reflect enhanced early perceptual processes, then we expect to see differences between deaf and hearing readers in the early ERP components in the three experiments. In contrast, if early perceptual and orthographic processes are similar for deaf and hearing readers, these we expect no group differences in these components.

2.3.1. Experiment 3a: Position of characters

2.3.1.1. Method

2.3.1.1.1. Participants

The participants were the same as in Experiment 1 and 2.

2.3.1.1.2. Materials

The stimulus pairs in the perceptual matching task consisted of two 4-character-long strings. The pairs contained either identical or different character strings (80 pairs in the "same" condition and 80 pairs in the "different" condition). "Different" pairs were created by modifying the internal characters of the reference string, either by interchanging their position (i.e., 40 transposed-characters; *NDXT-NXDT*), or through substitution by other characters (i.e., 40 replaced-characters; *NFLT-NXDT*). The uppercase version of the consonants B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, Y and Z were used in the strings. No item repetition occurred within the experiment other than that the each target string appeared twice (once requiring a "same" response and once requiring a "different" response). Two lists were constructed such that each target appeared once in each list associated with a different reference, and across both lists, each target appeared in the transposition for one list and replacement condition in other. Participants were randomly assigned to the one of the two lists.

2.3.1.1.3. Procedure

The experiment was run individually in a room with no acoustic or visual distractions. Presentation® software (Version 0.70, www.neurobs.com) was used for stimulus presentation and recording of response times and accuracy. Each trial began with the presentation of two lines of four hash marks (####), above and below the center of the screen for 500ms. Then, the reference stimulus (35-pt. Courier New) was presented above the center of the screen and the hash marks remained visible below the center of the screen for 300ms. Finally, the target stimulus was displayed below the center of the screen together with hash marks above the center of the screen for a maximum of 2000ms or until the participant responded (see Figure 15). Participants were instructed to press one of two buttons on the keyboard (‘M’ and ‘Z’) to indicate whether the pair of letter strings was identical or different and to respond as quickly and accurately as possible. The order of presentation of the stimuli was randomized for each participant and the two response buttons were counterbalanced for identical and different responses. Each participant completed eight practice trials prior to starting the experiment.

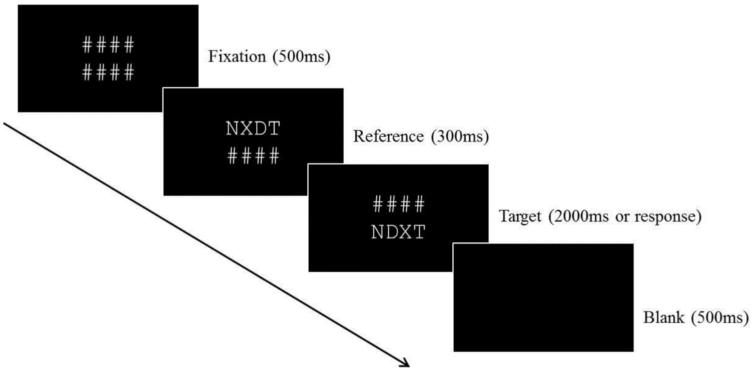


Figure 15. *Sequence of an experimental trial of Experiment 3 (a, b and c)*

2.3.1.1.4. Behavioral analysis

Mean error percentages and response latencies for deaf and hearing readers are presented in Table 3 and Figure 16. Because there was no manipulation on “same” pairs, only trials with “different” pairs were analyzed. Incorrect responses (12.21% of the data) and RTs above or below 2.5 standard deviations from the mean for each condition per participant were also excluded from the analysis of the response latencies (2.65% of the data). Participant and item based ANOVAs were conducted on response latencies and error percentages following a 2 (Group: hearing, deaf) x 2 (Type of Relationship: transposition, replacement) design.

2.3.1.1.5. EEG recording and analysis

The EEG was recorded with a 32-channel BrainAmp system (Brain Products GmbH) at a 500 Hz sampling rate. Scalp voltages were collected from 27 Ag/AgCl electrodes were placed in an EasyCap recording cap. The right mastoid was used as reference. An additional electrode at FCz served as ground, and 4 electrodes (2 on the orbital ridge below and 2 on the lateral junctions of both eyes) recorded the electro-oculogram (EOG). Impedance was kept below 5KΩ for mastoid and scalp electrodes, and below 10KΩ for EOG electrodes. The EEG signal was analyzed using Brain Vision Analyzer 2.0. EEG was filtered with a bandpass filter (Butterworth Zero Phase Filter, 1–20 Hz, 24 dB/octave). Epochs of the EEG corresponding to 800ms after target string presentation in the trials were averaged and analyzed. Baseline correction was performed using the average EEG activity in the 200ms preceding the onset of the target stimuli as a reference signal value. We removed the epochs with incorrect responses in all trials. The epochs were free of ocular or muscular artifacts, after performing an independent component analysis (ICA) and an artifact rejection process to average (86.98% of the data). We selected nine electrodes for repeated-measures ANOVA analyses, creating the factors Anterior-Posterior (frontal, central, parietal) and Hemisphere (right hemisphere, midline, left hemisphere). The frontal electrodes, which we selected, were F3 (left), Fz (midline) and F4 (right). The central electrodes were C3 (left), Cz (midline) and C4 (right), and the parietal electrodes were P3 (left), Pz (midline) and P4 (right). In addition to these factors, the main variables of interest and factors in the ANOVA were Group (deaf, hearing) and Type of Relationship (transposition, replacement). We selected one critical ERP time-window for analysis, based on visual inspection: 450-650ms post-target onset.

2.3.1.2. Results

2.3.1.2.1. Behavioral measures

Different pairs. The latency analysis showed a significant main effect of Type of Relationship [$F_1(1,36)=31.63$, $p<.001$, $ŋ^2=0.444$; $F_2(1,78)=89.06$, $p<.001$, $ŋ^2=0.532$] demonstrating slower responses for targets preceded by transposed-letter condition than replaced-letter references (743ms vs. 673ms). The effect of Group was significant by items but not by subjects [$F_1(1,36)=0.64$, $p>.250$, $ŋ^2=0.017$; $F_2(1,78)=9.40$, $p=.003$, $ŋ^2=0.108$]. The interaction between the two factors was not significant either [$F_1(1,36)=0.71$, $p>.250$, $ŋ^2=0.010$; $F_2(1,78)=1.18$, $p>.250$, $ŋ^2=0.015$]. The analysis of error percentages yielded a main effect of Group [$F_1(1,36)=5.00$, $p=.032$, $ŋ^2=0.117$; $F_2(1,78)=27.27$, $p<.001$, $ŋ^2=0.251$] showing that deaf readers were more accurate than hearing readers (13.88% vs. 20.26%). The main effect of Type of Relationship was also significant [$F_1(1,36)=91.13$, $p<.001$, $ŋ^2=0.701$; $F_2(1,78)=184.00$, $p<.001$, $ŋ^2=0.689$], showing that targets preceded by transposed-letter references were less accurate than those preceded by replaced-letter references (28.44% vs. 5.96%).

Table 3. Mean response latencies and error percentages for stimulus for deaf and hearing skilled readers in Experiment 3a.

	DEAF			**HEARING**		
	Reaction Time		*% Errors*	*Reaction Time*		*% Errors*
	Mean	SD	Mean	Mean	SD	Mean
Experiment 3a (Target: *NXDT*)						
Same responses (Reference: *NXDT*)	653	93	4.75%	729	177	10.00%
Transposed-letters (Reference: *NDXT*)	738	139	24.25%	747	123	32.63%
Replaced-letters (Reference: *NFLT*)	659	98	3.50%	687	106	7.88%

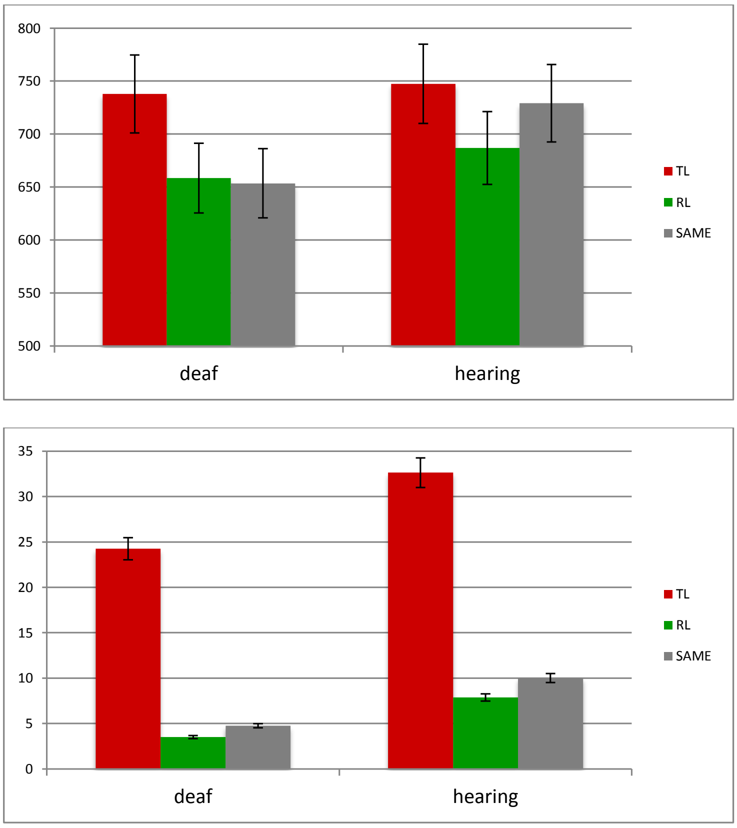


Figure 16. *Mean response latencies and error percentages for deaf and hearing in Experiment 3a. Error bars represent 95% confidence intervals.*

2.3.1.2.2. Electrophysiological measures

450-650ms post-target:

The main effect of Type of Relationship was significant [F(1,38)=26.41, $p<.001$, $\eta^2=0.407$], showing that in this time-window, targets preceded by transposed-letter references elicited larger negativities than those preceded by replaced-letter references. Group effect was not significant [F(1,38)=3.40, p=.070, $\eta^2=0.082$]. The interaction between these two factors was not significant either [F(1,38)=0.50, p=.484, $\eta^2=0.008$]. Regarding topographical factors, the interaction between Group and anterior-posterior regions was significant [F(2,76)=4.48, p=..14, $\eta^2=0.034$]. Although there are no differences between deaf and hearing readers in central [t(19)=1.72; p=.101] and parietal regions [t(19)=1.05; p>.250], there is a marginal difference between groups in the frontal sites [t(19)=2.06; p=.053].

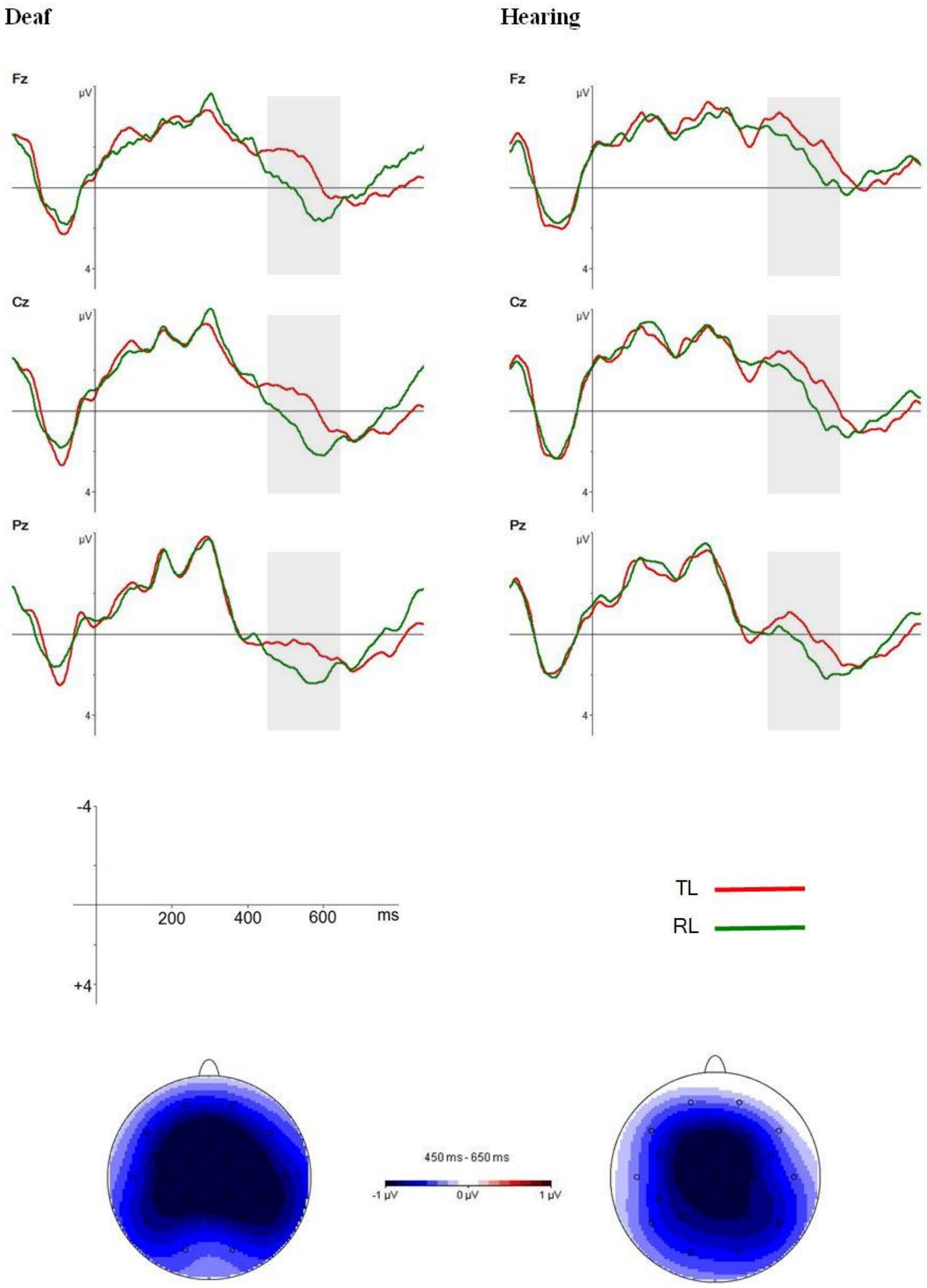


Figure 17. *Grand-averaged ERPs in Experiment 3a for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the transposed-letter references and replaced-letter references. Bottom: The N400 component in its corresponding time window (450-650ms) in topographical maps (created by subtracting the observed voltage for transposed-letter references minus replaced-letter references).*

As in Experiment 1a and 2a, we repeated the same analysis including incorrect trials.

<u>450-650ms post-target (errors included):</u>

The main effect of Type of Relationship was significant [F(1,38)=24.51, p<.001, ŋ^2=0.388], showing that in this time-window, targets preceded by transposed-letter primes elicited larger negativities than those preceded by replaced-letter references. Group effect was not significant [F(1,38)=4.03, p=.052, ŋ^2=0.096]. The interaction between these two factors was not significant either [F(1,38)=0.73, p=.395, ŋ^2=0.012]. Regarding topographical factors, the interaction between Group and anterior-posterior regions was significant [F(2,76)=4.97, p=.009, ŋ^2=0.034].

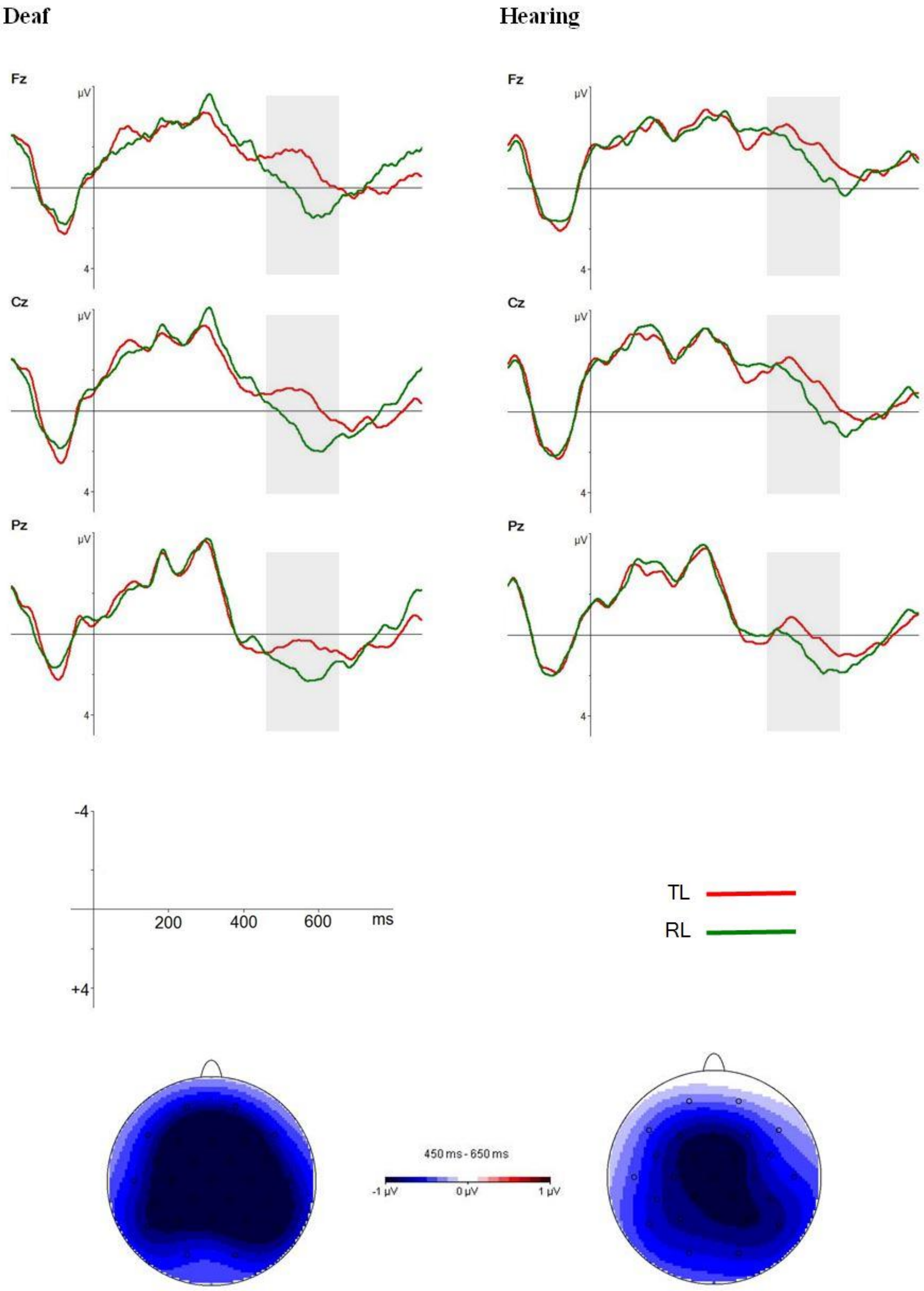


Figure 18. Grand-averaged ERPs in Experiment 3a (errors included) for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the transposed-letter references and replaced-letter references. Bottom: The N400 component in its corresponding time window (450-650ms) in topographical maps (created by subtracting the observed voltage for replaced-letter references minus transposed-letter references).

2.3.2. Experiment 3b: Visual similarity of the characters

2.3.2.1. Method

2.3.2.1.1. Participants

The participants were the same as in Experiment 1, 2 and 3a.

2.3.2.1.2. Materials

As in Experiment 3a, the stimulus pairs consisted of two 4-character-long strings. The two strings contained either identical or different character strings (80 pairs in the "same" condition and 80 pairs in the "different" condition). "Different" pairs were created by modifying the internal characters of the reference string, either through substitution by visually similar characters (i.e., 40 similar-character; 20 pairs in uppercase, *BWRC-BMPC*, and 20 pairs in lowercase, *zdqp-zbgp*), or substitution by other non-similar characters (i.e., 40 non-similar-characters; 20 pairs in uppercase, *BLVC-BMPC, and 20 pairs in lower case, zflp-zdgp*). The uppercase and lowercase version of the consonants b/B, c/C, d/D, f/F, g/G, h/H, j/J, k/K, l/L, m/M, n/N, p/P, q/Q, r/R, s/S, t/T, v/V, w/W, x/X, y/Y and z/Z were used in the strings. No item repetition occurred within the experiment other than that each target string appeared twice (once requiring a "same" response and once requiring a "different" response). The similarity of the characters was controlled through the similarity matrix published by Boles and Clifford (1989), taking the highest values. For the uppercase version, the mean value of similarity was 2.99 (range=2.58-4.08). For the lowercase version, the mean was 3.18 (range=2.66-4.67). Two lists were constructed such that each target appeared once in each list associated with a different reference, and across both lists, each target appeared in the visually similar condition in one list and in the visual dissimilar condition in the other. Participants were randomly assigned to the two lists.

2.3.2.1.3. Procedure

The procedure was the same as in Experiment 3a.

2.3.2.1.4. Behavioral analysis

Mean error percentages and response latencies for deaf and hearing readers are presented in Table 4 and Figure 19. Because there was no manipulation on “same” pairs, only trials with “different” pairs were analyzed. Incorrect responses (6.89% of the data) and RTs above or below 2.5 standard deviations from the mean for each condition per participant were also excluded from the analysis of the response latencies (2.75% of the data). Participant and item based ANOVAs were conducted on response latencies and error percentages following a 2 (Group: hearing, deaf) x 2 (Type of Relationship: similarity, non-similarity) design.

2.3.2.1.5. EEG recording and analysis

The EEG recording and analysis was the same as in Experiment 3a. The artifact - free epochs to average were 91.16% of the data. The main variables of interest factors in the ANOVA were Group (deaf, hearing) and Type of Relationship (similar, dissimilar). We selected two critical ERP time-windows for analysis, based on visual inspection: 100-200ms and 450-650ms post-target onset.

2.3.2.2. Results

2.3.2.2.1. Behavioral measures

Different pairs. The latency analysis showed a significant main effect of Type of Relationship [$F_1(1,36)=136.75$, $p<.001$, $\eta^2=0.755$; $F_2(1,78)=58.42$, $p<.001$, $\eta^2=0.365$] demonstrating faster responses for targets preceded by non-similar characters condition than primes with similar characters (615ms vs. 655ms). The effect of Group was not significant [ps>.250] and the interaction between the two factors was not significant either [ps>.250]. The analysis of error percentages showed a main effect of Type of Relationship [$F_1(1,36)=33.36$, $p<.001$, $\eta^2=0.462$; $F_2(1,78)=23.40$, $p<.001$, $\eta^2=0.228$], showing that targets preceded by non-similar references were more accurate than targets preceded by similar references (3.44% vs. 8.69%). The main effect of Group was also significant by items, not by subjects [$F_1(1,36)=2.82$, $p=.101$, $\eta^2=0.066$; $F_2(1,78)=12.92$, $p<.001$, $\eta^2=0.134$].

Table 4. Mean response latencies and error percentages for stimulus for deaf and hearing skilled readers in Experiment 3b. For the sake of simplicity, it is exemplify the design with uppercase version.

	DEAF			**HEARING**		
	Reaction Time		*% Errors*	*Reaction Time*		*% Errors*
	Mean	SD	Mean	Mean	SD	Mean
Experiment 3b (Target: *BMPC*)						
Same responses (Reference: *BMPC*)	612	99	6.56%	638	133	8.86%
Similar characters (Reference: *BWRC*)	654	87	7.63%	655	100	9.76%
Non-similar characters (Reference: *BLVC*)	615	95	2.38%	615	90	4.50%

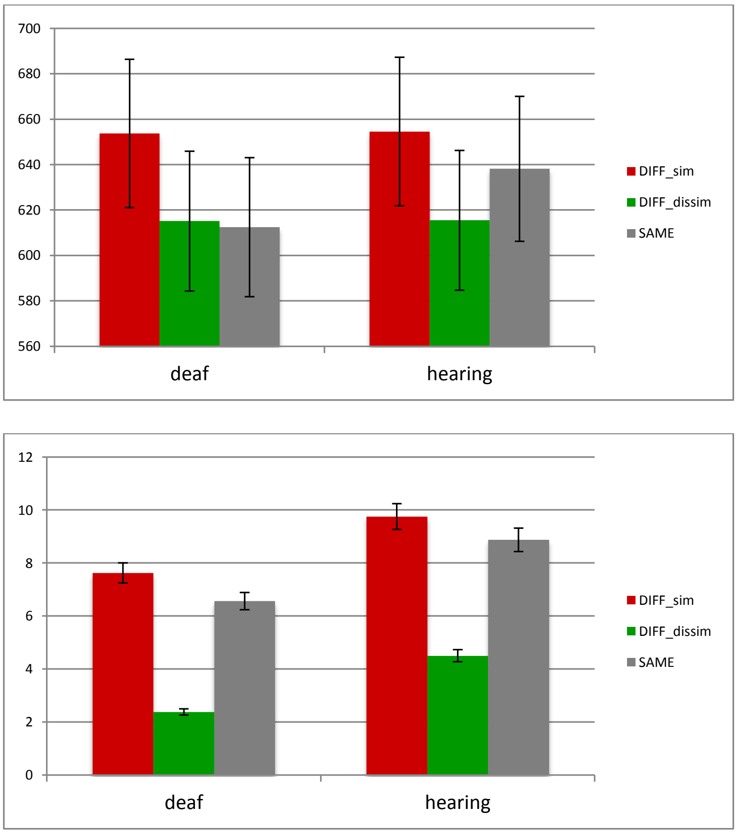


Figure 19. *Mean response latencies and error percentages for deaf and hearing in the Experiment 3b. Error bars represent 95% confidence intervals.*

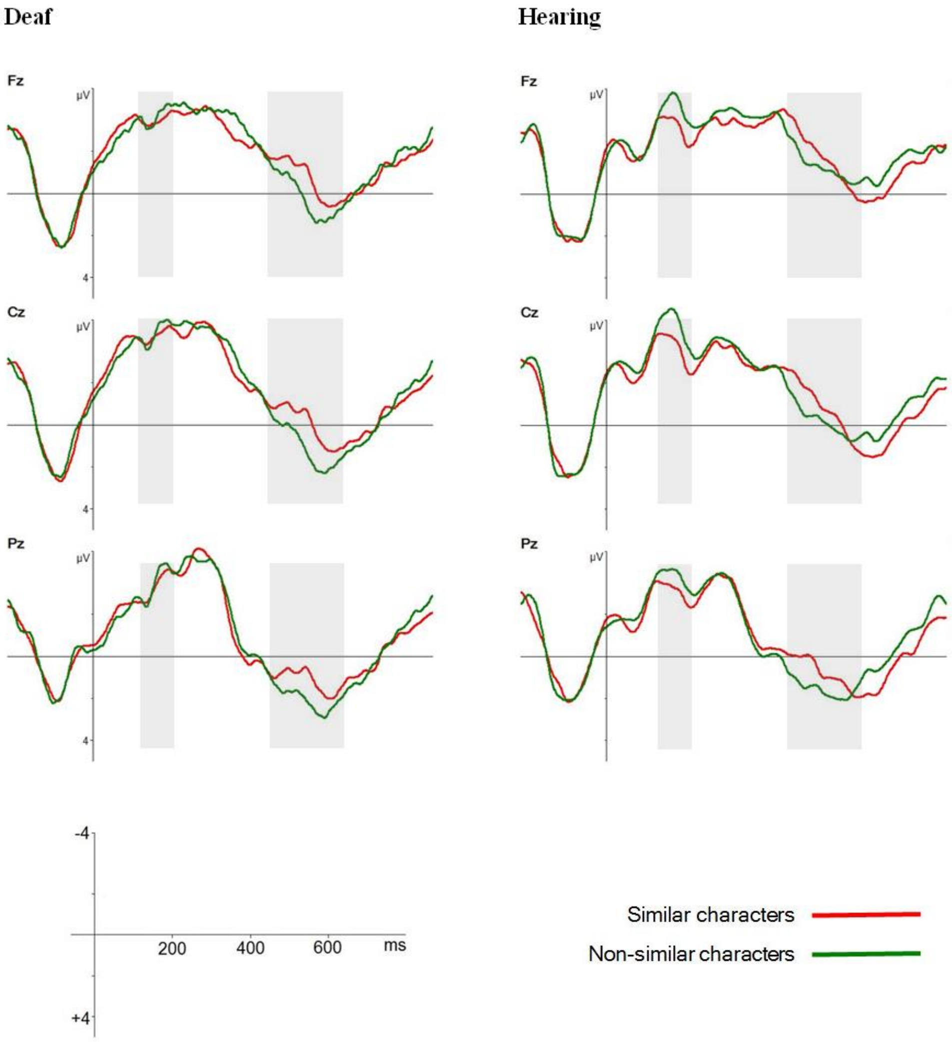
2.3.2.2.2. Electrophysiological measures

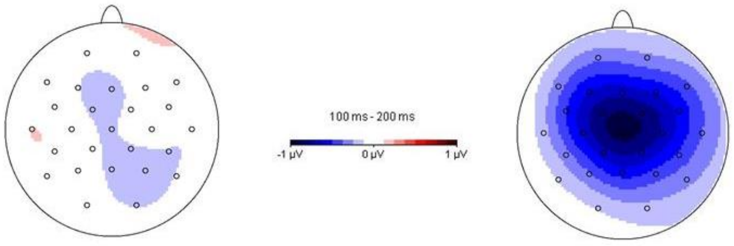
<u>100-200ms post-target:</u>

The main effect of Type of Relationship was significant [F(1,38)=5.05, p=.030, η^2=0.112], showing that in this time-window, targets preceded by non-similar references elicited larger negativities than those preceded by similar references. Group effect was not significant [p>.250]. The interaction between these two factors was not significant either [F(1,38)=2.22, p=.144, η^2=0.049]. There were no interactions with topographical factors.

450-650ms post-target:

The main effect of Type of Relationship was significant [F(1,38)=4.88, p=.033, ŋ^2=0.110], showing that in this time-window targets preceded by similar characters references elicited larger negativities than those preceded by non-similar references. Group effect was not significant [p>.250] and the interaction between these two factors was not significant either [F(1,38)=1.69, p=.201, ŋ^2=0.038]. There were no interactions with topographical factors.


Deaf
Hearing
Fz
Cz
Pz
µV
4
-4
+4
200
400
600
ms
Similar characters
Non-similar characters


100 ms - 200 ms
-1 µV
0 µV
1 µV

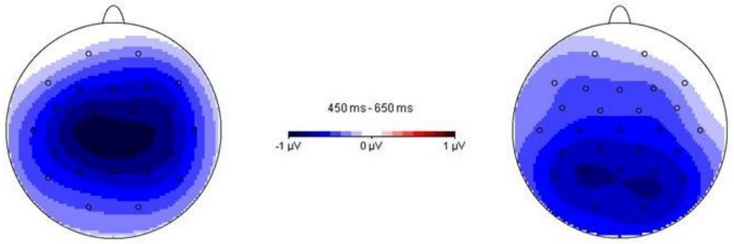


Figure 20. *Grand-averaged ERPs in Experiment 3b for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the similar-character and non-similar character conditions. Bottom: The N/P150 component and N400 component in their corresponding time window (150-200ms and 400-550ms) in topographical maps (100-200ms: created by subtracting the observed voltage for non-similar character references minus similar character references; 450-650ms: created by subtracting the observed voltage for similar character references minus non-similar character references).*

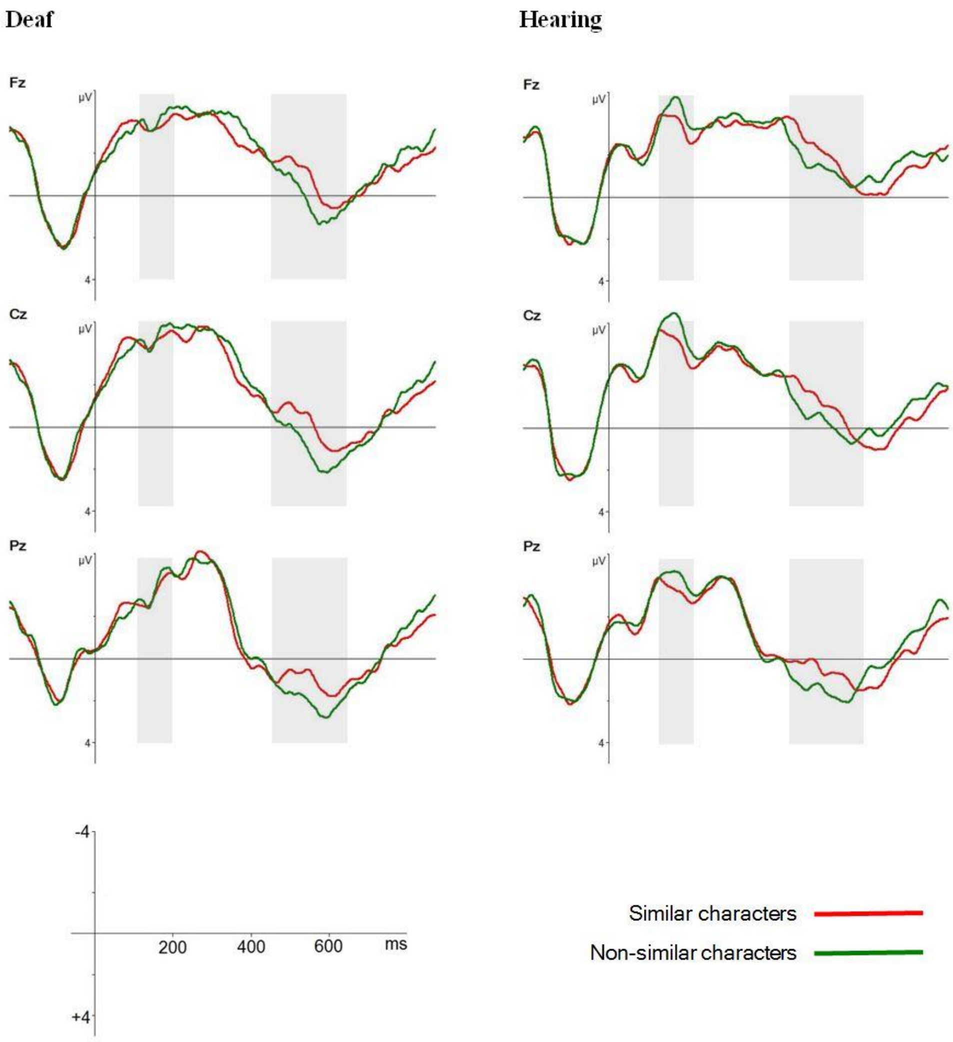
As in previous experiments, we repeated the same analysis including incorrect trials.

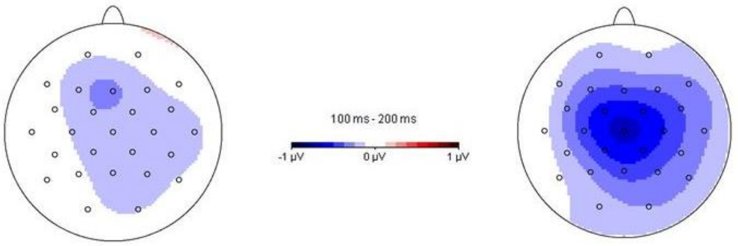
<u>100-200ms post-target (errors included):</u>

The main effect of Type of Relationship was not significant [F(1,38)=3.49, p=.069, ŋ^2=0.083], group effect [p>.250] and the interaction between these two factors was not significant either [F(1,38)=0.52, p>.250, ŋ^2=0.012]. There were not interactions with topographical factors.

<u>450-650ms post-target (errors included):</u>

The main effect of Type of Relationship was significant [F(1,38)=7.40, p=.010, ŋ^2=0.160], showing that in this time-window also, targets preceded by similar characters primes elicited larger negativities than non-similar references. Group effect was not significant [p>.250] and the interaction between these two factors was not significant either [F(1,38)=0.80, p>.250, ŋ^2=0.017]. There were not interactions with topographical factors.


Deaf
Hearing
Fz
Cz
Pz
µV
4
-4
+4
200
400
600
ms
Similar characters
Non-similar characters


100 ms - 200 ms
-1 µV
0 µV
1 µV

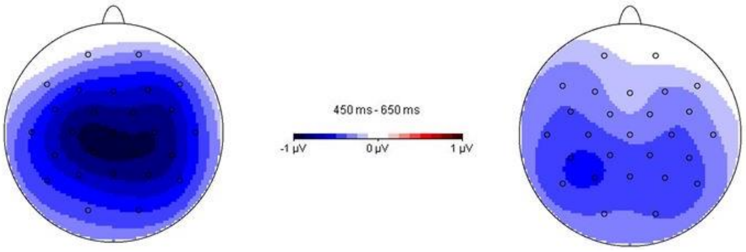


Figure 21. *Grand-averaged ERPs corresponding in Experiment 3b (errors included) for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the similar-character and non similar-character conditions. Bottom: The N/P150 component and N400 component in their corresponding time window (150-200ms and 400-550ms) in topographical maps (100-200ms: created by subtracting the observed voltage for non-similar character references minus similar character references; 450-650ms: created by subtracting the observed voltage for similar character references minus non-similar character references).*

2.3.3. Experiment 3c: Abstract identity of the characters

2.3.3.1. Method

2.3.3.1.1. Participants

The participants were the same as in Experiment 1, 2, 3a and 3b.

2.3.3.1.2. Materials

As in Experiment 3a and 3b, the stimulus pairs consisted of two 4-character-longs. The pairs of character strings either had the same or different letter identity (80 pairs in the "same" condition and 80 pairs in the "different" condition). The case of the characters in the strings was manipulated, such that there were 40 pairs with the same identity and same case (i.e., *STFV-STFV* or *MdpJ-MdpJ*), 40 pairs with the same identity but in different case (i.e., *StfV- STFV* or *MDPJ-MdpJ*), 40 pairs with different identity but the same case (i.e., *STFV-SKLV* or *MdpJ-MthJ*), and 40 pairs with different identity and different case (i.e., *STFV-SklV* or *MdpJ-MTHJ*). The uppercase and lowercase version of the consonants b/B, c/C, d/D, f/F, g/G, h/H, j/J, k/K, l/L, m/M, n/N, p/P, q/Q, r/R, s/S, t/T, v/V, w/W, x/X, y/Y and z/Z were used in the strings. No item repetition occurred within the experiment other than that each target string appeared twice (once requiring a “same” response and once requiring a “different” response). To avoid a visual similarity effect in the different identity condition, we controlled the similarity between uppercase and lowercase characters across all conditions. The similarity of the characters was controlled using the similarity matrix published by Boles and Clifford (1989), as in Experiment 3b, but in this case taking the lowest values. For the uppercase version, the mean value of similarity was 1.32 (range=1.08-1.43) and the mean for the lowercase version was 1.37 (range=1.00-1.77). Two lists were constructed such that each target appeared once in each list associated with a different reference, and across both lists, each target appeared in the same case condition in one list and different case condition in the other. Participants were randomly assigned to one of the two lists.

2.3.3.1.3. Procedure

The procedure was the same as in Experiment 3a and 3b.

2.3.3.1.4. Behavioral analysis

Mean error percentages and response latencies for deaf and hearing readers are presented in Table 5 and Figure 22. Because there was no manipulation on “different” pairs, only trials with “same” pairs were analyzed. Incorrect responses (8.51% of the data) and RTs above or below 2.5 standard deviations from the mean for each condition per participant were also excluded from the analysis of the response latencies (2.85% of the data). Participant and item based ANOVAs were conducted on response latencies and error percentages following a 2 (Group: hearing, deaf) x 2 (Type of Case: same case, different case) design.

2.3.3.1.5. *EEG recording and analysis*

The EEG recording and analysis was the same as in Experiment 3a and 3b. The artifact -free epochs to average were 89.86% of the data. The main variables of interest and factors in the ANOVA were Group (deaf, hearing) and Type of Case (same case, different case). We selected one critical ERP time-windows for analysis, based on visual inspection: 400-550ms post-target onset.

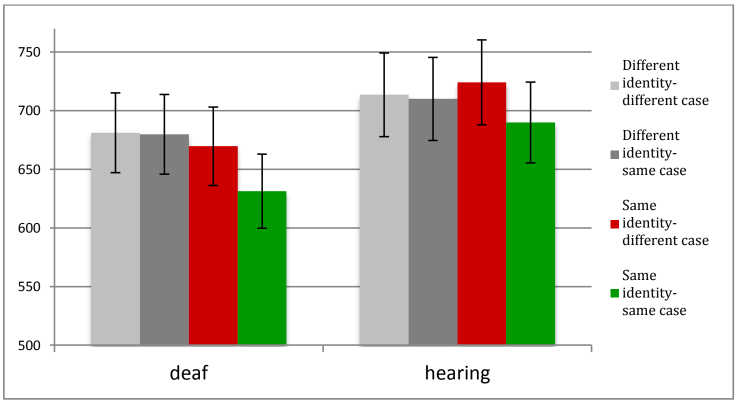
2.3.3.2. Results

2.3.3.2.1. *Behavioral measures*

Same pairs. The latency analysis showed a significant main effect of Type of Case [$F_1(1,36)=6.88$, $p=.013$, ŋ$^2=0.150$; $F_2(1,78)=30.89$, $p<.001$, ŋ$^2=0.252$] demonstrating faster responses for targets preceded by same case references than different case references (660ms vs. 697ms). The effect of Group was significant by items and marginally significant by subjects [$F_1(1,36)=3.89$, $p=.056$, ŋ$^2=0.092$; $F_2(1,78)=72.26$, $p<.001$, ŋ$^2=0.481$]. This result by subjects is in the same direction as the result by items. The interaction between these factors was not significant [$F_1(1,36)=0.27$, $p>.250$, ŋ$^2=0.006$; $F_2(1,78)=0.1$, $p>.250$, ŋ$^2=0.000$]. The analysis of error percentages showed a main effect of Type of Case by subjects, but not by items [$F_1(1,36)=5.06$, $p=.031$, ŋ$^2=0.117$; $F_2(1,78)=2.29$, $p=.134$, ŋ$^2=0.026$], being targets preceded by references with same case more accurate that references with different case (6.82% vs. 9.19%). The main effect of Group was also significant [$F_1(1,36)=6.15$, $p=.018$, ŋ$^2=0.122$; $F_2(1,78)=22.89$, $p<.001$, ŋ$^2=0.223$], showing that deaf group were more accurate than hearing in all conditions (6.00% vs. 10.00%).

Table 5. Mean response latencies and error percentages for stimulus for deaf and hearing skilled readers in Experiment 3c. For the sake of simplicity, it is exemplify the design with uppercase targets.

	DEAF			**HEARING**		
	Reaction Time		*% Errors*	*Reaction Time*		*% Errors*
	Mean	SD	Mean	Mean	SD	Mean
Experiment 3c (Target: *STFV*)						
Same identity-same case (Reference: *STFV*)	631	131	5.25%	690	143	8.38%
Same identity-different case (Reference: *StfV*)	670	99	6.75%	724	172	11.63%
Different identity-same case (Reference: *SGHV*)	680	92	10.50%	710	82	8.50%
Different identity-different case (Reference: *SghV*)	681	126	8.63%	713	94	8.50%



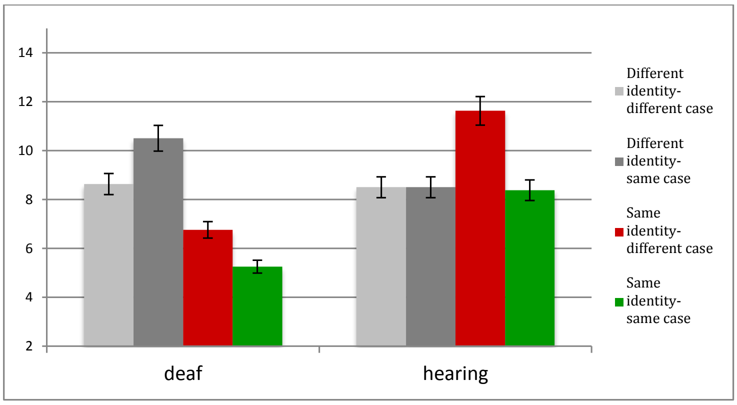


Figure 22. *Mean reaction times and error percentages for deaf and hearing in the Experiment 3c. Error bars represent 95% confidence intervals.*

2.3.3.2.2. Electrophysiological measures

<u>400-550ms post-target:</u>

The main effect of Type of Case was significant [F(1,38)=7.41, p=.010, η^2=0.162], showing that in this time-window, targets preceded by primes with different case elicited larger negativities than references with same case. Group effect was also significant [F(1,38)=9.99, p=.003, η^2=0.208], reflecting that differences between conditions in this time-window were larger in deaf than hearing. The interaction between these two factors was not significant [F(1,38)=0.37, p>.250, η^2=0.008]. Regarding topographic factors, the interaction between Type of Case and anterior-posterior was significant [F(2,76)=5.70, p=.005, η^2=0.130], showing differences between references with same and different case in central [t(39)=3.01; p=.005] and parietal region [t(39)=3.52; p=.001]. In the frontal region, the difference between conditions was not significant (p>.250).

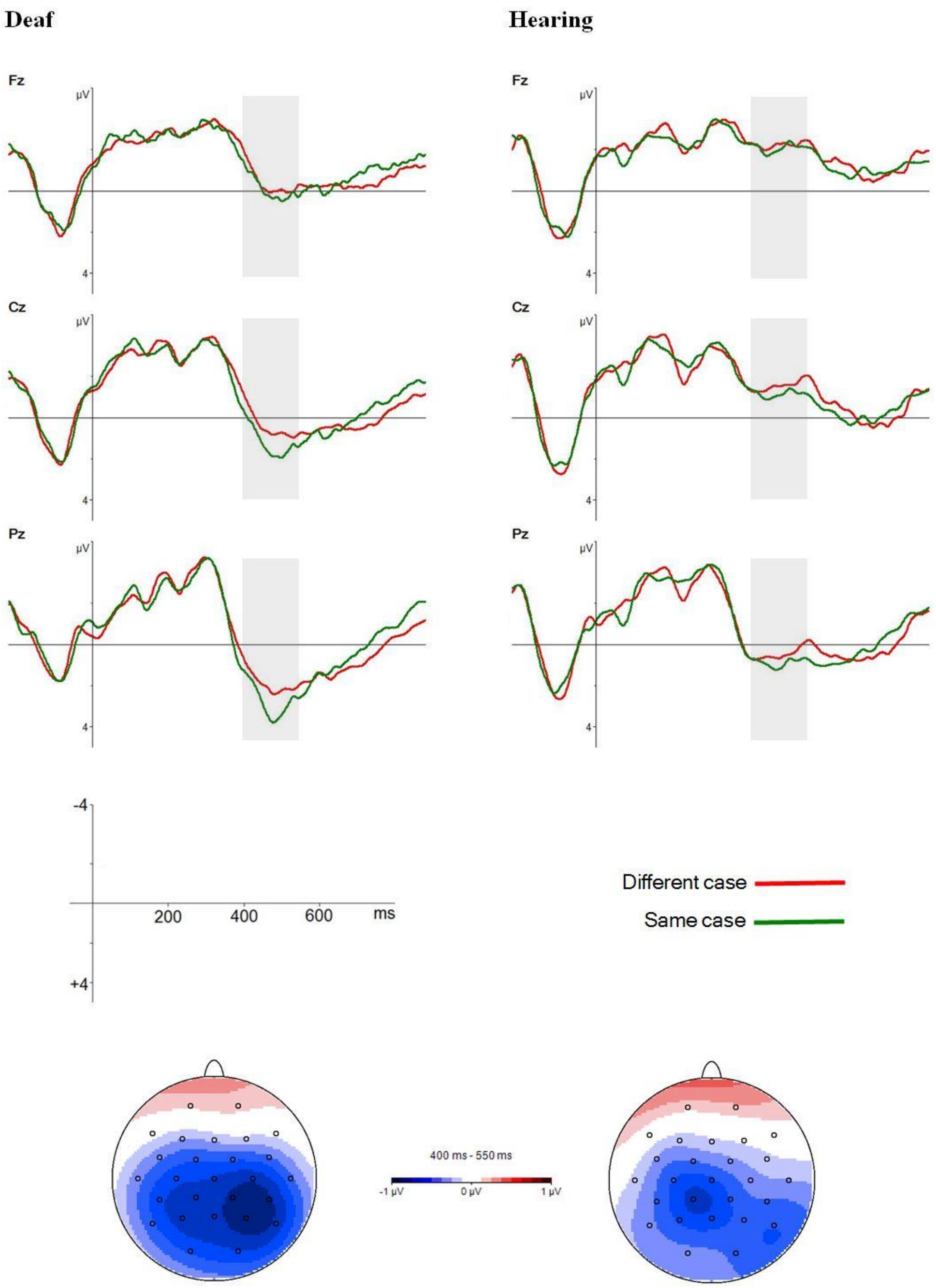


Figure 23. *Grand-averaged ERPs in Experiment 3c for deaf (left) and hearing (right) of the midline electrodes (Fz, Cz, Pz) for the different case references and same case references. Bottom: The N400 component in its corresponding time window (400-500ms) in topographical maps (created by subtracting the observed voltage for different case references minus same case references).*

As in previous experiments, we repeated the same analysis including incorrect trials.

400-550ms post-target (errors included):

The main effect of Type of Case was significant [F(1,38)=8.96, p=.005, η^2=0.189], showing that in this time-window, targets preceded by primes with different case elicited larger negativities than references with same case. Group effect was also significant [F(1,38)=9.88, p=.003, η^2=0.206], reflecting the differences between conditions in this time-window were larger in deaf than hearing. The interaction between these two factors was not significant [F(1,38)=0.40, p>.250, η^2=0.008]. Regarding topographic factors, the interaction between Type of Case and anterior-posterior regions was significant [F(2,76)=4.19, p=.019, η^2=0.097].

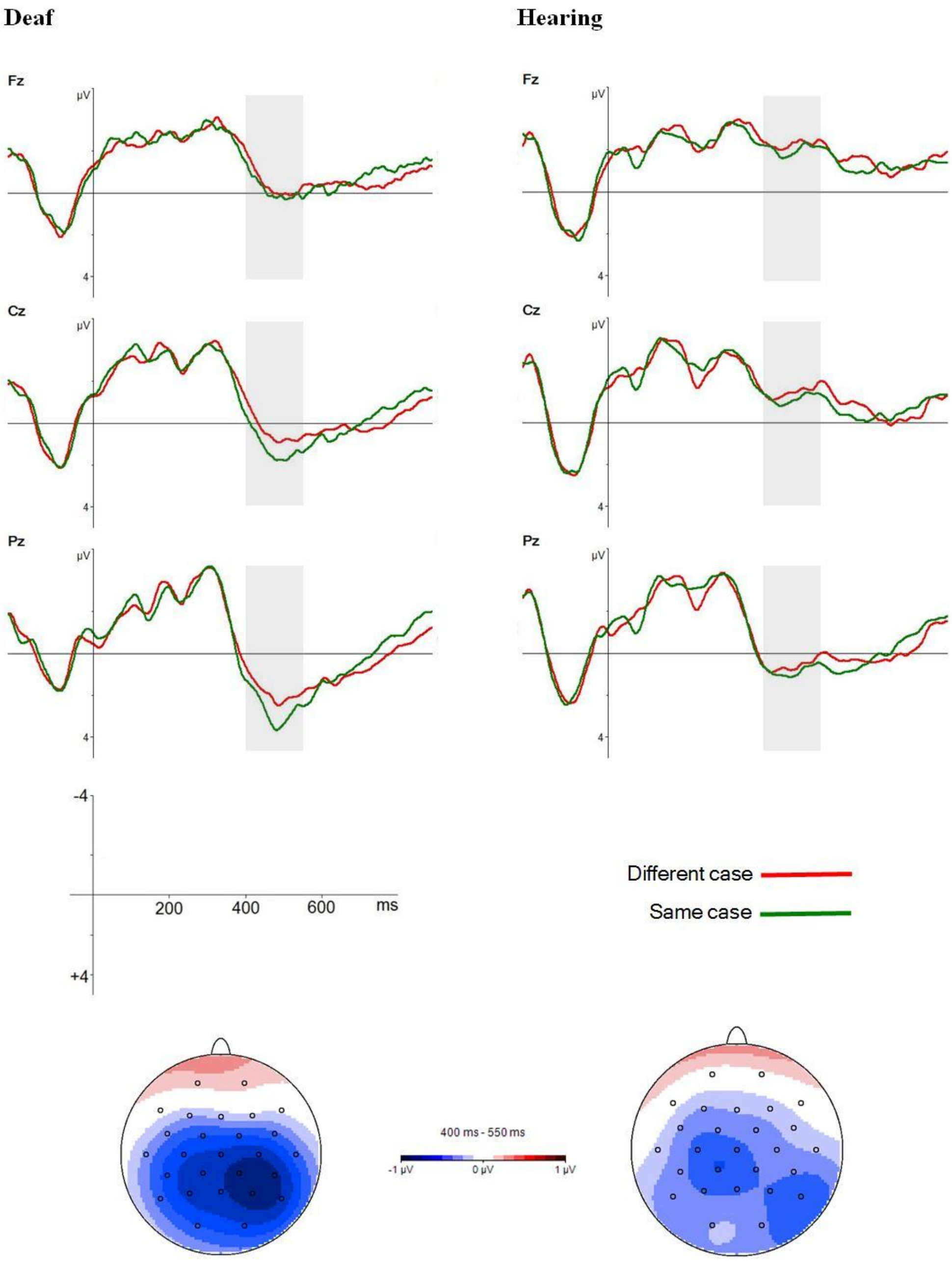


Figure 24. *Grand-averaged ERPs in Experiment 3c (errors included) for deaf and hearing of the midline electrodes (Fz, Cz, Pz) for the different case references (red lines) and same case references (green lines). Bottom: The N400 component in its corresponding time window (400-500ms) in topographical maps (created by subtracting the observed voltage for different case references minus same case references).*

2.3.4. Discussion of Experiment 3:

The behavioral results of Experiment 3a showed a transposed-letter effect in both groups, in the same line as in Experiment 2a, with longer reaction times and lower accuracy for TL than RL references in both groups. In the electrophysiological analysis, we found a significant time window (450-650ms), showing differences between conditions, with a greater negativity for targets preceded by TL references.

Experiment 3b showed longer reaction times and lower accuracy for pairs of letter strings with high visual similarity in both groups. In the ERP analysis, we found two time windows that showed differences between conditions. First, the 100-200ms time window showed a main effect of similarity, with a higher negativity for non-similar letter strings. Second, the 450-650ms time window showed an effect of condition with a greater negativity for targets preceded by visually similar references in both groups.

Finally, Experiment 3c showed longer reaction times and lower accuracy for targets preceded by letter strings with the same identity but in different case in both groups. In addition, the deaf readers were overall more accurate than the hearing readers and showed a trend towards faster reaction times. In the ERP analysis, the 400-550ms time window showed an effect of case, with greater negativity for pairs of letter strings presented in different case, and a group effect, with greater amplitude for deaf readers than hearing readers.

Together, the results from these three experiments show that deaf and hearing skilled readers are sensitive to manipulations of letter position and identity in perceptual matching tasks, suggesting important similarities between hearing and deaf skilled readers in several orthographic subprocesses critical to word reading. In section 1.2.1, we mentioned that the key steps to achieving efficient visual word recognition are the letter identity and letter position coding. According to Dehaene et al. (2005) and Pelli et al. (2006), word recognition depends on the analysis of letters. Therefore, the fact that the deaf readers do not show differences compared to hearing readers in these subprocesses indicates that the mechanisms underlying Experiments 1a (see section 2.1.1.2) and 2a (section 2.2.1.2), which are lexical decision tasks, are the same. Also, the similar results between both groups suggest that these orthographic subprocesses do not have a phonological locus, because if this had been so we would have found differences between deaf and hearing readers, in line with Experiments 1a and 1b.

3. GENERAL DISCUSSION AND CONCLUSIONS

Despite the difficulties faced by deaf individuals to become proficient readers, a minority of deaf people (about 10%) can reach a reading level equivalent to their hearing peers (Marschark, 1997). The main goal of this project was to investigate differences and similarities in phonological and orthographic processes between this group of deaf skilled readers and hearing readers. Our interest in deaf skilled readers is motivated by a desire to know how reading skills can be acquired in the context of deafness. What processes underlie proficient reading in deaf individuals and how these may differ from those of hearing readers? Since hearing loss appears to influence the way deaf readers learn to read, we can expect to find differences in the underlying processes they rely on during reading.

There has been some previous work on deaf readers with these charactertics (Bélanger, Mayberry, & Rayner, 2013; Bélanger, Slattery, Mayberry, & Rayner, 2012; Emmorey, Weisberg, McCullough, & Petrich, 2013; Miller, et al., 2012). However, as pointed out in section 1.1.3, much of this work has investigated reading in opaque orthographies, particularly English. Since the degree of orthographic depth of languages can modulate the role of phonological and orthographic coding during reading (Ehri, 1986; Fritg, 1985; Harm & Seidenberg, 2004; Share, 1995), the lack of evidence for phonological coding in deaf readers of English may be due to the opaque nature of the orthography. Therefore, the focus of our study was on the processing of phonology and orthography in deaf skilled readers of a transparent orthography (Spanish) using the neuroimaging technique of event-related potentials (ERPs), described in section 1.3.2. Although previous studies with deaf readers have used the ERP technique, they had different aims to our study. For example, one study examined the co-activation of sign language during word reading (Meade, Midgley, Sehyr, Holcomb, & Emmorey, 2017). Another study focused on the phonological processing of rhyme in French, but the deaf participants saw pictures, not words (Colin, Zuinen, Bayard, & Leybaert, 2013). MacSweeney, Goswami and Neville (2013) used electrophysiology to study the time-course of processing during a word rhyme task in English in deaf and hearing adults, and found that the ERP results of explicit phonological judgments are similar in both groups. Thus, to the best of our knowledge, this is the first study to use ERPs with deaf skilled readers with linguistic stimuli in Spanish, using tasks which phonology is implicit. In addition, considering that most of the research on deaf people and reading has been conducted in English, it is important to emphasize our behavioral and neurophysiological results on the phonological and orthographic processing in deaf readers in a language with transparent orthography, such as Spanish.

3.1. Summary of findings

Throughout the experimental section (see section 2), we described in detail several experiments which used different paradigms and investigated different processes. In this section, we present a summary of the results obtained across all the experiments of the project.

In Experiment 1 (section 2.1), we tested phonological coding during visual word recognition. Experiment 1a (section 2.1.1) used a lexical decision task, in which participants had to decide whether the string of letters presented on the screen corresponded to a real word in Spanish or a nonword. The experiment included two different types of nonwords: pseudohomophones (i.e., nonwords that sound like real words) and control nonwords (i.e., nonwords that do not sound like real words). In this experiment we measured behavioral and electrophysiological responses. Behavioral results showed a pseudohomophone interference effect in hearing readers, that is, they made more errors in rejecting pseudohomophones as words than they did for control nonwords. This difference in error rates between pseudohomophones and control nonwords for the hearing readers replicates previous studies of this type (Briesemeister et al., 2009; Ferrand & Grainger, 1994; Ziegler et al., 2001). The pseudohomophone effect in hearing readers demonstrates interference of phonological information during lexical access, which provides evidence for phonological coding during visual word recognition. In contrast, for deaf skilled readers error rates were similar for pseudohomophones and control nonwords, suggesting that they did not activate phonological codes during visual word recognition. Although the analysis of reaction times did not reveal differences between the two conditions, the deaf readers responded faster than the hearing readers in all conditions, and this finding will be discussed in more detail below.

The ERP analyses revealed an effect of lexicality in the 350-550ms window. Nonwords elicited larger negativities than words at around 400ms. In addition, while hearing readers also showed a difference between pseudohomophones and control nonwords, deaf readers did not (although the group by condition interaction was not statistically significant). Deaf readers showed larger N400 amplitude in both nonword conditions compared to the hearing readers, who showed a reduced N400 for pseudohomophones. These results are consistent with the behavioral findings and provide further evidence for phonological coding in hearing readers. The electrophysiological activity of the hearing readers indicates that they seem to process the pseudohomophones like real words; the pseudohomophones facilitate semantic integration and reduce negativity around 400ms (Briesemeister et al., 2009; Kramer & Donchin, 1987). The absence of a difference in amplitude in the same time window between the two nonword conditions for deaf readers suggests that they did not activate phonological codes.

Experiment 1b (described in detail in section 2.1.2) used a go/no go semantic categorization task with masked priming. Participants read words preceded by primes that were either pseudohomophones or control nonwords. In this experiment, only electrophysiological measures were collected. The analysis of the 200-400ms window showed an interaction between group and nonword condition. Specifically, only the hearing readers showed an N250 difference between target words preceded by pseudohomophones and target words preceded by control nonwords. This result replicates previous studies that showed sensitivity of the N250 component to sub-lexical effects (Duñabeitia et al., 2009; Holcomb & Grainger, 2006), and suggests that hearing readers do not only activate phonological codes at the lexical level, as shown in Experiment 1a, but also at the sub-lexical level. In contrast, the absence of differences in the N250 component between the two nonword conditions for the deaf readers further demonstrates the limited role of phonological coding in their visual word recognition.

In Experiment 2 (see section 2.2) we investigated whether orthographic processes in hearing and deaf skilled readers are different or similar. Like Experiment 1a, Experiment 2a (described in detail in section 2.2.1) used a lexical decision task, but in this experiment the two nonword conditions consisted of nonwords with transposed letters (TL) or replaced letters (RL). Behavioral results revealed a transposed-letter effect in both groups, with higher reaction times and greater number of errors for TL nonwords than for RL nonwords. Letter transposition effects have been investigated in many previous studies with hearing readers and are used as an index of orthographic processing in visual word recognition: because TL nonwords are very similar to real words, readers take longer to reject TL nonwords as real words compared to nonwords that are less similar to real words (Perea & Fraga, 2006; Perea & Lupker, 2004; Perea & Carreiras, 2006). The ERP analyses in Experiment 2a revealed a difference in amplitude between words and nonwords in both groups in an early time window, i.e. 350-425ms. Nonwords elicited a greater negativity than real words, indicating an effect of lexicality. Furthermore, TL nonwords elicited a smaller negativity than RL nonwords. This result is consistent with previous studies that found that nonwords that are very similar to real words (which is the case for TL nonwords) facilitate semantic integration and they are associated with reduced amplitude around 400ms (Carreiras et al., 2007; Kramer & Donchin, 1987; Vergara-Martínez et al., 2013).

Experiment 2b (section 2.2.2) employed a masked priming paradigm (similar to Experiment 1b) with TL and RL nonword primes. The results revealed no significant effects. The failure to find any significant results may be due to a lack of power in terms of subjects and items per condition.

Experiment 3 (see section 2.3) examined different sub-processes related to orthographic coding using different perceptual matching tasks. In Experiment 3a (described in detail in section 2.3.1) we tested letter position effects through a same-different judgment task, and obtained a transposed-letter effect in the behavioral responses of both groups, similar to the results of the lexical decision task of Experiment 2a. In Experiment 3b (described in detail in section 2.3.2) we investigated the effect of letter visual similarity, and obtained a main effect in the behavioral responses, with higher reaction times and error rates for targets preceded by references with similar letters compared to primes with non-similar letters. Finally, Experiment 3c (section

2.3.3) tested letter identity judgment, and revealed differences in reaction time and error rates between deaf and hearing readers in behavioral responses. Hearing readers demonstrated a larger "cost" in this task than deaf readers in all conditions, with longer reaction times and more errors.

The ERP analyses revealed differences between conditions in the same time window in Experiments 3a and 3b, i.e. 450-650ms, with a larger negativity for the conditions of interest (targets preceded by TL references in Experiment 3a and targets preceded by visually similar references in Experiment 3b). In Experiment 3c, the differences were found in an earlier time-window, 400-550ms, with larger negativity for targets preceded by references with the same identity but different case. Modulation of the N400 component by the conditions of interest was observed in both hearing and deaf readers and could reflect orthographic neighborhood effects, which may appear with strings of letters, and not just with words (Holcomb, Grainger, & O'Rourke, 2002; Laszlo & Federmeier, 2011). However, the N100 component was found only in Experiment 3b, which studied visual similarity. We argue that this finding may be compatible with the claim that this component is associated with discrimination processes when the type of task required attentional demands (Duñabeitia et al., 2012): the greater negativity associated with targets preceded by non-similar references suggests that this type of string needed greater attentional resources.

3.2. Insights into reading processes in deaf skilled readers

In summary, the results of the current study indicate important differences between hearing and skilled deaf readers in the role of phonological coding during visual word processing. This section looks first at the differences, then at the similarities, and concludes with a discussion of the possibility of reading in the absence of phonological knowledge.

3.2.1. Differences between deaf and hearing skilled readers

The most notable difference between the two groups was, the pseudohomophone effect observed for hearing readers in lexical decision, but not for deaf readers (Experiment 1). Furthermore, only hearing readers showed an effect of phonological access on sublexical processing in a go/no go semantic categorization task. These results suggest that Spanish deaf skilled readers do not activate phonological codes during implicit word reading and cast doubt on the assumption that deaf individuals need to access phonology in reading tasks to be competent readers (Perfetti & Sandak, 2000). Moreover, it appears that phonological mediation is not a obligatory or automatic step when reading in a language with transparent orthography, such as Spanish, as some studies have proposed (Carreiras et. al, 2009; Pollatsek et al., 2005). The finding that skilled deaf readers in the current study did not activate phonological codes suggests that phonological access is not required for functional and skillful reading in Spanish. Although it is possible that phonological knowledge facilitates learning to read in a language with transparent orthography, the present results demonstrate that this does not mean that it is impossible to be a competent reader without it. These results are in the line of the studies by Bélanger et al. (2012, 2013), demonstrating that deaf readers (skilled and less-skilled) do not benefit from phonological information during parafoveal processing. Another study that made use of pseudohomophones (as we did in Experiment 1), showed that deaf children did not use phonological information during word reading, while hearing children did show an automatic activation of phonology (Ormel, Hermans, Knoors, Hendriks, & Verhoeven, 2010).

Although some studies show a high correlation between phonology and reading skills in deaf individuals (Campbell & Wright, 1988; Colin, Magnan, Ecalle, & Leybaert, 2007; Dyer et al., 2003; Luetke-Stahlman & Nielsen, 2003), our results regarding the absence of phonological coding during visual word recognition in the deaf brings new evidence to the debate on what role phonology plays in reading skills in the prelingually deaf. Our results question, in line with previous studies, the importance of phonological coding for proficient reading in the deaf (Hanson & Fowler, 1987; Izzo, 2002; Kyle & Harris, 2006; Leybaert & Alegría, 1993; Mayberry et al, 2011). Miller (2010) claims that phonological awareness does not play a central role in the development of reading skills in prelingual and profoundly deaf readers, while it does in hearing readers.

Another notable finding was that reaction times of deaf readers were significantly faster than those of hearing readers, but only in the lexical decision experiments (Experiments 1 and 2) and the abstract identity judgment experiment (Experiment 3c). Faster responses for deaf readers than hearing readers have previously been reported in the literature (Brown & Brewer, 1996; Hanson & Fowler, 1987; Morford et. al, 2015). Pavani and Bottari (2012) conducted a review of studies of non-linguistic visual abilities of deaf individuals, and concluded that they did not have better visual perceptual skills compared to hearing individuals, but they showed enhanced reactivity in simple visual detection tasks. This conclusion does not stand up against our findings because the deaf readers in the current study were not faster than hearing readers in Experiment 3a or 3b, which were also tasks with visual stimuli (a same-different judgment between two consonants strings). A possible explanation for the discrepancy between experiments is that deaf readers demonstrate faster responses than hearing readers in word recognition and abstract identity judgment as a consequence of the diminished activation among phonological competitors for deaf readers (cf. Morford et al., 2015).

3.2.2. *Similarities between deaf and hearing skilled readers*

In contrast to the role of phonological coding, the transposed-letter inhibitory effects observed in the lexical decision task for both groups of readers demonstrated that deaf readers were sensitive to subtle orthographic changes in words and made use of orthographic coding in word recognition (Experiment 2). According to Miller (2010), orthographic sensitivity is present in both hearing and deaf people.

The findings also suggest that deaf and hearing skilled readers codify letter position and identity in the same way (Experiment 3). These results are in line with those authors (Chauncey et al., 2008; Petit et al., 2006) who demonstrated that skilled (hearing) readers are able to distinguish similar written stimuli by recognizing letters with different features, such as the font, size or case. We now know that deaf skilled readers are able to perform correct letter encoding, which is essential to carry out correct visual word recognition (Duñabeitia, et al., 2012).

3.2.3. *Reading without phonology*

Our results suggests that deaf skilled readers do not activate the phonology during visual word recognition, but they are sensitive to orthographic manipulations, showing similarities with hearing readers referring to orthographic processes. Is it possible that deaf readers achieve a high reading level without access to the phonology? According to our results, the answer is yes. While hearing readers show sensitivity to phonological and orthographic manipulations (implying that they use the phonological and orthographic awareness for lexical access during word reading), deaf readers only show sensitivity to orthographic manipulations. It is possible that the absence of phonological mediation makes this population more prone to alternative strategies. Deaf skilled readers are able to encode a word without the activation of phonology; in the absence of phonological coding, they perhaps encode the word as a visual image based on orthographic features and access the meaning of the printed word through a visu-orthographic strategy.

3.3. Implications for models of letter coding and visual word recognition

Polk et al. (2009) raised the following question in relation to letter identity coding: how can the visual system develop an abstract representation in which visually dissimilar stimuli like “a” and “A” have similar codes. Several authors have tried to answer this question without a definitive solution. Bowers and Michita (1998) or Grainger and Ziegler (2001) claim that phonology plays an important role in the processing of the abstract letter representation. In contrast, Bigsby (1998) and Coltheart (1981) suggest that it is not phonology that plays a crucial role, but other abstract representations based on orthography. Our results for abstract letter identity coding suggest that there is no activation of the phonological codes in this type of process, in contrast to Bowers and Michita (1998). Likewise, other studies (Frankish & Barner, 2008; Frankish & Turner, 2006; Perea & Lupker, 2004) have suggested that there is a phonological mediation in letter position coding, influencing the transposed-letter effect in masked priming paradigms and lexical decision tasks. If there were activation of this type, we would have found differences between deaf and hearing individuals, especially in the results of Experiment 2a, 2b and 3c. Even so, note that in the experiments with transposed-letter nonword condition, the transposition was done with nonadjacent letters, while studies showing phonological mediation did a manipulation of adjacent letters. For this reason, we cannot conclude with certainty that phonology does not play a role in letter position coding. For this reason, it would be necessary to carry out experiments with deaf readers which use the same manipulations of previous studies to corroborate or to reject the role of phonology in letter processing. However, Polk et al. (2009) suggest that, while adult readers do not require phonology for letter coding, phonology can play an important role during the development and acquisition of abstract letter identity. Therefore, even though deaf skilled readers do not automatically activate phonology in reading tasks or in letter coding, it might be possible that they have acquired phonological codes which allowed them to learned and develop abstract letter identity. In this respect, there are several studies that provide evidence of the role of phonology in the deaf population through meta-phonological tasks and/or phonological awareness tasks, in which phonological judgments are explicitly required (Aparicio, Gounot, Demont & Metz-Lutz, 2007; Campbell & Wright, 1988; Dyer, MacSweeney, Szczerbinski, Green & Campbell, 2003; Transler, Leybaert, & Gombert, 1999; Waters & Doehring, 1990). Thus, although deaf readers do not use phonology in implicit tasks, they may be able to use it if the task requires it. Therefore, they could also make use of phonology for the development of the abstract letter identity. The question now becomes: how are deaf people able to acquire phonology if they have hearing loss?

Wang, Trezek, Luckner and Paul (2008) conducted a series of studies focusing on alternative routes for acquiring phonological codes, such as speechreading, articulatory feedback, Visual Phonics and Cued Speech. These systems provide access to phonological information via means that do not depend on auditory information. For example, Visual Phonics is a multisensory system of hand cues and corresponding written symbols to represent phonemes (Trezek, Wang, Woods, Gampp, & Paul, 2007); and Cued Speech is a sound-based visual communication system that uses different handshapes at four locations to disambiguate the mouth movements of speech (Cornett, 1967). Wang et al. (2008) claim that the use of these alternative systems can lead to the development of phonological knowledge in deaf individuals. We did not collect information about the use of these systems. For this reason, it is important to carry out studies that take into account these alternative routes of phonology acquisition and investigate their correlation with reading (described in detail in section 3.5).

According to the PDP model (Harm & Seidenberg, 1999; Plaut et al., 1996; Seidenberg & McClelland, 1989), pseudohomophones activate orthographic and phonological representations in parallel. This phonological representation of the pseudohomophone activates semantics, while that of a control nonword does not. Semantic activation of pseudohomophones interferes with lexical decision because the meaning does not distinguish a pseudohomophone from a real word, resulting in errors and slower reaction times. The results from deaf readers in the current study show that deaf readers may not activate the two pathways in parallel and they may exploit the orthographic representations to access the meaning.

In the DRC model (Coltheart et al., 2001), pseudohomophones activate a lexical representation because the phonemic system is activated through the sublexical route. As a result, reaction times for pseudohomophones are slower than for other nonwords, which do not activate any phonemic representation. Within the framework of the DRC model, deaf readers may have trained their lexical route without relying on grapheme-phoneme conversion and thus are able to reject pseudohomophones without the mediation of phonology. According to Ziegler and Jacobs (2001), the sublexical route is slower than the lexical route. If we accept the premise that hearing people reading in a transparent language (such as Spanish) automatically activate phonological representations as some studies have suggested (Carreiras et al., 2009; Frost & Katz, 1992; Pollatsek, Perea & Carreiras, 2005), then it possible that hearing readers use both the lexical and sub-lexical route to access the meaning of words. Furthermore, if deaf readers use only the lexical route or activate only the orthographic representations for visual word recognition, then this may also explain why deaf readers had faster reaction times overall in the lexical decision task. At the same time, this suggests that when both routes are used (as is the case for hearing readers), word recognition does not occur as soon as the quicker (lexical) route has been resolved; the presence of a slower and, in this case, infelicitous route impacts on the overall outcome of the word recognition process.

If phonological mediation were essential for children learning to read (e.g., Goswami, Gombert, & de Barrera, 2008), then many languages with opaque orthographies would be unreadable. In addition, there are languages with nonalphabetic systems, such as logographic systems, in which readers cannot use a sound-to-letter route. Petitto et al. (2016) propose an alternative model, applicable to hearing and deaf readers, in which Universal Phonology plays an important role. Universal Phonology is the human capacity to segment, organize and categorize language, that is, the knowledge of sublexical structure, either in sign language or spoken language. Many theories on orthographic systems hold that printed text is equivalent to phonological representations and visual word recognition is dependent on the processing of phonological information as associated with printed words (Adams, 1990; Adams, Treiman, & Pressley, 1997; Share, Jorm, MacLean, & Matthew, 2984; Stanovich, 2000; Torgesen, Wganer & Rashotte, 1994; Wagner & Torgesen, 1987). In contast, McQuarrie and Parrila (2014) argue that orthography is not equivalent to spoken language and auditory information. In the model by Petitto et al. (2016), children need early exposure to a language system, whether signed or spoken, to facilitate the development of segmentation and categorization skills. As a result, the child will have acquired necessary skills to decode the written language through semantic and orthographic representations, as well as phonological representations consistent with the native language. Importantly, these phonological representations need not be based on audition or speech-based phonology. In the case of deaf children, early exposure to sign language may help to develop the capacity to segment orthographic patterns through sign-phonetic units.

The model proposed by Petitto et al. (2016) is supported by other studies that argued that appropriate development of reading and writing depends upon an early immersion in a linguistic system, regardless of the modality of that system (Fernández-Viader & Pertusa, 1995; Perfetti & Sandak, 2000; Wilcox, 1994). Indeed, several studies have found a strong correlation between sign language skills and reading proficiency in deaf readers (Izzo, 2002; Prinz & Strong 1998; Padden & Ramsey, 1998). Given that the deaf readers in the current study were also signers, it is possible that they decode written words through the sub-lexical units of sign language, without the need for an activation of speech-based phonology.

None of the current visual word recognition models are able to account for the results, since most of them include phonological processing as a path to access the lexicon (which does not seem to be at work in the case of deaf skilled readers) and do not contemplate alternative routes to arrive at the meaning of the word, such as access through the sign language lexicon.

3.4. Limitations of this study

It should be noted that the sample of deaf participants of this project is not representative of the deaf population, because only a minority of deaf readers achieve a proficient reading level. We might be tempted to think that our results are applicable to deaf less-skilled readers, but additional studies with this population are necessary to obtain robust conclusions that are valid for the majority of deaf people. Furthermore, it is necessary to understand why some deaf individuals achieve a high level of literacy, while others do not. This is one of most important limitations of our project.

Another issue to take into account is that our experiments (Experiment 1 and 2) involved visual word recognition tasks in which phonological or orthographic coding are considered implicit processing and not consciously made use of. The fact that deaf skilled readers do not activate the phonology in these kinds of automatic tasks, such as reading and visual word recognition is not sufficient to determine that deaf readers lack phonology, as we have discussed above in section 3.2.3, based on the study by Wang et al. (2008). There are studies which use explicit tasks of phonological awareness and meta-phonological tasks (rhyme judgment, syllabic or phonemic awareness), and in which deaf readers show similar results to hearing, demonstrating that they are able to acquire phonological awareness (Aparicio, Demont, Metz-Lutz, & Alegría, 2013; LaSasso, Crain, & Leybaert, 2003; Leybaert & Alegría, 1995; Sutcliffe, Dowker, & Campbell, 1999). Also, there is evidence that deaf people are able to acquire phonology by alternative non-auditory routes (Wang et al., 2008). With our results, we can only conclude that a specific population of deaf people, in this case deaf skilled readers, does not activate phonological coding during a task like word reading that, in other populations, may require phonology as an implicit part of the process.

These limitations demonstrate that research on reading in deaf people should continue. It is necessary to clarify various issues and to better understand how people with hearing loss achieve good reading and why many of them do not. The research on this topic is essential to developing specific models of reading for this population, which may be applicable to teaching methodologies for literacy in deaf students.

3.5. Applications and future directions

The findings of the current study have important implications. As discussed at the end of the previous section, a better understanding of visual word processing in deaf people with a proficient reading level can be used to inform educational methods to teach literacy to deaf children, and provide empirical constraints to further develop and test theoretical and computational models of word reading for deaf readers. This is just a first step on a long road and much research remains to be done.

In countries whose languages have an opaque orthography, many studies have been carried out on the reading processing in deaf people and what is the role of phonology and orthography during this task. But, as we described in section 1.2.2, the role that phonology plays in reading depends on the degree of transparency of the language in which reading occurs. Thus, a future aim is to still carrying out studies in Spanish, language with transparent orthography in which is assumed word recognition process is supported by phonological mediation (Carreiras et al., 2009; Frost & Katz, 1992; Pollatsek et al., 2005). In some experiments of this project, we have carried out implicit tasks, such as visual word recognition, in which we showed non-activation of phonology in deaf skilled readers. Even so, it is necessary to carry out explicit tasks in Spanish, to know if deaf people are able to acquire phonological codes, even though they do not activate them during reading and advance the knowledge on this population and its cognitive processing. Also, as we have mentioned in section 3.4, this project has focused on a specific sample of deaf people: skilled readers. It is important to perform studies with deaf individuals who have different reading skills and levels, to know the differences and similarities among them, taking into account other factors such as the teaching methodology, the use of sign language or other communication systems.

According to Wang et al. (2008) (see section 3.4), future investigations should also focus on the relationship between phonology acquisition through alternatives routes and phonology activation in deaf readers, and how this correlates with reading level.

To conclude, the present project revealed both differences and similarities between hearing and deaf skilled readers. In particular, the findings suggest that, in contrast to hearing readers, phonological activation is not necessary for deaf readers when reading words in a language with a transparent orthography, such as Spanish. Deaf and hearing readers were both sensitive to orthographic manipulations, suggesting that orthographic awareness alone may sustain proficient reading, without the need for phonological coding, although language competence, including sign language knowledge, may provide support for the development of reading skills. Automatic phonological processing may commonly be the default mechanism for reading in transparent orthographies, but it is clearly not required for successful visual word recognition. The special case of skilled deaf readers demonstrates that word recognition may rely solely on other processes, such as visual-orthographic processing or the decoding of the written word through sub-lexical units of sign language. Future studies should investigate how these processes support skilled deaf readers in acquiring a high level of literacy and how these mechanisms could be exploited and fostered to improve reading skills in deaf students.

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APPENDICES

APPENDIX I: *Stimulus of Experiment 1a*

WORDS	PSEUDOHOMO-PHONES	CONTROL NONWORDS
moza	sako	saho
guapa	ruví	runí
mudo	rovo	rono
neto	nuve	nuce
barato	cirko	cirto
tanque	piko	pifo
hondo	roka	roha
muelle	arko	arfo
pila	nabe	nate
atleta	boka	boña
loma	cubo	cuho
postal	ájil	áyil
balcón	monge	monye
trío	vervo	verco
horno	nabío	nahío
sutil	huebo	hueto
robot	nobio	nofio
pollo	curba	curha
ficha	ageno	ayeno
gota	dijna	dipna
saludo	ruvio	rulio
rancho	barva	barma
abrigo	avuso	anuso
trofeo	abiso	afiso
mago	trivu	tricu
pánico	savio	sario

broma	llabe	llafe
cisne	suabe	suahe
persa	chika	chila
posada	trage	traye
pascua	dévil	déñil
dieta	cueba	cuefa
queja	barko	barfo
violín	abión	ahión
plana	árvol	ármol
cruce	grabe	grate
burro	única	única
rumor	ánjel	ányel
araña	oliba	olifa
bola	vegez	veyez
ancha	clabo	clafo
huella	lababo	ladabo
mármol	peage	peape
plomo	javón	jacón
varón	flako	flafo
beso	bóbeda	bóleda
tronco	lejión	lepión
cartel	volkán	voltán
yelmo	bevida	bemida
ocio	tronko	tronlo
célula	pasage	pasaye
pino	olbido	olfido
hueso	avuela	añuela
asesor	peka	peha
parada	tavaco	taraco
talla	ajenda	ayenda
ciego	llubia	lluhia

azar	abance	atance
crudo	lójica	lóyica
vaca	eskudo	esludo
túnel	ovispo	onispo
paja	marjen	marpen
regalo	virjen	virpen
rector	juebes	juetes
tregua	dékada	délada
umbral	prueva	prueca
sólido	linage	linape
pierna	nebada	nehada
mina	avorto	azorto
miel	garage	garaye
pozo	cuerbo	cuerlo
hilo	nerbio	nerdio
boda	revaño	renaño
palo	bokado	bodado
cena	nabaja	nasaja
baño	saliba	saliha
humo	májica	máyica
reto	sebera	setera
mapa	frájil	frápil
olor	natiba	naliba

APPENDIX II: *Stimulus of Experiment 1b*

TARGETS	PSEUDOHOMOPHONE PRIMES	CONTROL NONWORD PRIMES
saco	sako	saho
rubí	ruví	runí
robo	rovo	rono
nube	nuve	nuce
circo	cirko	cirto
pico	piko	pifo
roca	roka	roha
arco	arko	arfo
nave	nabe	nate
boca	boka	boña
cubo	cubo	cuho
ágil	ájil	áyil
monje	monge	monye
verbo	vervo	verco
navío	nabío	nahío
huevo	huebo	hueto
novio	nobio	nofio
curva	curba	curha
ajeno	ageno	ayeno
digna	dijna	dipna
rubio	ruvio	rulio
barba	barva	barma
abuso	avuso	anuso
aviso	abiso	afiso
tribu	trivu	tricu
sabio	savio	sario

llave	llabe	llafe
suave	suabe	suahe
chica	chika	chila
traje	trage	traye
débil	dévil	déñil
cueva	cueba	cuefa
barco	barko	barfo
avión	abión	ahión
árbol	árvol	ármol
grave	grabe	grate
única	únika	únita
ángel	ánjel	ányel
oliva	oliba	olifa
vejez	vegez	veyez
clavo	clabo	clafo
lavabo	lababo	ladabo
peaje	peage	peape
jabón	javón	jacón
flaco	flako	flafo
bóveda	bóbeda	bóleda
legión	lejión	lepión
volcán	volkán	voltán
bebida	bevida	bemida
tronco	tronko	tronlo
pasaje	pasage	pasaye
olvido	olbido	olfido
abuela	avuela	añuela
peca	peka	peha
tabaco	tavaco	taraco
agenda	ajenda	ayenda
lluvia	llubia	lluhia

avance	abance	atance
lógica	lójica	lóyica
escudo	eskudo	esludo
obispo	ovispo	onispo
margen	marjen	marpen
virgen	virjen	virpen
jueves	juebes	juetes
década	dékada	délada
prueba	prueva	prueca
linaje	linage	linape
nevada	nebada	nehada
aborto	avorto	azorto
garaje	garage	garaye
cuervo	cuerbo	cuerlo
nervio	nerbio	nerdio
rebaño	revaño	renaño
bocado	bokado	bodado
navaja	nabaja	nasaja
saliva	saliba	saliha
mágica	májica	máyica
severa	sebera	setera
frágil	frájil	frápil
nativa	natiba	naliba

APPENDIX III: *Stimulus of Experiment 2a*

WORDS	**TRANSPOSED-LETTER NONWORDS**	**REPLACED-LETTER NONWORDS**
accidente	denifición	demitición
actuación	feredación	fenebación
adversario	enditad	enlifad
atmósfera	kimóletro	kisótetro
bautista	mecidina	mesifina
bienvenida	namiciento	naviniento
personaje	parmalento	parcatento
burguesía	prosópito	proróyito
búsqueda	requitiso	requilivo
lenguaje	tefélono	tehékono
jerarquía	befenicio	betericio
grabación	conumista	cocuñista
calendario	ditupado	difugado
normativa	esipodio	ecigodio
doctorado	elavuación	efaruación
fantasma	fecilidad	femitidad
festival	hunamidad	husaridad
fiscalía	invididuo	incitiduo
herencia	liretatura	limefatura
grandeza	pecitión	perivión
asturiano	sadiburía	safituría
austriaco	crinimal	crisiral
auxiliar	ecogólico	ecopófico
cantante	farovable	fasonable
castellana	ecomónica	ecosórica
científico	potisiva	pohimiva

valiente	predisido	prelirido
habilidad	pritimiva	prikiciva
votación	ranozable	ravocable
tragedia	satinario	safirario
cristiano	acamédico	acarético
cuadrado	automónica	autoróñica
oscuridad	conorado	cosocado
tormenta	elinimado	elinivado
dramático	filanista	fitacista
infantil	mofidicado	mohilicado
flamenco	nuremosa	nunecosa
flexible	retepida	refegida
funcional	salétite	saféhite
horizontal	sotemida	sofeñida
baloncesto	casimeta	canireta
gabinete	liredazgo	linebazgo
catedral	deretioro	decefioro
invierno	dicifultad	disilultad
misterio	enerlética	enerjética
navegación	molividad	mofinidad
monasterio	docimilio	doriñilio
traslado	galosina	gaforina
garganta	pafícico	pabímico
divorcio	halitación	havitación
garantía	momunento	mocurento
licencia	nolevista	notesista
petróleo	patrinomio	patrisorio
potencia	seroñita	sezomita
periodismo	edicifio	edirihio
recepción	actinidad	actibidad
registro	fisolofía	firotofía

sacerdote	futlobista	futhodista
secretaria	dicdatura	dicfalura
vacaciones	honemaje	horecaje
caliente	calótico	calófico
inocencia	cemárica	cezárica
tolerancia	direfente	dimetente
geografía	judírico	jufínico
violencia	retalivo	refadivo
derivado	poredoso	posehoso
derrotado	digirente	diyimente
nacimiento	litimado	lificado
horizonte	moredado	monefado
medieval	pacerida	pañevida
miserable	palarelo	patacelo
necesaria	sejemante	sepecante
deportiva	pocilial	ponilial
regional	serapada	senayada
reciente	revelante	relecante
recogido	brinático	briváfico
ridículo	clitámico	clifárico
secundaria	sorebano	socedano
socialista	tetámica	telácica
terrible	falimiar	faticiar

APPENDIX IV: *Stimulus of Experiment 2b*

TARGETS	**TRANSPOSED-LETTER PRIMES**	**REPLACED-LETTER PRIMES**
definición	denifición	demitición
federación	feredación	fenebación
entidad	enditad	enlifad
kilómetro	kimóletro	kisótetro
medicina	mecidina	mesifina
nacimiento	namiciento	naviniento
parlamento	parmalento	parcatento
propósito	prosópito	proróyito
requisito	requitiso	requilivo
teléfono	tefélono	tehékono
beneficio	befenicio	betericio
comunista	conumista	cocuñista
diputado	ditupado	difugado
episodio	esipodio	ecigodio
evaluación	elavuación	efaruación
felicidad	fecilidad	femitidad
humanidad	hunamidad	husaridad
individuo	invididuo	incitiduo
literatura	liretatura	limefatura
petición	pecitión	perivión
sabiduría	sadiburía	safituría
criminal	crinimal	crisiral
ecológico	ecogólico	ecopófico
favorable	farovable	fasonable
económica	ecomónica	ecosórica
positiva	potisiva	pohimiva

presidido	predisido	prelirido
primitiva	pritimiva	prikiciva
razonable	ranozable	ravocable
sanitario	satinario	safirario
académico	acamédico	acarético
autonómica	automónica	autoróñica
coronado	conorado	cosocado
eliminado	elinimado	elinivado
finalista	filanista	fitacista
modificado	mofidicado	mohilicado
numerosa	nuremosa	nunecosa
repetida	retepida	refegida
satélite	salétite	saféhite
sometida	sotemida	sofeñida
camiseta	casimeta	canireta
liderazgo	liredazgo	linebazgo
deterioro	deretioro	decefioro
dificultad	dicifultad	disilultad
energética	enerlética	enerjética
movilidad	molividad	mofinidad
domicilio	docimilio	doriñilio
gasolina	galosina	gaforina
pacífico	pafícico	pabímico
habitación	halitación	havitación
monumento	momunento	mocurento
novelista	nolevista	notesista
patrimonio	patrinomio	patrisorio
señorita	seroñita	sezomita
edificio	edicifio	edirihio
actividad	actinidad	actibidad
filosofía	fisolofía	firotofía

futbolista	futlobista	futhodista
dictadura	dicdatura	dicfalura
homenaje	honemaje	horecaje
católico	calótico	calófico
cerámica	cemárica	cezárica
diferente	direfente	dimetente
jurídico	judírico	jufínico
relativo	retalivo	refadivo
poderoso	poredoso	posehoso
dirigente	digirente	diyimente
limitado	litimado	lificado
moderado	moredado	monefado
parecida	pacerida	pañevida
paralelo	palarelo	patacelo
semejante	sejemante	sepecante
policial	pocilial	ponilial
separada	serapada	senayada
relevante	revelante	relecante
británico	brinático	briváfico
climático	clitámico	clifárico
soberano	sorebano	socedano
temática	tetámica	telácica
familiar	falimiar	faticiar

APPENDIX V: *Stimulus of Experiment 3a*

TARGETS	SAME PRIMES	TRANSPOSED-LETTER PRIMES	REPLACED-LETTER PRIMES
BJMN	BJMN	BMJN	BRHN
CYNM	CYNM	CNYM	CQBM
DXPL	DXPL	DPXL	DMBL
FHQK	FHQK	FQHK	FVYK
GVRJ	GVRJ	GRVJ	GVPJ
HTSH	HTSH	HSTH	HWQH
JSTG	JSTG	JTSG	JWMG
KRVF	KRVF	KVRF	KDZF
LQWD	LQWD	LWQD	LTFD
MPXZ	MPXZ	MXPZ	MJXZ
NNYB	NNYB	NYNB	NRDB
PMLZ	PMLZ	PLMZ	PFRZ
QLBY	QLBY	QBLY	QZWY
RKCX	RKCX	RCKX	RHZX
SJDW	SJDW	SDJW	SMZW
THFV	THFV	TFHV	TVCV
VCHT	VCHT	VHCT	VGYT
WFJS	WFJS	WJFS	WKVS
XNKR	XNKR	XKNR	XQFR
YCLQ	YCLQ	YLCQ	YXHQ
ZBGP	ZBGP	ZGBP	ZFNP
BNMZ	BNMZ	BMNZ	BSQZ
CMZY	CMZY	CZMY	CJDY
DLPX	DLPX	DPLX	DVGX
FKQW	FKQW	FQKW	FYJW
GJRV	GJRV	GRJV	GZKV

HJST	HJST	HSJT	HXKT
JGMS	JGMS	JMGS	JPNS
KQZR	KQZR	KZQR	KBLR
LPWQ	LPWQ	LWPQ	LNWQ
MJXP	MJXP	MXJP	MDBP
NCYZ	NCYZ	NYCZ	NDTZ
PZND	PZND	PNZD	PQCD
QYBF	QYBF	QBYF	QZRF
RXCG	RXCG	RCXG	RHSG
SWDH	SWDH	SDWH	SVPH
TVFJ	TVFJ	TFVJ	TGHJ
VTHK	VTHK	VHTK	VCXK
WSJL	WSJL	WJSL	WKTL
XRKM	XRKM	XKRM	XLJM
FKXH	FKXH	FXKH	FDJH
GBYJ	GBYJ	GYBJ	GSWJ
HYZK	HYZK	HZYK	HBDK
JZBL	JZBL	JBZL	JMRL
KXCM	KXCM	KCXM	KHLM
LWDN	LWDN	LDWN	LYTN
MVFB	MVFB	MFVB	MGRB
NTHY	NTHY	NHTY	NZVY
PGJX	PGJX	PJGX	PZNX
QFKW	QFKW	QKFW	QJGW
RDLV	RDLV	RLDV	RWMV
SKGT	SKGT	SGKT	SFGT
TBMS	TBMS	TMBS	TQJS
VNPR	VNPR	VPNR	VMDR
WMNQ	WMNQ	WNMQ	WCSQ
BFQM	BFQM	BQFM	BTGM
CDRL	CDRL	CRDL	CXZL

DZSK	DZSK	DSZK	DMCK
FCTJ	FCTJ	FTCJ	FSYJ
GNVH	GNVH	GVNH	GDBH
HMWG	HMWG	HWMG	HLRG
JZXF	JZXF	JXZF	JPDF
KXYD	KXYD	KYXD	KRCD
LWNZ	LWNZ	LNWZ	LBFZ
MVPB	MVPB	MPVB	MWQB
NHMZ	NHMZ	NMHZ	NSCZ
PGNY	PGNY	PNGY	PBFY
QPRX	QPRX	QRPX	QYMX
RGQW	RGQW	RQGW	RHKW
SDTV	SDTV	STDV	SXNV
TFVS	TFVS	TVFS	TPGS
VLST	VLST	VSLT	VYST
WBMR	WBMR	WMBR	WJVR
XYCQ	XYCQ	XCYQ	XNSQ
YWDP	YWDP	YDWP	YXTP
ZVFY	ZVFY	ZFVY	ZWHY
BTHX	BTHX	BHTX	BCSX
CSJZ	CSJZ	CJSZ	CBXZ
DRKW	DRKW	DKRW	DJZW
FQLV	FQLV	FLQV	FGMV

APPENDIX VI: *Stimulus of Experiment 3b*

TARGETS	SAME PRIMES	SIMILIAR PRIMES	NON-SIMILAR PRIMER
BJMN	BJMN	BYWN	BHCN
CYNM	CYNM	CTZM	CGFM
DXPL	DXPL	DKBL	DBML
FHQK	FHQK	FNCK	FCHK
GVRJ	GVRJ	GMPJ	GFVJ
HTSG	HTSG	HFZG	HWJG
JSTH	JSTH	JRFH	JKXH
KRVF	KRVF	KBMF	KYQF
LQWD	LQWD	LCMD	LHCD
MPXZ	MPXZ	MDKZ	MVRZ
NMYB	NMYB	NWXB	NJZB
PNLZ	PNLZ	PXJZ	PFSZ
QLBY	QLBY	QFRY	QXNY
RKCX	RKCX	RNGX	RQFX
SJDW	SJDW	SYQW	SHYW
THFV	THFV	TNPV	TCWV
VCHT	VCHT	VGNT	VNZT
WFJS	WFJS	WPTS	WJCS
XNKR	XNKR	XZLR	XPSR
YCLQ	YCLQ	YGJQ	YFXQ
FKDH	FKDH	FNCH	FSYH
GPYJ	GPYJ	GBPJ	GWZJ
HYZK	HYZK	HVSK	HLXK
JZBL	JZBL	JNDL	JVNL
KXCM	KXCM	KVQM	KRHM
LWDN	LWDN	LMBN	LSYN

MVFB	MVFB	MXPB	MTJB
NTHY	NTHY	NFPY	NWCY
PGJX	PGJX	PCTX	PNHX
QFKW	QFKW	QPRW	QVGW
RDLV	RDLV	RQJV	RKSV
SKGT	SKGT	SXCT	SJXT
TBMS	TBMS	TRWS	TNCS
VNPR	VNPR	VKBR	VFMR
WFNQ	WFNQ	WPKQ	WJSQ
BDQM	BDQM	BPGM	BWHM
CMRL	CMRL	CWBL	CGVL
DZSK	DZSK	DNRK	DQLK
FCVJ	FCVJ	FGMJ	FXRJ
GNTH	GNTH	GKFH	GFSH
zbgp	zbgp	zdqp	zflp
bnmz	bnmz	bhwz	bgdz
cmzy	cmzy	cnsy	cbhy
dlpx	dlpx	dtgx	dcmx
fkqw	fkqw	fhpw	fnjw
gjrv	gjrv	glcv	gkwv
hjst	hjst	hfzt	hxyt
jgms	jgms	jqws	jlys
kqzr	kqzr	kdcr	ktdr
lpwq	lpwq	lbmq	lvrq
mjxp	mjxp	mgkp	mbsp
ncyz	ncyz	nrvz	nkfz
pznd	pznd	psmd	phsd
qybf	qybf	qjdf	qljf
rxcg	rxcg	rkrg	rykg
swdh	swdh	svbh	sgnh
tvhj	tvhj	tynj	tmzj

vtjk	vtjk	vlgk	vrbk
wsfl	wsfl	wztl	whpl
xrkm	xrkm	xcbm	xlsm
hdwg	hdwg	hpmg	hnbg
jzxf	jzxf	jskf	jvpf
kwyd	kwyd	kvjd	kdfd
lxnz	lxnz	lkmz	ltsz
mvpb	mvpb	myqb	mglb
nhmz	nhmz	nnwz	nxtz
pgny	pgny	pqhy	pzhy
qprx	qprx	qgfx	qvkx
rgqw	rgqw	rjpw	rlzw
sdtv	sdtv	shfv	snqv
tlvs	tlvs	tfws	t cfs
vbst	vbst	vpzt	vjyt
wtmr	wtmr	wfnr	wpbr
xycq	xycq	xqsq	xflq
ywdp	ywdp	yvbp	yksp
zvfy	zvfy	zwty	zdmy
bthx	bthx	blnx	brsx
crjz	crjz	ctgz	ckwz
dskw	dskw	dzxw	dvzw
fqlv	fqlv	fptv	fknv

APPENDIX VII: *Stimulus of Experiment 3c*

	Primes with same case	
TARGETS	**SAME IDENTITY-DIFFERENT CASE**	**DIFFERENT IDENTITY-DIFFERENT CASE**
GJDT	GjdT	GfbT
HLBS	HlbS	HcdS
JMFR	JmfR	JwpR
KNYQ	KnyQ	KhvQ
LCTP	LctP	LdfP
BFZN	BfzN	BrsN
CPXM	CpxM	CfkM
DKWL	DkwL	DxvL
FSVK	FsvK	FzyK
GVSH	GvsH	GwzH
HWPJ	HwpJ	HmqJ
JXFG	JxfG	JkpG
KZCF	KzcF	KsnF
LTPD	LtpD	LlbD
MRKZ	MrkZ	MflZ
NSCB	NscB	NzvB
PVLZ	PvlZ	PwbZ
QWRY	QwrY	QmjY
RDSX	RdsX	RbzX
SHXW	ShxW	SkvW
TCZV	TczV	TdsV
VSWT	VswT	VzmT
WPRS	WprS	WfcS
XVSR	XvsR	XyzR
YHDQ	YhdQ	YkbQ

ZTVP	ZtvP	ZlnP
BCKZ	BckZ	BdxZ
CZJY	CzjY	CstY
DKCX	DkcX	DlbX
FRZW	FrzW	FksW
GFHV	GfhV	GtnV
HDVT	HdvT	HbwT
JBWS	JbwS	JdkS
KTSR	KtsR	KlzR
LCDQ	LcdQ	LvhQ
MKGP	MkgP	MxcP
NJPZ	NjpZ	NtqZ
PRGD	PrgD	PkbD
QLPF	QlpF	QhrF
RFBG	RfbG	RhdG
HndG	HNDG	HMPG
JybF	JYBF	JXDF
KtyD	KTYD	KJVD
LqrZ	LQRZ	LPCZ
MrqB	MRQB	MVDB
NbmZ	NBMZ	NQWZ
PfjY	PFJY	PTKY
QglX	QGLX	QPHX
RhgW	RHGW	RNQW
SjfV	SJFV	STPV
TldS	TLDS	TJCS
VmbT	VMBT	VWRT
WnyR	WNYR	WMXR
XctQ	XCTQ	XBZQ
YwqP	YWQP	YMRP
ZfnY	ZFNY	ZJVY

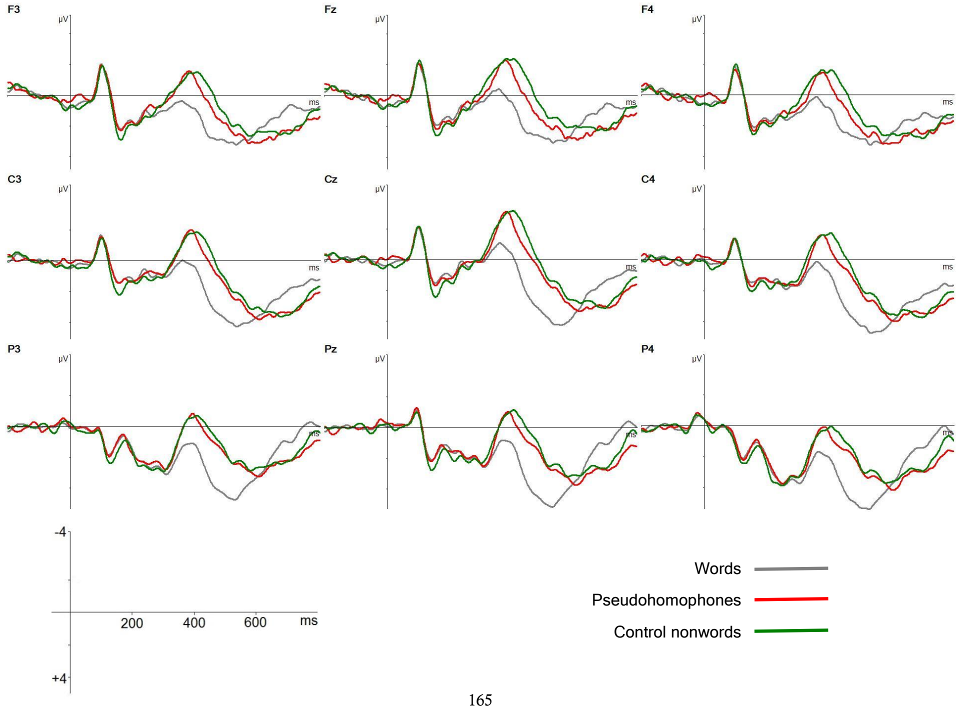
BrmX	BRMX	BCNX
CbjZ	CBJZ	CPTZ
DglW	DGLW	DQHW
FhgV	FHGV	FKRV
XbyH	XBYH	XDVH
GctJ	GCTJ	GBZJ
HfzK	HFZK	HJSK
JghL	JGHL	JPNL
KznM	KZNM	KSHM
LjmN	LJMN	LCWN
MlcB	MLCB	MHGB
NmsY	NMSY	NWZY
PnhX	PNHX	PMKX
QzgW	QZGW	QSPW
RtfV	RTFV	RZJV
SqdT	SQDT	SPQT
TrbS	TRBS	TCDS
VdtR	VDTR	VCJR
WfrQ	WFRQ	WTPQ
BgqM	BGQM	BRDM
ChnL	CHNL	CMVL
DsmK	DSMK	DZWK
FwhJ	FWHJ	FMKJ
GzfH	GZFH	GSTH

	Primes with different case	
TARGETS	**SAME IDENTITY-SAME CASE**	**DIFFERENT IDENTITY-SAME CASE**
TQMV	TQMV	TDWV
VWNT	VWNT	VMXT
WRBS	WRBS	WKPS
XTVR	XTVR	XFYR
YPCQ	YPCQ	YRGQ
ZYXP	ZYXP	ZVKP
BLSZ	BLSZ	BJZZ
CKZY	CKZY	CXSY
DJFX	DJFX	DYRX
FHDW	FHDW	FLBW
GFJV	GFJV	GPCV
HGHT	HGHT	HCNT
JDGS	JDGS	JQCS
KSLR	KSLR	KZFR
LZKQ	LZKQ	LSXQ
MXYP	MXYP	MKVP
NCPZ	NCPZ	NGRZ
PVTD	PVTD	PWFD
QBRF	QBRF	QPKF
RNQG	RNQG	RMCG
HQMG	HQMG	HDWG
JMNF	JMNF	JWKF
KRBD	KRVD	KPMD
LTVZ	LTBZ	LFRZ
MYCB	MYCB	MVGB
NPXZ	NPXZ	NBKZ
PLZY	PLZY	PJSY

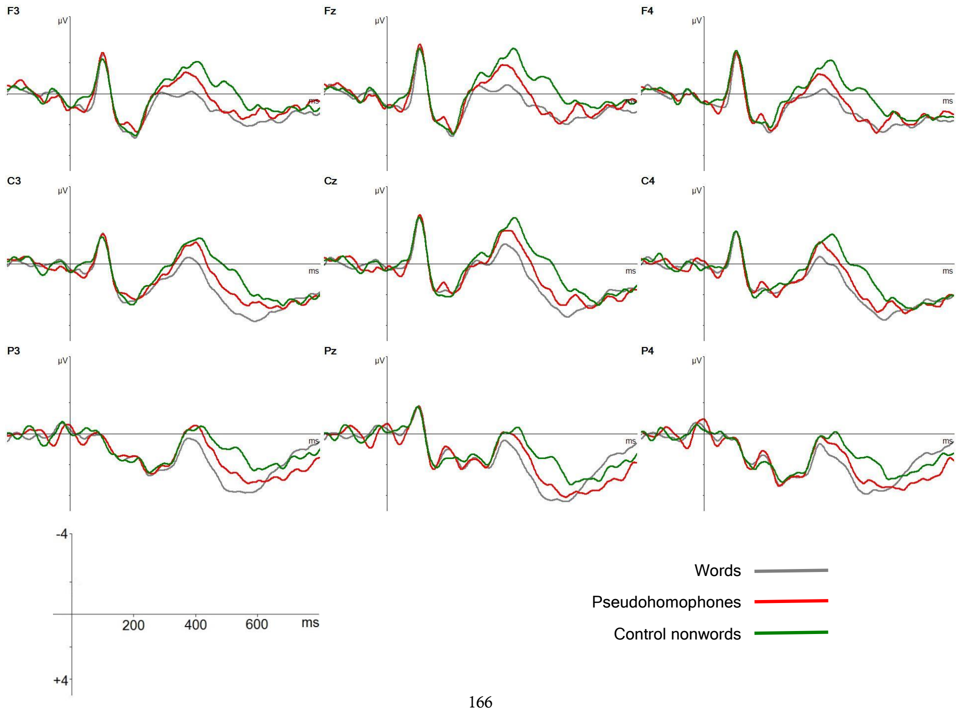
QKSX	QKSX	QNZX
RJDW	RJDW	RYQW
SHFV	SHFV	SNPV
TFGS	TFGS	TPCS
VGHT	VGHT	VQNT
WDJR	WDJR	WBTR
XSKQ	XSKQ	XZNQ
YZLP	YZLP	YSJP
ZXPY	ZXPY	ZKBY
BCYX	BCYX	BGVX
CVTZ	CVTZ	CWFZ
DBRW	DBRW	DPFW
FNWV	FNWV	FZMV
XpzH	XpzH	XqsH
GyxJ	GyxJ	GjkJ
HtcK	HtcK	HlnK
JrvL	JrvL	JcwL
KwnM	KwnM	KvcM
LqbN	LqbN	LpdN
MslB	MslB	MztB
NdmY	NdmY	NbwY
PfkX	PfkX	PthX
QgjW	QgjW	QylW
RjhV	RjhV	RtnV
ShgT	ShgT	SbqT
TkdS	TkdS	TxbS
VmfR	VmfR	VwtR
WlsQ	WlsQ	WtzQ
BnqM	BnqM	BrgM
CbwL	CbwL	CdmL
DvrK	DvrK	DxnK

FctJ	FctJ	FrfJ
GxyH	GxyH	GkjH
HzpT	HzpT	HsqT
GqmS	GqmS	GpwS
JwnR	JwnR	JmcR
KrbQ	KrbQ	KnhQ
LtvP	LtvP	LfyP
BycN	BycN	BvrN
ClxM	ClxM	CtkM
DpzL	DpzL	DqsL
FksK	FksK	FxzK
GjdH	GjdH	GlbH
HgfJ	HgfJ	HqtJ
JhgF	JhgF	JnpF
KdhG	KdhG	KbnG
LfjD	LfjD	LtlD
MskZ	MskZ	MzxZ
NzlB	NzlB	NstB
PxyZ	PxyZ	PkvZ
QcpY	QcpY	QngY
RvtX	RvtX	RwfX
SbrW	SbrW	SdcW

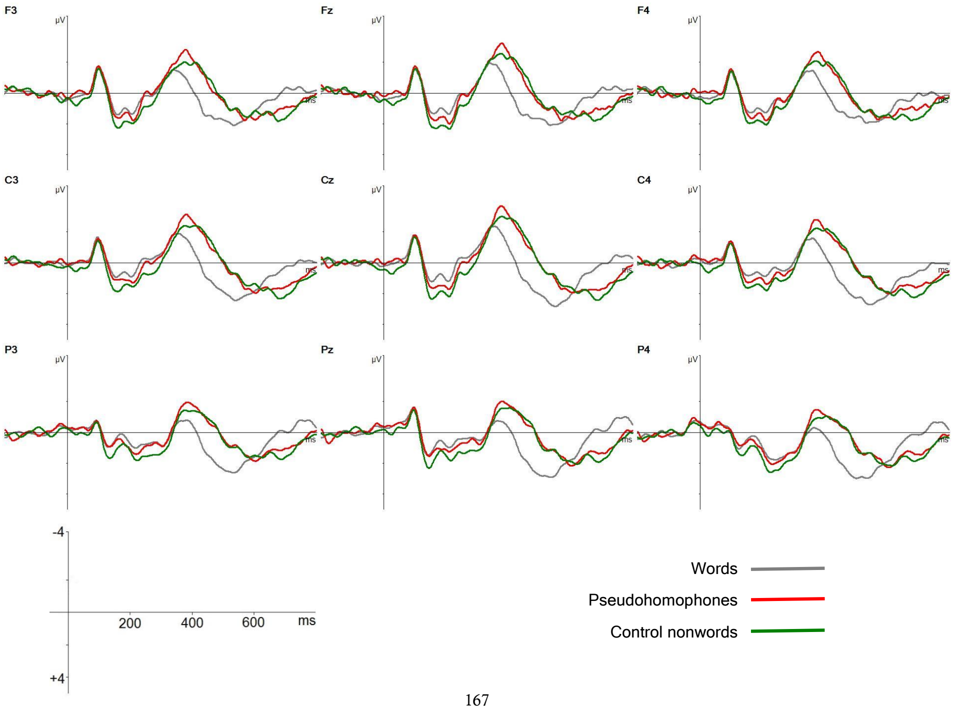
APPENDIX VIII: *Grand-averaged ERPs corresponding to the Experiment 1a (errors excluded) for* ***deaf group****.*



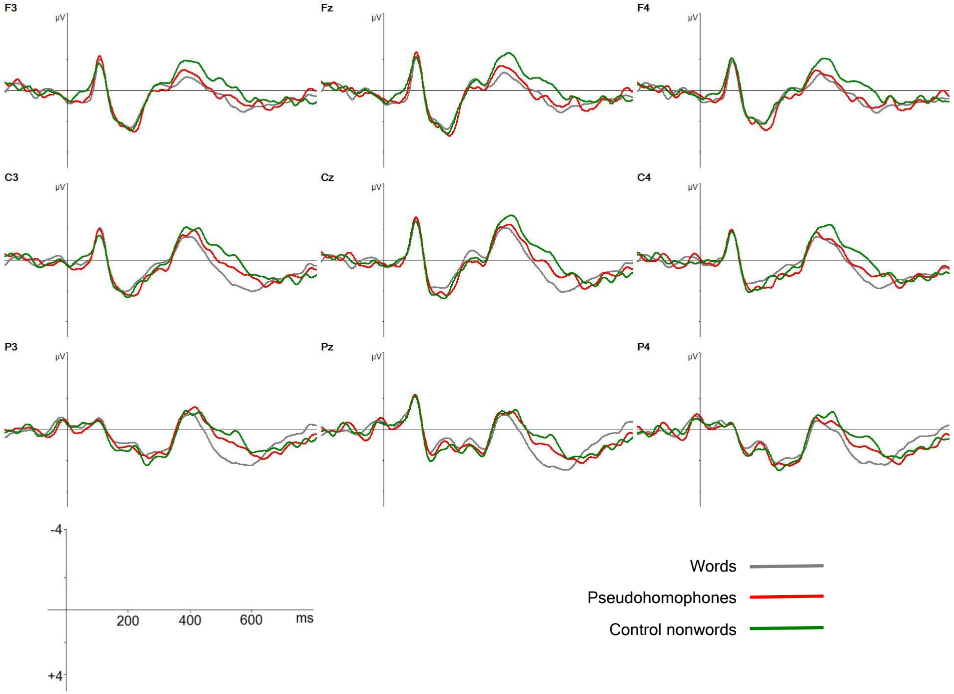
APPENDIX IX: *Grand-averaged ERPs corresponding to the Experiment 1a (errors excluded) for* ***hearing group****.*



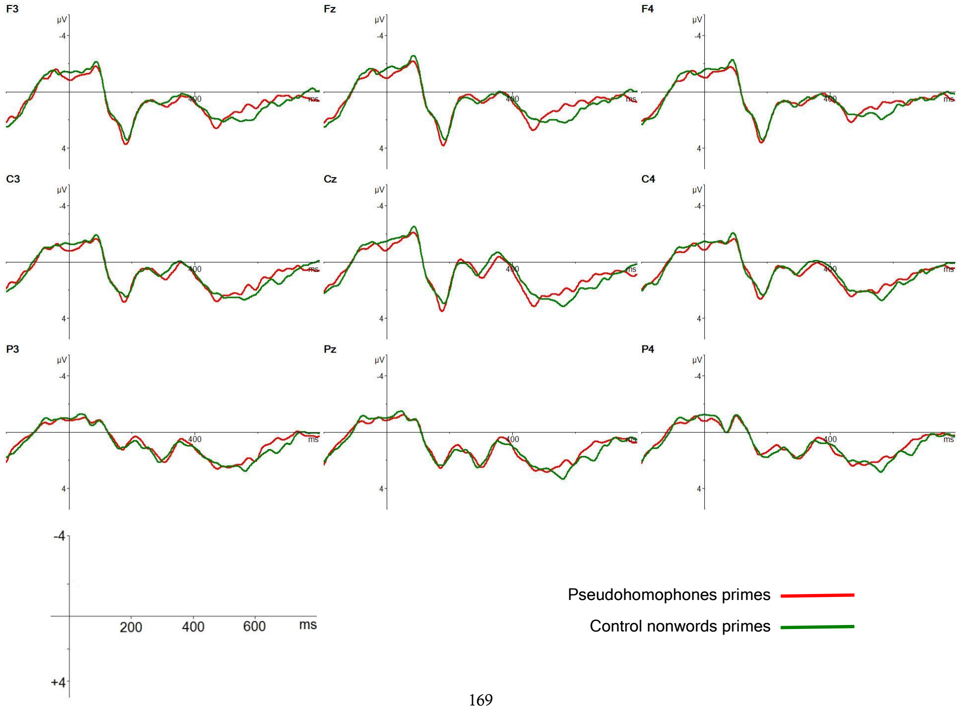
APPENDIX X: *Grand-averaged ERPs corresponding to the Experiment 1a (errors included) for* ***deaf group****.*



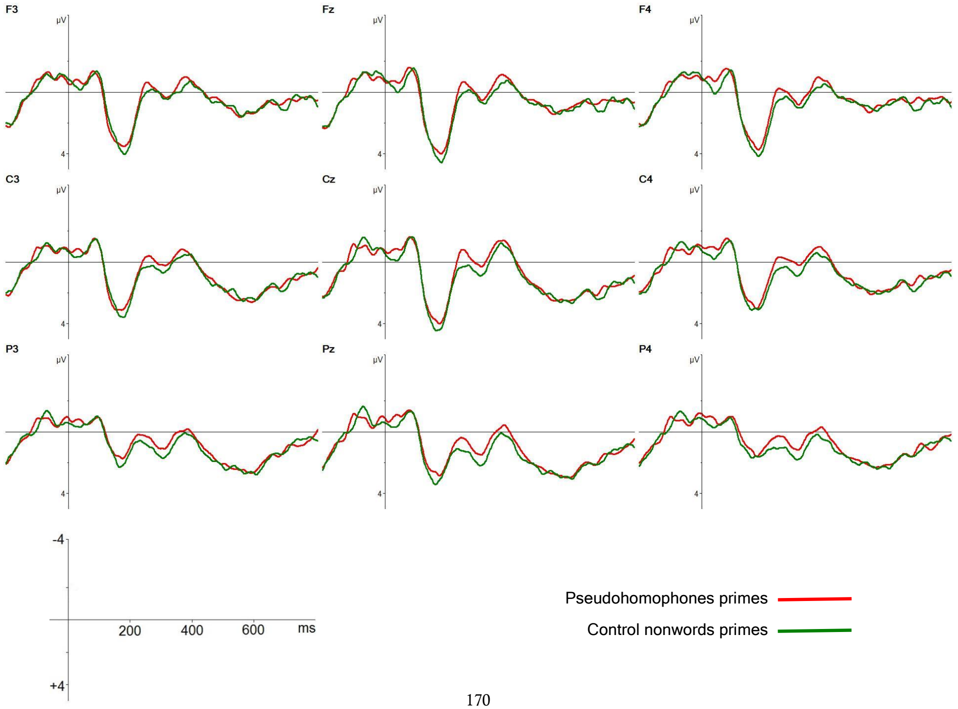
APPENDIX XI: *Grand-averaged ERPs corresponding to the Experiment 1a (errors included) for* ***hearing group****.*



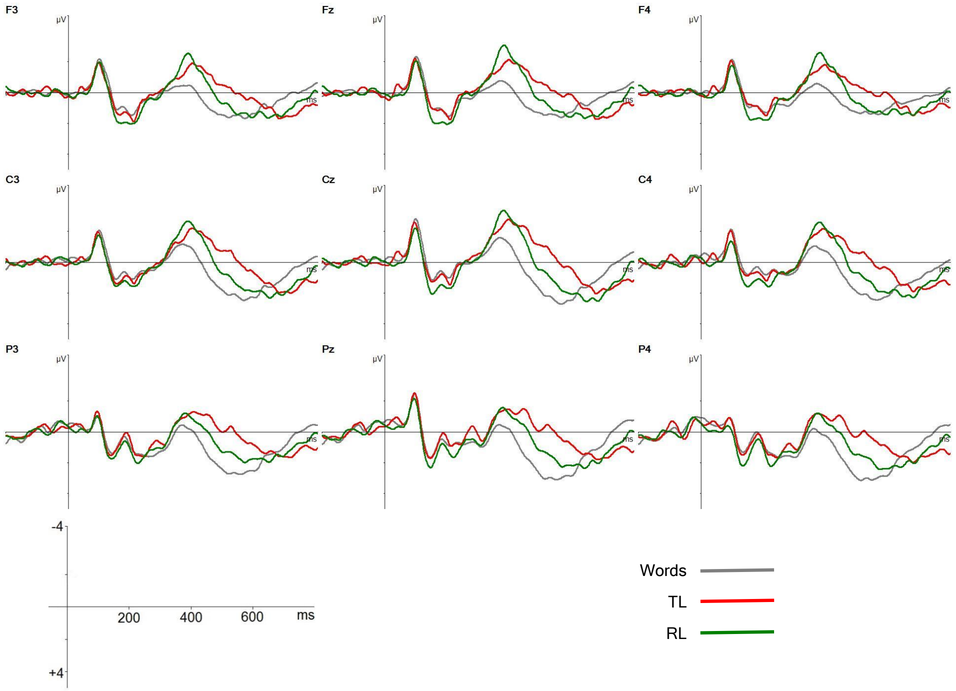
APPENDIX XII: *Grand-averaged ERPs corresponding to the Experiment 1b for* ***deaf group****.*



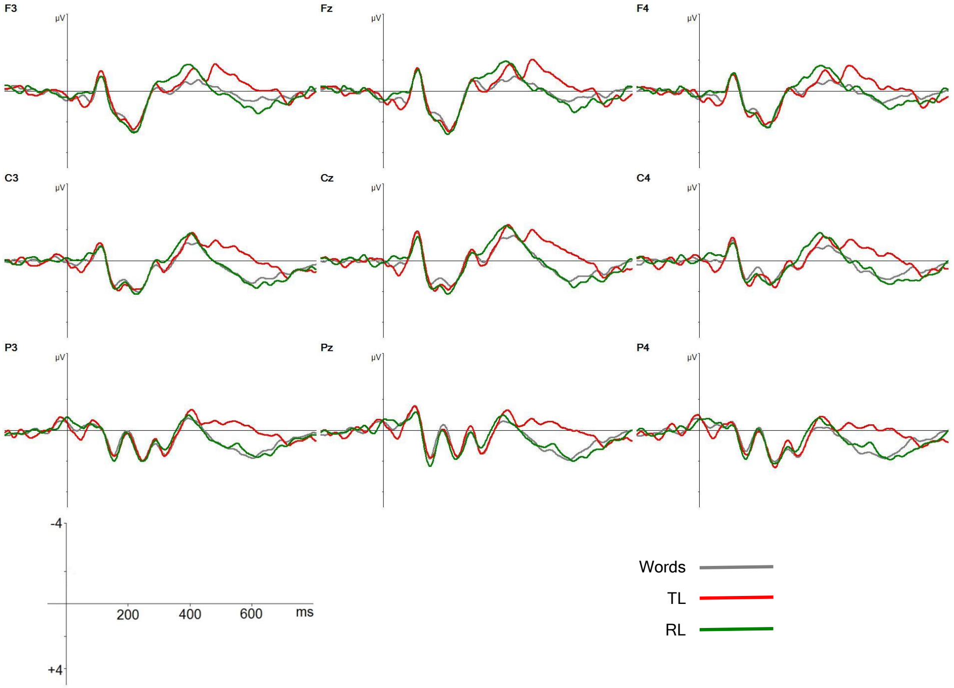
APPENDIX XIII: *Grand-averaged ERPs corresponding to the Experiment 1b for* ***hearing group****.*



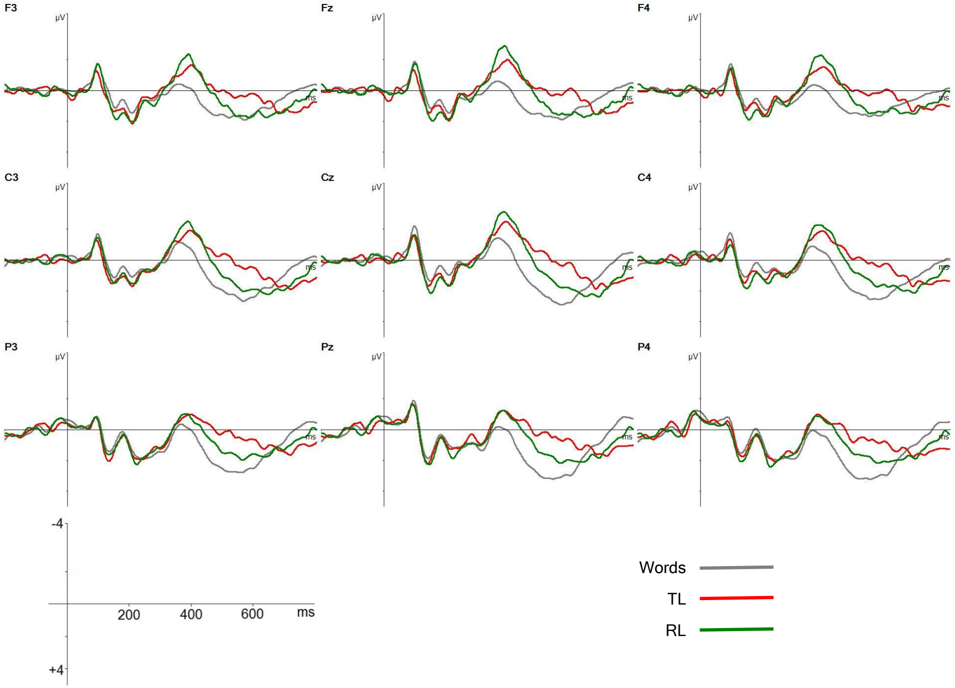
APPENDIX XIV: *Grand-averaged ERPs corresponding to the Experiment 2a (errors excluded) for* ***deaf group****.*



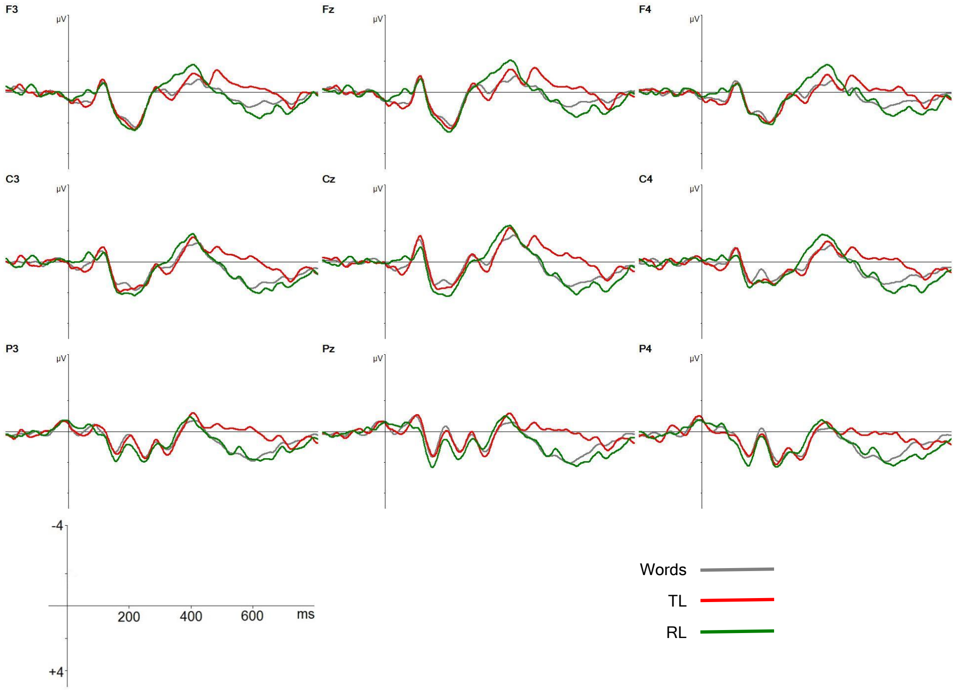
APPENDIX XV: *Grand-averaged ERPs corresponding to the Experiment 2a (errors excluded) for* ***hearing group****.*



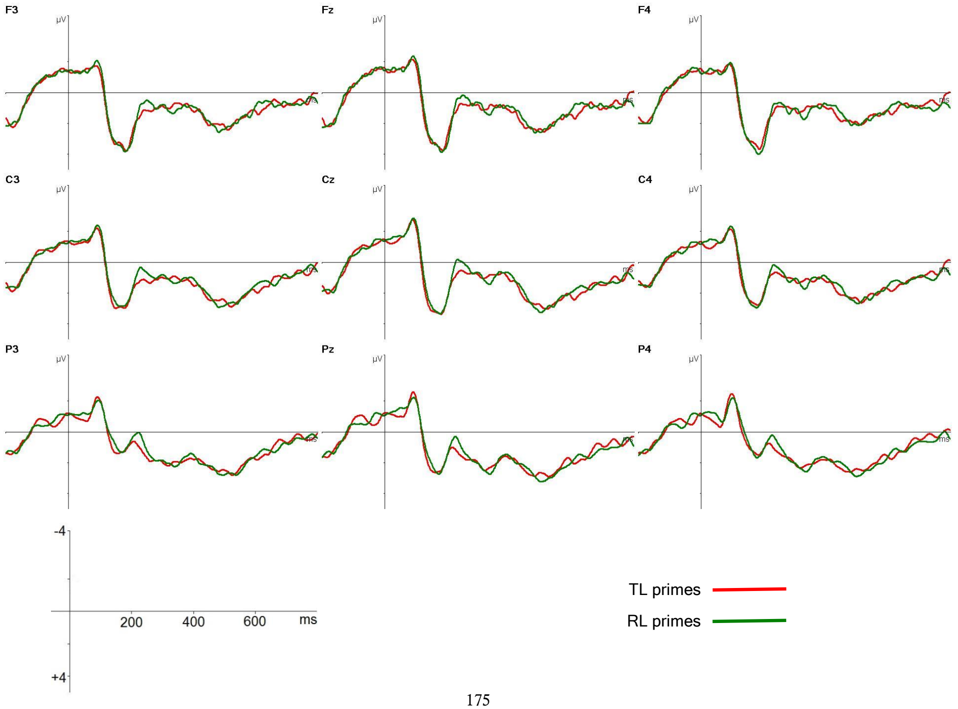
APPENDIX XVI: *Grand-averaged ERPs corresponding to the Experiment 2a (errors included) for* ***deaf group****.*



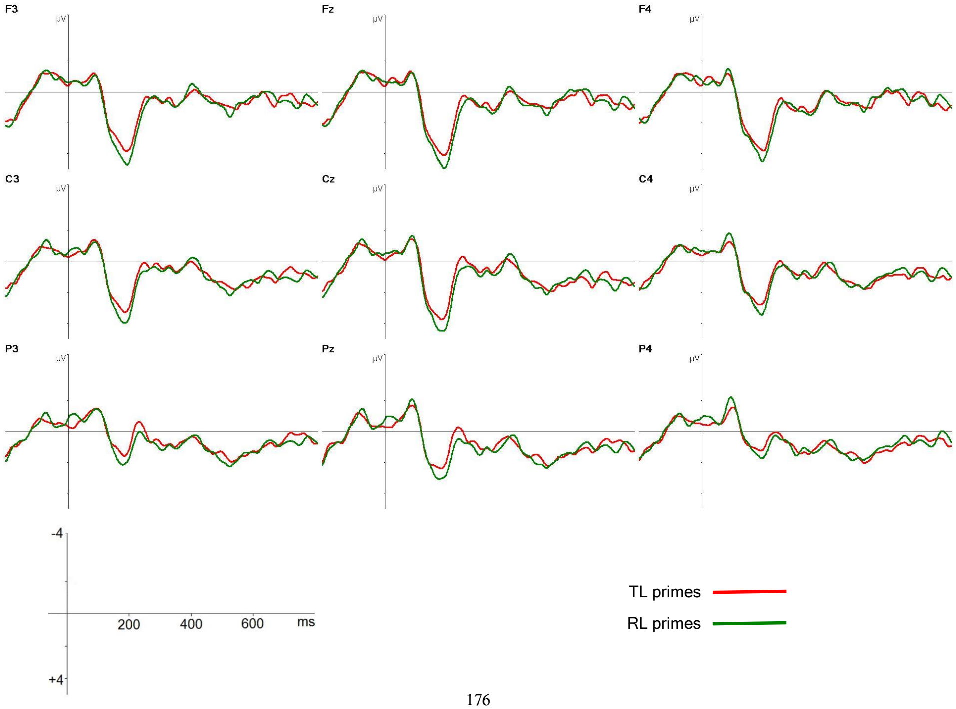
APPENDIX XVII: *Grand-averaged ERPs corresponding to the Experiment 2a (errors included) for* ***hearing group***.



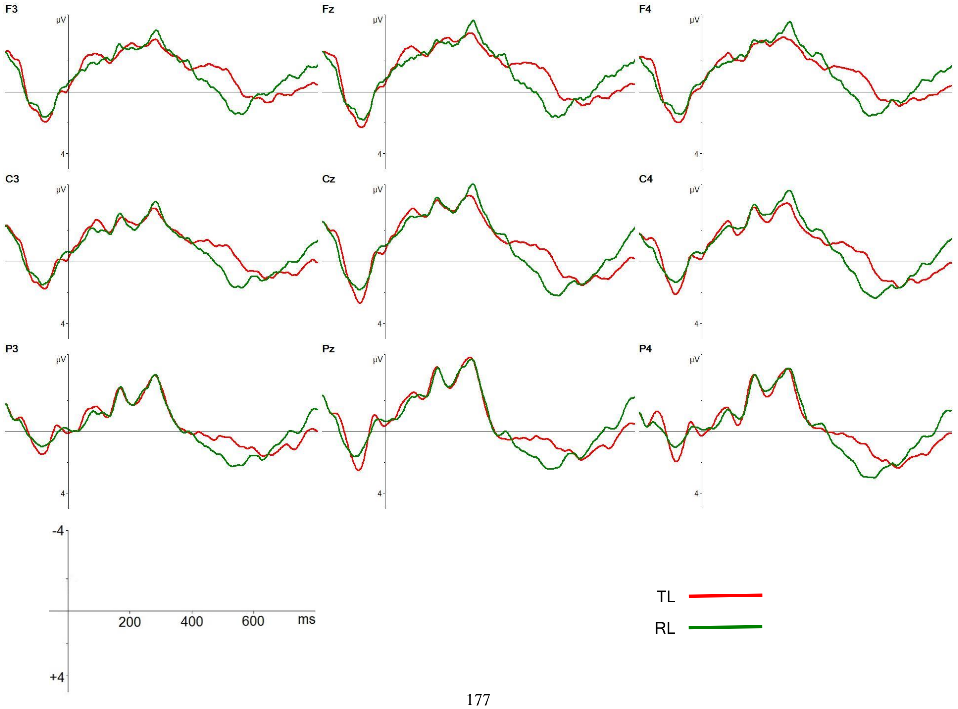
APPENDIX XVIII: *Grand-averaged ERPs corresponding to the Experiment 2b for* ***deaf group****.*



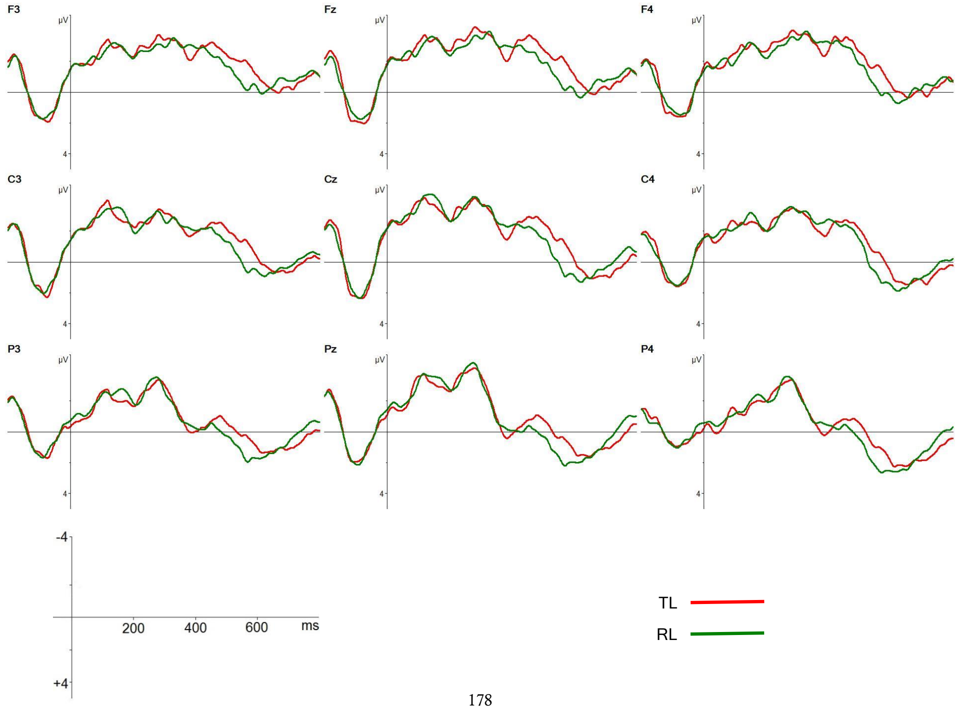
APPENDIX XIX: *Grand-averaged ERPs corresponding to the Experiment 2b for* ***hearing group****.*



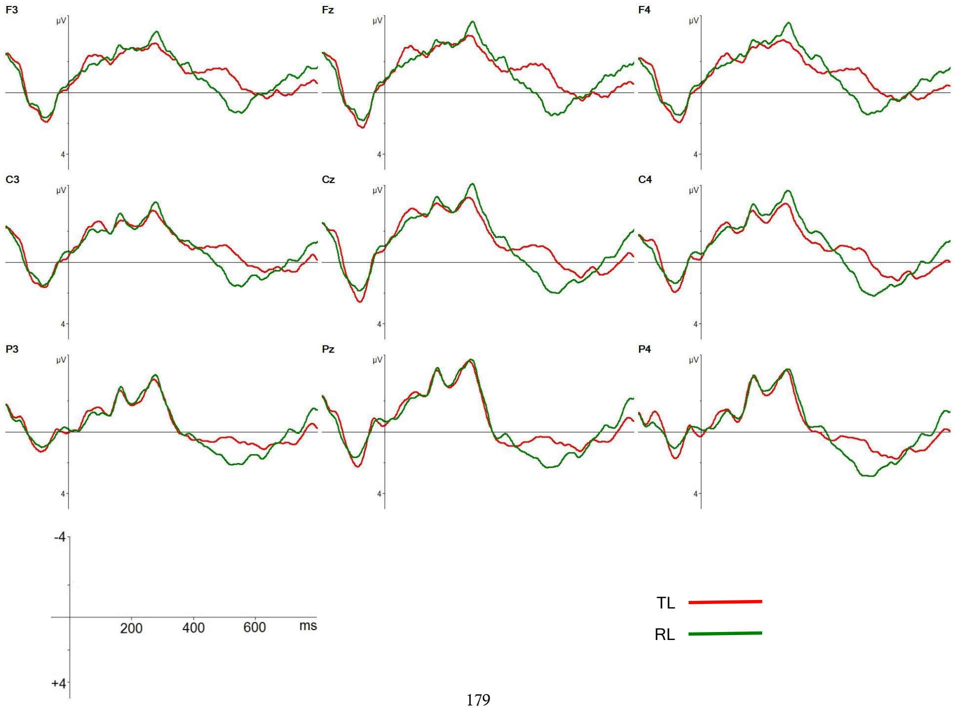
APPENDIX XX: *Grand-averaged ERPs corresponding to the Experiment 3a (errors excluded) for* ***deaf group***.



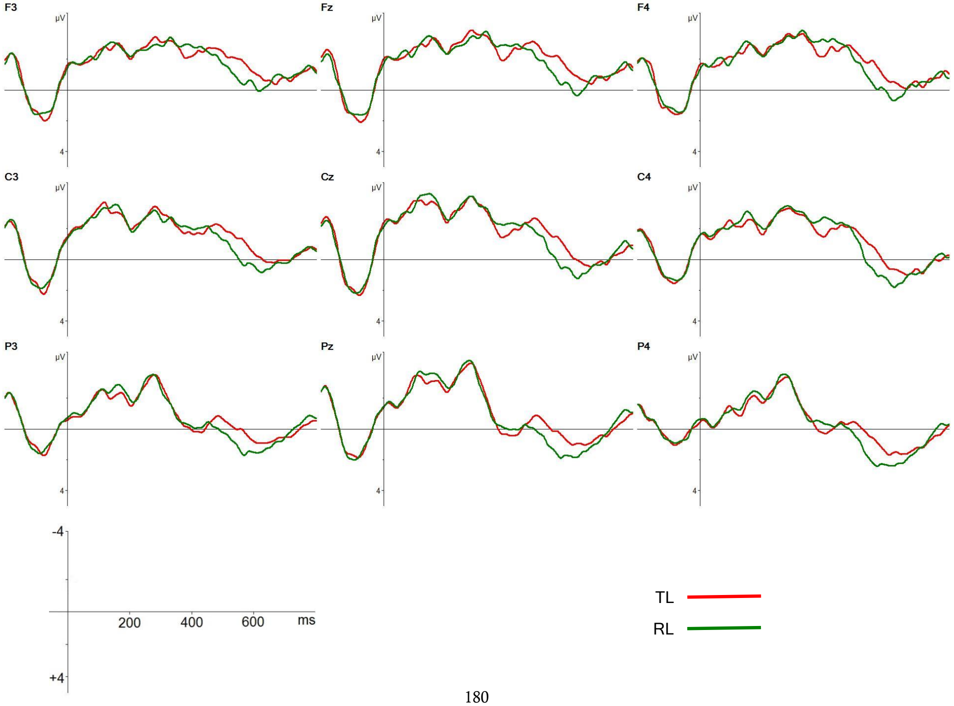
APPENDIX XXI: *Grand-averaged ERPs corresponding to the Experiment 3a (errors excluded) for* ***hearing group****.*



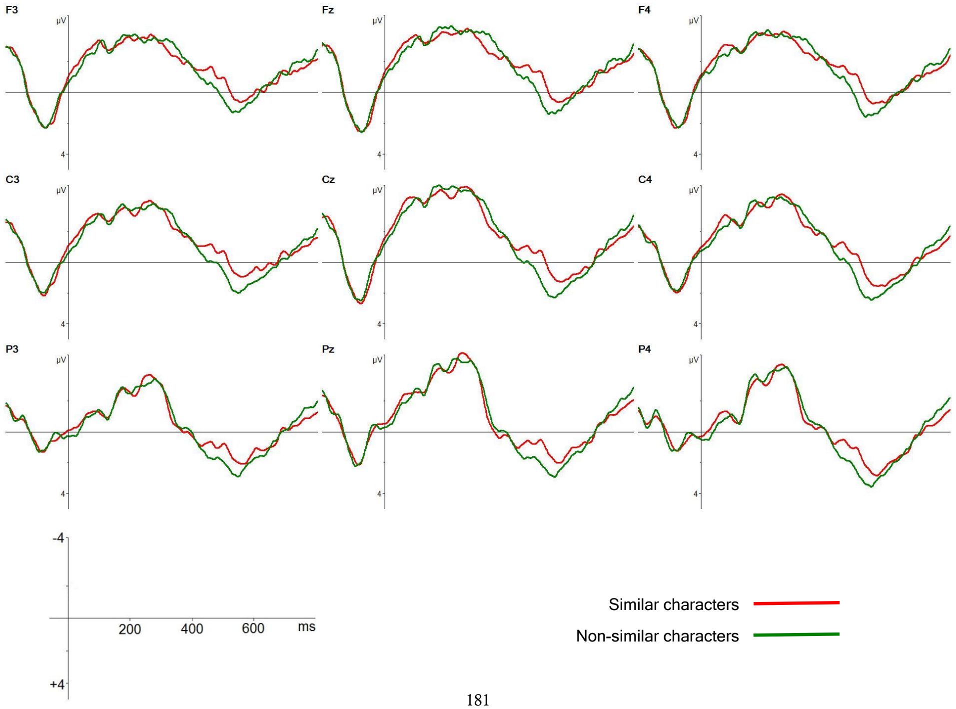
APPENDIX XXII: *Grand-averaged ERPs corresponding to the Experiment 3a (errors included) for **deaf group**.*



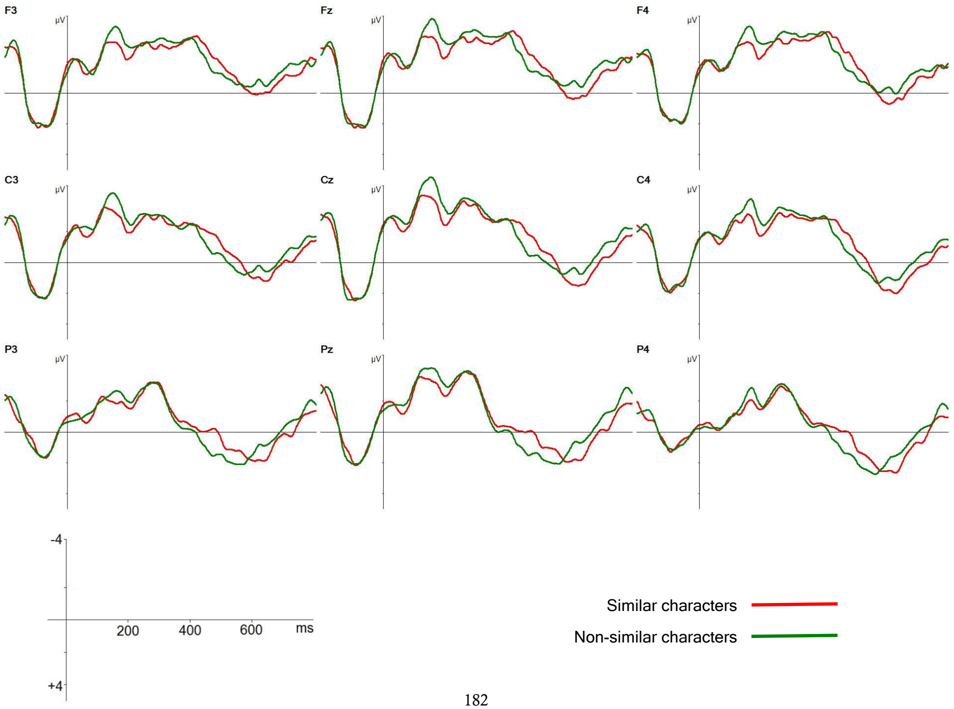
APPENDIX XXIII: *Grand-averaged ERPs corresponding to the Experiment 3a (errors included) for* ***hearing group****.*



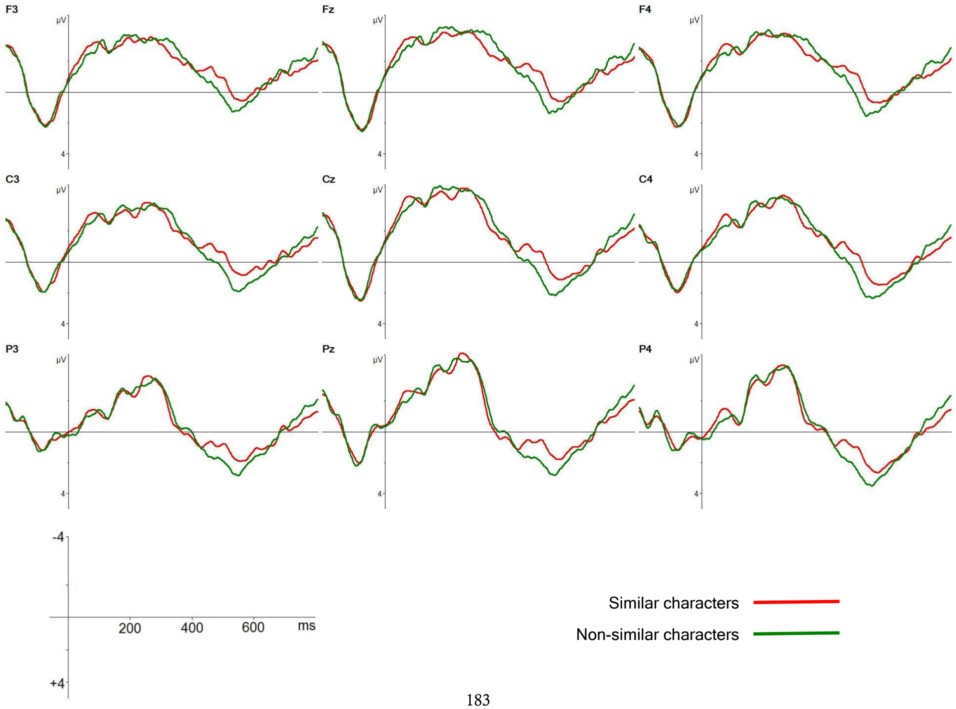
APPENDIX XXIV: *Grand-averaged ERPs corresponding to the Experiment 3b (errors excluded) for* ***deaf group****.*



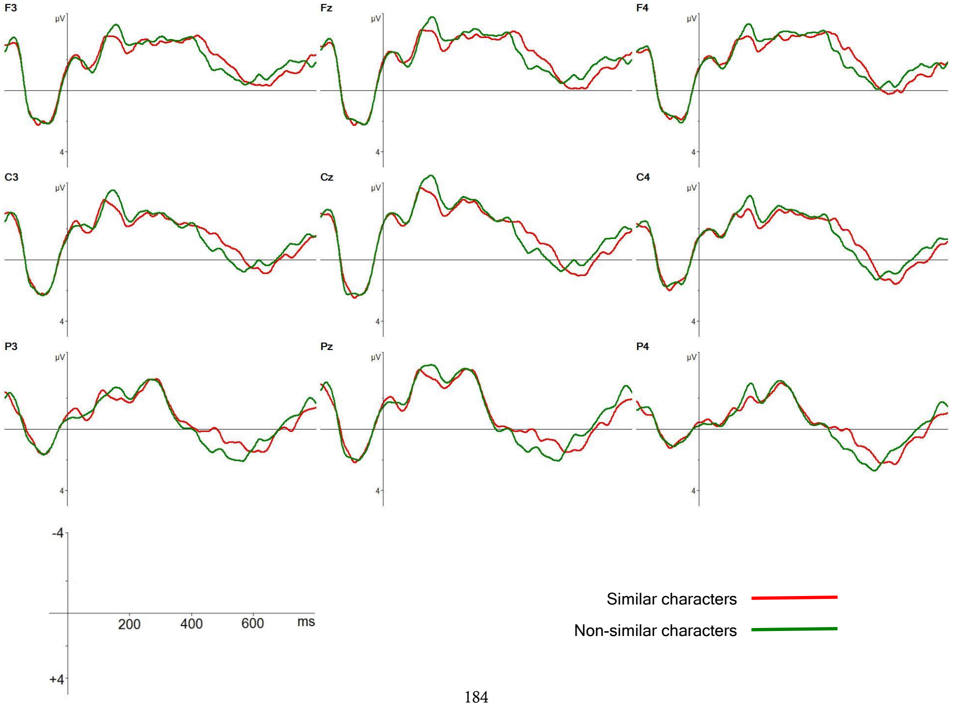
APPENDIX XXV: *Grand-averaged ERPs corresponding to the Experiment 3b (errors excluded) for* ***hearing group****.*



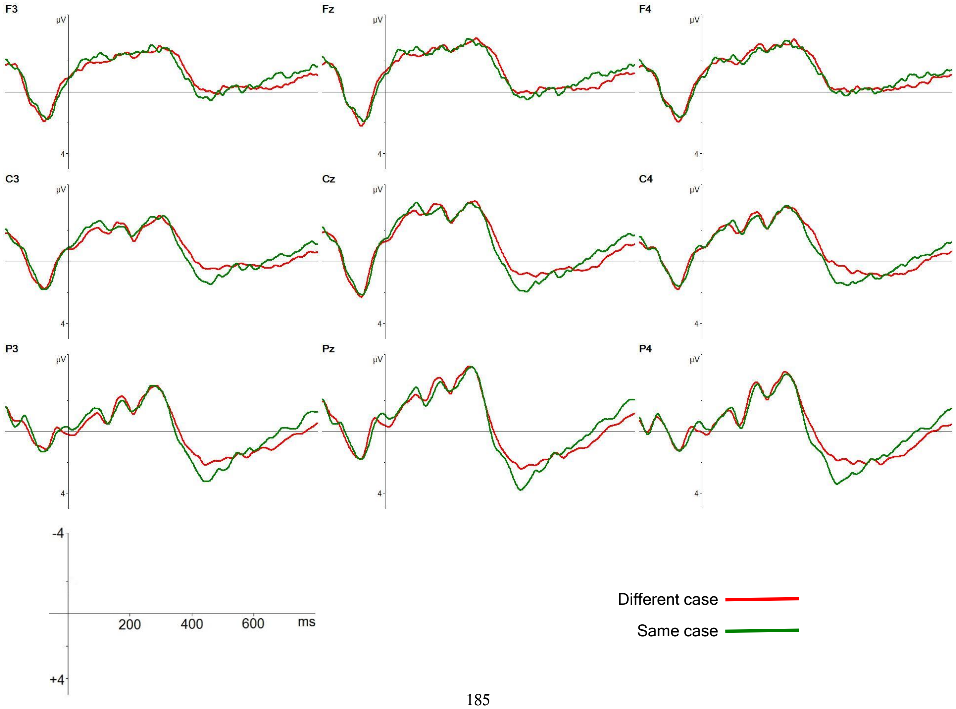
APPENDIX XXVI: *Grand-averaged ERPs corresponding to the Experiment 3b (errors included) for* ***deaf group****.*



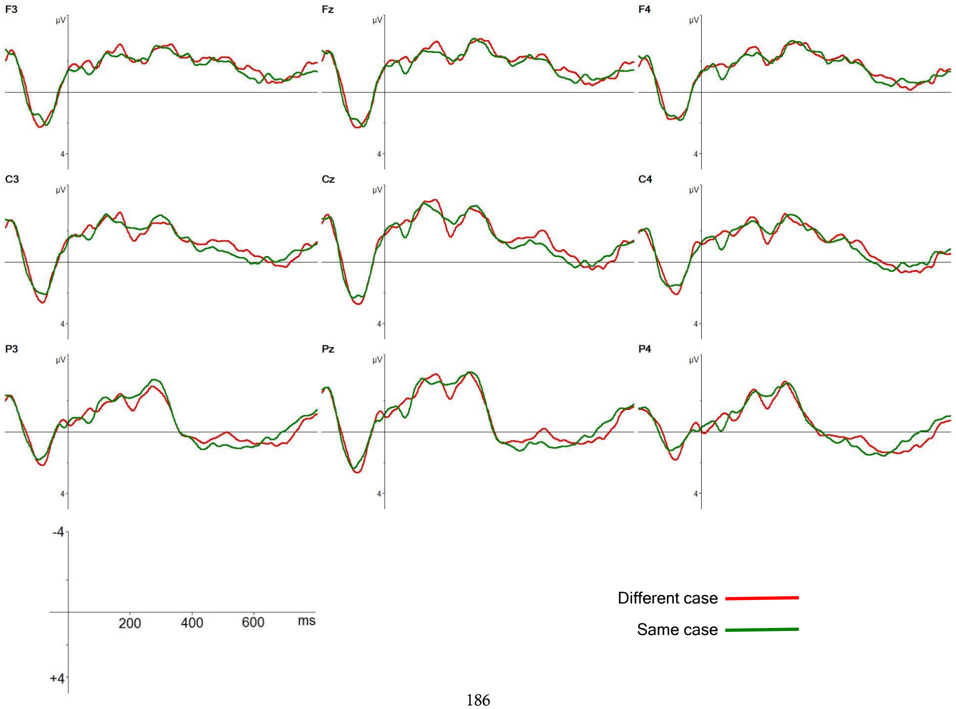
APPENDIX XXVII: *Grand-averaged ERPs corresponding to the Experiment 3b (errors included) for* ***hearing group****.*



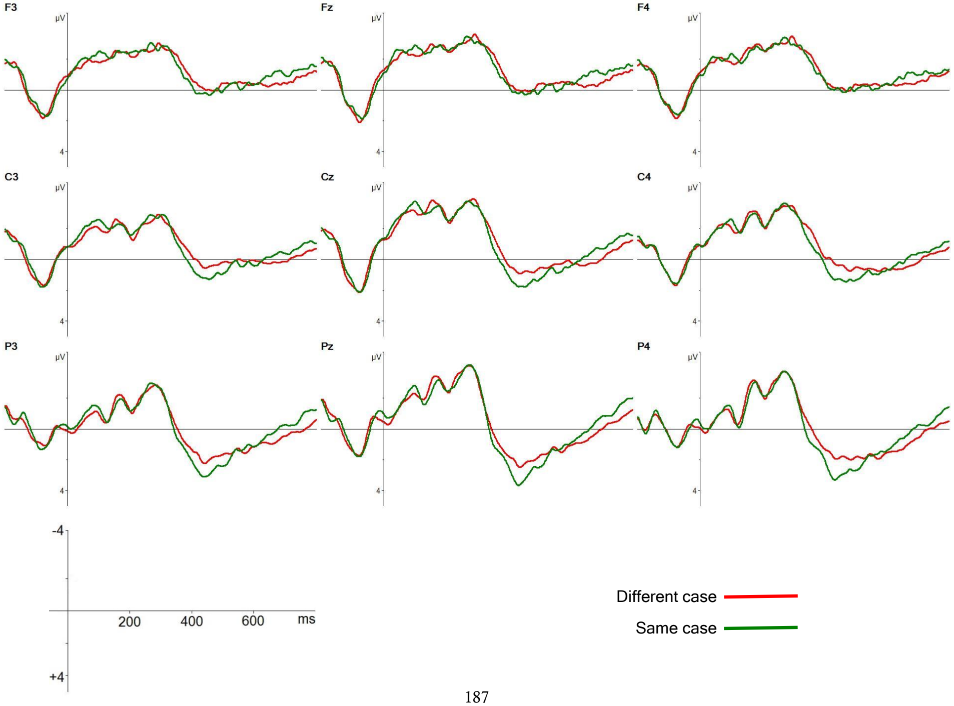
APPENDIX XXVIII: *Grand-averaged ERPs corresponding to the Experiment 3c (errors excluded) for* ***deaf group****.*



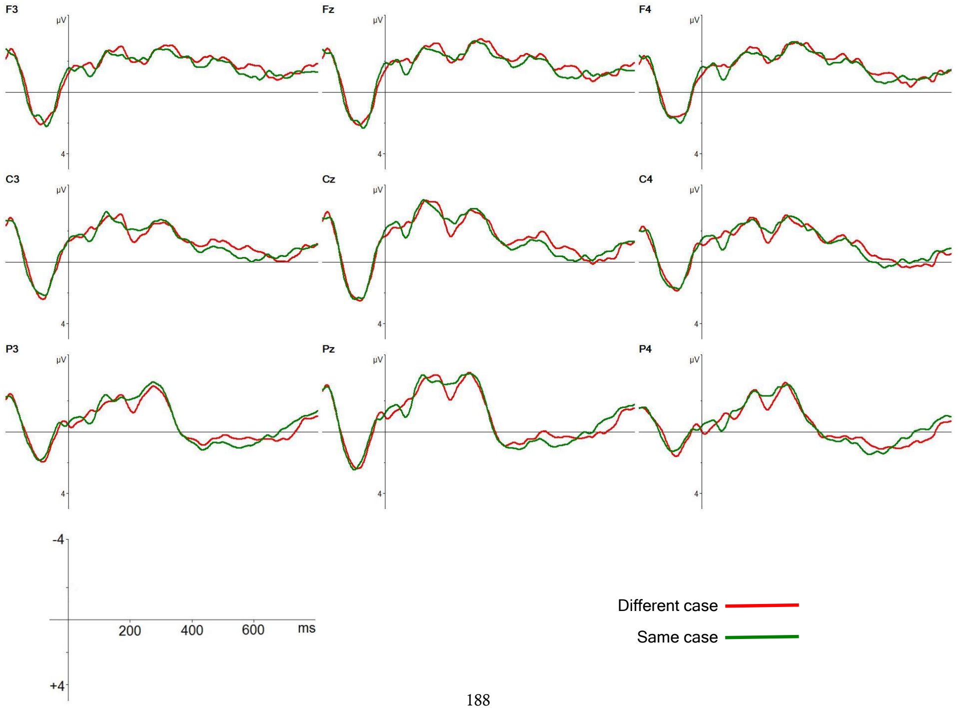
APPENDIX XXIX: *Grand-averaged ERPs corresponding to the Experiment 3c (errors excluded) for* ***hearing group****.*



APPENDIX XXX: *Grand-averaged ERPs corresponding to the Experiment 3c (errors included) for* ***deaf group****.*



APPENDIX XXXI: *Grand-averaged ERPs corresponding to the Experiment 3c (errors included) for* ***hearing group****.*



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