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VISUAL PERCEPTION AND SIGNED ORAL LANGUAGE IN DEAFNESS

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Alla mia famiglia,

a Riccardo

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Preface

Recent advances in early hearing screening along with technologies for digital hearing aids and cochlear implants have given access to the auditory input of spoken language to many children with a diagnosis of hearing loss. However, the enduring delays in academic achievements of deaf students in comparison to hearing peers lead to question the effectiveness of educational interventions focused exclusively on oral communication, reconsidering the role that sign language or signing systems may have for increasing their comprehension and enriching the linguistic environment.

The Individual Differences, Language and Cognition Lab at the University of Seville has been for long been exploring the extent to which deaf students lag their hearing peers in reading comprehension, and the cognitive and linguistic predictors involved in this process. More recently, the research interests of the Lab for comprehension difficulties in deaf individuals were extended to spoken language comprehension and to augmentative systems that might potentially increase oral communication, such as sign-supported speech. Along this trajectory of research, I took part, as early stage researcher, in a project supervised by Dr. Isabel R. Rodriguez-Ortiz and co-supervised by the Lab Director Dr. David Saldaña, within the European Innovative Training Network (ITN) *LanPercept* (grant number: 316748). This ITN aimed to provide a more-in-depth knowledge on the interaction between two central cognitive systems, language and perception, in typical as well as in atypical populations, by using cutting-edge behavioural and neurophysiological techniques. The network included eight university partners and two private-sector partners. Each of these institutions hosted one or more conferences or training courses intended to develop research skills and acquire interdisciplinary techniques, advanced scientific methods and complementary skills, such as research project management or writing and oral presentation skills. In this terrifically stimulating environment, I had the opportunity to develop this doctoral project. The project examined the relationship between language and perception in a population of Spanish deaf school-age individuals. The extent to which sign-supported speech eventually increases comprehension compared to spoken language only was tested in congenitally deaf adolescents with early-activated cochlear implants (before the age of five). During language perception, eye-tracking data were collected to explore the role of attention to lip movements and signs in deaf perceivers.

The thesis is written as a compilation of studies. The central chapters of the thesis report the four experiments realised included in the three studies. By the time of submitting the thesis study 1[1] was published, study 2[2] was accepted for publication and study 3 was under review.

The first chapter of the thesis is a general introduction of the research problem. The current debate around the methods used in deaf education and the existing educational settings are discussed. The two main profiles of deaf individuals considered in our research, with cochlear implants, on one hand, and native signers, on the other hand, are presented. The possible role of sign-supported speech in increasing communication and comprehension for the new generation of deaf students with better restored audition is addressed. Eye-tracking technology and its application in the current thesis are also described.

[1] Mastrantuono, E., Saldaña, D., & Rodríguez Ortiz, I. (2017). An eye-tracking study with deaf adolescents on the efficacy of sign-supported speech. *Frontiers in Psychology, 8*(1044). doi:10.3389/fpsyg.2017.01044
[2] Mastrantuono, E., Saldaña, D., & Rodríguez-Ortiz, I. (in press). Inferencing in deaf adolescents during sign-supported speech comprehension. *Discourse Processes*. doi: 10.1080/0163853X.2018.1490133

The second chapter describes the topic and the goals of the thesis.

The third chapter reports Experiment 1, which addressed the research problem of the effectiveness of sign-supported speech for discourse-level comprehension. Using a within-subject design we compared the perception of language in spoken language only, sign language only, and in sign-supported speech. We tested the capacity of these communicative systems to equate comprehension in deaf participants with that of spoken language in hearing participants.

The fourth chapter reports Experiment 2. This experiment tested the capability of deaf adolescents to generate inferences during spoken language comprehension, and if the use of sign-supported speech increased participants' comprehension. A more in-depth investigation on the inference-making abilities of deaf children is desirable to compensate the paucity of studies addressing this issue across the deaf population (Kyle & Cain, 2015).

The fifth chapter reports experiments 3 and 4 integrated in a single study. Two eye-tracking experiments aimed to detect the extent in which deaf individuals do rely on signs during the perception of sign-supported speech. Experiment 3 shifted observers' foveal attention to the preferred linguistic source in sign-supported speech, by magnifying the face area and by constraining the visual field through a gaze-contingent paradigm. Experiment 4 explored the reliance on signs in SSS by producing a mismatch between signs and speech.

The sixth and final chapter considers jointly the conclusions of the four experiments, extracts an overall view of the results, and offers suggestions about the practical implications of this study for education.

Part 1

Introduction and Goals

CHAPTER 1

INTRODUCTION

1.1 The Education of Deaf Children

1.2 Visual Components of Language

1.3 The Specificity of Deaf Profiles

1.4 Eye Tracking

CHAPTER 2

TOPIC AND GOALS OF THIS THESIS

Chapter 1

Introduction

1.1 The Education of Deaf Children: Towards an Inclusive Education

In recent years, a global shift in educational philosophy is leading to the adoption of a more inclusive education (Knoors, Tang, & Marschark, 2014). The philosophical perspective underlying the phenomenon of inclusion is driven by the idea of egalitarianism among all learners and the role of the institutions of promoting integration (Fernandez-Viader, 2004; Stinson & Antia, 1999). Inclusion is fundamental to prepare individuals for life, giving the opportunity to learners with special educational needs to have normal life experiences and learning from typical peers and, at the same time, to teach and apply democracy at school by challenging social rejection (Stinson & Antia, 1999). This philosophical approach resulted in laws, such as the *Individuals with Disabilities Education Act* (IDEA), that regulate the issue of inclusion in the wider field of special education (Stinson & Antia, 1999). Inclusive education implies that all learners should attend regular classrooms, and teachers, in collaboration with special educators, should adapt the structure of the classroom to facilitate their learning. In agreement with this currently dominant philosophy, the education for deaf students is also changing direction.

Traditionally, when enrolling their children at school, parents of deaf or hard of hearing children had two main options (Stinson & Kluvin, 2014; Tang & Yiu, 2016). The first option, usually preferred for deaf children with greater access to audition, was a mainstream school with oral communication programs. Generally, in public schools, there are only one or two deaf students per classroom. In regular classrooms, deaf students receive consultation or additional instruction through a teacher of the deaf, who in many educational systems is an itinerant teacher. This itinerant teacher can only devote a limited time to each student, having to teach to many deaf students with very diverse profiles in a day (Stinson & Kluvin, 2014). At the best, students in mainstream environments can also benefit of speech language therapy and additional services at high-school level to support communication access and learning, such as notetakers, interpreters, real-time speech-to-text services, might also be supplied (Schirmer, 2001; Stinson et al., 1999; Stinson & Foster, 2000). Mainstream schools are usually fitted with resource rooms and separate classes. The resource rooms are a workable option for mainly orally educated deaf children. In fact, they attend resource rooms only for reviewing specific subjects and spend most of the time in regular classrooms. By contrast, separate classes are a less inclusive option, where deaf students receive their entire instruction from a specialised teacher of deaf education, rarely interacting with hearing students in regular classrooms.

The second option was traditionally the special school for deaf, mainly chosen for children with lower or no access to audition. In these special schools, deaf children mainly communicate with each other using natural sign languages or any signed system, separately from the spoken language. Special schools usually provide with a range of special services, such as psychologists, audiologists, and counsellors, and propose a wide variety of academic, vocational courses and athletic and social programs. Recent studies based on large datasets of the United States reveal that students attending special schools are more likely to use sign language and less likely to use spoken language than students attending mainstream institutions (Allen & Anderson, 2010; Shaver, Marschark, Newman, & Marder, 2014), and have major conversational difficulties (Shaver et al., 2014).

In the 21st century, a consequence of the extension of the philosophy of integration, more inclusive educational placements have become the preferred option, and 80-90% of deaf or hard-of-hearing students now attend mainstream schools (Tang & Yiu, 2016). Nevertheless, average deaf students in regular classrooms still achieve poorer academic outcomes than their hearing peers (Knoors & Marschark, 2015; Marschark & Hauser, 2008). These difficulties are evident even in children with cochlear implants (CIs). Despite substantial evidence that the use of CIs enhances spoken-language acquisition, and improves speech perception and production (Watson, Archbold, & Nikolopoulos, 2006; Watson, Hardie, Archbold, & Wheeler, 2008), a positive impact of cochlear implantation on literacy is still not demonstrated (Harris, 2016). In reading comprehension, deaf children have the same difficulties as hearing poor comprehenders (Kyle & Cain, 2015), and struggle with generating inferences (Miller, 2002).

Considering these unsatisfactory outcomes, practitioners in deaf education started to rethink an environment that could be linguistically richer and would facilitate communicative exchanges between deaf and hearing students: models of sign bilingual education were implemented in mainstream classrooms. These models are sustained by research on sign bilingualism (Humphries et al., 2012; Marschark, Tang, & Knoors, 2014), which indicate a positive effect of sign language, together with spoken language, on the language development of deaf and hard-of-hearing children. Models of *co-enrollment* teaching are becoming increasingly popular in many countries. Co-enrollment teaching differs from the traditional mainstream teaching in regular classrooms in how it promotes integration between hearing and deaf students. First, in a co-enrollment setting it is necessary to create a real community of bimodal bilingual users. To this aim, hearing students should necessarily be involved in programs to acquire sign language. Crucially, with the aim to create an educational setting in which bimodal languages effectively co-exist, a significant number of deaf signers should attend the same classrooms (at least in a deaf-hearing ratio estimated around 1:3 or 1:4) (Tang & Yiu, 2016). School teachers should engage themselves in collaborating with the teachers for deaf students, team-teaching with them, and they are encouraged to integrate regular education practices with those from special deaf education, with the aim of breaking down barriers to learning and promoting the active participation of deaf students in the classroom. In a co-enrollment classroom much time need to be devoted to the organisation of teaching, as it is provided in two languages.

Ground-breaking experiences of co-enrollment were started with the TRIPOD program in California in 1982. Compared to deaf students of the same age, the participating deaf students had improved outcomes in communicative interactions, social acceptance and academic skills, (Kirchner, 2014). Kirchner stressed some aspects that ideally a program of co-enrollment should promote: (a) direct communication of deaf students with hearing peers and teachers, with no mediation of interpreters or special teachers, b) equal access to an ordinary curriculum, (c) involvement of deaf students in academically challenging tasks, and (d) creation of bimodal bilingual peer groups in support of socio-emotional status.

1.1.1 Deaf education in Spain.

A recent survey of the Spanish National Health Service of the population over 15 years old provides interesting data on the Spanish deaf population (Gobierno de España, Ministerio de Sanidad, Servicios Sociales e Igualidad, 2014). Spanish population was classified as follows: hearing with no difficulties, hearing with some difficulties (hard of hearing), hearing with many difficulties, and no hearing. A total of 13 % of the Spanish population (5.041.300 individuals) is hard of hearing, of whom 4.3 % (190.900 individuals) is aged between 15 and 24 years. Another 3.6 % (1.418.700 individuals) hears with many difficulties, and of them 0.23% (10.400 individuals) is aged between

15-24 years. No individuals of the youngest range of age, 15 to 24, are classified with no hearing, thanks to the use of hearing aids. In fact, 3.5 % of the Spanish population uses hearing aids or CIs, and the majority of them are aged between 15 and 24 years (2 %).

According to data from the Spanish Department for Education, Culture and Sport, in the year 2014-15, there were 7531 deaf students in the public educational system, from preschool to high school (4.3% of all students with special needs). The majority of deaf students (a total of 7024) are in public (5388 students) or private (1636) mainstream education, while only 507 deaf students attend special schools for deaf (Gobierno de España, Ministerio de Educación, Cultura y Deporte, 2016).

In Spain, bimodal bilingual education was introduced to counter the poor outcomes of deaf students (Valmaseda Balanzategui, 1998). At the end of compulsory education, the performance of deaf adolescents matched the scores of hearing peer in their first years of primary school, especially in reading (Rodríguez-Ortiz, 2005). These poor educational outcomes discouraged the development of oral communication which in turn impacted negatively on social integration (Rodríguez-Ortiz, 2005). This coincided with the advances in sign language studies (Stokoe, 1960) and the advantages in academic achievements of native deaf signers compared to non-native deaf signers that were being reported (Meadow, 1980; Musselman, Lindsay, & Wilson, 1988; Wilbur, 1986). The cognitive and communicative benefits of learning sign language in the early years was apparent.

These factors contributed to the adoption of bimodal bilingual education. A first regulation of bimodal bilingual education for deaf students was approved in 1995, within executive regulations for special education (Real Decreto 696/95). With respect to deaf education, these rules required mainstream education to recognise sign language and promote its use and study in schools attended by deaf or hard-of-hearing students. Also, the Real Decreto required appropriate sign-language training for teachers and other practitioners involved in the education of deaf students. Contents referring to both communicative systems, oral communication and sign language, became part of the students' curriculum (Art.8, ap.6).

The next great achievement for Spanish deaf individuals was the legal recognition of the national Spanish Sign Language (LSE), in 2007 (LEY 27/2007[3]), and, soon after, of Catalan Sign Language (LSC), in 2010 (LEY 17/2010[4]). In 2011 the *Centro de Normalización Lingüística de la Lengua de Signos Española* (Institute for the Linguistic Normalisation of Spanish Sign Language) was created, with the purpose of disseminating and standardising LSE. The same year, in Andalusia a law that regulated the use of sign language was approved (LEY 11/2011[5]).

These laws also regulated the issue of oral communication support for deaf individuals. Schools had to provide available bimodal bilingual educational models to deaf students, who should be able to choose their preferred educational approach, oral or signed communication. However, in practice the interpretation of bimodal bilingual education is extremely fuzzy: some schools might be defined as bimodal bilingual, but use signs minimally (Pérez Martin, Valmaseda Balanzategui, & Morgan, 2014). Bimodal bilingual education found some limitations due to the structure of mainstream classrooms: deaf students, even in bimodal bilingual programs, typically attended regular classrooms with a vast majority of hearing students and only one or two deaf students. This made it difficult to carry out a bilingual program involving teachers and hearing classmates and did not help deaf individuals to have a positive perception of bimodal bilingual education. Cabeza-Pereiro

[3] Ley 27 /2007, de 23 de octubre, por la que se reconocen las lenguas de signos españolas y se regulan las medias a la comunicación oral de las personas sordas, con discapacidad auditiva y sordociegas (BOE, nº 255, de 24 de octubre de 2007).
[4] Ley 17/2010, de 3 de junio, de la lengua de signos catalana (BOE, nº 156, de 28 de junio de 2010).
[5] Ley 11/2011, de 5 de diciembre, por la que se regula el uso de la lengua de signos española y los medios de apoyo a la comunicación oral de las personas sordas, con discapacidad auditiva y con sordoceguera en Andalucía (BOE, nº 312, de 28 de diciembre de 2011).

and Ramallo (2016) carried out a survey on 138 deaf sign-language users about deaf education, among other topics. Participants had more positive opinions of the educational sector than of culture, tourism, healthy system, transports, or access to multimedia information. However, the youngest participants of the survey, aged 18 to 35 —who had attended schools when inclusive education was the more supported option— were the most critical of the educational system. The authors suggested that this might be due to unsuccessful integration of deaf and hearing students in the classroom. Also, as much as 36 % of deaf individuals were unaware of the existence of bilingual schools, and 69% were dissatisfied with the insufficient number of interpreters for deaf students. Bimodal bilingual interpreters, LSE-Oral Spanish, are a key figure for the successful implementation of bilingualism (Rodríguez Ortiz & Mora Roche, 2007). Despite regulations about interpreting, including the 2007 law, and the creation of a professional degree for sign-language interpreters, the deaf community appeared to be dissatisfied with this service.

In addition, bimodal bilingual education is rarely applied in its strictest form. A bimodal bilingual educational setting involves the opportunity to use and develop both languages, oral and signed. The proponents of the use of pure natural languages, oral and signed, argued that bimodal bilingual settings should not include the simultaneous use of signs and oral language, because they might impoverish users' competence in both language modalities (Fernández & Villa, 2017). The guiding principle of this interpretation of bimodal bilingual education is that advanced skills in sign language favour cognitive development and spoken language in deaf children. In reality, various forms of signed communication are usually adopted in bimodal bilingual settings to meet the needs of individual deaf students.

Co-enrollment aimed to overcome these difficulties of applying bimodal bilingual teaching in mainstream schools. From nineties, co-enrollment became an option for deaf students, and schools for special deaf education also opened to hearing students (Pérez Martin et al., 2014). These bilingual educational settings are re not an initiative of the educational authorities. It is more of a bottom-up process, which develops in individual schools, teachers, deaf communities, and families of deaf pupils (Morales-López, 2008) and is therefore expanding at a slower pace.

Four schools in Madrid are a virtuous example of the passage from being special schools for the deaf to bimodal bilingual centres with co-enrollment. In 2014, 24% of all school-age deaf children in Madrid attended these schools and more than half of them (53% of all students) wore CIs (Pérez Martin et al., 2014). In these bilingual schools, one fourth of the students in a classroom are deaf (5-6 deaf students and 15-20 hearing students). The more balanced proportion of deaf and hearing students than in the past makes it possible to practice and instruct all students in the classroom with bilingual teaching. Bilingual input is already used at the nursery and all pupils, deaf and hearing, share the same curriculum. Classrooms have distinct working areas for mathematics, art, LSE, Spanish, etc. In each area, a group of deaf and hearing students are supported in the study of the specific subject, and teaching is adjusted to their individual levels. Four additional practitioners are involved in co-enrollment in Spain: deaf LSE specialists, co-tutors, speech and language therapists, and interpreters (Pérez Martín et al., 2014). Deaf LSE specialists, often qualified teachers or educators, are primarily required to teach LSE to deaf and hearing students, train families and hearing teachers in LSE and visual communication and promote deaf cultural activities among the school staff. Two co-tutors, participating at the classroom activities nearly all the time, are responsible for facilitating close collaboration in teaching and planning. Speech and language therapists, in close collaboration with co-tutors, provide children with auditory stimulation to enhance their speech development. Finally, the interpreters, who have an active role in the classroom mainly at the level of secondary education, guarantee that classroom contents are fully conveyed in both languages.

Practitioners in one of the schools —GAUDEM, in Madrid— also point to *project-based teaching (trabajo por proyecto)* as a relevant characteristic of co-enrolment a practiced there (Alonso, Rodríguez, & Echeita, 2009). The purpose of the projects is the inclusion and the individual development areas of weakness, with the aim of acquiring basic knowledge. These projects are built around a network involving the family, other classrooms, and even the entire school or pairs of students, not necessary from the same classroom or equal in age.

Pérez Martín et al. (2014) has evaluated spoken and sign-language linguistic skills, and socio-emotional development in children with CIs, aged 0 to 6 years, enrolled in co-enrollment programs. Children were assessed with chronological- and hearing-age appropriate tasks. They found their performance was equivalent to typically developing children for spoken language, audition, receptive and expressive vocabulary, and receptive grammar. Contrary to hearing children, deaf participants scored higher in expressive than receptive vocabulary, confirming a trend already detected in prior research (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009) and attributed to language teaching strategies that emphasize naming. Although within normative percentile ranges, receptive grammar scores were in the lower ranges and highly variable among participants even in children with CIs and early bilingual skills, thus confirming its status as one of the most challenging linguistic area for deaf children (Inscoe, Odell, Archbold, & Nikolopoulos, 2009). The evaluation of LSE skills indicated that these children had good developmental trajectories in both comprehension and production, although they had mainly received LSE input from the school. Children also had good socio-emotional skills. In their conclusions, Pérez et al. noted the great variability in children's outcomes, and urged careful observation of pupils' progress early on to target interventions appropriately before chronic delays appear.

Ultimately, the global shift toward inclusive education of deaf students has reintroduced the debate about the role of sign language and signing systems in educational settings. A real integration between hearing students and deaf students requires shared communication. Signing systems that use simultaneously acoustic and visual linguistic inputs are accessible to both hearing and deaf students. The next section recounts the distinct paradigms that came in succession in deaf education, focusing on the alternating relevance awarded to signing systems and visual components of language across decades. The role of visual linguistic inputs, provided by signing systems, is illustrated in depth, addressing how it might be effective in supporting spoken language acquisition even in children wearing CIs and, therefore, with restored audition.

1.2 Visual Components of Language

Visual components of language play a fundamental role in communication in deaf individuals. Even in the cases of children with CIs, visual components are still important. Visual aspects are not only essential in sign languages, but also in spoken language communication. In speech perception, deaf individuals strongly rely on speechreading, which allows them to infer or integrate the content of speech by observing lip and facial movements. However, even individuals with excellent speechreading skills find it difficult to extract sufficient meaningful information from speechreading; the main reason being that the tongue, a major articulator in speech, is often only partially visible, and many phonemes are similarly articulated and not easily discernible (Kelly & Barac-Cikoja, 2007). On average, speechreading conveys only 10-30% of words (Bernstein, Demorest, & Tucker, 2000), and 40-60% of phonemes in words (Montgomery & Jackson, 1983) and 30% in non-words (Rees, Fitzpatrick, Foulkes, Peterson, & Newton, 2017).

Over the years, the visual component in communication has been increasingly recognised in the educational and clinical contexts. To support the visual information provided by speechreading, well-structured signing systems with specific visual-manual actions can be used concurrently with speech. In addition to standardised signing systems, sometimes more spontaneous communication strategies can be adopted. In these cases, communication relies on all devices available, both visual and non-visual: listening, speechreading, formal signs, natural gestures, tactile cues, fingerspelling, and body language. In spite of broad recognition of the need for visual input, approaches to the education of the deaf have fluctuated on a continuum between a more deregulated adoption of visual devices —using what became known as a Total Communication (TC) approach—, to complete opposition to the use of any visual device in favour of pure auditory stimulation, in strictly Oral Communication (OC) settings.

1.2.1 Whatever works: The total communication philosophy and the signing systems.

TC is a philosophical approach in deaf education that contemplates the use of any visual and spoken device to achieve the goal of successful communication (Schlesinger, 1986; Scouten, 1984). According to Mayer (2016), it advocates inclusion of signed and spoken language free of any normative guideline, where speech only, signs only, or speech and signs concurrently can be used, depending on the communication needs of the user. Consequently, the implementation of TC can vary hugely from one child to another (Williams & Mayer, 2015). Depending on the gradient of signs used to convey spoken information —whether signs are meant to convey morphological or phonological information or whether they only reinforce semantic meanings— different forms of signing systems have been conceived. The signing systems that intend to inform deaf students about morphological components of spoken language together with semantic meanings, represent every single word of spoken language with signs. Besides genuine signs from the indigenous sign language, these systems deliberately use invented signs, affixes, or sign markers to render the spoken language morphology. The most popular signing systems in North America–defined by Maxwell (1990) as Manually Coded English –are Seeing Essential English (Anthony, 1971), Signing Exact English (Gustason, Pfetzing, & Zawolkow, 1980), the Linguistics of Visual English (Wampler, 1971) and Signed English (Bornstein, Hamilton, Saulnier, & Howard, 1975). These systems, invented to teach English to deaf children in the United States, were adapted for deaf students of other countries depending on the characteristics of local spoken languages. In Spain, this system is known as Español Signado.

Cued Speech is another artificial signing system, which uses artificial manual cues to convey information about syllables and phonemes of spoken language. Cued Speech conveys phonological information otherwise ambiguously transmitted by speech only (Cornett, 1967). It is a synergistically combination of manual cues, auditory information and lipreading. Cued Speech manual parameters specify information about consonants through handshapes, and about vowels though distinct hand placements near the mouth. Cued Speech was first conceived by Cornell, has been adapted to 65 languages (Leybaert, Bayard, Colin, & LaSasso, 2016), and is still currently used for speech training of children wearing CIs. The Spanish adaptation was realised by CIs perform best when deaf children also have lipreading skills (Lachs, Pisoni, & Kirk, 2001). Since Cued Speech eliminates the ambiguity inherent to lipreading (Leybaert & LaSasso, 2010), the combination of Cued Speech and CIs is a powerful tool that enhances speech perception; this combination has positive effects in at least in three languages, French, English and Spanish (Leybaert et.al., 2016). Cued Speech will continue to be a useful visual tool to discriminate phonological units of speech until CIs are fully efficient, in fluctuating background noise, and in providing useful information about the point of articulation to disambiguate minimal word pairs (Leybaert et al., 2016).

These signing systems, Signed English and Cued Speech resort to artificial ad-hoc manual cues to convey morphological and phonological information of spoken language with no correspondence in sign languages. Other forms of bimodal communication, using only genuine signs of sign language, prescribe a more flexible and simultaneous use of spoken and sign language. These forms of bimodal communication are mainly referred to as Sign-Supported Speech (SSS) in the European literature and Simultaneous Communication (SimCom or SC) in American literature, but also with a variety of other terms, such as Key Signs system, Conceptually Accurate Signed English, or Sign-Supported English. In Spanish language, SSS is known as Comunicación Bimodal. The umbrella term used to describe these forms of bimodal communication is Contact Signing (Lucas & Valli, 1992) or forms of pidgins (Knoors & Marschark, 2014), depending whether their morphological and syntactic system are more (Contact Signing) or less (pidgins) elaborated. All these terms refer to a practical communicative technique, used in the education of deaf students, which is not a natural sign language, such as American or Spanish Sign language, nor a formalised signing system, such as Signing Exact English or Signed English. Rather, SSS is referred to as some form of spoken language on the hands (Mayer, 2016). It integrates semantic information of speech through signed lexicon, without changing the order of spoken language. The signed lexicon accompanying speech is borrowed from the corresponding sign language, sign markers are used minimally, and not every single spoken word is necessarily signed, although speech and signs are simultaneously produced as much as possible (Mayer, 2016). An example of sentence in SSS can be found in Experiment 1, Figure 1.

1.2.2 The alternating fortunes of the total communication approach and sign-supported speech in education.

During its more than 40-year history, TC had a fluctuating popularity in the education of deaf students. Its practice survived over the years despite the new opportunities of auditory access offered by universal newborn hearing screening programs, and advances in hearing technologies (such as the last generation of digital hearing aids and mono- or bilateral cochlear implantation) (Mayer, 2016). During the Seventies and the Eighties, TC was a common approach in deaf education in the United States (Mayer, 2016). At that time, access to auditory input was unthinkable for most deaf learners. Natural sign languages were not used in the education before adolescence, due to the misconception that the use of sign language delayed or impeded the development of spoken language (Spencer, 2016). In North America, sign languages were about to be recognised as languages of deaf communities, thanks partly to the pioneering linguistic account provided by Stokoe (1960). In other countries, they were still far from being accepted. In Spain, sign language was officially recognised much later, in the late 2000s (Ley 27/2007). Due to the lack of knowledge and misconceptions about natural sign languages, in their place various forms of SSS and signing systems were adopted in educational settings to enhance the access to oral language.

In the late Eighties-beginning of the Nineties, an increased discontent with the outcomes of SSS and signing-system programs led to question their efficacy in supporting the development of oral language (Johnson, Liddell, & Erting, 1989). Starting in 1969, data on the Stanford Achievement Test (Stanford) for deaf and hard-of-hearing children was regularly collected. The comparison between more recent and older academic achievements reports –collected across three decades, from 1974 to 2003–of deaf and hard-of-hearing children in the United States did not show significant improvements before and after the adoption of TC and SSS methods: SSS did not increase language or literacy skills (Traxler, 2000; for a review, see Qi & Mitchell, 2012). The various signing systems (Signing Exact English, Signed English, etc.) produced some slow improvements in the acquisition of some syntactic structures of spoken language (Schick & Moeller, 1992), but did not bring the hoped-for support in enhancing spoken language. Deaf or hard-of-hearing children barely achieved the same spoken language development as their hearing peers (Spencer & Marschark, 2010). Deaf students often had Stanford test scores below their age or grade level (Qi & Mitchell, 2012).

The disappointing outcomes of SSS and other signing systems in educational settings, together with new interest in natural sign languages, resulted in increased popularity of programs adopting natural sign language (Israelite, Ewoldt, & Hoffmeister, 1992). A main problem of SSS communication was that it was inaccurately used. Accompanying signs only rarely replicated the syntactic structures of spoken language; thus, deaf children were not exposed to the actual spoken language through signing, nor, in general, to a real language (Cokely, 1990; Johnson et al., 1989; Marmor & Petitto, 1979; Spencer, 2016). In the Nineties, this problem was often remedied by adopting natural sign languages in deaf education programs, first in Sweden, followed by United Kingdom and United States (Spencer, 2016). The advantage of developing a natural language, no matter which, spoken or sign language, is the opportunity to access to the complex devices of a real language. The linguistic skills acquired in a first language, signed or spoken, can then be transferred for learning a second language. Despite these benefits recognised to sign languages, they often had a secondary role with respect to oral language and did not serve to promote direct interaction between hearing and deaf students. In regular schools, there were only one or two deaf students per classroom, individually assisted by sign-language interpreters and itinerant signing teachers (Russel, 2010). This contrasted with the view held by schools implementing sign bilingualism, as originally conceived in special schools for the deaf in Europe and United Stated in the Seventies-Eighties. They looked at sign language as a fundamental skill for the acquisition of literacy, to be shared by all students and teachers (Hoffmeister, 2000), and a cornerstone of the linguistic and cultural heritage of deaf communities (Padden & Humphries, 1990). From the Nineties and over the 2000s, bilingual education slowly spread across various countries. Deaf education became more inclusive, with the expansion of co-enrolment teaching experiences described above.

While the importance of sign languages in deaf education was growing, extraordinary advances in hearing technology and early intervention renewed the discussion about which educational setting provided deaf children “with the best possible opportunities for educational and personal success” (Knoors & Marschark, 2012, p.2). The average age of hearing loss identification has decreased to 2 months in the United Kingdom and to 3 months in the United States. Since the beginning of the 2000s, cochlear implantation was already available in children 18 months old or even younger and, by the mid-Nineties, individually programmed digital hearing aids were available in industrialised countries. Therefore, despite the recognition of the relevance of natural sign language in education of deaf children, many parents of children with CIs preferred to enrol their children in educational programs exclusively based on OC.

Between the Nineties and 2000s, additional research has fed into the debate between proponents of OC for children using CI, and advocates of bilingual or TC settings. It has been suggested that SSS has the important function of supporting spoken language in children with CIs with bilingual bimodal skills thanks to the redundant multichannel message that it provides (Knoors & Marschark, 2012). For example, lexemes unfamiliar in one linguistic modality can be known in the other. However, research data are inconsistent in supporting this idea. On one hand, compared to children with CIs in TC programs, those enrolled in OC programs have better speech perception (Archbold et al., 2000; Geers, Brenner, & Davidson, 2003), production (Geers, 2004; Geers, Nicholas, & Sedey, 2003; Tobey et al., 2000; Uchanski & Geers, 2003), and overall language (Geers et al., 2003; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2000; Svirsky, Robbins, Kirk, Pisoni, & Richard, 2000). However, these improvements in speech were usually only marginal (Archbold et al., 2000; Geers et al., 2003; Svirsky et al., 2000). On the other hand, studies have found significant advantages in vocabulary acquisition for early-implanted children in TC settings compared to those attending OC programs (Connor, Hieber, Arts, & Zwolan, 2000; Yoshinaga-Itano, 2006), which emphasizes early language stimulation (Connor et al., 2000). SSS might have a significant role in the promotion of early communicative exchanges, supporting deaf children's socio-emotional growth (Yiu & Tang, 2014). SSS receptive skills positively predicted learning in one study (Convertino, Marschark, Sapere, Sarchet, & Zupan, 2009), but in others communicative modes did not impact learning (Robbins, Bollard, & Green, 1999), with deaf students learning in the classroom as much from SSS as from other forms of communication (Cokely, 1990; Marschark, Sapere, Convertino, Seewagen, & Maltzen, 2004). A recent systematic review of studies with children with CIs published between 1999 and 2013 analysed which communicative mode better predicted successful linguistic outcomes. The authors concluded that very limited evidence exists to determine whether the simultaneous use of signs and spoken words is more effective than spoken language alone to foster oral language (Fitzpatrick et al., 2016).

Differences in the outcomes from different studies testing the effectiveness of educational approaches can be due to a range of factors. A limited number of participants or comorbid disturbances not diagnosed that might affect participants performance are some. More common complications concern the lack of standardised tests for assessing sign language competence (Mann

& Haug, 2016; Spencer, 2016), and inconsistency in the implementation of TC programs (Mayer, 2016), due to the lack of standardisation in the signs used in SSS (Caccamise, Ayers, Finch, & Mitchell, 1997; Mayer, 2016). Deaf learners often found the forms of SSS used by the teachers confusing (Johnson et al., 1989). In turn, they found SSS hard (Bernstein, Maxwell, & Matthews, 1985), because of the limited training in sign language, especially when TC programs were first implemented (Power, 2009). Knoors and Marschark (2012) highlighted the importance of intensive training in SSS of parents and practitioners involved in the education of deaf children; they must acquire the ability to continue to speak fluently and express semantic content with conceptually appropriate signs.

More importantly, most of this research assessed children's language skills either in TC/SSS settings or in OC settings, but rarely within the same group of participants (Giezen, Baker, & Escudero, 2014), and this mostly in case studies (Klatter-Folmer, van Hout, Kolen, & Verhoeven, 2006). The comparison of OC and SSS methods within the same group of individuals with CIs revealed more encouraging and promising results for SSS (Blom & Marschark, 2015; Blom, Marschark, & Machmer, 2016; Giezen et al., 2014; van Berkel-van Hoof, Hermans, Knoors, & Verhoeven, 2016). SSS with students with CIs has been found to impact positively the acquisition of new vocabulary (Giezen et al., 2014) even in learning pseudo words for unfamiliar objects (van Berkel-van Hoof et al., 2016). This was consistent with the Dual Coding Theory (Paivio, 2010; Paivio, Clark, & Lambert, 1988), according to which information processed by dual channel, visual-manual and auditory-oral, creates a stronger connection in memory. SSS had positive results compared to OC also in transmitting information in classroom contexts, when transmitting complex contents (Blom & Marschark, 2015) and during noisy situations (Blom et al., 2016). CIs are undoubtedly very efficient in one-to-one interactions, but less so in noisy contexts like classrooms (Battmer et al., 2010).

Importantly, there is no evidence that sign language or SSS impede spoken language development in children with or without CIs (Spencer & Marschark, 2010). The redundant information provided by signs can sustain spoken information, conveying meaning even when speech is auditory or visually barely perceived. In this perspective, SSS would not be expected to improve linguistic skills, but it should simply be used as a device to integrate and sustain spoken message. In some contexts, children could greatly benefit from using sign language or SSS. First, because before cochlear implantation, in the first months of life, children will need the richest linguistic environment possible to develop fundamental linguistic and cognitive skills; this will necessarily be visual and can be provided by sign language. Second, signed communication will also be important in the first period after implantation, as a bridge of communication. Third, even when children have completed their training in the use of CIs, they will not always able to profitably use the CIs, for example in noisy contexts, or simply when equipment temporarily malfunctions occur or batteries are dead. Finally, SSS will be especially important when the child is very young or when the student is instructed to carry out a very demanding task (Knoors & Marschark, 2012).

There is a substantial agreement in that early identification of hearing loss and early intervention guarantee better outcomes in language and literacy development (Spencer, 2016). Children with early implantation, who are more likely to develop better spoken language than children fitted with CIs at a later age, are usually enrolled in OC programs. Parents of children who barely managed to develop language after cochlear implantation might prefer to enrol their children in TC programs (Archbold et al., 2000). This relationship between the age of implantation and the use of OC clearly emerged in a study by Holt, Svirsky, Neuburger, and Miyamoto (2004), where most children implanted before 12 months of age (88 %), were likely to use OC exclusively, while only 44.3% of children implanted at the 4th year of age did so. However, it has been suggested that all children, with or without CIs, should have an early exposure to signed communication because it can be an additional resource in communication.

After an exhaustive review of deaf children development in distinct educational environments —spoken, sign language or sign-supported speech based—, Lederberg, Schick and Spencer (2013) concluded that the ideal strategy for enhancing language in deaf children would be to monitor children needs at various stages of language development and adapt the most fruitful approach for each specific stage and communicative need. Depending on the learner's needs, signs, in concert with spoken language input, will be used to a greater or less extent, all the way from conveying only some key lexemes to even marking spoken morphology. Children with a full range of options offered by visual and auditory channels benefit from the opportunity to shift across different communicative modalities, especially when implanted at an early stage (Tait, De Raeve, & Nikolopoulos, 2007; Watson et al., 2006).

In conclusion, we could rethink the role of TC in terms of how it helps deaf learners to access information. Functional communication, all the way from initial parent-child exchanges, strongly affects quality of life. For deaf individuals, this can be achieved by using the language modality —spoken language, sign language or sign-supported speech— most appropriate for each specific case (Kushalnagar et al., 2011). Knoors and Marschark (2012) encouraged hearing parents of children with CIs to learn and use sign language on regular basis, especially for supporting spoken language. Children with a richer early linguistic input, signed or oral, are more likely to develop better reading skills (Harris & Beech, 1998; Lichtenstein, 1998), improved social exchanges, and linguistic and academic outcomes, at least during the early years (Calderon & Greenberg, 1997). Deaf parents mostly choose bilingual-education options for their deaf children. In contrast, hearing parents with deaf children need to carefully evaluate the different educational options for their children. For hearing parents, a sign bilingual education implies the additional effort of learning a sign language and the cultural values involved.

1.3 The Specificity of Deaf Profiles

"Deaf children are not simply hearing children who cannot hear": the provocative quotation from Marschark and Knoors (2012, p.112) aims to stress the importance for education of bearing in mind the differences in learning and cognition between deaf and hearing students. Prior research had provided evidence of differences in academic performance. Deaf students lag their hearing peers in different areas (Marschark, Sapere, Convertino, & Pelz, 2008), including visual-spatial processing (Blatto-Vallee, Kelly, Gaustad, Porter, & Fonzi, 2007; Marschark, Morrison, Lukomski, Borgna, & Convertino, 2013). This is contrary to the common belief that deaf individuals are more skilful than hearing persons in visual tasks. Despite the reliance on vision for language, deaf learners are not necessarily visual learners (Marschark et al., 2013). Deaf and hearing students show a different organisation and use of concept knowledge, and different cognitive strategies and experiences that can affect academic outcomes (Marschark, 2003). Identifying the ways in which deaf or hard of hearing students differ from hearing students is an essential step to adjust instructional materials and methods (Knoors & Marschark, 2015; Marschark & Knoors, 2012).

However, deafness refers to a widely heterogeneous population which differs on many dimensions. Some of the more relevant are aetiology, age of onset of hearing loss, and the degree of the loss. A hearing loss can be genetic or acquired and, in the latter case, can have prenatal, perinatal, or postnatal causes. Language development is critically affected by whether the onset of deafness onset is prior to or follows language acquisition (prelingual or postlingual deafness, respectively) as well as the degree (severity) of hearing loss. A commonly used classification of hearing loss severity is provided by the International Bureau for Audiophonology (BIAP Recommendation 02/1, 1996). In a normal or subnormal hearing, the average tone loss is below 20 dB. A mild hearing loss, with an average tone loss between 21 and 40 dB, causes difficulties if the voice perceived is low-pitched or distant from the subject. A moderate hearing loss of 1^{st} degree, from 41 to 55 dB, and 2^{nd} degree, from 56 to 70 dB, allows to perceive speech if the voice is loud. If the hearing loss is severe, of 1^{st} degree, from 71 to 80 dB, and 2^{nd} degree, from 81 to 90 dB, speech is perceived is the voice is loud and close to the ear. If the hearing loss is between 91 to 119 dB, across three degrees of progressive seriousness, it is classified as very severe hearing loss, also known as profound hearing loss (Clark, 1981). Finally, if the average tone loss is over 120 dB, the individual suffers of a total hearing loss, or cophosis.

Based on the combination of these variables, the term deafness is an umbrella-term for a great variety of cases. The variety within deaf population is increased by the technology eventually used to access audition, either hearing aids or CIs, and by the preferred language to communicate, either sign or oral language. Research on language and cognition in deafness mainly focused on individuals severely to profoundly deaf either with CIs or with native knowledge of sign language.

Research on children with CIs, in particular children with early access to audition due to early implantation, before 12 months of age, addresses the issue of the effects of language deprivation even if only for the first months after birth. On the other hand, native deaf signers, who are deaf children born from deaf parents, learning sign language as their native first language, give the possibility to study the impact of deprivation of audition, but not language deprivation, on cognitive and linguistic output.

In the following, research on CI users and native deaf signers will be discussed more in-depth, highlighting the respective role in cognitive and linguistic development of deprivation of audition and native exposure to sign language. In fact, the association between good language skills and higher-level cognitive skills in deaf population (Figueras, Edwards, & Langdon, 2008; Horn, Davis, Pisoni, & Miyamoto, 2005; Kronenberger, Pisoni, Harris, et al., 2013; Kronenberger, Colson, Henning, & Pisoni, 2014) can be explained either referring to the reduced period of auditory deprivation (children with early CIs) or to an early language exposure (native signers).

1.3.1 Children with cochlear implants.

A cochlear implant (CI) is an electronic hearing prosthesis, surgically implanted, which replaces hair cells of the cochlea with electrodes. It is not very beneficial if deafness is caused by problems in other parts of the hearing system, such as the brainstem, midbrain, or cortical areas. CIs are effective only in children with a profound or, occasionally, severe degree of hearing loss. As in many other industrialised countries, in Spain cochlear implantation for deaf children became popular from the beginning of the Nineties (Juárez-Sánchez & Monfort, 2010; Manrique & Huarte, 2002). At that time, a large body of research provided evidence for the improved speech perception and linguistic outcomes of children with CIs, compared to children with analogous hearing loss but using hearing aids (Dawson, Blamey, Dettman, Barker, & Clark, 1995; Tomblin, Spencer, Flock, Tyler, & Gantz, 1999). CIs have been demonstrated to be especially effective when activated at an early age, before two years (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Holt & Svirsky, 2008; Manrique, Cervera-Paz, Huarte, & Molina, 2004; Miyamoto, Houston, Kirk, Perdew, & Svirsky, 2003; Nikolopoulos, Dyar, Archbold, & O'Donoghue, 2004; Tomblin, Barker, Spencer, Zhang, & Gantz, 2005). Nevertheless, it is important to bear in mind that CIs do not restore normal hearing and do not involve rapid adaptation, entailing tuning and continuous adjustment of the perceptual processes. The variability in performance of children with CIs is quite high. Even when cochlear implantation is provided early, children born deaf have necessarily to face the earliest months of life with no sound, thus their auditory experience is not equivalent to that of hearing children. Critically, deprivation of sound at early developmental stages might affect processes that are not directly related to hearing and audition systems. Deficient performance in children, regardless of CI devices, might reflect dysfunction of multiple processing systems associated with deafness and language delay (Leigh, 2008). The duration of deprivation of audition, before cochlear implantation, is also associated to delays in socialisation and daily living skills. However, the motor development does not directly correlate to the period of deprivation of audition, although it can be affected by spoken language skills (Horn et al., 2005).

In the next sections, the brain cross-modal reorganisation, the executive functions and the linguistic outcomes in children with CIs are presented in greater detail.

1.3.1.1 Brain plasticity.

Research on neuroplasticity has consistently reported the impact of sensory deprivation in one modality on the development of the remaining modalities.

Deaf individuals show increased tactile accuracy (Levänen & Hamdorf, 2001) and enhanced visual attention, primarily in the peripherally visual field (Bavelier et al., 2000; Dye & Bavelier, 2013; Proksch & Bavelier, 2002). Studies on brain plasticity indicate that primary sensory areas, which normally would serve to process information from the deprived auditory modality, are involved in cross-modal compensatory adaptation, processing information from the remaining modalities. Thus, auditory areas are active during visual and somatosensory processing in deaf individuals (Auer, Bernstein, Sungkarat, & Singh, 2007; Finney, Fine, & Dobkins, 2001).

Children with CIs offer a unique view from a neurodevelopmental perspective to observe brain and neural reorganisation after a period of auditory deprivation and, consequently language delay (Pisoni et al., 2008). The more effective and extensive cross-modal plasticity is, the less sensory implants —aimed to restore the idle sensory modality— are likely to be successful. Thus, the effectiveness of CIs might be hindered by cross-modal reorganization before implantation, that implies a visual 'takeover' of the auditory modality and could compromise the ability of auditory cortex to process spoken language after the activation of CIs (Kral & Sharma, 2012; Lyness, Woll, Campbell, & Cardin, 2013). Campbell, Macsweeney, and Woll (2014), focusing on profound prelingual deaf children who never received acoustic input before cochlear implantation, argued that the exposure to non-auditory signals before implantation distorts the function of the auditory cortex, negatively impacting on CIs effects and speech outcomes. There are critical periods for the phases of sensory development, and experience can significantly modify human behaviour and related aspects of brain functioning during this sensitive period. Cross-modal reorganisation in deaf children implies a visual takeover of the auditory modality, limiting the benefits from the amplification provided by CIs (Kral & Sharma, 2012). For this reason, sign language exposure in the sensitive period of language acquisition has been considered a risk for the preservation of the potential of the auditory cortex to process auditory input in future after cochlear implantation (Giraud & Lee, 2007). Even forms of visual language associated to spoken language, such as speechreading, if used before cochlear implantation, could have an impact on crossmodal plasticity, and hinder the functioning of the auditory modality in favour of the compensatory changes in the visual modality (Hirano et al., 2000). In some implantation programs, training of the auditory modality is strongly promoted to the expense of visual support, and sign language, speechreading, or cued speech are banned from the language training of deaf children prior to implantation (Chan, Chan, Kwork, & Yu, 2000; Ingvalson & Wong, 2013; Yoshida, Kanda, & Miyamoto, 2008).

1.3.1.2 Executive functions in children with cochlear implants.

Different studies have explored how cognitive functioning in CIs users changes following brain and neural reorganisation (Beer, Kronenberger, & Pisoni, 2011; Hintermair, 2013; Kronenberger, Colson, et al., 2014; Pisoni, Conway, Kronenberger, Henning, & Anaya, 2010). Executive functioning is one of the more interesting areas of research. Speech perception and spoken language comprehension and the development of executive functions could influence each other. Not only do executive functions affect outcomes in language development but also, reversely, linguistic skills predict the development of executive functions. For example, early language and processing speed abilities in two-year-old children have been found to predict later working memory capacity (Marchman & Fernald, 2008).

Deaf children born to hearing parents provide a unique opportunity to explore the relation of executive functioning and early exposure to language, both in spoken and signed modalities. Even children who received CIs at an early age (before 12 months) have a comparatively late exposure to language (Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014; Pisoni et al., 2010). In addition, research programs on executive functioning are necessary to explain individual differences in outcomes after cochlear implantation (Pisoni et al., 2008).

Some studies have measured executive function in deaf children by using the Behavioural Rating Inventory of Executive Functions (BRIEF) questionnaire, developed by Gioia, Isquith, Guy, & Kenworthy (2000). Studies using this questionnaire reported limitations in executive functions in deaf children with and without CIs, as measured by parents and teachers (Beer et al., 2011; Hintermair, 2013; Kronenberger, Colson, et al., 2014; Pisoni et al., 2010). Their results were consistent with those obtained using a variety of other assessment tools, such as the Child Behaviour Checklist, Parenting Stress Index, or the Strengths and Difficulties Questionnaires, among others (Abidin, 1995; Achenbach & Rescorla, 2000; Barker et al., 2009; Dammeyer, 2010; Goodman, 1997).

A large body of research has been produced looking more specifically at short-term and working memory (Cowan, 2005). Studies by Geers and her colleagues of the Central Institute for the Deaf (CID) (Geers, Brenner, & Davidson, 2003; Pisoni & Geers, 2001) with a large group of CI users revealed that children with CIs had an atypical short-term memory capacity, more limited than hearing peers, and that this difference significantly correlated to spoken word recognition, also poorer in CI children. Overall, CI children had shorter digit spans, slower speed of verbal rehearsal, and delays in scanning and retrieving verbal information from short-term memory, compared to hearing peers. Geers and collegues suggested that children with CIs and hearing children had different verbal coding strategies and automatized phonological processing skills.

In recent studies (Kronenberger, Pisoni, Harris, et al., 2013; Kronenberger, Colson, et al., 2014), early implanted CI users with long-term experience with CI stimulation, were compared in working memory capacity, fluency-speed and inhibition-concentration to age-matched hearing children. Despite the above-average nonverbal IQ, CI users performed lower than hearing controls on nearly all measures.

The role of executive functions in long-term CI users has even been tested even in processes that are not directly related to hearing, such as repetition priming, procedural learning, and the encoding and storing of temporal sequences in long-term memory. Deafness appears to have a broad effect on the allocation of attentional resources and processing of sequences and temporal patterns, independently from the input modality (Marschark & Wauters, 2008; Pelz, Marschark, & Convertino, 2008).

Executive functions are also related to higher-order cognitive skills, such as conceptual thinking and concept formation (Castellanos et al., 2015). Deaf participants matched on nonverbal IQ to hearing age-match control participants, have more difficulties in concept formation, specifically when it involves multiple comparisons between visual objects or relational concepts. These difficulties in deaf CI users were predicted by measures of language and executive functions, namely working memory and inhibition-concentration.

1.3.1.3 Linguistic outcomes after cochlear implantation.

The variability in spoken language achievements of CI users is one of the most investigated and unresolved issues in the field of deafness (Pisoni et al., 2010). Apart for those early CI users referred to as “stars” by Pisoni and Cleary (2003), who perform similarly to hearing controls in spoken language tasks only two years after implantation, the majority of implanted children perform below average on language scores, with substantial variability (Pisoni et al., 2008). Spencer (2016) also noticed a great variability in children implanted in the first months after birth. Considering deafness as a disability that involves not only the auditory system, but also a more complex range of integrated cognitive functions, might help to explain these persistent differences. Castellanos, Pisoni, Kronenberger, and Beer (2016) point out that it is impossible to identify, before or during the first years after cochlear implantation, the children who will develop atypical speech, language, and cognitive trajectories. There are no behavioural or electrophysiological measures that could reliably detect symptoms of future poor comprehension and disturbances in cognitive system. Low-functioning deaf children are a very heterogeneous group, and deafness can often occur with several comorbid disturbances which further complicate language processing and make outcome from the use of CIs unpredictable. Introducing sign language after cochlear implantation to the aim of creating a grammatical bulk for the development of information processing skill might be too late and atypical language development might already be manifest.

Despite variable outcomes after implantation, the linguistic skills of CIs users are below-average. This should not obscure the fact that they still outperform children with similar hearing loss but not using CIs (Lyness et al., 2013; Stacey, Fortnum, Barton, & Summerfield, 2006).

An early age of implantation is crucial for obtaining the best performance with CIs, as it is related to better development of spoken language. Improvements of deaf children in language development, vocabulary size, syntactic, and pragmatic skills, are related to early identification of hearing loss and early intervention (Connor et al., 2006; Miyamoto et al., 2003; Tobey et al., 2013). Children who receive the CIs before the age of two have a greater possibility of reaching age-appropriate linguistic milestones at the age of five or six years, than if they are implanted at a later age (Nicholas & Geers, 2007; Svirsky, Teoh, & Neuburger, 2004). Speech production and speech comprehension in children implanted before the age of two is also higher than in children implanted between two and six years of age (Manrique, Cervera-Paz, Huarte, & Molina, 2004). Children implanted before the age of two frequently achieved age-appropriate linguistic proficiency in several measures: 50% of participants were age-appropriate on measures of receptive vocabulary, 58% on expressive vocabulary, 46% on verbal intelligence, 47% on receptive language, and 39% on expressive language (Geers et al., 2009). An even earlier window has been found for vocabulary acquisition (Connor et al., 2000; Kirk et al., 2000), with differences found for implantation ages as low as 12 to 14 months (Colletti, Mandalà, & Colletti, 2012; Leigh, Dettman, Dowell, & Briggs, 2013; Nicholas & Geers, 2013).

Nevertheless, even with early implantation, many children with CI show delays in their language development. The delay varies according to the linguistic domain being considered (Nicholas & Geers, 2013). Although CI users show poor vocabulary compared to age-appropriate levels, (Connor et al., 2000; Fagan, 2015), acquisition of grammar is even more likely to be delayed (Caselli, Rinaldi, Varuzza, Giuliani, & Burdo, 2012; Duchesne, Sutton, & Bergeron, 2009), although in different degrees depending on the language. Inflectional morphology and functional words are more challenging for deaf individuals, with or without CIs.

Numerous recent studies assessed the progress in grammar acquisition in relation to the age of implantation and to the type of implantation (unilateral or bilateral). There is a substantial consensus in identifying a borderline of two years of age for the prediction of different speech and language outcomes in grammar acquisition. Less agreement exists around the limit of 12 months: some studies find positive evidence (Cuda, Murri, Guerzoni, Fabrizi, & Mariani, 2014; Leigh et al., 2013), but others do not (Dunn et al., 2014; Szagun & Stumper, 2012). Even with respect to the type of implantation, the eventual additional benefits for grammatical development due to bilateral implantation are unclear, again with positive (Boons et al., 2012) and negative findings (Caselli et al., 2012; Nicholas & Geers, 2013; Niparko et al., 2010).

Another relevant factor for observing improvements in language acquisition, specifically grammatical knowledge, is the amount of time since the cochlear implantation (Cuda et al., 2014; Nicholas & Geers, 2013; Rinaldi & Caselli, 2014). Some studies have specifically found that vocabulary knowledge is commensurate to the duration of cochlear implant experience (Fagan & Pisoni, 2010), stressing the relevance of auditory experience in spoken word learning. However, these advantages are primarily found in children. Discouraging results indicate that CIs are not a predictor of academic performance in secondary-school students (Harris & Terlektsi, 2011;

Marschark, Shaver, Nagle, & Newman, 2015) or in college students (Convertino et al., 2009). Furthermore, the use of CIs does not increase the chance of incidental learning and the access to word and world knowledge, as emerged by the comparison of college students with and without CIs (Convertino, Borgna, Marschark, & Durkin, 2014). It should be highlighted that these outcomes might relate to the age of implantation of participants, relatively late by current standards, with a mean age of 8 years.

1.3.2 Native sign language users.

Native sign language users (deaf children born in deaf family) are a vast minority, representing only 5% of the total of the deaf population. Deaf children born in deaf families are usually exposed to a natural sign language from birth. Sign language spontaneously develops within a community of deaf individuals and is transmitted across generations. Its phonology, morphology and syntax, evolves naturally within this community, develops increasingly richer structures and becomes as complex as spoken languages.

Like hearing infants, if exposed to a natural sign language from birth within their deaf families, deaf babies are reported to babble with their hands and are likely to become proficient users of their native sign language. Contrarily, deaf children raised by hearing parents will barely achieve the same proficiency in sign language as native signers (Pinker, 1994).

In the absence of confounding factors, such as comorbidity associated with deafness, native deaf signers provide a natural experiment with which to explore brain plasticity and to test the hypothesis according to which the lack of auditory stimulation in deaf individuals is compensated with the remaining modalities (Bavelier, Dye, & Hauser, 2006).

1.3.2.1 Brain plasticity.

Congenitally deaf native signers are an interesting population for studying neural plasticity. This is because changes in the brain neuroanatomy can be connected to both cognitive factors —related to the learning of a signed language, for example—, and factors related to sensory deprivation. Cognitive factor and sensory deprivation would affect distinct substrates anatomically and functionally. Sign language learning causes plastic changes in the left superior temporal cortex, while auditory deprivation causes plastic effects in the right superior temporal cortex, as emerged by comparing profound deaf native signers to orally educated profound deaf non-signers (Cardin et al., 2013). Functional neuroimaging studies provide evidence for an additional activation of the left parietal lobe during sign language processing that it is not detected in spoken language processing (Emmorey, Mehta, & Grabowski, 2007; MacSweeney, Capek, Campbell, & Woll, 2008). This difference is reported for signers, both deaf and hearing, compared to non-signers, and consequently has been attributed to sign language expertise (Allen, Emmorey, Bruss, & Damasio, 2008).

A recent MRI study, comparing profoundly congenitally and genetically deaf persons with native America Sign Language to hearing individuals, detected a network of brain areas with an enhanced responsiveness to peripheral visual stimuli in deaf individuals. In particular, higher responsiveness to peripheral rather than perifoveal visual stimuli was evident in the Heschl's gyrus regions, were human primary auditory cortex is located, highlighting a functional connection between the primary auditory cortex and the cross-modal compensatory processing (Scott, Karns, Dow, Stevens, & Neville, 2014).

1.3.2.2 Visual cognition in deaf native signers.

With regards to visual cognition in deaf native signers, Bavelier, Dye, and Hauser (2006) pointed out that changes following congenital deafness are highly specific. No differences between deaf and hearing individuals have been found in sensory measures, such as brightness discrimination, visual flicker, aspects of contrast sensitivity, or direction and velocity of motion (Bosworth & Dobkins, 1999, 2002; Brozinsky & Bavelier, 2004; Finney et al., 2001). Deaf native signers have been found to have better visual-spatial skills than hearing individuals in some domains, but not in others. Studies on visual attention, controlling for confounding variables such as language fluency and aetiology of hearing loss, show enhanced visual cognition in deaf native signers with respect to hearing individuals, with faster shifts of visual attention (Rettenbach, Diller, & Sireteanu, 1999) and increased peripheral visual attention (Proksch & Bavelier, 2002). Deaf native signers and hearing controls performed differently especially when visual stimuli, peripheral located or in motion, required attentional selection (Neville & Lawson, 1987a; Neville & Lawson, 1987b). In fact, studies on attentional orienting and executive attention, do not find differences between deaf and hearing participants in the processing of central stimuli. Differences were found when experimental tasks opposed central and peripheral stimuli to each other. In the well-known series of studies by Proksch and Bavelier (2002), using the useful field of view (UFOV) paradigm, deaf and hearing participants were required to identify a shape appearing in the central region, around the locus of fixation. Reactions times revealed that native deaf signers were longer in processing the trials with distractors in the periphery and faster when the distractors appeared in the central region of fixation, contrarily to hearing participants. However, when participants were involved in a peripheral task and were asked to ignore central distractors, hearing individuals were more distracted than deaf individuals. Taken together these findings suggest that the distraction effect does not provide evidence for a deficiency in visual attention in deaf individuals, rather it indicates the emergency of a compensatory mechanism that results in a different distribution of attentional resources across the visual field in deaf and hearing individuals (Bavelier et al., 2006).

1.3.2.3. Executive functioning in deaf native signers.

While native and non-native signers have in common the initial deprivation of audition, they do not have equivalent experiences of early linguistic input. In fact, native signers are exposed from birth to the sign language of their parents and family. Around 50% of deaf children of hearing families who qualify for a CIs effectively undergo implantation, unlike children of deaf parents, who a very rarely implanted (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017b). Exposure to language during the prenatal period and the first months of life, seems to be determinant for the development of child language and cognitive functioning. Native signers are exposed to signs immediately after birth, initially by touch and soon after, also visually (Knoors, 2016).

As consequence, the study of deaf native signers allows us to explore the link between language skills and executive functions, controlling for the amount of auditory deprivation. Differences between deaf children with and without native sign language are understood to be the result of an integrated system that includes the auditory system and the cognitive functions, primarily executive functions.

Research in this area indicates that early exposure to a language has a strong impact on the development of executive functions, and other cognitive and behavioural functions. Deaf native signers performed similarly to hearing children with respect to theory of mind (Courtin, 2000; Schick, de Villiers, de Villiers, & Hoffmeister, 2007), IQ (Braden, 1987) or sustained attention (Dye & Hauser, 2014). In Hall et al. (2017b), deaf native signers were reported to have age-typical executive functions on the BRIEF questionnaire, although with slightly lower scores in working memory and inhibition than a hearing age-equivalent control group.

Within executive functions, working memory has been extensively studied. While deaf children with no native sign language have, on average, shorter working memory spans in different tasks (Pisoni et al. 2008), native signers have a comparable working memory to hearing individuals (Boutla, Supalla, Newport, & Bavelier, 2004), and, even a superior visual-spatial memory than individuals with no sign languages (Hall & Bavelier, 2010). Marshall et al. (2015) found that deaf children who experienced a period of language deprivation scored worse than hearing children, while deaf native-signing children had a memory performance comparable to that of hearing controls.

The differences in working memory tasks could descend from language-based executive functioning (Marschark, Spencer, et al., 2015; Pisoni et al., 2010). Deaf individuals, regardless of their preferred language modality, have been found to perform similarly to hearing individuals in visual-spatial memory tasks which do not allow easy labelling or verbal-sequential coding. Deaf native signers even outperformed hearing peers in visual-spatial memory tasks, such as the Corsi Blocks task (Wilson, Bettger, Niculae, & Klima, 1997) and showed longer backward memory span than hearing controls —who are usually found to have longer forward than backward memory span (Wilson et al., 1997). The comparable forward and backward spans in deaf native signers could be explained through their use of visual spatial coding, such as visual imagery, in sequential memory tasks (Hall & Bavelier, 2010). On the contrary, non-native deaf signers had major difficulties (Alamargot, Lambert, Thebault, & Dansac, 2007; Marschark et al., 2013).

But recent findings suggest that performance on visual-spatial working memory tasks might be more related to the proficiency in a language —spoken or signed—, rather than to the native knowledge of sign language (Marschark, Spencer, et al., 2015). The performance in visual-spatial working memory tasks, comparable in deaf and hearing individuals when not involving linguistic decoding, appears to be independent not only from sign language skills, but also from the hearing status, which is irrelevant whether participants wear CIs (López-Crespo, Daza, & Méndez-López, 2012; Marschark, Sarchet, & Trani, 2016). These results might have important pedagogical implications. In fact, deaf education, especially for native signers, often resorts to the use of visual material and methods, based on the assumption that native signers would be visual learners (Hauser, Lukomski, & Hillman, 2008; Marschark & Hauser, 2012). If visual-spatial working memory is no better in deaf than in hearing students, the advantages of visually oriented teaching methods could be called into question.

1.3.3 Deaf native signers with cochlear implants.

Bimodal bilingual deaf children who are native signers and who underwent cochlear implantation are even fewer than non-implanted deaf native signers. Only recently the attitude toward cochlear implant within deaf communities is becoming more positive (Paludneviciene & Leigh, 2011). Encouraging outcomes of deaf native signers with CIs revealed that these children were able to perform similarly to bimodal bilingual hearing controls with native sign language, in a full range of linguistic measures which include vocabulary, articulation, syntax, general language skills, and phonological awareness (Davidson, Lillo-Martin, & Pichler, 2014). Deaf native signers with CIs achieved higher spoken language scores than those predicted for monolingual CI users (Nicholas & Geers, 2008). A longitudinal study on the verbal acquisition of a deaf child with CIs and with deaf signing parents highlighted the positive impact of early exposure to sign language on the construction of conceptual representations and spoken language, which reached levels of his hearing peers (Rinaldi & Caselli, 2014).

Neuroimaging techniques, together with standardized testing and experimental behavioural research, have been extensively used to explain linguistic outcomes and processing in deaf children, both with CIs and with native sign language. Recently, research on deaf cognition has increasingly also incorporated eye-tracking technology, useful for the observation of visual behaviour in relation to the perception of linguistic inputs.

1.4 Eye tracking

Eye tracking is a state-of-the-art research tool increasingly used in a variety of disciplines. Eye-tracking technology allows direct and continuous measurement of overt visual attention. Eye movements during language perception might provide behavioural data supplementary to reaction time measures.

In the following sections, eye-tracking research in deaf studies will be shortly reviewed to give a general picture of the possibilities offered by this technique and to pinpoint the use that the current research has done of eye movement data. A description of the different measures of eye movements will be outlined. For the current doctoral thesis, eye-movement data were collected with the purpose of obtaining information about where overt attention is driven when a deaf perceiver is attending SSS.

1.4.1 Measures of eye movements.

Eye-movement events can be described in over a hundred of different measures. Eye-tracking measures can be grouped in four main classes: movement measures, position measures, numerosity measures, and latency and distant measures (Holmqvist et al., 2011).

Movement measures, which track eye movements through space, provide information about direction, amplitude, velocity, acceleration, shape, scanpath comparison, areas of interest, and transition. Position measures provide information with respect to where participants are looking (basic position measures), the extent to which gaze data are focused or distributed (position dispersion measures), the similarity in the position of two groups of gaze data (position similarity measures), the duration of the gaze in a determined position (position duration measures), and how pupil dilates looking at a position (position dilation measures). Numerosity measures provide number, proportion or rate of countable eye-movement events, such as saccades, glissades, microsaccades, smooth pursuit, blinks, fixations, dwells, transitions, regressions and some others. Latency and distance measures convey time and space information of an eye-movement event related to another event, respectively. Specifically, latency measures concern time delay, recording the time between the on- or the offset of an eye-movement event to the on- or offset of another event, while distance measures concern the distance from one point to another at the same time.

Two basic eye-tracking events are *saccades* and *fixations*. Saccades and fixations can be calculated directly from the raw data samples, through algorithms based on position, velocity and acceleration data. Saccades are rapid movements of the eyes with velocities as high as 500º per second, during which eyes are less sensitive to visual input (saccadic suppression). Between the saccades, the eyes remain approximately in the same position during fixations, when sensitivity to the visual input is high. Fixations are considered reliable when they are longer than a threshold of 70-80 milliseconds (ms). The duration of a saccade depends on the distance covered, which usually is shorter in reading tasks and longer in scene perception tasks (Abrams, Meyer, & Kornblum, 1989).

Saccades are frequent because of the limitations of the acuity of our visual system. Acuity is very good in the foveal region —the central 2º of vision— and is progressively reduced in the parafoveal region —extending from 2º to 5º from the eye fixation. Acuity is further reduced in the peripheral region, beyond 5º from the fixation point. Depending on its perceptual characteristics, a stimulus in the periphery can require a saccadic movement to be centrally perceived and recognised, or it can be identified through peripheral vision. For example, in reading tasks, a large letter or an object can be peripherally identified (Pollatsek, Rayner, & Collins, 1984), whereas a normal-size word could be more easily discerned by making a saccade and being perceived in the foveal region (Rayner & Morrison, 1981).

1.4.2. Eye-tracking in deaf studies.

Eye-tracking studies with deaf observers have investigated how attention is distributed across the visual field when processing language in reading or in sign-language communication. Eye-tracking data provided further evidence for the observations related to the increased peripheral vision of deaf observers, manly native deaf signers, found in visual attention studies (see paragraph 1.3.2.2).

In reading tasks, skilled deaf readers, diagnosed with a severe to profound hearing loss, with early onset of deafness, had enhanced perceptual span compared to hearing peers, with longer saccades and less regressions back into the text (Bélanger, Slattery, Mayberry, & Keith, 2012).

In sign language communication, a main issue concerns the area that deaf individuals visually attend to when looking at someone signing. In these studies, patterns of gaze fixations of skilled deaf signers with native or nearly native knowledge of sign language are compared to patterns of gaze fixations of late or naïve signers and expert hearing signers. Deaf perceivers have been found to fixate mainly the face area during comprehension of signed communication. This was found both when messages in sign language were produced live by a signer (Emmorey, Thompson, & Colvin, 2009) and when sign language was video-recorded and presented on a screen (Agrafiotis, Canagarajah, Bull, & Dye, 2003; Muir & Richardson, 2005). Differences emerged in the area of the face attended to: it was around the eyes when perceiving sign language produced live by a signer and around the mouth when attending to video-recorded sign language content (Agrafiotis et al., 2003). Furthermore, more frequent fixations towards the mouth were detected in naïve signers, compared to native signers, to pick up additional information conveyed by mouthing (Emmorey et al., 2009). Results of these studies suggest that peripheral vision is adequate to perceive signs and body movements that occur away from the face region of the signer.

Similarly, a study that analysed SSS perception (De Filippo & Lansing, 2006) found that signs were mostly peripherally perceived even when they were fundamental to disambiguate the sentence meaning. Importantly, SSS was presented with no sound, meaning that only the variables of the visual linguistic components, signs and lip movements, were included in this experiment.

Eye movements have also been explored as a marker of deaf students' attention in classroom contexts. The preference for visualising a lecture presented on a video-screen by an instructor in SSS or interpreted in sign language was tested across three groups of students, hearing students, skilled deaf signers and new signers and correlated to learning (Marschark et al., 2005). Two conditions of lectures were compared. In the first condition, the lecture was signed by the instructor himself using SSS (simultaneous speech and signing). In the second condition, the lecture was presented by the same instructor, but spoken only and interpreted by an experienced educational sign language interpreter. When the lecture was also interpreted in sign language, skilled signers' visual gaze was mainly allocated to the interpreter region, but new signers split their visual attention between the instructor and the interpreter, and hearing students kept their visual gaze on the instructors, shifting some attention away from the instructor and towards the interpreter. The two groups of deaf students did not differ in their learning under any condition (Marschark et al., 2005): albeit deaf students came into the classroom with less content knowledge and scored lower on learning assessments, they learned just as much, proportionally, as their hearing peers in both conditions. Interestingly, in these latter studies (De Filippo & Lansing, 2006; Marschark, et al., 2005), eye-movement data were related to comprehension and learning.

Chapter 2

Topic and Goals of this Thesis

The goal of the present thesis was to explore the effectiveness of SSS in increasing language comprehension in deaf students. I specifically focused on the advantages that this communicative mode might also bring to students with CIs, since they are largely trained in oral language. Findings are intended to guide educational approaches in the classroom, with an aim to create an inclusive environment for hearing and deaf students in bimodal bilingual contexts of co-enrollment. Two main aims guided the design of the different experiments:

1) To determine the impact on comprehension of the use of SSS in different groups of individuals with deafness (with CIs and native sign language), with a special focus on the production of inferences necessary for the construction of textual representation.

2) To study if signs of SSS were primarily perceived via peripheral vision, to an increasingly higher extent depending on sign language expertise, similarly to the gaze patterns observed during sign language perception (Emmorey, Thompson, & Colvin, 2009).

Considering previous research, this doctoral project addressed the research problem as follows:

1) First, the possible advantages of the use of a bimodal communication in increasing comprehension were explored in comparison to the use of unimodal languages, oral and signed. The capability of each communicative system in equating comprehension of deaf students to comprehension of hearing students in spoken language was investigated.

2) Secondly, the effectiveness of SSS in transmitting information was compared to effectiveness of spoken language-alone within the same group of deaf students. Most studies, examining the effects of the communicative mode on language skills, adopted a between-subjects design, comparing group of deaf children exposed either to total communication/SSS or to OC (Connor & Zwolan, 2004; Janjua, Woll, & Kyle, 2002; Jiménez, Pino, & Herruzo, 2009; Miyamoto, Kirk, Svirsky, & Sehgal, 1999; Nicholas & Geers, 2003). Critically, a between-subjects design cannot control all variables that might affect the linguistic outcomes. This issue was overcome in this thesis by adopting a within-subject design.

3) Thirdly, the effectiveness of SSS was tested at discourse- and sentence-level. Positive results in comprehension of isolated words transmitted by SSS rather than OC were observed in within-subject studies (Giezen et al., 2014; Giezen, 2011) but there is a lack of research with regards to the impact of SSS on discourse-level comprehension (Giezen et al., 2014). In reading, it has been provided evidence for a major difficulty of deaf comprehenders, compared to hearing comprehenders, in discourse processing and inference generation (Kyle & Cain, 2015; Miller, 2002). This thesis investigated the eventual improvement of discourse comprehension thanks to the use of SSS, focusing on the construction of situation models and production of inferences.

4) Fourthly, the ability of deaf students in generating inferences and, therefore, constructing adequate textual representations, was explored by comparing comprehension of inferential information to comprehension of literal information and by comparing different types of inferences, involving at different extent higher cognitive skills.

5) Fifthly, the use of eye-tracking technology in this thesis aimed to increase existing knowledge related to language processing and to the distribution of overt visual attention while perceiving communication simultaneously transmitted via two channels, speech/lip movements and signs. The focus of visual attention in perceiving a multimodal communication as SSS might reveal a bias for either speech or signs as source of information. Eye-tracking data, recorded for diagnostic purposes, are typically used to detect (overt) attentional patterns of a user with respect to a given stimulus, in off-line assessments. Differently, interactive applications have been conceived to respond to or interact with the user on the basis of the eye movements (Duchowski, 2002). Both kinds of eye-tracking applications, diagnostic and interactive, were implemented in this thesis:
    a. The diagnostic use of eye tracking, that provides objective and quantitative evidence of the observer's overt attentional processes (Duchowsky, 2002), complied with the purpose of exploring where deaf individuals allocated their eye gaze while perceiving SSS.
    b. the interactive use of the eye tracking was implemented in one of the experiments to reveal the actual bias for obtaining information from lip movements or signs. A contingent moving window reduced the useful visual field either to the face area or to the signs, depending on the observer's focus of attention.

The recruitment of participants considered different requirements. Overall, participants were prelingually and severely to profoundly deaf, with knowledge of sign language. The sample included a group of deaf participants, familiar with sign language, who underwent cochlear implantation at a relatively early age, to test the hypothesis that the richer linguistic input provided by SSS was beneficial to their comprehension (Knoors & Marschark, 2012). A control group of deaf participants not wearing CIs was also included to highlight the unique relationship between SSS and lexical processing in individuals with CIs (Giezen et al. 2014). Another group of participants were native sign language users. These participants allowed me to study the use of peripheral vision in perceiving unimodal vs bimodal communication in greater depth.

Participants were adolescents, aged between 12-19 years. The choice of a sample of adolescents allowed me to meet two requirements. First, individuals by the age of 10-11 years have completed the development of event comprehension, succeeding in identifying the superordinate goal that connects different events of a text (Curran, Kintsch, & Hedberg, 1996; van den Broek, Bauer, & Bourg, 2013). Recruiting adolescents as participants thus provided control over developmental aspects in the assessment of comprehension. Secondly, participants with CIs in this age range, were all long-term CI users, and therefore it was possible to observe stable benefits produced by this technology. Moreover, previous studies on SSS effectiveness that have compared it with OC in within-subject tasks, have assessed children with CIs aged between 5 to 6 years (Giezen et al. 2014) and college students, CI users (Blom and colleagues, 2015, 2016). A study involving deaf adolescents would fill a gap in the research related to the possible benefits obtainable by the use of SSS in a growing population of deaf children with early CIs.

These aspects of the research problem have been treated in four experiments, gathered in three studies.

1) Study 1 (Experiment 1) tested the effectiveness of SSS within the same group of deaf adolescents for discourse-level comprehension, by comparing it to unimodal languages, spoken and sign language only. The capacity of these communicative systems to equalise comprehension in deaf participants with that of spoken language in hearing participants

was tested. Stimuli were video-recorded texts that included spatial descriptions, alternately transmitted in spoken language, sign language and sign-supported speech. The capability of participants of constructing a spatial situation model, and the extent to which SSS could increase the construction of the situation model was tested. Eye movements of deaf and hearing participants were tracked and data of dwell times spent looking at the face or body area of the sign model were analysed. Within-group analyses focused on differences in the use of peripheral vision of native and non-native signers.

2) Study 2 (Experiment 2) tested whether the use of SSS increased participants' comprehension and the capability to generate inferences. In reading, young deaf students have been found to struggle not only with generating inferences (Miller, 2002) but also in processing lower-level semantic components, such as word recognition (Kyle & Harris, 2006, 2011). In spoken communication, the use of SSS might facilitate lexical processing, leaving cognitive resources available for higher-level cognitive processing, such as generating inferences. Stimuli were short texts randomly presented in SSS and in spoken language.

3) Study 3 included two experiments (Experiment 3 and 4) that aimed to detect the extent to which attention, albeit covertly, is directed towards signs. Experiment 3 attempted to shift observers' foveal attention in SSS, either lip movements or signs, by magnifying the face area, thus modifying the perceptual accessibility of lip movements, and by constraining the visual field to either the face or the sign with a moving window paradigm by implementing an interactive application of eye tracking. Experiment 4 aimed to further explore the reliance on signs in SSS, by occasionally producing a mismatch between sign and speech. In both experiments stimuli were subject-verb-object sentences.

Part 2
Experimental Research

Chapter 3

Study 1: An Eye-tracking Study on the Perception and Comprehension of Unimodal and Bimodal Linguistic Inputs by Deaf Adolescents

Chapter 4

Study 2: Inferencing in Deaf Adolescents during Sign-Supported Speech Comprehension

Chapter 5

Study 3: The Role of Multiple Articulatory Channels of Sign-Supported Speech Revealed by Visual Processing

Chapter 3

Study 1: An Eye-tracking Study on the Perception and Comprehension of Unimodal and Bimodal Linguistic Inputs by Deaf Adolescents

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Abstract

An eye tracking experiment explored the gaze behaviour of deaf individuals when perceiving language in spoken and sign language only, and in sign-supported speech. Participants were deaf (n = 25) and hearing (n = 25) Spanish adolescents. Deaf students were prelingually profoundly deaf individuals with cochlear implants used by age 5 or earlier, or prelingually profoundly deaf native signers with deaf parents. The effectiveness of sign-supported speech has rarely been tested within the same group of children at discourse-level comprehension. Here, video-recorded texts, including spatial descriptions, were alternately transmitted in spoken language, sign language and sign-supported speech. The capacity of these communicative systems to equalise comprehension in deaf participants with that of spoken language in hearing participants was tested. Within-group analyses of deaf participants tested if the bimodal linguistic input of sign-supported speech favoured discourse comprehension compared to unimodal languages. Deaf participants with cochlear implants achieved equal comprehension to hearing controls in all communicative systems while deaf native signers with no cochlear implants achieved equal comprehension to hearing participants if tested in their native sign language. Comprehension of sign-supported speech was not increased compared to spoken language, even when spatial information was communicated. Eye movements of deaf and hearing participants were tracked and data of dwell times spent looking at the face or body area of the sign model were analysed. Within-group analyses focused on differences between native and non-native signers. Dwell times of hearing participants were equally distributed across upper and lower areas of the face while deaf participants mainly looked at the mouth area; this could enable information to be obtained from mouthings in sign language and from lipreading in sign-supported speech and spoken language. Few fixations were directed towards the signs, although these were more frequent when spatial language was transmitted. Both native and non-native signers looked mainly at the face when perceiving sign language,

although non-native signers looked significantly more at the body than native signers. This distribution of gaze fixations suggested that deaf individuals – particularly native signers – mainly perceived signs through peripheral vision.

Keywords: eye-tracking, deaf students, cochlear implants, native signers, discourse-level comprehension, sign-supported speech, peripheral vision.

Chapter 4

Study 2: Inferencing in Deaf Adolescents during Sign-Supported Speech Comprehension

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Abstract

We tested the capability of deaf adolescents, including a group of users of cochlear implants, to generate inferences during spoken language comprehension, and whether they benefited from the use of sign-supported speech (SSS). Stimuli consisted of twenty-four short video-recorded texts in spoken language and in SSS. Participants responded to literal and inferential multiple-choice questions. In spoken language, cochlear implant users had more difficulty in processing inferential than literal information and found predictive inferences harder than associative inferences. The level of spoken language proficiency was related to inference generation, especially for predictive inferences. Similarly, deaf native signers had more difficulties in generating predictive inferences, although SSS increased their comprehension. Lipreading skills and working memory were positively related to accuracy in SSS. The inclusion of SSS only had a positive impact on the comprehension of native signers. Results suggest that cochlear implant users would benefit from an intervention to enhance verbal skills.

Keywords: spoken language comprehension, sign-supported speech, predictive inferences, associative inferences, native signers, cochlear implant users.

Chapter 5

Study 3: The Role of Multiple Articulatory Channels of Sign-Supported Speech Revealed by Visual Processing

Abstract

Purpose: The use of sign-supported speech (SSS) in the education of deaf students has been recently discussed in relation to its usefulness with deaf children using cochlear implants. To clarify the benefits of SSS for comprehension, two eye-tracking experiments aimed to detect the extent to which attention is directed towards signs.

Method: Participants were 36 deaf adolescents, including cochlear implant users and native deaf signers. Experiment 3 attempted to shift observers' foveal attention to the linguistic source in SSS from which most information is extracted, lip movements or signs, by magnifying the face area, thus modifying lip movements perceptual accessibility (magnified condition), and by constraining the visual field to either the face or the sign through a moving window paradigm (gaze contingent condition). Experiment 4 aimed to explore the reliance on signs in SSS, by occasionally producing a mismatch between sign and speech. Participants were required to concentrate upon the orally transmitted message.

Results: In experiment 3 analyses revealed a greater number of fixations toward the signs and a drop in accuracy in the gaze contingent condition across all participants. Fixations towards signs were also increased in the magnified condition in native signers. In experiment 4, results indicated less accuracy in the mismatching condition across all participants. Participants with cochlear implants looked more at the sign when it was inconsistent with speech.

Conclusions: All participants rely on signs when attending SSS. Hence, when focusing on the face area, they might be monitoring signs through peripheral vision to integrate speech.

Keywords*:* sign-supported speech, eye tracking, cochlear implant users, native deaf signers, peripheral vision.

Part 3

Summary and Discussion of Results

CHAPTER 6

SUMMARY AND DISCUSSION OF RESULTS

Chapter 6

Summary and Discussion of Results

In the final part of the thesis, the main findings of the experiments are summarised, focusing on the implications for cochlear implant users and native signers. Limitations of our research are discussed and possible directions for future investigation in this field are suggested.

This thesis focused on the effectiveness of Sign-Supported Speech (SSS) to increase comprehension for participants with different levels of access to auditory input and of native exposure to sign language. For this purpose, the deaf students who participated in our studies were grouped according to specific characteristics. The group of participants with greater access to auditory input had undergone cochlear implantation before the age of five years and had significantly restored residual hearing (CI group). The group of participants with native expertise in sign language was composed of profoundly deaf students who had developed a rich language background by using sign language with their deaf parents since birth (LSE group). A group (CD) of deaf participants not wearing cochlear implants and not having a native knowledge of sign language served as comparison group.

In addition to the evaluation of SSS comprehension, eye-tracking data of participants were collected during language perception with the aim of exploring individual differences in visual attention in bimodal (SSS) and unimodal (spoken and sign language) languages and communication settings, and possible links between the area visually attended and the amount of information uptake.

Participants were adolescents, aged between 12 and 19 years. This age range allowed the testing of participants who had completed the period of developmental language acquisition. Moreover, all participants who were CI users were long-term users by the time they took part in this study.

5.1 Summary of results

In Experiment 1, comprehension of SSS was compared to comprehension of spoken language only and sign language only. Comprehension of deaf participants in the different modalities was compared to comprehension of spoken language by hearing-age peers. The use of eye tracking aimed to reveal where deaf participants allocated their overt attention when attending to language in different modalities. Although SSS did not negatively affect comprehension, compared to spoken language, the results did not indicate improved comprehension either, both for participants of the CI or the LSE groups. CI users achieved the same comprehension scores as hearing students in spoken language and SSS, while participants in the LSE group scored below hearing-age peers in these two modalities, although they achieved the same level of comprehension when attending to stimuli in their native sign language. These results highlighted the benefits in spoken language comprehension gained by using CIs, while no effects were evidenced for the use of SSS. We had hypothesized that SSS, because of its spatial nature, would especially favour the comprehension of spatial descriptions included in the texts. Contrary to expectations, the use of SSS did not enhance comprehension compared to spoken language when focusing the analysis on spatial information either.

The eye tracking data provided however interesting results. They confirmed previous research in which the face of the sign model was the area primarily attended to by all deaf perceivers — not only native signers—, during sign language perception (Emmorey et al., 2009), while the signs were attended to via peripheral vision. Greater focus on the lower area of the face of the sign model was detected, consistent with other studies in which sign language was transmitted through video recordings (Agrafiotis et al., 2003; Muir & Richardson, 2005). Although all deaf participants mainly looked at the face area during sign language perception, native signers significantly differed from non-native signers in that they looked towards the signs for a shorter overall period. This difference between native and non-native signers was not detected in SSS, during which native signers looked at the hand longer than they did when perceiving sign language. This was attributed to the fact that SSS is an artificial system and cannot be automatized as a natural language, so the use of peripheral vision to perceive signs presented some differences in the two modalities.

Experiment 2 extended the investigation on discourse comprehension by deaf adolescents and the effectiveness of SSS to the comprehension of literal and inferential information, specifically associative and predictive inferences. Cognitive functions, nonverbal IQ and working memory, as well as linguistic variables, lipreading and proficiency in spoken and sign language, were analysed as possible predictors of language comprehension. In previous studies (Cleary, Pisoni, & Geers, 2001; Pisoni et al., 2008; Pisoni & Geers, 2000), cognitive functioning, in particular executive functions, has been used to explain individual differences among deaf children who are non-native signers —and who, inevitably, suffered from an early deprivation of linguistic input— compared to deaf children who are native signers. Consistent with findings related to hearing individuals (Currie & Cain, 2015), participants with CIs processed inferential information less accurately than literal information. Predictive inferences were less accurate than associative inferences in participants from both the CI and the LSE group. Proficiency in spoken language contributed to explain predictive inference generation in CI users. It was suggested that predictive inferences were more challenging as they require a more complete comprehension of the text than associative inferences. In fact, predictive inferences involve the integration of more pieces of information in the text, while for generating associative inferences it might be sufficient to only grasp a key piece of information in the text and connect it to prior world knowledge. The use of SSS did not increase comprehension in CI users, suggesting that these participants were mainly focused on the orally transmitted message. On the contrary, SSS did enhance the performance of native LSE signers, compared to spoken language. Working memory capacity positively affected comprehension of SSS but did not have effects on spoken language. Lipreading played a significant role in comprehension of literal and inferential information across all groups of participants.

In the first two experiments, our main purpose was to evaluate the effectiveness of SSS in increasing discourse comprehension and inferential processing by deaf adolescents. Experiments 3 and 4 were more essentially centred on gathering evidence for the respective contribution of lip movements and signs in transmitting information during SSS perception, and on clarifying whether signs are actually attended to, even if it is peripherally. Eye-tracking data in the previous experiments had revealed a strong preference for looking at the face when attending to discourse in SSS, similarly to what has been found in sign language (Experiment 1). This gaze behaviour might be a consequence of the major perceptual difficulty of discerning lip movements compared to signs, something that would lead one to focus overt attention towards the lip movements, perceiving information from signs via peripheral vision (i). Alternatively, it might be that signs are simply overridden rather than peripherally perceived, and all information is obtained from spoken/lipread words (ii).

In Experiment 3, the visual presentation of SSS on a screen was manipulated and adopted two modes to test these hypotheses. For testing the perceptual hypothesis (i), the lip area was magnified compared to the chest area (*magnified* condition). This way, lip movement perception was facilitated, and overt attention could be more balanced between the face/lip area and chest/signing area. For testing the effective use of peripheral vision in perceiving signs (ii), an interactive gaze-contingent application of the eye tracker that limited the useful field of vision was implemented. The gaze-contingent display only allowed the area of the screen around the participant's locus of fixation to be visible (*gaze-contingent* condition). At any time, participants were able to obtain information from one linguistic channel only, either the face/lip movements area or the chest/signing area. In the magnified condition (i), participants of the LSE group and, more generally, participants with poorer lipreading skills and CI users with lower scores in working memory capacity, looked more frequently towards the signs, compared to what they did in normal visual conditions. On the other hand, the gaze-contingent window (ii) affected gaze behaviour and accuracy of all groups of participants, with an increased number of fixations towards the signing area, lower accuracy, and longer reaction times than in normal visual conditions. These latter results might suggest that deaf participants benefit from the bimodal channel of information and that they resort to signs to integrate, confirm or substitute information from spoken/lipread words. When the sources of information from SSS are not concurrently available, comprehension is hindered. However, these results must be carefully interpreted: they might have been driven by the experimental video presentation of the stimuli, which led participants to visualise the unfamiliar display differently, regardless of the linguistic channel from which they actually get information.

Experiment 4 aimed to clarify whether deaf perceivers really resorted to signs to obtain information, beyond spoken/lipread words. This objective was pursued by designing stimuli where speech and sign information was mismatched, with signs carrying a different meaning from the spoken words. Although they were instructed to pay attention to the orally transmitted message, participants of the CI group allocated overt attention more frequently towards the signs in the mismatch than in the matching condition. There were also slower and less accurate, because they often selected the representation referring to the sign. Native LSE signers had a dramatic drop in accuracy in the mismatching condition, mostly referring to the signs, even if their gaze behaviour and reaction times did not significantly change across conditions. These results might suggest that signs were processed by all participants: longer reaction times and more fixations towards the sign in CI users in the mismatching condition indicate that they processed the inconsistency between speech and signs, and that they occasionally relied on the signs when missing information from spoken/lipread words. When perceiving SSS in normal conditions, CI users might therefore be engaged in the semantic integration of signs and speech. As for native signers, the lack of effects in gaze behaviour and reaction times, despite the decrease in accuracy when processing the mismatching condition, showed that participants obtained information mostly from signs, ignoring spoken words.

5.2 Discussion

5.2.1 Discussion of the findings for cochlear implant users.

Overall, in CI users, discourse comprehension was not significantly improved with SSS compared to the use of spoken language only (Experiment 1), even when it involved the higher-level cognitive processes required by inference generation (Experiment 2). Although these participants, implanted before the age of five, had good-to-proficient skills in sign language and educational experiences with SSS, they did not benefit from the reinforced information provided by the bimodal linguistic channel of SSS. Comprehension by CI users of spoken language and SSS was equivalent to comprehension by hearing peers of spoken language (Experiment 1). It might be the case that there was little room left for improving comprehension using SSS, possibly due to the general difficulty of the task, which involved the construction of spatial situation models. Despite the lack of favourable results for the use of SSS with CI users, eye-tracking data during processing atomic sentences in visual conditions constraining the peripheral vision indicated that these participants allocated attentional resources toward signs (Experiment 3) and, when lexical items were conflicting, they frequently relied on signs, even though instructed to refer to spoken words (Experiment 4). Jointly considered, these findings reveal that CI users do resort to the visual linguistic source offered by signs in SSS. The attention to the signed lexicon found in the experiments using atomic sentences as stimuli, together with the longer reaction times in the comprehension task when the bimodal input of SSS was experimentally disrupted, can be related to the cognitive phenomenon that has been identified as code-blending facilitation (Emmorey et al., 2012), redundant signals effects (Miller, 1986) or the dual coding theory (Paivio, 2010; Paivio et al., 1988). This phenomenon is observed when two stimuli with the same meaning simultaneously presented via bimodal channels involve a semantic integration that leads perceivers to process two stimuli more easily and quickly than they would a single stimulus, because the redundant information is combined and coactivates a response. The coactivation of functionally independent but interconnected multimodal systems would create a stronger connection in memory and the information would be better retained (Paivio, 2010). This effect has been found in hearing-impaired individuals who are used to connecting auditory and visual linguistic stimuli through lipreading or signs, but it has not been detected in normal-hearing individuals or in individuals with specific language impairment (van Berkel-van Hoof et al., 2016). Recent findings related to single-word acquisition, have found that bimodal input provides a support for vocabulary acquisition or comprehension of novel or pseudowords (Giezen, 2011; Giezen et al., 2014; van Berkel-van Hoof et al., 2016).

Why did we not find this advantage at a discourse level (Experiment 1) or in short texts (Experiment 2)? The explanation might be connected to the greater number of variables (grammar knowledge, short-term memory, working memory, or sustained attention) that are involved in discourse comprehension, and the heterogeneity in cognitive and linguistic performance within the students with CIs. Discourse and long-sentence comprehension require mastery of the grammar of a language and SSS does not support this goal. The grammatical skills of CI users are frequently below age-appropriate standards, even when vocabulary size is equated to that of hearing-age peers (Caselli et al., 2012; Duchesne et al., 2009). For this thesis, due to time limitations, participants' grammatical skills were not assessed. Only a few measures of linguistic and cognitive skills were collected and correlated to language comprehension: nonverbal IQ, working memory, spoken receptive vocabulary size, lipreading skills, and proficiency in spoken and sign language comprehension. With respect to the receptive vocabulary measure, no variance among participants, with and without CIs, was found, with only few of them performing above baseline. Due to the lack of variance, in most of the experiments (Experiments 2, 3, and 4), the measure of spoken receptive vocabulary could not be included as a predictor of comprehension. Given the poor performance across all participants, spoken receptive vocabulary represented a substantial common difficulty for this population, and resorting to sign vocabulary would appear to be well-motivated.

Other linguistic skills affected comprehension in CI users. Proficiency in spoken language comprehension was especially relevant in increasing the generation of predictive inferences that, more than other types of inference, require a full understanding of the text and depend on the integration of more pieces of information across the entire text (Experiment 2). Lipreading was also an important predictor of comprehension across all participants, not only CI users, with more proficient lipreaders achieving higher levels of comprehension (Experiments 2 and 4) and poorer lipreaders fixating more on the signs in the magnified condition (Experiment 3).

Along with linguistic skills, CI users were also influenced by working memory: participants with a smaller working memory capacity looked more frequently at signs in the magnified visual condition, as poor lipreaders did (Experiment 3). Furthermore, these participants relied more frequently than their peers with greater working memory on signs, compared to speech, to obtain information when sign and speech mismatched (Experiment 4). It might be that the participants with poorer working memory in this sample recalled items in the visual-manual modality more easily than in the auditory-oral modality.

Despite the effective reinforcement that signs in SSS provided to participants with CIs with poorer linguistic skills and with working memory, the overall amount of information gained by CI users did not improve with SSS. These results are in contrast with some recent findings related to the successful use of SSS with CI users in classroom contexts (Blom & Marschark, 2015; Blom, Marschark, & Machmer, 2016). SSS was found to be more effective than spoken language when materials with greater complexity of content were proposed, but not with materials with simpler content (Blom & Marschark, 2015). Furthermore, SSS increased comprehension in comparison to spoken language in noisy contexts, such as classroom contexts with multi-talker babble, where much auditory information can easily be missed or misheard (Blom, Marschark, & Machmer, 2016). In our studies, testing materials were not differentiated for content complexity and stimuli were presented via video recordings in quiet rooms with good acoustic accessibility to ensure that participants, individually tested, perceived the same stimuli in analogous conditions. However, given the attention that participants devoted to signs, especially participants with poorer linguistic skills and working memory, it is plausible that SSS may make a difference in supporting comprehension in tasks with complex content and topic-specific vocabulary, and in noisy contexts.

5.2.2 Discussion of the findings for native LSE signers.

For native signers, comprehension was expected improve in SSS compared to spoken language only, thanks to the signs. Indeed, native signers had better production of predictive inferences, which entail a more complete comprehension of the overall context compared to other inferential processes (Experiment 2). The relevance of signs for these participants was confirmed by the orientation of visual attention towards them when visual conditions were manipulated (Experiment 3). Moreover, when speech and sign mismatched, native signers showed their reliance on signs, frequently referring to them rather than to spoken /lipread words

(Experiment 4).

However, in Experiment 1, SSS did not impact significantly on comprehension compared to spoken language only. This might be due to the difficulty and to the specificity of the task, which could be more suitably transmitted in sign language, as the text comprehension required the construction of a spatial situation model. While SSS did not make comprehension by native signers equivalent to the comprehension of spoken language by hearing peers, sign language did (Experiment 1). In conclusion, although various results of our thesis indicate that SSS increases the comprehension of native signers compared to spoken language, it is important to stress that SSS is not a natural language and can hardly guarantee the same comprehension that native signers can achieve in their native sign language. Differences in processing SSS and sign language were not only revealed by accuracy scores, but also by the spatial distribution of visual attention in native and non-native signers.

5.2.3 Spatial distribution of visual attention during SSS perception.

The most innovative aspect of this thesis concerns the combination of comprehension and eye-tracking data during language perception in SSS. As in sign language perception, deaf participants mostly fixated on the face area when attending to SSS (Experiment 1). In sign language, there is clear evidence that participants are perceiving signs peripherally. In SSS, however, where a bimodal channel of information is available, it was not clear that participants —particularly those with functional hearing— perceive signs via peripheral vision. It might be that they are just ignoring the signs and obtaining all the information from speech and lipreading. The use of a moving window that limited the useful field of vision to either the face or the signing area (Experiment 3), and the implementation of a paradigm with inconsistent meanings between sign and speech (Experiment 4), provided evidence to support the hypothesis that participants with CIs are also actively attending to the information from signs.

The findings of these experiments also draw attention to differences in visual processing of SSS and sign language, and between native and non-native signers. Deaf native signers, when perceiving sign language, had fewer gaze deviations towards the signs than deaf non-native signers (Experiment 1). This is consistent with earlier findings that attributed this difference to a more developed peripheral vision in native signers (Agrafiotis et al., 2003). On the other hand, no differences were detected between native and non-native signers' gaze behaviour in SSS (Experiment 1). This was attributed to the artificiality of SSS, which cannot be acquired as a natural language. Native signers have not automatized the use of peripheral vision in complex long texts as in sign language perception. However, eye movement data from Experiment 1 referred to long time windows, which tracked the eyes across the entire length of the stimuli, approximately 100 seconds each. However, when reviewing fixations over shorter time windows and texts, differences between native and non-native signers did emerge in SSS: native signers looked less towards signs than non-native signers when attending to the basic sentences presented in the baseline visual condition (Experiment 3) and in the time window of a critical word (Experiment 4). Although fixating on the face area, native signers, who were found to be significantly less expert lipreaders that their peers with CIs, seemed not to pay attention to lip movements, retrieving most information from the peripherally perceived signs. This occurred even when participants were explicitly instructed to retain orally transmitted information (Experiment 4). This account would confirm the division of labour hypothesis proposed in Mitchell (1996), which contemplates a limited-resource model for attentional resources. This hypothesis was well supported by studies investigating how the spatial attention that spills over from visual search tasks is distributed (Dye et al., 2009; Proksch & Bavelier, 2002). While hearing individuals save leftover attentional resources to process information at the fixation point rather than the periphery (Beck & Lavie, 2005), deaf individuals would mostly devote leftover attentional resources to stimuli in the peripheral visual field at the cost of centrally presented information (Proksch & Bavelier, 2002). Apparently, in Experiment 4, attentional resources were mostly dedicated to peripheral information, with native signers largely excluding the information at fixation, without signalling in any way the inconsistency between central and peripheral information, neither through gaze behaviour nor through reaction times.

5.3 Limitations of the Thesis

5.3.1 Sample size.

An important limitation of this study is the small number of participants. After attempting to recruit participants for the study in many ways, such as contacting deaf associations and speech therapy practices, the more favourable approach was found by directly contacting primary and secondary schools attended by deaf adolescents and inviting them to collaborate on the project. Recruitment took place over a substantial number of months. Although a higher number of students participated in Experiments 2, 3, and 4 compared to Experiment 1, the subgroups, (CI, LSE, and CD), included few participants, limiting the statistical power of the analyses. Although only participants with no comorbid disturbances were initially recruited, even some of the remaining individuals were not included in the studies due to their low nonverbal IQ, or because they did not fulfil the criterion for level of deafness.

Due to the limited number of deaf students who met the criterion for inclusion in the study and the difficulties in recruiting them, no students with the required characteristics were tested in the pilot studies. The experiments were piloted with age-equivalent hearing students and with older deaf students, aged between 20 and 28 years.

Given the difficulties in finding participants meeting the requirements for inclusion in the subgroups, it was also not possible to match participants of the compared groups in terms of cognitive and linguistic skills.

Although these limitations impact on the power of the studies, this is a common feature to most prior research in this field.

5.3.2 Range of measures.

Ideally, participants should have been matched across groups on the scores achieved for the different skills and they should have been assessed for a wider range of linguistic and cognitive skills. Receptive grammar and pragmatic skills are probably the most relevant predictors that could have been included. Time limitations and the difficulty in obtaining the consent for testing the students for a considerable number of sessions led us to select the most relevant measures for the purpose of the study.

The level of proficiency in Spanish spoken language and Spanish sign language could have also been tested by using texts of increasing difficulty, instead of only a single elementary-level text. This would have enabled a more comprehensive differentiation of participants' language profiles. Nonetheless, we could guarantee that participants at least had a basic competence in sign and spoken language and that this information could be sufficient for evaluating the effectiveness of comprehension of SSS. In addition, we found that higher performance in SSS was not predicted by higher proficiency in sign language.

Also, besides nonverbal IQ and working memory —evaluated through an n-back task—, other cognitive measures could have been relevant for tracking participants' profile of comprehension. Short-term memory and sustained attention are significantly activated in discourse comprehension and might be critical skills specifically for deaf individuals. Phonological short-term memory in the deaf population has been found to be deficient compared to that of the hearing population, with lexical items retained to a lesser degree if perceived via the visual-spatial channel than via the auditory channel (Bavelier et al., 2006; Koo, Crain, Lasasso, & Eden, 2008). On the other hand, poor understanding of complex sentences has been found to reflect less efficient language processing systems and a more limited attentional system capacity (Montgomery, 2005).

5.3.3 Ecological validity.

The generalization of the results of this thesis should be interpreted with the necessary caution, since they were obtained from experimental tasks designed to answer specific research questions. Comprehension of the bimodal input of SSS, as well as its visual perception, may vary substantially in naturalistic, noisy environments, such as in classroom contexts. The unnatural visual conditions in Experiment 3 might be especially critical for ecological validity. Nevertheless, overall coherence with previous findings in visual perception of deaf individuals indicates the eye-movement supports the validity of our results. Future research in more naturalistic environments would be desirable, evaluating SSS comprehension during lectures in the classroom and obtaining eye-movement data via custom-built wearable eye trackers.

5.4 Educational Implications and Future Directions

SSS has been used for educational purposes for mixed deaf/hearing audiences. Prior studies provided evidence for a positive effect of SSS on learning when correctly used by teachers and instructors (Swanwick, 2016; Knoors & Marschark, 2012). Results from this thesis indicate that SSS might have an overall positive impact when used in a classroom, specifically in the relatively recent educational co-enrolment teaching in Spain, which places a considerable number of deaf students in the same classrooms as hearing peers. The undoubted advantage of SSS over spoken language only is that its use allows deaf students to learn, sharing the same classrooms with their hearing peers, thus improving the effectiveness of the inclusion process, a crucial issue in current educational politicies. Deaf students' world knowledge is commonly poorer than that of hearing-age peers (Convertino et al., 2014). A pervasive use of SSS in the classroom might favour its broader use in peer communication as well and not only during learning, contributing to the enhancement of deaf students' world knowledge.

For deaf children with functional hearing, the bimodal language input offered by SSS does not harm comprehension with respect to spoken language, and it might even allow a better access to the more technical language of specific subjects, which could be more difficult to understand with the spoken lexicon only. In fact, the overt attention directed to signs when peripheral vision is disrupted (Experiment 3) and the evidence of resorting to signs rather than speech when they mismatch (Experiment 4), suggest that CI users are involved in processing both speech and sign information when attending to SSS. Consequently, although a difference did not emerge in comprehension of spoken language and SSS when using high-frequency vocabulary, the semantic reinforcement of signs could plausibly enhance comprehension of less frequent vocabulary.

For deaf children without functional hearing, the input obtained from SSS is visual, through lipreading and mostly through signs. With respect to spoken language, SSS enhanced comprehension of native signers, especially when a full comprehension of the text was required for inferential processing (Experiment 2). Nevertheless, SSS might be less informative than sign language, as emerged in Experiment 1, where native signers had a significantly increased comprehension in sign language compared to spoken language, while differences in comprehension were not significant between SSS and spoken language. However, in teaching, there is also evidence for equal effectiveness of SSS and sign language for deaf students who had sign language as the primary mode of communication (Marschark, Sapere, Convertino, & Pelz, 2008). It is important to stress that, for native signers, sign language is their first language and it is naturally processed. For these participants, the use of SSS is not intended to facilitate comprehension compared to sign language, but to enhance spoken language comprehension.

Future research should test the effectiveness of SSS in the classroom context using longitudinal studies. This thesis has revealed limitations in the linguistic skills of deaf participants with and without cochlear implants. Receptive vocabulary size was worryingly limited in all participants and the relevance of mastering spoken language was evidenced by the significant effect that lipreading skills and spoken language proficiency had in predicting comprehension in CI users across these experiments. Considering the limited linguistic skills and the evidence in favour of the supporting role of signs in the comprehension of lexical items, further research should investigate whether the continuous use of SSS in teaching can also contribute in increasing the spoken vocabulary of deaf students, thanks to the impact on lexical representations of dual presentation of the same item through the visual and the auditory systems.

5.5 Conclusions

The research problem investigated in this thesis concerns the role of the sign-supported speech (SSS), an augmentative system of communication used in the education of deaf students, of great relevance in the context of inclusive education and the recent technological advances in the early detection of hearing loss and hearing devices, such as cochlear implants.

Findings of this thesis highlighted only marginal benefits from the use of SSS. SSS did not increase discourse comprehension nor inference processing, compared to spoken language-only, in participants with CIs. Despite these findings, there was evidence that they did process the information transmitted by signs, in addition to speech.

For native signers, although findings of this thesis indicated that SSS is not as informative as sign language, it can support their spoken communication. This is especially the case when comprehension requires greater cognitive effort, such as when processing inferences.

Overall, the use of SSS could support the inclusion of deaf students, allowing that deaf and hearing students to share the same classrooms. The evidence that even CI users process signs suggests that the semantic redundancy provided by signs in SSS might favour improved comprehension in classes with a more technical or specific language. In conclusion, although

SSS did not significantly contribute at the purpose of increasing language comprehension, it did not harm it and might importantly support the process of inclusion of deaf students.

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