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Implicit Learning and Deafness: from the Assessment to the Design and Implementation of a Serious Game-based Training for Deaf Children with Cochlear Implants

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Di tutto restano tre cose:
la certezza che stiamo sempre iniziando,
la certezza che abbiamo bisogno di continuare,
la certezza che saremo interrotti prima di finire.

Pertanto dobbiamo fare dell’interruzione, un cammino nuovo,
della caduta, un passo di danza,
della paura, una scala,
del sogno, un ponte,
del bisogno, un incontro.

Fernando Pessoa

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ABSTRACT

Experiencing auditory deprivation during early childhood affects adversely children’s ability to process and acquire spoken languages. Deaf and hard-of-hearing children are therefore at risk of language delays. If compared with typically hearing peers, deaf children with cochlear implants are reported having poorer outcomes in spoken language and literacy, and that has been associated with deficient verbal working memory skills (Burkholder & Pisoni, 2003; Geers, 2003; Harris, et al., 2013; Pisoni & Cleary, 2003). Despite the ongoing investigation of the factors influencing speech, language, and literacy, large individual differences in language outcomes that are typically found in deaf children following cochlear implantation (Pisoni et al., 1999), and a considerable amount of this variability remains unexplained (Geers, 2002, 2006). A recent hypothesis suggests that it might be partially explained by deficits in implicit learning processes (Conway et al., 2009). Implicit learning is a domain-general ability to learn patterns of recurrent information without intention to learn, or awareness of the learning process. It was first described by Reber (1989) as an evolutionary precursor to explicit learning that happens incidentally, without intention, and in a manner that is opaque to explanation. It allows the implicit detection and elaboration of distributional statistical regularities that are recurring in inbound information. It plays a crucial role during the early stages of language development (Saffran & Kirkham, 2018; Romberg & Saffran, 2010), and is considered a fundamental mechanism for human development and everyday life (Abrahamse, 2012). According to the “auditory scaffolding hypothesis”, a lack of auditory stimulation at an early age, could affect language development directly due to the poor exposition to spoken language, and indirectly, adversely affecting implicit learning of linguistic regularities and therefore language development (Conway et al., 2009). This hypothesis is controversial and widely debated. In this thesis work, we investigated this hypothesis using two different paradigms: the artificial grammar learning and the simple reaction times. Our studies involved orally educated profoundly deaf children with cochlear implants between the age of 5 and 11 years old. These studies are described in the first part of the thesis. Their aim is

to contribute to the lively discussion about cognitive processes behind language acquisition in deaf children with cochlear implants. Also, based on these findings, we aim to develop a serious-game-based training that could potentially boost the basic cognitive processes that are deficient in this population, hopefully maximizing the language learning potential of hard-of-hearing children and deaf children with cochlear implants. The design, the implementation and the cycles of user experience assessment of “SELEDE” (a SErious game for training sequence LEarning in DEaf children) are described in the second part of the thesis. Proposing a training as a serious game captivates the children’s interest, and contributing to the success of the training. SELEDE was developed in collaboration with Fondazione Bruno Kessler (Trento). It comprises three mini-games in which auditory and visual sequences are used to train implicit and explicit sequence learning processes. The games were implemented using a co-design approach in which psychologists, computer scientists, audiologists, and speech and language therapists were involved. The design process resulted in the development of a game prototype that has been subjected to two cycles of evaluation of the user experience. To the best of our knowledge, this might be the first known attempt for developing a training tool that integrates implicit and explicit learning processes. SELEDE could represent an innovative starting point for new interventions addressed to all those children who are showing difficulties in processing temporally and sequentially distributed pieces of information (e.g. language).

ABSTRACT IN LINGUA ITALIANA

Una deprivazione uditiva precoce, durante la prima infanzia, influisce negativamente sulla capacità dei bambini di elaborare ed acquisire il linguaggio parlato. I bambini con problemi di udito o sordi rischiano quindi di sviluppare in ritardo o in modo deficitario le abilità linguistiche. Se confrontati con i loro coetanei udenti, i bambini sordi con impianto cocleare ottengono risultati peggiori nelle prove di linguaggio orale e scritto, e questo è stato associato ad una minore efficienza della memoria di lavoro verbale (Burkholder & Pisoni, 2003; Geers, 2003; Harris, et al., 2013; Pisoni & Cleary, 2003). Nonostante l'indagine dei fattori che influenzano lo sviluppo delle abilità di linguaggio orale e dell'alfabetizzazione sia in costante evoluzione, gli studi che si occupano di bambini sordi con l'impianto cocleare tipicamente osservano grandi differenze individuali nei risultati ottenuti nelle prove linguistiche (Pisoni et al., 1999), e non sono ancora stati in grado di spiegare una porzione notevole di questa variabilità (Geers, 2002, 2006). Una recente ipotesi suggerisce che questa potrebbe essere parzialmente spiegata da un deficit nei processi di apprendimento implicito (Conway et al., 2009). Per apprendimento implicito si intende la capacità di elaborare ed apprendere modelli di informazione statisticamente ricorrenti, senza volontà di imparare o consapevolezza del processo di apprendimento. L'apprendimento implicito è stato descritto per la prima volta da Reber (1989) come un precursore evolutivo dell'apprendimento esplicito che avviene incidentalmente, senza intenzione, e al di fuori della consapevolezza. Esso permette l'individuazione e l'elaborazione implicita della distribuzione delle regolarità statistiche che ricorrono nelle informazioni in entrata. Svolge un ruolo cruciale nelle prime fasi dello sviluppo del linguaggio (Saffran & Kirkham, 2018; Romberg & Saffran, 2010), ed è considerato un meccanismo fondamentale per lo sviluppo umano e per l'adattamento alla vita quotidiana (Abrahamse, 2012). Secondo la "auditory scaffolding hypothesis", la mancanza di stimolazione uditiva in età precoce potrebbe influenzare lo sviluppo linguistico sia in modo diretto, a causa della scarsa esposizione alla lingua parlata, sia indirettamente, influenzando negativamente l'apprendimento implicito delle regolarità linguistiche e quindi lo sviluppo del linguaggio (Conway et al., 2009). Questa ipotesi controversa è stata recentemente ampiamente

dibattuta. In questo lavoro di tesi, abbiamo indagato questa ipotesi utilizzando due diversi paradigmi sperimentali di valutazione delle abilità di apprendimento implicito: un compito di apprendimento di grammatiche artificiali e un compito basato sui tempi di reazione semplici. I nostri studi, descritti nella prima parte della tesi, hanno coinvolto bambini sordi profondi con impianto/i cocleare/i tra i 5 e gli 11 anni di età, con l'obiettivo di contribuire alla vivace discussione sui processi cognitivi alla base dell'acquisizione del linguaggio nei bambini sordi con impianto cocleare. Le conoscenze ottenute grazie a questi studi servono un secondo obiettivo, di tipo applicativo. Ossia, la creazione di un serious game che possa servire come training per esercitare i processi cognitivi di apprendimento carenti in questa popolazione, massimizzando, si spera, il potenziale di apprendimento linguistico dei bambini con problemi di udito e sordi con impianto cocleare. I processi di design, implementazione, ed i cicli di valutazione della user experience di "SELEDE" (a SErious game for training sequence LEarning in DEaf children) sono descritti nella seconda parte della tesi. Proporre un training sotto forma di videogioco può contribuire a catturare l'interesse dei bambini e ad accrescere le possibilità di successo. SELEDE è stato sviluppato in collaborazione con la Fondazione Bruno Kessler (Trento). Si compone di tre mini-giochi in cui sequenze uditive e visive sono utilizzate per allenare i processi di apprendimento di sequenze impliciti ed espliciti. I giochi sono stati realizzati seguendo un approccio di co-design nel quale sono stati coinvolti psicologi, tecnici informatici, medici audiologi, e logopedisti. Il processo di progettazione ha portato allo sviluppo di un prototipo di gioco che è stato sottoposto a due cicli di valutazione della user experience. Questo potrebbe essere il primo tentativo presente in letteratura di sviluppare uno strumento di training che integri entrambi i processi di apprendimento: impliciti ed espliciti. SELEDE potrebbe rappresentare un punto di partenza innovativo per interventi innovativi rivolti a tutti quei bambini che mostrano difficoltà nell'elaborazione di informazioni distribuite in sequenze temporali (es. linguaggio).

THESIS AIMS AND OUTLINE

The aim of this PhD work is twofold: theoretical and applicative. The thesis consists of two parts. **Part I** is dedicated to the theoretical framing of this work and to the discussion of the experimental studies that we ran in order to gain evidence supporting the applicative part, that is described in the second section of this volume. **Chapter 1** introduces the theoretical frame of our research, the auditory scaffolding hypothesis (Conway, et al., 2009) and the thesis aims. Firstly, this thesis is aimed to contribute to the discussion about the cognitive processes behind language acquisition in deaf children with cochlear implants. This serves the second, more practical aim of this work, that is to develop an innovative training designed to suit the needs of those children who are struggling with sequence learning, like deaf children. Subsequently, the collection of our studies is presented. They consist of three studies involving orally educated profoundly deaf children with cochlear implants between the age of 5 and 11 years old and are based on two paradigms commonly used to investigate implicit sequence learning. **Chapter 2** describes the first two studies, in which we investigated the influence of age and sensory (auditory) experience on implicit sequence learning this skill using an artificial grammar learning task, used in prior studies with deaf children with cochlear implants and hearing children. This investigation is necessary because it lays the foundations of the rehabilitation practice. In fact, given the importance of implicit learning of sequences on language and literacy development, if it is true that this process can be conditioned by experience and targeted through innovative training and therapies, it is also possible to expect some benefits for the development of the related skills (Deocampo, Smith, Kronenberger, Pisoni, & Conway, 2018; Giustolisi & Emmorey, 2018). **Chapter 3** describes our third study, in which we investigated implicit sequence learning in deaf children with cochlear implants using an experimental simple reaction times task designed to limit the interference of the explicit processes of working memory. The aim of this study was to provide complementary evidence regarding the relation between auditory deprivation and implicit learning of regularities avoiding confounding explicit factors in the assessment of the ability to implicitly process and integrate different levels of information. The acquired knowledge resulting from all these studies was a great source of information for the development of a sequence learning training on solid foundations. Overall, the results of our studies do not support the auditory scaffolding hypothesis, showing that deaf children with cochlear implants may not have a deficit in implicit learning. However, our results also suggest that implicit and explicit learning processes are developmentally related. Given the importance of implicit sequence learning ability for many aspects of linguistic development and its interaction with explicit learning processes, both these aspects must be taken into account during the rehabilitation practice. For this reason, a serious game-based training aiming to improve both implicit and explicit sequence learning processes is proposed. This is described in **Part II**, which includes: **Chapter 4** that describes the development of the training, and **Chapter 5** that is dedicated to the user experience assessment (both made in collaboration with Fondazione Bruno Kessler, Trento). The training is based on serious games aimed to boost the basic cognitive processes related to sequence learning that are deficient in the deaf and hard-of-hearing population, hopefully maximizing the language learning potential of these children. To the best of our knowledge, this might be the first known attempt for an integrated training of implicit and explicit learning skills and could represent an innovative starting point for new interventions addressed to all those children who are showing difficulties in processing temporally and sequentially distributed pieces of information (e.g. language).

PART I

CHAPTER I

INTRODUCTION

This first chapter describes the general characteristics of the clinical population of interest in our studies and gives the theoretical framework of this thesis work.

1.1 DEAFNESS

Over 5% of the World population (around 466 million people) has disabling hearing loss, and 34 million of these are children (World Health Organization, WHO, 2018). Hearing loss usually refers to reduced ability to hear sounds in the same way as normal hearing people, while deafness occurs when a person cannot understand speech through hearing, even when voice is raised, or sound is amplified with a hearing aid.

Although the epidemiology of hearing impairment is an essential component to service planning and research, there is still a lot to discover about the factors associated with hearing loss. The causes of hearing loss and deafness can be congenital or acquired. Congenital causes may lead to hearing loss being present at or acquired soon after birth. In this case, hearing loss can be due to genetic factors or to complications during pregnancy and childbirth, including: maternal infections (e.g. maternal rubella, syphilis) or inappropriate use of drugs (e.g. aminoglycosides, cytotoxic drugs, antimalarial drugs, diuretics) during pregnancy, low birth weight, birth asphyxia (lack of oxygen during birth), and severe jaundice which can damage the hearing nerve in new-borns. Acquired causes may lead to deteriorated hearing over time and can occur at any age. The main acquired causes include: infectious diseases (e.g. meningitis, measles, and mumps), chronic ear infections, collection of fluid in the ear (otitis media), use of certain medicines (e.g. for treatment of neonatal infections, malaria, drug-resistant tuberculosis, and cancer), traumas (e.g. injury to the head or ear, excessive noise or long exposure to loud sounds), degeneration of sensory cells due to ageing, and wax or foreign bodies blocking the ear canal.

Hearing loss has multiple impacts on individuals’ life. Spoken language development is often delayed in children with unaddressed hearing loss, and this can not only affect their ability to communicate with others but also adversely impact their academic performance (Arfé, Ghiselli, & Montino, 2016; Harris & Terlektsi, 2010; Marschark, Rhoten, & Fabich, 2007; Niparko, Tobey, Thal, et al., 2010; Sarant, Harris, & Bennet, 2015). Children with hearing loss can find it harder to concentrate when they go to school and are at risk for concentration fatigue, meaning that they use more of their cognitive resources in listening, lipreading or following signed conversations and have less energy for learning. They often have increased rates of grade failure and a greater need for education assistance in order to receive an optimal learning experience. Unfortunately, this assistance is not always available. Social activities may also be more challenging for these children than it is for children with no hearing problems. Limited communication can, in turn, affect socio-emotional life, causing feelings of loneliness, isolation, and frustration.

Hearing loss has also a great economic impact on the community. The global annual cost of unaddressed hearing loss is estimated by the WHO is US$ 750 billion, that includes health sector costs (excluding the cost of hearing devices), costs of educational support, loss of productivity, and societal costs (World Health Organization, 2018). In developing countries, children with hearing loss and deafness can rarely access to education, while adults have a high unemployment rate. Among those who are employed, a higher percentage of people with hearing loss are in the lower grades of employment compared with the general workforce (Nordqvist & Biggers, 2018).

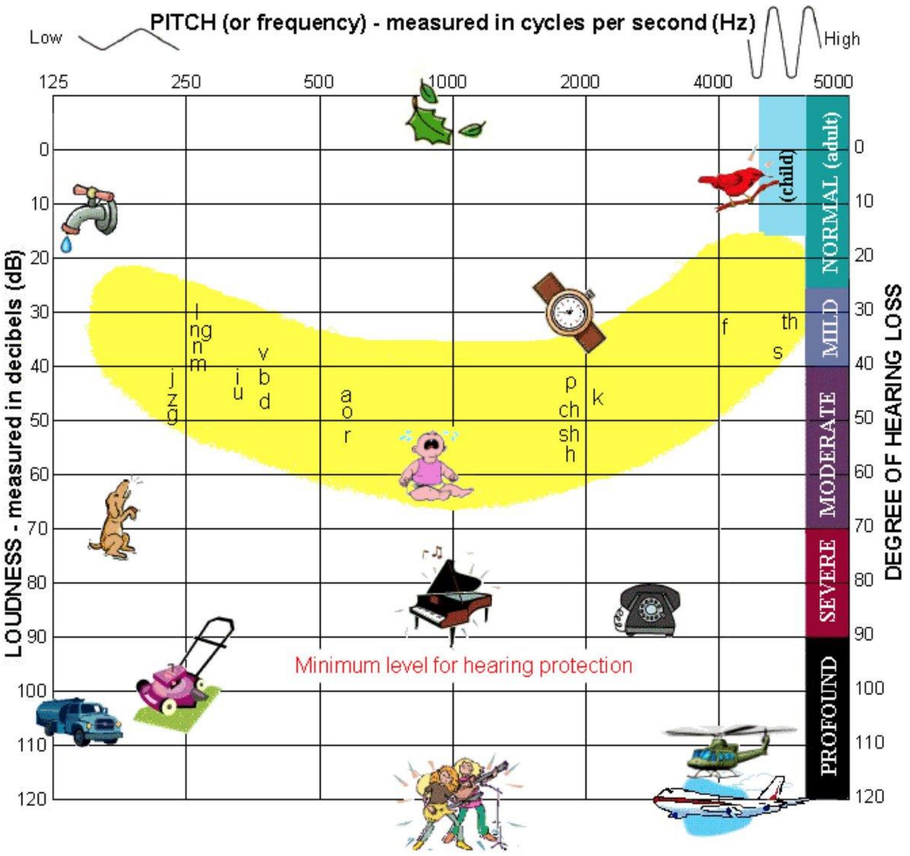
Depending on its onset and grade, hearing loss can affect speech ability differently, contributing to the great variability of the linguistic outcomes typically observed in this population. Onset is defined as “pre-lingual” when it occurs very early in life, before learning how to speak or fully understand spoken language. Hearing loss, in this case, is often congenital. When individuals acquired spoken language before their hearing was diminished, the onset is defined “post-lingual” and, in most cases, hearing loss progresses gradually. Also, hearing loss side is an important factor. Single-sided deafness, or unilateral deafness, refers to hearing impairment in just one ear, while bilateral deafness means a hearing impairment in both ears. Understanding what others are saying when there is a lot of environmental noise might be hard for people with unilateral deafness, however, their communicative abilities can be comparable to typically hearing people in situations with little to no background noise. This is not the case for people with bilateral deafness, who need a hearing aid in order to access sound. Hearing loss grade depends on the residual sensibility in the better ear in a free-field test without hearing aids. It spans from slight to profound hearing loss, with differences in individuals' performance depending on the level (Table 1.1).

Table 1.1. Grades of Hearing Impairment.

Grade of Hearing Loss	**Corresponding Audiometric ISO Value (better ear)**	**Performance without wearing Hearing Aids**
No Hearing loss (Normal Hearing)	25 dB or better	No or very slight hearing problems. Able to hear whispers.
Slight Hearing loss	26 – 40 dB	Able to hear and repeat words spoken with a normal voice at 1 metre of distance.
Moderate Hearing loss	41 – 60 dB	Able to hear and repeat words spoken using raised voice at 1 metre of distance.
Severe Hearing loss	61 – 80 dB	Able to hear some words when shouted into the better ear.
Profound Hearing loss (Deafness)	81 dB or greater	Unable to hear even a shouted voice.

As shown in Figure 1.1, people with severe or profound uncompensated bilateral hearing loss cannot access any of the phonemes of the world's spoken languages (the "speech banana" in yellow). That means that without the support of visual input (i.e. lipreading) they cannot perceive speech during spoken conversations, and this can significantly impair their everyday life and personal achievements.

Figure 1.1. Audiogram of familiar sounds with the “speech banana” highlighted in yellow. Image Source: The London Healthcare Science Trainee Network Twitter Profile (https://Twitter.Com/Londonhcstn/Status/974605024469962752)



In this thesis, we are interested in children with pre-lingual, bilateral, profound deafness compensated with cochlear implants (either monolateral or bilateral). This population is particularly interesting for scientific research because it allows the evaluation of the cognitive aspects of sensory deprivation and of its recovery (Kral, Kronenberger, Pisoni, & O'Donoghue, 2016).

Early implantation with new generation cochlear implants after a relatively short period of hearing loss contributes to significant improvements in spoken language acquisition, comparable to that of typically developed peers within a few years of implant activation (Geers & Sedey, 2011). However, although the gap between the linguistic performance of hearing children and deaf children with cochlear implantation has narrowed in recent years, the improved access to the spoken language alone does not represent a comprehensive solution for all the problems that children with prelingual deafness may experience in language and literacy learning (Arfé & Fastelli, in press). In fact, about a half (from 42 to 61%) of deaf children with cochlear implants have lower language performances than hearing peers at school entry (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). The variability language and learning outcomes of children with cochlear implants persists over the school years (e.g. Arfé, Ghiselli, & Montino, 2016; Harris & Terlektsi, 2010; Marschark, Rhoten, & Fabich, 2007; Niparko, Tobey, Thal, et al., 2010; Sarant, Harris, & Bennet, 2015).

Investigating the factors that may explain linguistic variability in deaf children is, therefore, a research priority. Studies in this field are beneficial for the deaf community because they can contribute finding an explanation for the individual differences in language outcomes following cochlear implantation. Better understand how deaf children with cochlear implants learn will support the development of instructional methods that match their strengths and needs. Furthermore, the obtained knowledge may help with the early identification of young deaf children who may be at risk for poor language outcomes following cochlear implantation. The contribution of these studies is also particularly interesting for scientific research in general, in fact, studies involving this clinical population (i.e. deaf children with cochlear implants) allow an ethically acceptable investigation of the cognitive processes development in case of sensory deprivation and after its recovery (Kral, Kronenberger, Pisoni, & O'Donoghue, 2016).

Some factors contribute to explaining the variance in the results obtained by deaf children and adolescents with cochlear implants in oral and written language. Factors related with the auditory compensation, such as bilateral or monolateral cochlear implantation, surgery success, precociousness of the implantation, and the prolonged use of cochlear implants (Archbold, Harris, O'Donoghue, Nikolopoulos, White, & Richmond, 2008; Geers, Tobey, Moog, & Brenner, 2008; Harris, 2015; Sarant Harris, & Bennet, 2015), as well as environmental factors like speech therapy, socio-economic status of the family, birth order, parental involvement in children's learning activities, and time spent reading books are known for playing an important role in spoken language and literacy acquisition (Marschark, Rhoten, & Fabich, 2007; Niparko, Tobey, Thal, et al., 2010; Sarant, Harris, & Bennet, 2015). Nevertheless, the academic outcomes obtained by deaf children with cochlear implants at 8 years of age are only partly explained by these factors, even when are combined with the intelligence (IQ) scores: in fact, a substantial proportion of the variance (between 31 and 65%) remains unexplained (Sarant, Harris, & Bennet, 2015).

1.2 THE AUDITORY SCAFFOLDING HYPOTHESIS

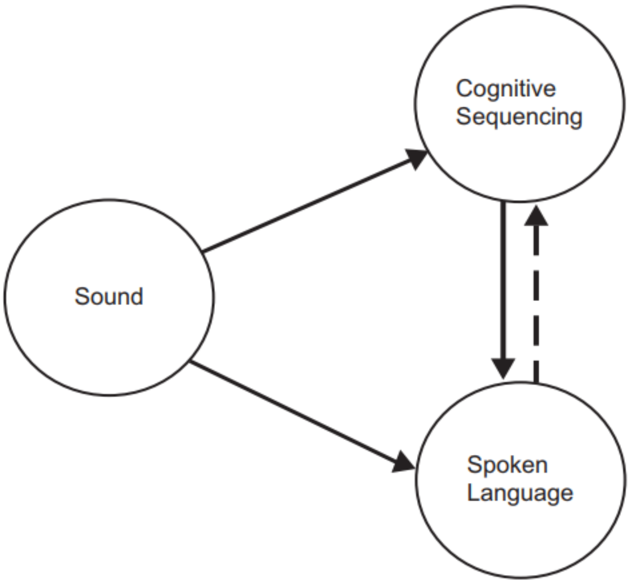
The amount of time spent receiving a limited acoustic stimulation (i.e. the time elapsed between the loss of hearing and the cochlear implantation) is found to explain the differences in linguistic results of deaf children with cochlear implants better than the precociousness of cochlear implant compensation per se (Marschark, Rhoten, & Fabich, 2007). Early access to sounds allows neuronal cells to connect in integrated functional systems that are used to encode the stimuli in perception processes and to efficiently maintain and retrieve abstract information from the environment. Hence, auditory deprivation has effects on brain development, altering the way sensory systems are connected to each other and to the other centres serving higher-order neurocognitive functions. As a result, interindividual variability in the brain’s adaptation to hearing loss could underpin some of the observed variability in outcomes after cochlear implantation (Kral, Kronenberger, Pisoni, & O'Donoghue, 2016).

This evidence has led researchers to conjecture that early auditory stimulation might have scaffolding effects on the child's developing brain. This hypothesis is known as "auditory scaffolding hypothesis" (Conway, Pisoni, & Kronenberger, 2009).

Since sound is by its own nature a sequence of temporally-distributed signals, the *auditory scaffolding hypothesis* suggests that experiencing sound may “scaffold” the development of general cognitive abilities related to encoding and maintaining temporal and sequential patterns. Consequently, early sensory impairment can be detrimental for the development of neurocognitive networks serving these abilities, leading to the delay and/or reorganisation of general cognitive and perceptual sequencing skills, and to long-term effects on children's learning (Conway, Pisoni, & Kronenberger, 2009).

As depicted in Figure 1.2, sound perception may not only affect language development directly, but also have an indirect effect on it, since experiencing and processing temporally-distributed auditory stimuli in regular and meaningful sequences (e.g. linguistic stimuli) may affect the domain-general skills for processing and learning sequences (Conway, Pisoni, & Kronenberger, 2009; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011b).

Figure 1.2. The general framework for the interactive relationship between sound, sequencing skills, and spoken language development (Conway, Pisoni, & Kronenberger, 2009). The solid lines represent the hindering effects of auditory deprivation on the development of spoken language and on non-auditory sequencing functions. The dotted line represents the additional unspecified influence of spoken language skills on the development of general cognitive sequencing abilities.



The claim that general sequence learning abilities impairment in children with congenital deafness goes beyond auditory domain is supported by studies that observed deficits in processing sequential information in the visual, auditory-verbal, and motor sequences domains (Cleary, Pisoni,

& Geers, 2001; Conway, Karpicke, Anaya, Henning, Kronenberger, & Pisoni, 2011a; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011b). These results have been interpreted as evidence of the domain-general effect of early hearing loss on sequence learning.

In this framework, some of deaf children's unexplained linguistic outcomes variability is therefore interpreted as a consequence of the functional deficit in general sequence learning ability. In regards of language learning, deaf children with cochlear implants are typically found having weak explicit sequence learning and memory processes (i.e. use of memorization strategies and techniques to encode and recall information) (Arfé, Rossi, & Sicoli, 2015; Bebko, Bell, Metcalfe-Haggert, & McKinnon, 1998). The phonological loop is particularly involved in these processes (Arfé, Rossi, & Sicoli, 2015; Arfé, 2015; Cleary & Pisoni, 2004), as it is the component designed for holding and elaborating verbal/linguistic information, maintaining it active in memory for the time necessary to perform verbal tasks (Baddeley, 2003), and it seems to be less efficient in deaf children with cochlear implants (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003).

There is some piece of evidence showing that the sequence learning deficit in deaf and hard of hearing individuals also involves implicit sequence learning (i.e. automatic encoding and unintentional learning of stimulus sequences). This has been found by studies involving profoundly deaf children with cochlear implants (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011b), as well as deaf and hard of hearing individuals with cochlear implants and/or hearing aids: either children (Gremp, Deocampo, Walk, & Conway, 2019), or adults (Lévesque, Théoret, & Champoux, 2014).

However, other studies involving orally-educated profoundly deaf children with cochlear implants (Arfé, Fastelli, Mulatti, Scimemi, & Santarelli, 2017; Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017; Klein, Walker, Tomblin, 2018; von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018) have found that deaf and normally hearing individuals do not differ in their implicit learning skills of regularities. These results have also been confirmed by studies involving deaf individuals who use sign language, both children (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017) and adults (Giustolisi &

Emmorey, 2018). The conflict between these findings has contributed to an enriching discussion about the auditory scaffolding hypothesis and the effects of auditory deprivation on implicit learning.

1.3 IMPLICIT LEARNING

Implicit learning is the ability to learn patterns of recurrent information without intention to learn nor awareness of the learning process. It was first described by Reber (1989) as an evolutionary precursor to explicit learning that happens incidentally, without intention, and in a manner that is opaque to explanation.

This form of learning does not depend on consciously controlled strategies (Reber, 1993) and emerges spontaneously as a consequence mere exposure to the stimuli (Saffran, Johnson, Aslin & Newport, 1999). It is based on automatic computations of the frequency with which a stimulus recurs or the conditional probability of a happening event. The ability to implicitly process statistical regularities promotes adaptation to the environment and economic use of cognitive resources. It is therefore considered fundamental for evolutionary adaptation (Mathews & Roussel, 1997). It is believed to be an early learning mechanism in humans and can be observed in infants from the age of 7 months (Saffran, Aslin & Newport, 1996), and in primary school children (Meulemans & Van der Linden, 1998), as well as in adults (Conway, & Christiansen, 2005).

Implicit learning can be measured with a variety of tasks (e.g. a non-exhaustive list of commonly used tasks includes: serial reaction time task, artificial grammar learning task, statistically-induced chunking recall task, serial interception sequence learning task, two-alternative forced-choice task). Despite their different nature (this issue will also be addressed in Chapters II and III), implicit learning tasks usually share the following characteristics: (1) participants are exposed to an input governed by concealed rules/regularities in incidental learning conditions; (2) implicit learning is assessed based on the participants' performance variations throughout the task; and (3) participants' perceived awareness about the task's regularities can eventually be assessed at the end of the task and should be poor. Learning is considered implicit when participants' performance improved according to the task's regularities but they are not aware of what they just have learned (Cleeremans, Destrebecqz, & Boyer, 1998).

1.4 SEQUENCE LEARNING

Implicit Learning has been studied since the 1960s (e.g. Reber, 1967). However, research in this field had a new boost in the 1990s with the studies by Saffran and her collaborators. They investigated children's early ability to recognize single words within the speech flow (e.g. Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996; Saffran, Newport, Aslin, Tunick, Barrueco, 1997). That was attributed to the ability to identify statistically frequent recurrences of sounds present in the mother language and was called "statistical learning" (Saffran, Aslin, Newport, 1996). Subsequently, this became the term of preference used in studies aimed at the investigation of implicit learning of linguistic elements. Nevertheless, the terms implicit learning and statistical learning seem to describe the same phenomenon (Perruchet & Pacton, 2006), and have recently been used as synonyms, or can be found conjugated in the term "implicit statistical learning" (Conway & Christiansen, 2006). Implicit statistical learning of sequences is referred to as "implicit sequence learning" (Cleeremans & Jimenez, 1998). In this thesis, we use the term "implicit learning" to refer to implicit learning of either sequential or temporal statistical regularities.

CHAPTER II

STUDY OF THE VARIANCE OF IMPLICIT SEQUENCE LEARNING IN DEAF CHILDREN WITH COCHLEAR IMPLANTS AND TYPICALLY HEARING CHILDREN

The studies described in this chapter result from the joint collaboration of the following authors: Ambra Fastelli (University of Padua & Bruno Kessler Foundation), Barbara Arfé (University of Padua), Claudio Mulatti (University of Padua), Pietro Scimemi (University of Padua & San Giovanni e Paolo Hospital of Venice), Rosamaria Santarelli (University of Padua & San Giovanni e Paolo Hospital of Venice), and are going to be proposed as a paper to a peer-reviewed journal. The provisional title of this work is “Developmental Variance of Implicit Sequence Learning in Deaf Children with Cochlear Implants and Typically Hearing Children”.

In this study, I contributed as follows: I discussed the design of the study with my Barbara Arfé and Claudio Mulatti; I carried out the data collection with all deaf children with cochlear implants and with part of the hearing children, I also co-supervised (with Barbara Arfé) one of the three master students who collected part of the hearing children data; I analysed the data under the supervision of Barbara Arfé; I wrote the paper that is going to be reviewed by the other authors before submission.

2.1 INTRODUCTION

If compared with hearing peers, deaf children with cochlear implants are reported having poorer speech perception (Pisoni & Cleary, 2003), reduced articulation speed (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003), poorer expressive and receptive syntactic skills (Harris, Kronenberger, Gao, Hoen, Miyamoto, & Pisoni, 2013), and poorer reading and writing skills (Arfé, Ghiselli, & Montino, 2016; Arfé, Fastelli, Trevisi, & Martini (in preparation); Geers, 2003). In all these cases, deaf children's poor outcomes in spoken language and literacy are associated with deficient verbal working memory. In fact, language development, that is the development of vocabulary, comprehension, reading, and speech production is largely associated with the phonological component of working memory: the phonological loop (Gathercole & Baddeley, 1993). The phonological loop is the component designed for holding and elaborating verbal/linguistic information, maintaining it active in memory for the time necessary to perform verbal tasks (Baddeley, 2003). This working memory component seems to be particularly lacking in deaf children with cochlear implants (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003), limiting their ability to retain and process verbal information (Geers, Strube, Tobey, Pisoni, & Moog, 2011; Pisoni & Cleary, 2003), and adversely impacting language development (Pisoni & Geers, 2000), even 10 years after receiving cochlear implantation (Pisoni, Kronenberger, Roman, & Geers, 2011).

Verbal recoding and subvocal rehearsal are the cognitive processes specific to the phonological loop (Baddeley, 2003). Verbal recoding consists of the spontaneous recoding of visual stimuli into a phonological form, while subvocal/verbal rehearsal is the mechanism appointed for refreshing relevant phonological information and is usually measured using forward digit span or word span tasks (Acheson & MacDonald, 2009; Arfé, Rossi, & Sicoli, 2015; Baddeley, 2003; Gathercole, Pickering, Ambridge, & Wearing, 2004). While verbal recoding seems particularly important in reading (Adams, Simmons, Willis, & Porter 2013), verbal rehearsal is typically found to be closely related with general language learning (Baddeley, Gathercole, & Papagno, 1998). These active and explicit (conscious) learning processes are quite closely related and typically emerges together around the age of 7 in children with typical development (Baddeley, Gathercole, & Papagno, 1998; Flavell, Beach, & Chinsky, 1966; Gathercole, & Hitch, 1993; Hitch, Halliday, Dodd, & Littler, 1989a; Hitch, Woodin, & Baker, 1989b). Deaf children seem to start using verbal rehearsal with an average delay of about 3-4 years compared to children with typical development (Bebko, & McKinnon, 1990), and use it less efficiently (Bebko & McKinnon, 1990; Bebko, LaCasse, Turk, & Oyen, 1992; Hall, & Bavelier, 2010; Harris, & Moreno, 2004).

Despite the ongoing investigation of the factors influencing speech, language, and literacy in cochlear implanted deaf children, large individual differences in language outcomes that are typically found in deaf children following cochlear implantation (Pisoni, Cleary, Geers, & Tobey, 1999), and a considerable amount of this variability remains unexplained (Geers, 2002, 2006). Investigating this variability could contribute to the development of instructional methods matching deaf children's strengths and needs, and help with the early identification of those factors that might put young deaf children at risk for poor language outcomes following cochlear implantation.

The auditory scaffolding hypothesis suggests that the variability of linguistic outcomes obtained by deaf children after cochlear implantation might be partially explained by deficits in implicit learning of sequences (Conway, Pisoni, & Kronenberger, 2009). Implicit learning is a fundamental mechanism for human development and everyday life (Abrahamse, 2012) because it allows the implicit detection and elaboration of distributional statistical regularities that are recurring in inbound information and plays a crucial role during the early stages of language development (Saffran & Kirkham, 2018; Romberg & Saffran, 2010). Conway, Pisoni, & Kronenberger (2009) suggested that the efficiency of implicit learning might be related to the elaboration of the input. Since sound is inherently a temporal and sequential signal, its elaboration may scaffold the development of general cognitive abilities related to representing temporal or sequential patterns. Accordingly, deaf children's heavily limited or absent access to auditory information during early childhood may limit the efficiency of implicit learning and result in disturbances to sequencing skills. Given the importance of implicit learning of sequences for language development, these disturbances will, in turn, contribute to difficulties with language development. The *auditory scaffolding hypothesis* is supported by some experimental studies that found impaired sequence learning in deaf children with cochlear implants (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011; Gremp, Deocampo, Walk, & Conway, 2019). However, other studies have *not* found implicit sequence learning impairments in these children or in hard-of-hearing children in general (Arfé, Fastelli, Mulatti, Scimemi, & Santarelli, 2017; Fastelli & Arfé (under review); Giustolisi & Emmorey, 2018; Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017; Klein, Walker, Tomblin, 2018; von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018).

From a theoretical standpoint, this controversy seems to concern the characteristic of variance versus invariance of implicit learning depending on other internal (i.e. age) and/or external (i.e. sensory experience) factors. Implicit learning was originally described by Reber as an evolutionary precursor to explicit learning characterized by its invariability across individuals (Reber, 1989, 1993; Reber, Walkenfeld, & Hernstadt, 1991). Implicit learning skills are believed to develop very early and have been observed in 7-months-old infants (Fiser & Aslin, 2002; Saffran, 2003; Saffran, Aslin, & Newport, 1996). Some results suggest that implicit learning skills are developmentally invariant since differences between children and adults are very little or not significant (e.g. Cherry & Stadler, 1995; Howard & Howard, 1989; Meulemans, Van der Linden, & Perruchet, 1998; Seger, 1994; Thomas & Nelson, 2001). However, other results are not in agreement with this model, and found evidence that implicit learning skills do change over childhood (Janacsek, Fiser, & Nemeth, 2012; Thomas, Hunt, Vizueta, Sommer, Durston, Yang, & Worden, 2004), and during lifespan (Daltrozzo & Conway, 2014).

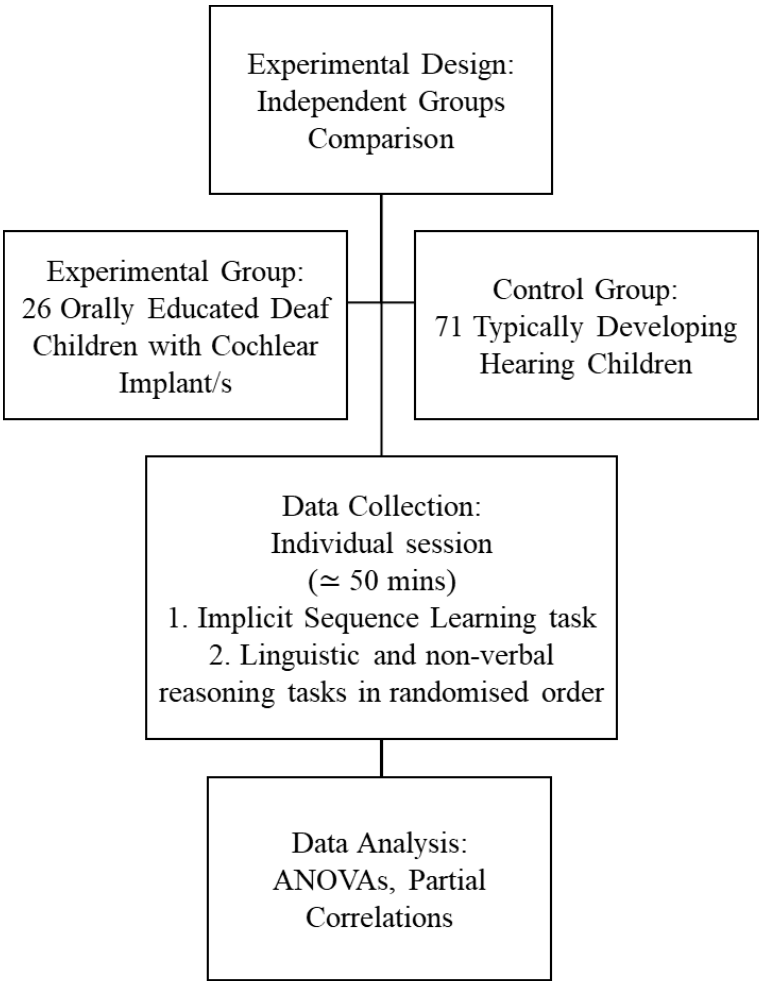
The variance versus invariance controversy is relevant because the auditory scaffolding hypothesis has its foundations on the variance account, in which a period of hearing loss with early onset in life - i.e. early sensory (auditory) experience - is believed to influence implicit learning. This might have a great impact on rehabilitation practice. In fact, if implicit learning of sequences can be conditioned by experience, targeting this process through innovative training and therapies could also be beneficial for the development of related skills, like language and literacy (Deocampo, Smith, Kronenberger, Pisoni, & Conway, 2018; Giustolisi & Emmorey, 2018).

The aim of the studies described in this chapter is to provide complementary evidence and contribute in the discussion about the variance versus invariance nature of implicit sequence learning with particular regard to deaf children with cochlear implants and the auditory scaffolding hypothesis. In the first part of this chapter is described the study A in which we investigated implicit learning of sequences in a group of deaf children with cochlear implants and a large sample of hearing children matched on chronological age. The aim of study A was to explore the sequence learning process and investigating its relevance for language acquisition taking into account the auditory scaffolding hypothesis and the other explicit memory processes involved in language acquisition (verbal rehearsal). If there is a link between the hearing condition and implicit sequence learning as proposed by the auditory scaffolding hypothesis, then deaf children with cochlear implants should perform worse than hearing children in sequence learning task because of their reduced auditory experience. Furthermore, their performance should be correlated with linguistic outcomes. In the second part of the chapter is described the study B, in which we explored the developmental differences in sequence learning in hearing children of different age groups. If implicit learning is developmentally variant, the performance at an implicit sequence learning task should get better with age.

2.2 STUDY (A)

2.2.1 METHOD (A)

Table 2.1. Scheme of the experimental design of Study (A).



2.2.1.1 PARTICIPANTS (A)

A total of 97 children participated in this study: 26 deaf children using cochlear implants (16 males) and 71 hearing children (36 males). All were between 5 and 11 years of age. Cochlear implanted deaf children were recruited through audiology and speech-language pathology service in the north of Italy. Typical hearing children were recruited in mainstream schools and kindergartens of the north and the centre of Italy. Data regarding the normal hearing children that were used as a control group in this study have been gathered by master students as part of a separate project. The two groups were matched by chronological age. Table 2.2 summarises the characteristics of the two groups.

We excluded data from those children whose performance on non-verbal intelligence (measured with the Italian version of the Progressive Coloured Matrices; Belacchi, Scalisi, Cannoni, & Cornoldi, 2008) was lower than 2 standard deviations from the group mean. Data from children who either wanted to withdraw from the testing, or displayed inattention, tiredness, or lack of motivation were also excluded. These criteria resulted in five deaf and sixty hearing participants being excluded from subsequent analyses. Inclusion criteria for the group of children with cochlear implants were onset of profound bilateral hearing loss (90 dB or greater) before the age of 2 with no additional cognitive, motor, or sensory impairment, cochlear implantation by the age of four, use of at least one cochlear implant for a minimum of three years, and Italian as native or dominant language. Cochlear implantation was monolateral for all our deaf participants. Even though one child had been exposed to Italian Sign Language by deaf parents, all children were educated using an oral/aural approach and were using spoken language. Participation was entirely voluntary. No benefits were offered in exchange for participation; however, all participants received a certificate to thank them for their contribution. The study was approved by the Ethical Review Board of the second author’s institution.

Table 2.2. Participants' characteristics.

	Deaf (*n* = 26)		Hearing (n = 71)			
Measure	**M**	**(SD)**	**M**	**(SD)**	***t*(95)**	***p***
Age	8.16	(1.94)	7.57	(1.72)	-1.45	.15
Age at Implantation[1]	2.09	(1.36)	-	-	-	-
Duration of Implantation[1]	3.10	(1.55)	-	-	-	-

Notes: All measures are given in years; [1] Cochlear Implantation.

2.2.1.2 PROCEDURE (A)

Potential participants with deafness were identified by their audiologists while hearing potential participants were identified by their teachers. Children's families received an information sheet and a consent form. In order to participate, families of participants had to return the questionnaire and the consent form completed and signed. Children were asked to confirm their willingness to participate before starting the session. Children were assessed individually by one researcher (the first author). Deaf participants took part in the study on occasion of one of their routine cochlear implant check at the health service while hearing participants participated during their school hours and were individually taken from their class in order to participate in the study. The assessment lasted for approximately 50 minutes, with breaks provided as needed, and took place in a quiet room at the health service (for the cochlear implanted deaf children) or at the school (for the typically hearing children).

The assessment included an experimental implicit learning task adapted from Conway et al., 2011. In order to limit the detrimental effect of tiredness on the experimental task during the assessment, the implicit learning task was proposed as first during the assessment session. Apart from that, the order of the other tasks was randomized.

2.2.1.3 MATERIALS (A)

2.2.1.3.1 Linguistic and non-verbal reasoning measures

The receptive vocabulary was measured by the Peabody Picture Vocabulary Test (Peabody PPVT-R, Italian adaptation, Stella, Pizzoli, & Tressoldi, 2000). The syntactic knowledge subtest of the battery for neuropsychological evaluation (BVN 5-11, Bisiacchi, Cendron, Gugliotta, Tressoldi, & Vio, 2005; BVN 12-18, Gugliotta, 2009) was used to assess receptive grammar. Both of these tasks required a non-verbal response to verbal input. Children are asked to point to the one out of four pictures that correspond to the stimuli that are verbally presented by the experimenter, respectively a word for the PPVT-R and a sentence for the syntactic understanding subtest. Expressive grammar skills were measured using an oral sentence generation task (Arfé, & Pizzocaro, 2015). The task requires children to generate as many oral sentences as they can from a given pair of words (i.e., cat-dog and water-tower) in a limited amount of time (2 minutes for each word pair). Verbal working memory (verbal Rehearsal) was assessed using the forward digit-span task of the Wechsler's intelligence scale for children (WISC-IV, the Italian edition of Wechsler Intelligence Scale for Children-Fourth ed.; Orsini, Pezzuti, & Picone 2012). In this task, children are required to verbally repeat sequences of digits of increasing length, in the same order (forward) or in the reverse order (backwards) as they were verbally presented by the experimenter. The number of digits correctly recalled in the forward task provides an estimate of verbal rehearsal skills and working memory store capability, while the task backwards is considered a measure of the executive control mechanisms of working memory. Since our study concerns the investigation of verbal rehearsal, we only included forward digit span measures.

Since the sequence learning task involved visual stimuli arranged over four locations on the screen, we decided to assess visuospatial memory using the visual-spatial memory subtest of the Italian edition of the Test of Memory and Learning (TEMA, Test di memoria e apprendimento; Reynolds & Bigler, 2003). In this task, children are asked to remember patterns of dots of increasing complexity and reproduce them by touching a grid.

In order to measure general non-verbal reasoning abilities, we used the Coloured Progressive Matrices (CPM; Italian version, Belacchi et al., 2008). The test consists of three series of visual patterns from which a part is missing. The child is presented six options and is instructed to select one in order to complete the pattern.

2.2.1.3.2 Implicit Sequence Learning task

Experimental design

The experimental implicit learning task used in Conway et al. (2011) was adapted for the purposes of the present study. The task was based on immediate serial recall of visual sequences (spanning from 2 to 5 items) and aimed to measure implicit sequence learning. To accomplish the task, children were asked to repeat each sequence in the correct order by touching a touch-sensitive screen. Unbeknownst to the participant, the experiment consisted of a training phase (16 trials) and a test phase (24 trials). The two phases were proposed without transitions nor pauses. Sequences were generated by two distinct artificial grammars: grammar A was used for all the sequences of the training phase and for half of the sequences in the test phase, while grammar B was used for the other half of the sequences of the test phase. Artificial grammars refer to an arbitrarily determined set of rules that govern the sequences of stimuli presentation. The artificial grammars embedded in the task specified the probability of each subsequent item to occur within a sequence given the previous one (see Conway et al., 2011 for details about grammars and transitional probabilities), dictating the order in which items can occur in the sequence unbeknownst to the participants (Karpicke & Pisoni, 2004). The procedure was identical for the whole task and participants were not given any explicit instruction about its covert structure. Better recall of the sequences that complied with the trained grammar (grammar A) was taken as a measure of implicit sequence learning. To the extent that sequence learning has occurred, one would expect recall for the trained grammatical patterns to exceed those for the untrained ones (Jamieson & Mewhort, 2005; Karpicke & Pisoni, 2004).

The design was identical to that described in Conway et al. (2011) (the artificial grammars are depicted in Table 2.3) except for the stimuli used. The items used by Conway et al. (2011) consisted in series of coloured squares, while our items were black and white symbols of foreign alphabets (i.e., Greek and Cyrillic) that were unfamiliar to the children. Items were presented one at a time in one of the four possible locations of a 2x2 grid (i.e., upper left, upper right, lower left, lower right).

Table 2.3. Grammars A and Grammar B used in the implicit learning task (Conway et al., 2011).

Colours⁄ locations (n)	Grammar A (n + 1)				Grammar B (n + 1)			
	1	2	3	4	1	2	3	4
1	0.0	0.5	0.5	0.0	0.0	0.0	0.0	1.0
2	0.0	0.0	1.0	0.0	0.5	0.0	0.0	0.5
3	0.5	0.0	0.0	0.5	0.0	1.0	0.0	0.0
4	1.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0

Note: Grammars show transition probabilities from position n of a sequence to position n + 1 of a sequence for four colours labelled 1–4.

Scoring

Following Conway et al., (2011), a sequence was scored correct if the participant reproduced each test sequence correctly in its entirety. Accuracy scores (% of correct responses) were computed for the Learning phase and Test phases separately. Performance in the Learning phase is believed to reflect children’s ability to accurately reproduce visual sequences from immediate memory, while, performance in the Test phase provides a measure of children’s ability to implicitly learn sequences that follow an artificial grammar. This is achieved by comparing recall performance for the sequences generated with the trained grammar (used in both learning and test phases) relative to test sequences generated with the untrained grammar.

Procedure

Participants were given the following instructions:

> *“You are going to see four squares on this computer screen. Each square can contain a symbol that will appear on the screen. Your aim is to pay attention to the symbols and try to remember their order. After each sequence, you will see all four symbols on the screen. You need to touch the symbols in the same order in which they just appeared.”*

Three practice trials consisting of three sequences of three items were used to familiarize each child with the task before starting the testing. The items used in this phase were the same as the ones used in the task. The presentation order was the same for all the participants and not consistent with any of the grammars used in the task.

Apparatus

A Lenovo Yoga 2 Pro was used for the data collection. It has an Intel® Core™ i7, 4th generation processor, and a 13,3" IPS Quad HD+ (3200 x 1800) monitor with multi-touch technology. The resolution was set on 1920x1080 pixels. The touch-sensitive monitor displayed the visual stimuli and recorded participant responses for the sequence learning task.

2.2.2 RESULTS (A)

Coloured progressive matrices (Belacchi, et al., 2008) scores were used to control the participants' non-verbal reasoning skills. Although all participants' non-verbal IQ was within the normal range (i.e., greater than -2σ), deaf children's standard scores in the coloured progressive matrices (Belacchi et al., 2008) were significantly lower than the hearing $F(2, 87) = 32.93$, $p < .001$, $\eta_p^2 = .43$.

ANOVAs with age covariate were run to investigate the differences between deaf participants with cochlear implants and typically hearing in receptive vocabulary, syntactic knowledge, verbal working memory, and non-verbal visuospatial memory. Table 2.4 summarizes the results of these analyses.

Table 2.4. Language and non-verbal reasoning tasks mean.

	Deaf (*n* = 26)		Hearing (*n* = 71)				
Measure	M	SD	M	SD	*F*	*p*	η_p^2
Digit span forward	4.60	(1.10)	4.74	(1.29)	9.91	<.001	.186
Receptive vocabulary	85.00	(31.13)	110.06	(25.38)	61.95	<.001	.582
Syntactic knowledge	14.12	(2.85)	14.44	(2.51)	15.58	<.001	.271
Visual-spatial memory	14.08	(8.01)	9.80	(6.61)	15.47	<.001	.250

Notes: Age covariate. All measures are reported in raw scores. Effect sizes (η^2) express the magnitude of the difference between groups.

Hearing children performed significantly better than deaf children in all linguistic measures. The two groups differed significantly in forward digit span F(2, 87) = 9.91, p < .001, η_p^2 = .186, indicating weaker verbal working memory skills in deaf children. Deaf children scored significantly lower than the hearing peers for both the linguistic tasks: receptive vocabulary F(2, 89) = 61.95, p < .001, η_p^2 = .582, and syntactic knowledge F(2, 84) = 15.58, p < .001, η_p^2 = .271. These results are consistent with the literature and therefore were attended.

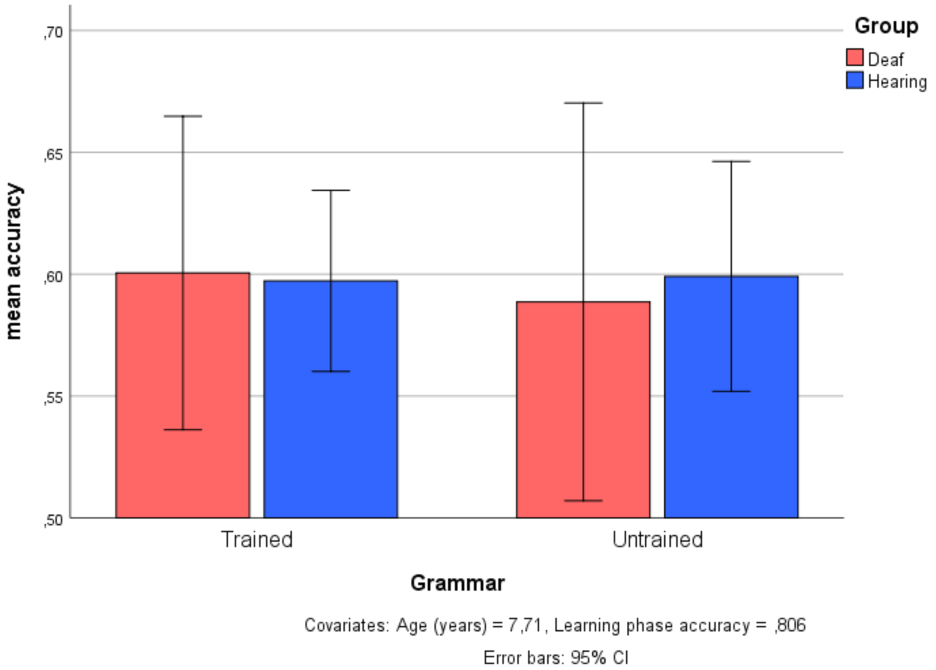
However, deaf children's performance for non-verbal visual-spatial memory was significantly better than the hearing children's F(2, 93) = 15.47, p < .001, η_p^2 = .250.

The performances of the two groups of children at the implicit sequence learning task were analysed with one-way ANOVA.

Learning phase. The two groups differed in accuracy. During the learning phase, the deaf children performed worse than the hearing controls, F(2, 93) = 29.91, p <.001, η_p^2 = .391.

Implicit learning (test phase). Given the significant difference between groups during the learning phase, learning phase accuracy was a covariate in the analysis of the implicit learning effect (based on test phase accuracy). Age was also covariate. As shown in Figure 2.1, the two groups did not differ significantly in implicit learning. The only significant effect for the difference in accuracy for sequences generated through trained and untrained grammars was in learning phase accuracy F(1,92) = 91.31, p <.001, η_p^2 = .498. The effects of age F(1,92) = .392, p = .533, and group F(1,92) = .009, p = .926, were not significant.

Figure 2.1. Implicit learning (Test phase Accuracy mean).



No significant correlation was found between implicit learning (accuracy mean) and performances at any of the other tasks (age and learning phase accuracy were covariate) in the Deaf group. Correlations are displayed in Table 2.5. These correlations remained non-significant even after controlling for the duration of cochlear implants use.

Table 2.5. Partial Correlations for the Deaf group.

	Implicit sequence learning	Digit span forward	Receptive vocabulary	Syntactic knowledge	Visual-spatial memory
Implicit sequence learning	-				
Digit span forward	-.01	-			
Receptive vocabulary	-.21	.34	-		
Syntactic knowledge	-.22	.57	.83**	-	
Visual-spatial memory	-.01	-.14	-.10	-.29	-

Notes: Partial correlations. Age and learning phase accuracy are covariate.
* $p < .05$, ** $p < .01$, *** $p < .001$, unflagged values are *ns*.

Since Conway et al. (2011) reported a correlation between the linguistic outcomes and sequence learning, hierarchical linear regression was calculated to predict syntactic knowledge based on chronological age, implicit sequence learning skills, receptive vocabulary, and verbal rehearsal for the deaf group. Significant regression equations were found: F(4,7) = 9.41, p <.05, with an R^2_{adj}=.754 for the deaf children. Receptive vocabulary accounted for .77 of unique variance in this model. Age, implicit sequence learning, and verbal rehearsal did not significantly account for variance in this model.

2.2.3 DISCUSSION (A)

The aim of this study was to investigate the sequence learning process and its association with the language skills of deaf children with cochlear implants, based on the auditory scaffolding hypothesis. Our results show that there is *not* a significant difference in implicit sequence learning between cochlear implanted deaf and typically hearing children when this ability is assessed using a sequence learning task. These results are therefore not supporting with the "auditory scaffolding hypothesis" (Conway, Pisoni, & Kronenberger, 2009). Consistently with Conway et al. (2011), our deaf participants received the diagnosis of profound deafness in their early years and were cochlear implanted before the age of four. However, experiencing a period of auditory deprivation did not seem to be detrimental for the development of implicit sequence learning skills in our deaf participants; in fact, performances at the implicit learning sequence learning task were comparable in the two groups. On the contrary, the process related to the conscious learning of a sequence of digits, in other words, verbal rehearsal, was weaker in our deaf participants compared with the hearing peers. In fact, cochlear implanted children that participated in our study performed significantly worse than their hearing peers in the forward digit span task. This is consistent with literature that reports verbal rehearsal typically as less efficient in the deaf population (Arfé et al., 2016; Pisoni, Kronenberger, Roman, & Geers, 2011).

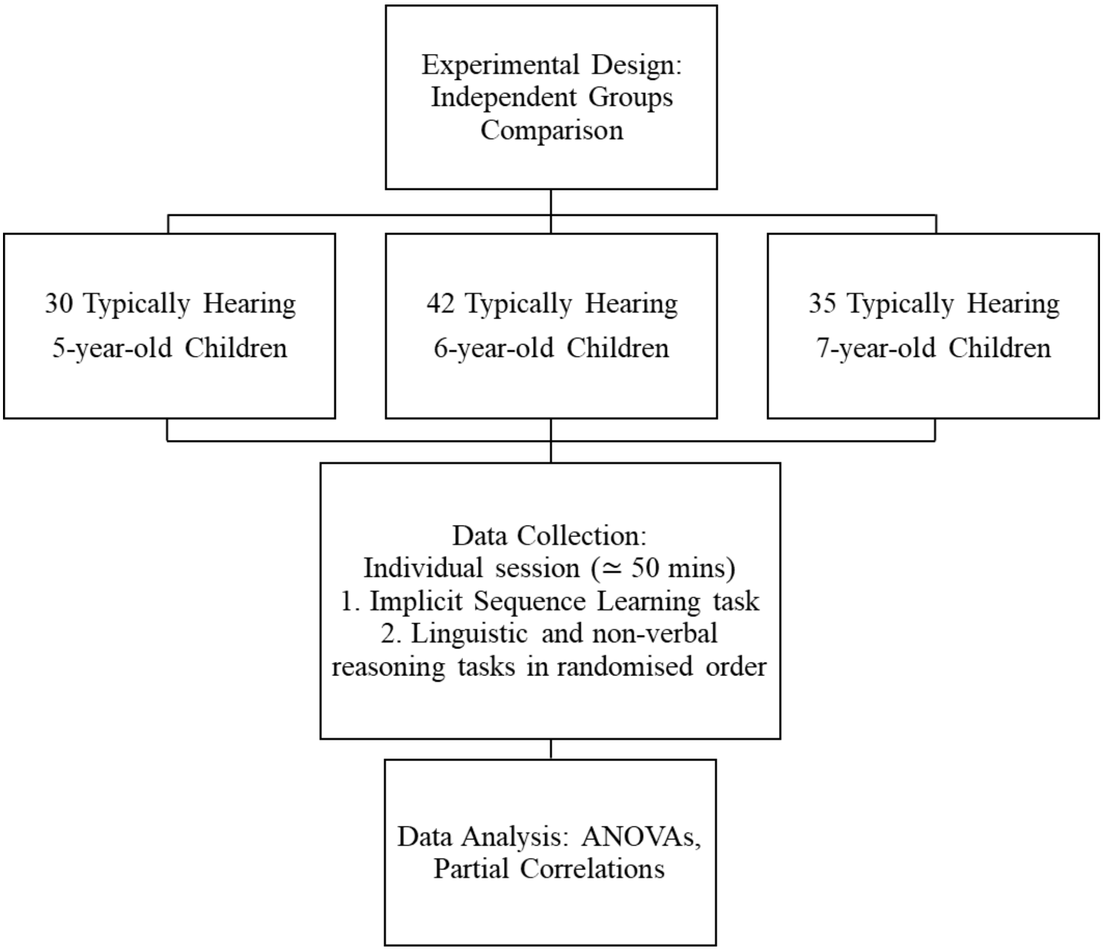
Overall, study A results suggest that implicit sequence learning and verbal rehearsal are independent mechanisms that both cochlear implanted deaf and typically hearing children use to process and maintain sequential information. However, while the ability to consciously process and learn sequences (verbal rehearsal) seems to be affected by auditory deprivation, implicit learning processes seems not to be influenced by the auditory experience. The analysis of linguistic outcomes (syntactic knowledge) in our deaf participants also suggests that the language deficit in this group is explained by their poor vocabulary rather than weak implicit sequence learning.

2.3 STUDY (B)

In this part of the chapter is presented a second study (study B). In this study, we explored the developmental differences in implicit and explicit sequence learning in three groups of hearing children of different age (five, six, and seven years old). Based on previous studies available in literature, this age-range was chosen because it was identified as critical for the development and/or appearance of explicit learning processes, namely verbal recoding and verbal rehearsal (Baddeley, Gathercole, & Papagno, 1998; Flavell, Beach, & Chinsky, 1966; Gathercole, & Hitch, 1993; Hitch, Halliday, Dodd, & Littler, 1989a; Hitch, Woodin, & Baker, 1989b).

2.3.1 METHOD (B)

Table 2.6. Scheme of the experimental design of study (B).



2.3.1.1 PARTICIPANTS (B)

One hundred-seven typically hearing children took part in this experiment. Thirty-five of these children also served as a control group in study A. Three groups were created based on children's chronological age. Participants were thirty 5-year-olds, forty-two 6-year-olds, and thirty-five 7-year-olds.

2.3.1.2 PROCEDURE AND MATERIALS (B)

Implicit sequence learning was measured using the same task described in study A. As verbal rehearsal was taken as a measure of for explicit (conscious) learning of sequences, the digit span forward subtest of the Wechsler's intelligence scale for children (WISC-IV, Italian edition of Wechsler Intelligence Scale for Children-Fourth ed.; Orsini, Pezzuti, & Picone 2012) was adopted in this study. To control for visuospatial memory, we used the visual-spatial memory subtest of the Italian adaptation of the Test of Memory and Learning (TEMA, Test di memoria e apprendimento; Reynolds & Bigler, 2003). General non-verbal reasoning abilities were assessed using the Coloured Progressive Matrices (CPM; Italian adaptation, Belacchi et al., 2008). The assessment procedure was identical to the one used with the typically hearing participants of study A.

2.3.2 RESULTS (B)

Coloured progressive matrices (Belacchi, et al., 2008) scores were used to control the participants' non-verbal reasoning skills. All participants' non-verbal IQ was within the normal range (i.e., greater than -2σ).

One-way ANOVA was used to investigate the differences between the three age groups of participants' verbal rehearsal skills, measured with the digit span forward (WISC-IV; Orsini, Pezzuti, & Picone 2012). This measure differed significantly between the three groups, as typically expected with age. A post hoc Tukey HSD test indicated that the only significant difference was between the 7-year-olds' mean score (M = 6.71, SD = 2.42) and the other two groups: the 6-year-olds (M = 4.93, SD = 1.54) and receptive vocabulary the 5-year-olds (M = 4.14, SD = 1.41). Table 2.7 summarizes the post hoc comparison results for the digit span scores.

Table 2.7. Post-Hoc Comparison for the Digit Span Forward.

Digit span forward		**Mean difference**	***p***
5-year-olds	6-year-olds	-.79	.184
	7-year-olds	-2.58	<.001
6-year-olds	5-year-olds	.79	.184
	7-year-olds	-1.79	<.001
7-year-olds	5-year-olds	2.58	<.001
	6-year-olds	1.79	<.001

The performances of the three groups of children at the implicit sequence learning task were analysed with one-way ANOVA.

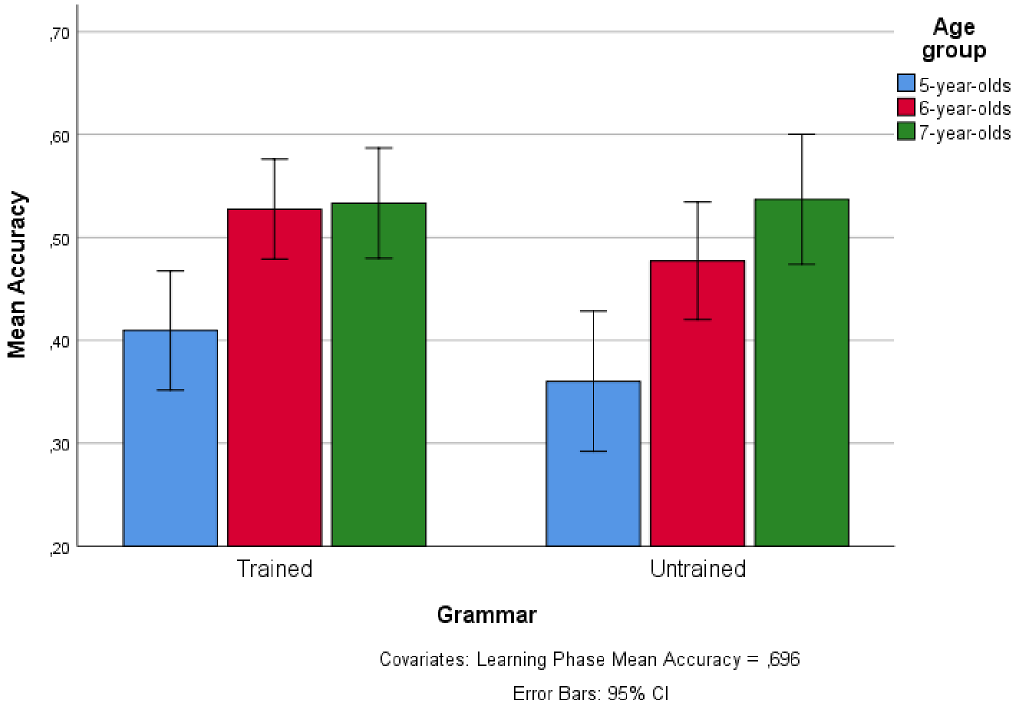
Learning phase. Learning phase accuracy mean was increasing with age. The overall model was significant F(2, 103) = 4.09, $p < .05$, $\eta_p^2 = .07$. Table 2.8 summarizes the post hoc comparison results for the learning phase accuracy mean scores.

Table 2.8. HSD Tukey Post Hoc Comparison for the Learning Phase Accuracy Mean.

		Mean difference	***p***
5-year-olds	6-year-olds	-.08	.313
	7-year-olds	-.16	<.05
6-year-olds	5-year-olds	.08	.313
	7-year-olds	-.08	.268
7-year-olds	5-year-olds	.16	<.05
	6-year-olds	.08	.268

Implicit learning (test phase). As shown in Figure 2.2, the 7-year-old children did not show a strong effect of implicit learning F(1,34) = .14, ($p = .711$), meaning that their level of accuracy for the sequences following the trained grammar was not significantly different from the accuracy for sequences following the untrained grammar. The younger groups of children showed a significant effect of implicit sequence learning in this task: F(1,29) = 4.34, $p < .05$, $\eta_p^2 = .13$ for the 5-year-olds, and F(1,40) = 4.70, $p < .05$, $\eta_p^2 = .11$ for the 6-year-olds.

Figure 2.2. Implicit learning (Test phase Accuracy mean).



Performance at the implicit sequence learning did not significantly correlate with any of the other tasks.

2.3.3 DISCUSSION (B)

In study B, we aimed to contribute to the discussion about the variance versus invariance nature of sequence learning exploring the developmental differences in sequence learning in hearing children of different age groups. Our results show that only our youngest participants (5- and 6-years old children) showed an effect of implicit learning in the sequence learning task, as evidenced by the difference between their level of accuracy for sequences following the trained grammar compared with the ones generated through the untrained grammar. General accuracy was linearly increasing with age, however, there was not a significant implicit learning effect for the older group (7-years old children). Consistently with the available literature, verbal rehearsal skills also increased linearly with age. The group of 5-year-olds performed significantly worse than the 7-year-olds in the forward digit span task.

2.4 GENERAL DISCUSSION

In this chapter are described two studies in which we investigated the nature of implicit sequence learning with regards to auditory experience (study A) and age (study B). In study A we investigated implicit sequence learning in deaf children with cochlear implants, taken into account the auditory scaffolding hypothesis. In order to limit the interference of verbal rehearsal, we used sequences of unfamiliar stimuli that were difficult to name, finding no deficit in implicit sequence learning in deaf children with cochlear implants. In addition, no correlation was found between deaf children performance at the implicit sequence learning task and the linguistic outcomes, even after controlling for the duration of cochlear implant use. The receptive vocabulary was the main predictive factor for syntactic knowledge in our deaf participants.

Overall, our findings suggest that sequence learning is a complex ability that relies on two separate processes: implicit sequence learning and explicit sequence learning based on working memory (i.e., verbal rehearsal). This finding is consistent with other studies that found no relationship between implicit sequence learning and working memory (for a short review see Janacsek & Nemeth, 2013). The results obtained in study A show that both deaf children with cochlear implants and typically hearing children use these two learning processes. Even though verbal rehearsal appears to be deficient in our group of deaf participants, implicit sequence learning is comparable to the typical hearing. The ability of implicitly learn sequential regularities does not seem affected by the auditory condition, hence, our findings are not supporting the auditory scaffolding hypothesis and are not consistent with the studies that found a deficit in implicit learning of sequences in this population (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011; Gremp, Deocampo, Walk, & Conway, 2019). However, similar results had been obtained by other studies (Arfé, Fastelli, Mulatti, Scimemi, & Santarelli, 2017; Giustolisi & Emmorey, 2018; Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017; Klein, Walker, Tomblin, 2018; von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018). This discrepancy could be due to various reasons.

First, this could be a confounding effect of other factors. Evidence suggests that implicit learning and explicit working memory are two systems that seem to work separately, however, if the sequence learning is explicit/intentional, differences in working memory processes will emerge during the sequence learning task (Unsworth & Engle, 2005). In other words, the explicitness of the sequence can be a factor influencing the results in a sequence learning task because it will engage in conscious working memory processes. Consequently, if it is possible to engage explicit learning processes in a sequence learning task, participants with weak working memory abilities will be more likely to obtain poor results. In the case of deaf children with cochlear implants, their poor/delayed verbal rehearsal skills might explain the results obtained by Conway et al. (2011) and the discrepancy with our findings. In the study by Conway et al. (2011), the sequence learning task was based on sequences of coloured squares that could potentially have been verbally recoded and rehearsed by the participants in order to reproduce the sequences (e.g. ‘blue – red – yellow – blue’). Since, therefore, deaf children’s poor performance in Conway et al. study might be explained by their poor rehearsal skills, it is not possible to draw clear-cut conclusions on their implicit sequence learning ability.

Another reason that could explain the inconsistency of the findings could be related to the structure of the task. As pointed out by Hall, Eigsti, Bortfeld, & Lillo-Martin (2017), the failure to find evidence of implicit learning could reflect a task confound; a child with excellent explicit memory skills could have good performance on both the trained and untrained grammars, making it impossible to detect implicit learning despite learning of the grammar. Based on the means reported on Conway et al.’s paper, it seems plausible that our deaf participants were performing generally better than theirs at the sequence learning task.

In study B we investigated developmental invariance implicit learning based on age with typically hearing children from 5 to 7 years old. Despite the fact this study involved typically hearing children, we also aim to contribute to the discussion regarding the auditory scaffolding hypothesis. In fact, this hypothesis is only viable under the developmental variance account, in which implicit learning is influenced by factors like age and experience (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017). Only our younger groups of children (5- and 6-years old) showed an effect of implicit learning in the sequence learning task, while the older group (7-years old) did not. We also observed that verbal rehearsal skills linearly increased with age, with the oldest group significantly outperforming the youngest, consistently with literature (Baddeley, Gathercole, & Papagno, 1998; Flavell, Beach, & Chinsky, 1966; Gathercole, & Hitch, 1993; Hitch, Halliday, Dodd, & Littler, 1989a; Hitch, Woodin, & Baker, 1989b). Taken together, these results suggest that as soon as children start to use explicit memory strategies effectively, their performance at remembering sequences (for both the trained and the untrained grammar) increase and the implicit sequence learning effect become not detectable (or masked). Based on our results we are not able to provide compelling evidence of improvements (or deteriorations) of implicit learning of sequences with age, however, our findings suggest some developmental changes in the relationship between implicit and explicit sequence learning processes. This is compatible with the original description of implicit learning as an evolutionary precursor of explicit learning made by Reber (1989, 1993), and recall Karmiloff-Smith's representational re-description model (1992) according to which knowledge is stored in memory on different levels of representation and redescribed thanks to experience. The outcome of the redescriptions is the building up of multiple representations of similar knowledge in the mind, in which the first level is implicit and then other levels follow with increasing degree of detail and explicitness. This consideration exceeds what can be empirically demonstrated by our studies, so we encourage future research to further investigate this hypothesis.

Study limitations. The evidence for a group difference provided by Conway et al. (2011) relied largely on the observation that the typically hearing group reached significance while the deaf group did not. This has been criticised as it does not represent strong evidence for reliable group differences (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017). Given that our procedure replicated Conway et al. (2011), this also represents a noteworthy limitation of our studies. Our study also replicated the strict inclusion criteria that were adopted by Conway and colleagues (2011). Unfortunately, that led to a small sample size for the quite wide age range considered. Finally, considering the complexity of language development, it is not easy to derive conclusions based only on the few linguistic abilities that we were able to assess. It is possible that considering the interaction of implicit sequence learning with different language skills (e.g. learning of new oral or written words) could lead to dissimilar results to the ones we obtained.

2.5 CONCLUSIONS

In conclusion, the overall findings obtained by study A and B suggest that implicit sequence learning and verbal rehearsal are two separate processes that both cochlear implanted deaf children and typically hearing children use to process and maintain sequential information. As soon as children start using explicit learning processes efficiently, implicit sequence learning is no longer detectable.

CHAPTER III

INVESTIGATING IMPLICIT LEARNING IN DEAF CHILDREN WITH COCHLEAR IMPLANTS WITH A SIMPLE REACTION TIME TASK

The study described in this chapter is the result of the collaboration between the following authors: Ambra Fastelli (University of Padua & Bruno Kessler Foundation), Chloë Ruth Marshall (UCL Institute of Education, University College London, London) Giovanni Mento (University of Padua), Barbara Arfé (University of Padua). This work is going to be submitted to a peer-reviewed journal. and are going to be proposed as a paper to a peer-reviewed journal. The provisional title of the article is “Implicit Learning of Non-verbal Regularities in Deaf Children with Cochlear Implants”.

In this study, I contributed as follows: I discussed the design of the study with the other authors; I carried out the data collection with all the children; I analysed the data under the supervision of Giovanni Mento and Barbara Arfé; I wrote the paper that is being reviewed by the other authors before submission.

3.1 INTRODUCTION

In the previous chapter, two studies involving deaf children with cochlear implants between the age of five and eleven years old (study A) and hearing children of five, six, and seven-year-old (study B) were described. The aim of the studies was to investigate implicit sequence learning variability based on sensory experience (i.e. deafness) and development (i.e. age). The theoretical framework of the two studies is the auditory scaffolding hypothesis (Conway et al., 2009), and the research protocol was inspired by the study by Conway et al. (2011) so that the implicit learning task was based on the artificial learning grammar paradigm. The results of the two studies led to interesting findings, however, the task shared some limitations with the original paper by Conway et al. (2011). These limitations are both theoretical and methodological.

The first issue concerns the auditory scaffolding hypothesis itself. Since the participants involved in our and Conway’s studies experienced various degrees of language deprivation along with the auditory deprivation, and it is therefore not possible to attribute the cause of any impairment in the implicit learning of temporal or sequential regularities to auditory deprivation alone (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017). Variability in language outcomes likely depends on many instances on auditory deprivation. Thus, the two factors can have an additive effect.

Secondly, it is necessary to consider the possible interaction of other factors that may explain the results. For example, the differences in implicit learning between deaf and hearing participants may reflect a confound with explicit factors, such as verbal recoding and verbal rehearsal (von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018; Arfé, Fastelli, Mulatti, Scimemi, & Santarelli, 2017), that are less efficient in the deaf population (Pisoni, Kronenberger, Roman, & Geers, 2011). In fact, implicit learning measures of deaf and hard of hearing and normal hearing children are not significantly different in studies that used unfamiliar stimuli that could not be easily labelled (von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018), and the variability of their performances is better explained by age and explicit learning skills (Arfé, Fastelli, Mulatti, Scimemi, & Santarelli, 2017).

Gremp et al. (2019) investigated the possible interaction effect of the input nameability (the ease with which an input could be verbally recoded and labelled) and sequential processing in deaf and hard-of-hearing and normal hearing children using an experimental computer-based task. The deaf and hard-of-hearing group performed worse than the normal hearing group regardless of the condition (easily nameable VS difficult-to-name stimuli). The authors interpret these results as supporting the auditory scaffolding hypothesis. However, again, other important factors have been neglected. In particular, one-third of the deaf and hard-of-hearing participants in this study were reported to have an additional diagnosis of ADHD. Since the three primary characteristics of this condition are inattention, hyperactivity, and impulsivity, it is possible that this could have interfered with the execution of the task, contributing to some of the observed results.

The problem of confounding explicit factors is accompanied by other methodological issues. The evidence for a group difference provided by the artificial learning grammar paradigm as applied in the studies by Conway et al. (2011) and us relied largely on the observation that the typically hearing group reached a level of significance while the deaf group did not. This criterion has been criticised as it does not represent strong evidence for reliable group differences (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017).

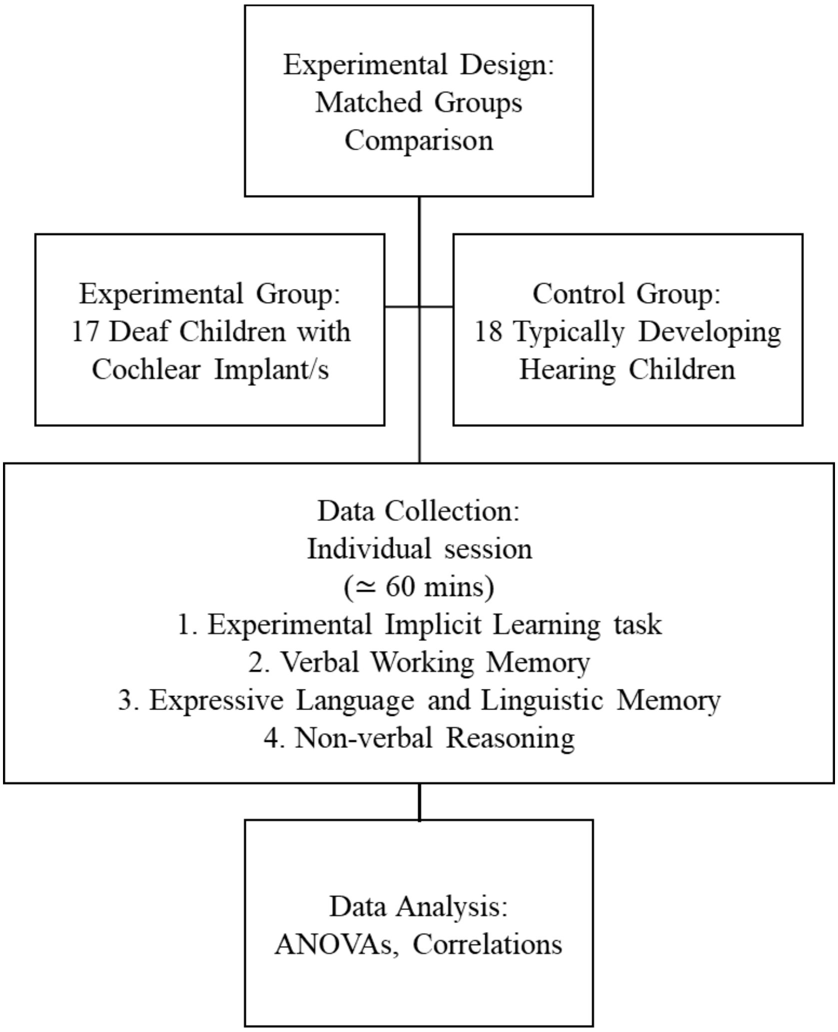
In general, research in this field suffers from the lack of standardised tasks to assess the implicit learning of regularities. The results obtained with different paradigms are not easily comparable with each other, making it difficult to draw clear-cut conclusions. In fact, it is possible that the broad variety of experimental tasks employed for this purpose so far could show a different grade of validity measuring the variable they intend to measure, namely implicit learning. Albeit different from one another, typical implicit learning experimental tasks are composed of two integrated phases. In the first phase (familiarisation), participants are exposed to strings of stimuli that follow a covert pattern of regularities. Then, during the second phase (test), the participant's implicit learning of the regularities is assessed. In other words, if participants' performance is better (i.e. better accuracy or faster reaction times, depending on the task) for the familiarised sequences, then this is considered as an indication of implicit learning. However, that means that a child with good memory skills could have good performance remembering and repeating both the familiarised and unfamiliarised sequences, and a consequent low score in implicit learning. That would make the task not very reliable for the assessment of implicit learning (Hall, Eigsti, Bortfeld, and Lillo-Martin, 2017).

In addition, to the best of our knowledge, implicit learning has been investigated using patterns of regularities that were based on only one level of complexity. Although this might suit experimental environments, everyday life implicit learning is most likely based on the ability to process and integrate various levels of complex information. Neuroimaging studies based on an auditory local-global violation paradigm found that 3 months-old infants already process sequences of auditory information at two hierarchical levels, one local (detail-focused) and one global (holistic) (Basirat, Dehaene, & Dehaene-Lambertz, 2014). For example, at the very early stages of language acquisition, infants rely on the processing of salient stimuli local probabilities (e.g. prosodic information such as rhythm or pitch) to segment the speech stream in word units. Yet, within the first months of life, infants become progressively more able to integrate the temporal and hierarchical structure of various linguistic elements and discover the global regularities, for example, the non-adjacent rules necessary for morphosyntactic acquisition (de Diego-Balaguer, Martinez-Alvarez, & Pons, 2016). The ability to process and integrate information dynamically, at both global and local levels, is necessary in order to process the general structure, make classification, and form generalizations in different contexts (D'Souza, Booth, Connolly, Happé, & Karmiloff-Smith, 2016).

In this chapter, I describe a study in which we investigate dynamic implicit learning in deaf children with cochlear implants using a simple reaction time task. The aim of this study is to contribute to the discussion about the auditory scaffolding hypothesis and provide complementary evidence regarding the relation between auditory deprivation and implicit learning of regularities. If there is a link between sequencing ability and hearing condition as proposed by the auditory scaffolding hypothesis, then deaf children with cochlear implants should perform worse than hearing children in a sequential statistical learning task because of their reduced auditory experience. We also aim to propose an assessment tool for implicit learning that can avoid confounding explicit factors. Our experimental task is designed to limit the interference of the explicit processes of working memory and has been already found reliable in a study involving hearing adults (Mento & Granziol, 2019). To avoid verbal recoding and rehearsal, the task relies on temporal regularities instead of sequences. That means that the participant is asked to respond to each stimulus individually instead of small groups (sequences) and this eliminates the possibility of using verbal recoding and rehearsal. In addition, stimuli are temporally distributed and presented in the same location on the screen, which avoids visuospatial working memory involvement. Finally, the temporal regularities used in our task are distributed on two levels, local and global, in order to assess the ability of our participants to implicitly process and integrate different levels of information. This allows us to investigate implicit learning on a higher level of complexity, not only assessing the ability to process and learn regularities, but also the ability to adapt behavioural responses to this implicit knowledge throughout the task. As the inherent structure of the task employed in this study require the participants to adapt their responses to the stimulus-onset-asynchrony (SOA) between the cue and the target appearance, as described in detail in the following “experimental design” section (see 3.2.1.2.1).

3.2 METHOD

Table 3.1. Scheme of the experimental design of the study.



3.2.1 PARTICIPANTS

Thirty-five children, 17 who are profoundly deaf and wear cochlear implants (mean age = 8;08, age-range = 5;03 - 11;07) and 18 normal hearing controls (mean age = 8;07, age-range = 5;02 – 11;04), participated in this study. Children were recruited in mainstream and special schools in London and the southeast of England. Non-verbal IQ was measured using Progressive Coloured Matrices (Raven, 2008) and all participants scored within the normal range (i.e., greater than 25th percentile). The two groups were matched by chronological age, gender, and socio-economic status (geographical area of residence, and parents' self-reported educational level and profession). Eighteen children (ten deaf) were monolingual native speakers of English, while seventeen children (seven deaf) had English as their dominant language despite being bilinguals. The linguistic background of all the participants is summarised in Table 3.2.

Table 3.2. Participants' linguistic background and parental socioeconomic status.

		Deaf	**Hearing**
Language	English (monolinguals)	10 (58.8%)	9 (50%)
	English (bilinguals)	7 (41.2%)	9 (50%)
SES	Number of unemployed mothers	4 (23.5%)	0 (0%)
	Number of unemployed fathers	1 (5.9%)	1 (5.6%)
	Number of mothers with a university degree	11 (64.7%)	14 (77.8%)
	Number of fathers with a university degree	10 (58.8%)	11 (61.1%)

Notes: Data based on voluntary parental reports.

Inclusion criteria included chronological age between 5 and 11 years old, English as the native and/or dominant language, and no record of cognitive, motor, or sensory impairment (with the exception of hearing loss for the deaf group). Children scoring <25th percentile on a test of non-verbal intelligence (Coloured Progressive Matrices; Raven, 2008) were excluded. Children in the deaf group all used cochlear implants. They all had a profound bilateral hearing loss (90 dB or greater) with onset by the age of 2;03 years (most of the children received the diagnosis within the first three months of life, only two children received after the second year), had been fitted with a cochlear implant in at least one ear by the age of four, and had been using the cochlear implants for a minimum of three years. Implantation was unilateral for twelve children and bilateral for five. All children were orally educated. Table 3.3 summarises the characteristics of the two groups. Participation was entirely voluntary. No benefits were offered in exchange for participation; however, all participants received a certificate as a thank you for their contribution. The study was approved by the Ethical Review Board of the Xth author's institution.

Table 3.3. Participants' characteristics.

	Deaf ($n = 17$)			Hearing ($n = 18$)				
Measure	M	(SD)	Range	M	(SD)	Range	$t(33)$	p
Age	97.65	(22.54)	64-141	96.83	(18.97)	62-137	-0.12	0.91
Age at Diagnosis	3.91	(9.13)	0-30	-	-	-	-	-
Age at Compensation[1]	19.24	(15.35)	2-49	-	-	-	-	-
Duration of Compensation[1]	78.41	(27.20)	42-128	-	-	-	-	-
Age at Implantation[2]	26.25	(15.29)	2-49	-	-	-	-	-
Duration of Implantation[2]	73.06	(28.26)	42-119	-	-	-	-	-

Notes: All measures are given in months; [1]First compensation either with HA or IC; [2]Cochlear Implantation.

3.2.1.1 PROCEDURE

Potential participants were identified by their teacher, and their families received an information sheet, a consent form, and a questionnaire. In order to participate, families of participants had to return the questionnaire and the consent form completed and signed. Children were asked to confirm their willingness to participate before starting the session. Children were assessed individually by one researcher (the first author). The assessment lasted for approximately one hour, with breaks provided as needed, and took place in a quiet room. The task order was fixed for all participants as follows: 1. Experimental implicit learning task; 2. Digit span (WISC-IV, Wechsler Intelligence Scale for Children-Fourth ed.; Wechsler, 2004); 3. Formulated sentences (CELF-4, Clinical Evaluation Language Fundamentals – Fourth ed.; Semel, Wiig, & Secord, 2006); 4. Coloured progressive matrices (CPM, Raven, 2008). Standardised scores were calculated for the last three tasks.

3.2.1.2 TASKS

3.2.1.2.1 Experimental design of the Simple Reaction Time task

Procedure

An experimental task adopted from Mento & Granziol (2019) based on a Dynamic Temporal Preparation (DTP) paradigm was used to assess participants' behavioural responses (reaction times and accuracy) in order to investigate their ability to implicitly learn and flexibly adapt their responses to the patterns in the presentation rates of the stimuli throughout the task.

E-prime 2 software (Psychology Software Tools, Pittsburgh, USA) was used to create and administer the task. The data collection apparatus consisted of a Samsung laptop with an Intel® Core™ i7, 4th generation processor, and a 15" IPS Quad HD+ (3200 x 1800) anti-glare screen. The resolution was set on 1280x768. The task consisted of speeded target detection and the paradigm is the same as described in Mento & Granziol (2019). Participants sat comfortably in front of the screen, holding the index finger of their dominant hand on the space bar, and were required to press the space bar as quickly as possible at target-occurrence.

Participants were given the following instruction:

> *"Hi! This is the BARBAPAPA family! Here is Barbapapa, Barbamama, and their seven children. The Barpapapas are playing hide and seek in the woods. Your job is to take a photo of them as soon as they appear in view of your camera. You can take a photo by pressing the space bar. Find them all! But take care, if you press the bar too soon or too late they will run away!"*

Before starting the experimental session, a short training of 60 trials (20 trials per local condition, explained below) was presented in order to ensure participants understood task instructions. Only during this training did participants receive feedback on their performance at the end of each trial according. The feedback depended on the accuracy of their responses, based on reaction times (RT). Specifically, a yellow emoticon with a neutral expression was displayed in case of anticipatory (before target onset) or premature (< 150 ms after target onset) responses; a yellow smiling emoticon was displayed in case of RT between 1000 and 1500 ms from the target onset; and a green smiling emoticon was displayed for RT between 150 and 1000 ms. No feedback was given during the experimental session.

Experimental design

Each trial began with the display of a visual cue followed by the presentation of a target stimulus that remained on the screen for a maximum of 5000 ms. The visual cue consisted of a black circle representing the lens of a camera (total size of the stimulus: 840 × 840 pixels, 144 dpi, 10.62° × 10.54° of visual angle). The target stimulus was displayed centrally within the camera lens and consisted of a picture of one character of the Barbapapa family, a cartoon created by Tison and Taylor in 1976. The inter-trial-interval (ITI) was randomly manipulated between 600 and 1,500 ms. Since the visual stimuli and the required response were always the same across the experiment; the only difference between conditions was the level of target predictability.

Local Predictive Context. To investigate the effect of the local prediction, a local predictive context was created by manipulating the stimulus-onset-asynchrony (SOA) between the cue and the target appearance. The SOA could vary trial-by-trial within each experimental block in three possible fixed intervals: short (500 ms), medium (1,000 ms), or long (1,500 ms). This manipulation was intended to investigate the local prediction as to the effect of the stimulus presentation rate on task performance.

Global Predictive Context. To investigate the effect of the global prediction, a global predictive context was created by manipulating the different probability distribution per each SOA interval in each block, as described below.

Short-biased Distribution (SB) block: in these blocks, the SOA distribution was biased towards the short SOA, meaning that the probability of having a short SOA was higher. The SOA frequency in SB blocks was 60%, 32%, and 8% for the short, medium, and long SOA, respectively.

Uniform Distribution (U) block: in this case an even distribution of the three SOAs was used, meaning that the frequency of each SOA in U blocks was about 33% for short, medium, and long SOA.

Long-biased Distribution (LB) block: in these blocks, the SOA distribution was biased towards the long SOA and therefore specular compared to the SB blocks. Specifically, the SOA frequency in LB blocks was 8%, 32%, and 60% for the short, medium, and long SOA, respectively. The structure of the experimental simple reaction time task for the evaluation of implicit learning skills is summarised in Table 3.4.

Table 3.4. Simple Reaction Time task structure.

		Local		
		short (500 ms)	medium (1000 ms)	long (1500 ms)
Global	Short-Biased (SB)	60%	32%	8%
	Uniform (U)	33%	33%	33%
	Long-Biased (LB)	8%	32%	60%

In the design of this study, SOA distribution (short, medium, or long) and block-type (SB, U, or LB) were manipulated to investigate the effect of local and global predictive contexts. The task consisted of a total of 9 blocks, three blocks per type (i.e., three SB, three U, and three LB). Each block included 30 trials, for a total of 270 trials. The total length of the experiment was approximately 15 minutes with short resting breaks given, if necessary, between blocks. In order to investigate the presence of group differences in relation to the ability to implicitly adjust behavioural performance in terms of speed (reaction times or RTs) and accuracy (percentages of not anticipated responses) as a function of either local or global predictive rules, no indication was given about between-block different probabilistic distribution, so that participants were not consciously aware of distribution changes. Block-type order was counterbalanced between subjects. This was to avoid spurious effects bias on performance due to the introduction of local or global fixed predictive contexts.

3.2.1.2.2 Standardised tasks

3.2.1.2.2.1 Digit Span (WISC-IV)

The Digit Span subtest of the WISC-IV (Wechsler, 2004) was administered to assess verbal working memory skills. This task is composed of two parts (forward and backwards). It requires the participant to repeat sequences of digits in the same order (forward task) first, and then in the reverse order (backward task) as they are presented by the examiner. Sequences progressively increase in length (from two to nine digits), and there are two trials of each length. A score of 1 is awarded to every trial correctly repeated by the participant. The task is discontinued if the participant fails to repeat both trials of the same length. For consistency of presentation, a computerised version of the task was used in this study, as recommended by Woods, Kishiyama, Yund, Herron, Edwards, Poliva, Hink, and Reed (2011). Digits from one to nine were pronounced by a native speaker of British English and digitally video-recorded, obtaining nine video tracks. The videos included the close-up of the speaker's full-face to facilitate lip-reading. Each track was then used to compose the standardised sequences and used in the trials at the presentation speed of one digit per second.

3.2.1.2.2.2 Formulated Sentences (CELF-4)

The Formulated Sentences task (CELF-4, Clinical Evaluation Language Fundamentals – Fourth ed.; Semel, Wiig, & Secord, 2006) was used as a measure of expressive language and linguistic memory. The participant is asked to formulate complete, semantically and grammatically correct, spoken sentences using given target words (e.g., car, if, because) and contextual constraints imposed by illustrations. The nature of the target words (e.g., nouns, adverbs, adjectives, correlative conjunctions, subordinating conjunctions) stimulates the production of sentences of increasing length and complexity (i.e., simple, compound, and complex sentences). These abilities reflect the capacity to integrate semantic, syntactic, and pragmatic rules and constraints while using working memory. A score of 2 is given for every complete sentence that is semantically and syntactically correct; a score of 1 is given for complete sentences with a correct structure and only one or two deviations in syntax or semantics; A score of 0 is given for incomplete or incorrect sentences. The starting point of the task is based on the chronological age of the participant, and the task is discontinued after a score of 0 in five consecutive trials. For the consistency and the clarity of the task delivery, each target word was produced by a native speaker of British English and digitally video-recorded. The videos included the close-up of the speaker's full-face to facilitate lip-reading. The videos at their natural speed were later used to administer the task in this study, following the same procedure as if they had been presented orally.

3.2.1.2.2.3 Coloured Progressive Matrices

Coloured Progressive Matrices were used to assess participants' non-verbal intelligence and reasoning ability (Raven, 2008). The task comprises three sets of 12 items each. The participant is asked to select a missing element from a 3×3 matrix in order to complete a pattern. A score of 1 is awarded for every correct trial. The raw scores can be converted to percentiles. All participants scored within the normal range on this task.

3.3 RESULTS

CPM (Raven, 2008) scores were used to control the participants' non-verbal intelligence. Although all participants' non-verbal IQ was within the normal range (i.e., greater than 25th percentile), deaf children's standard scores in the CPM (Raven, 2008) were significantly lower than the hearing $F(1, 32) = 15.14$, $p < .001$, $\eta_p^2 = .32$. ANOVAs with age covariate were run to investigate the differences between deaf and hearing participants in verbal working memory (digit span forward and backward), and language (formulated sentences). Table 3.5 summarizes the results of these analyses. Hearing children performed significantly better than cochlear implanted deaf children in both forward and backward digit span, indicating greater verbal working memory skills. The formulated sentences scores also differed significantly between the groups, whereas the difference was not significant for category switching scores ($p = .13$). The next analysis compared performances of the two groups of children at the simple reaction time task.

Table 3.5. Standardised Tasks means.

	Deaf ($n = 17$)		Hearing ($n = 18$)				
Measure	M	SD	M	SD	F	p	η_p^2
Digit Span Forward	5.82	2.10	7.89	2.06	13.04	.001	.29
Digit Span Backward	4.71	2.54	7.06	1.47	18.47	<.001	.37
Formulated Sentences	5.00	4.33	9.67	3.88	15.51	<.001	.33

Notes: Age covariate. Effect sizes (η^2) express the magnitude of the difference between groups. WISC-IV Forward Digit Span, raw score; WISC-IV Backward Digit Span, raw score; CELF-4 Formulated Sentences, scaled score.

3.3.1 DATA ANALYSIS OF THE SIMPLE REACTION TIME TASK

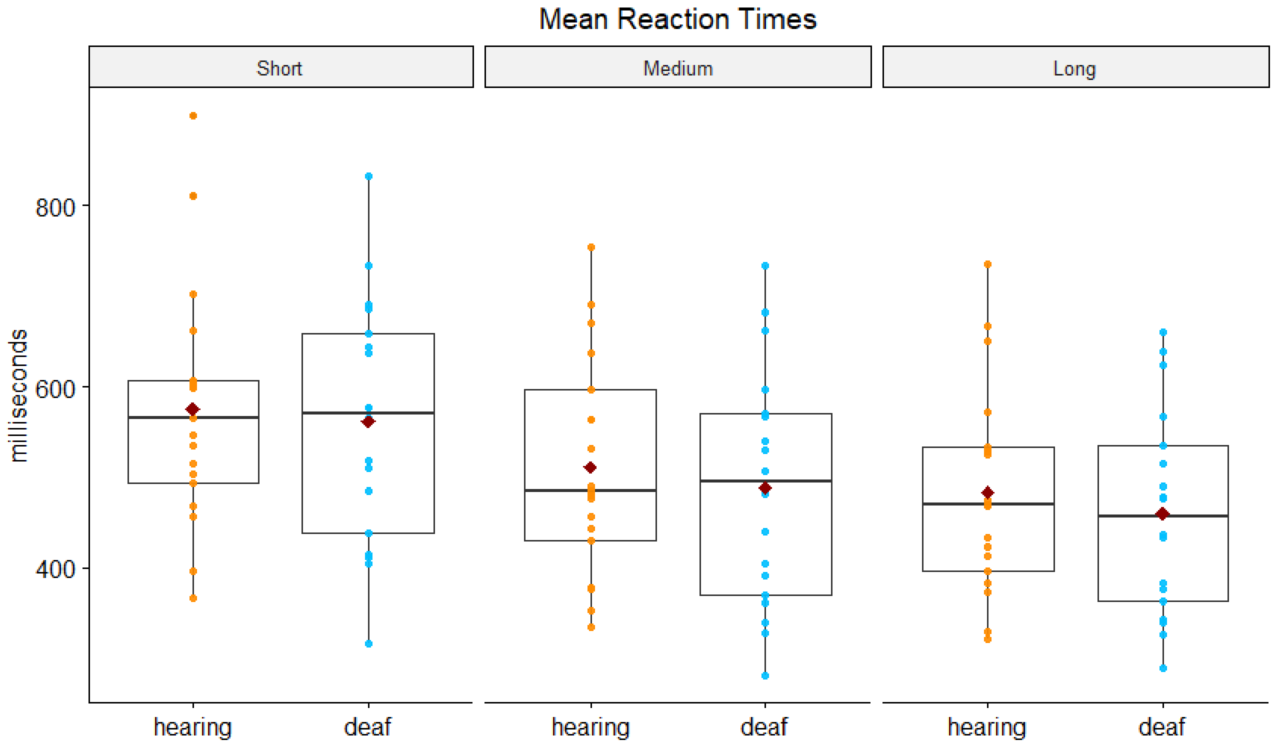
Two independent sets of analyses were run to assess children's performance based on accuracy and reaction times. Group (deaf or hearing), Local level (short vs. medium vs. long), and Global Predictive Context (short-biased vs. uniform vs. long-biased) were considered as independent variables. Mean RTs (milliseconds) and accuracy mean (percentage) were the dependent variables. Omissions, anticipated responses (within the cue and 150 ms after target onset), and delayed responses (1,500 ms after target onset) were considered errors and excluded from the analysis.

Reaction Times. Mean RTs scores and standard deviations for each condition and group are reported in Table 3.6 and plotted (per SOA condition) in Figure 3.1. RTs data were analysed using a 2 × 3 × 3 mixed ANOVA. Age was included as a covariate. There were no statistically significant differences between group means $F(1, 32) = .51$, $p = .48$, $\eta_p^2 = .02$. Also, all other main effects and interactions were non-significant $F \leq 2.20$, $p \geq .14$, $\eta_p^2 \leq .06$. Results of the Spearman correlation indicated a significant negative association between age and local predictive contexts, respectively $r_s = -.64$, $p < .001$ with short SOA, $r_s = -.68$, $p < .001$ with medium SOA, and $r_s = -.69$, $p < .001$ with long SOA. No significant correlation was found between RTs and hearing history (i.e. duration of the hearing compensation) when age was controlled.

Table 3.6. Means and Standard Deviations for Reaction Times (milliseconds).

		Condition								
		Short-Biased			Uniform			Long-Biased		
		short	medium	long	short	medium	long	short	medium	long
Group	Deaf	515.77	436.85	443.09	555.41	487.44	456.65	611.19	536.67	484.61
		(125.98)	(127.75)	(116.36)	(137.59)	(142.22)	(120.16)	(181.30)	(158.19)	(143.37)
	Hearing	544.79	500.82	461.46	589.44	517.54	496.46	611.58	536.58	505.71
		(132.67)	(115.88)	(121.68)	(124.65)	(137.29)	(129.72)	(173.04)	(113.30)	(115.89)

Figure 3.1. Reaction Times means per SOA condition (local context).



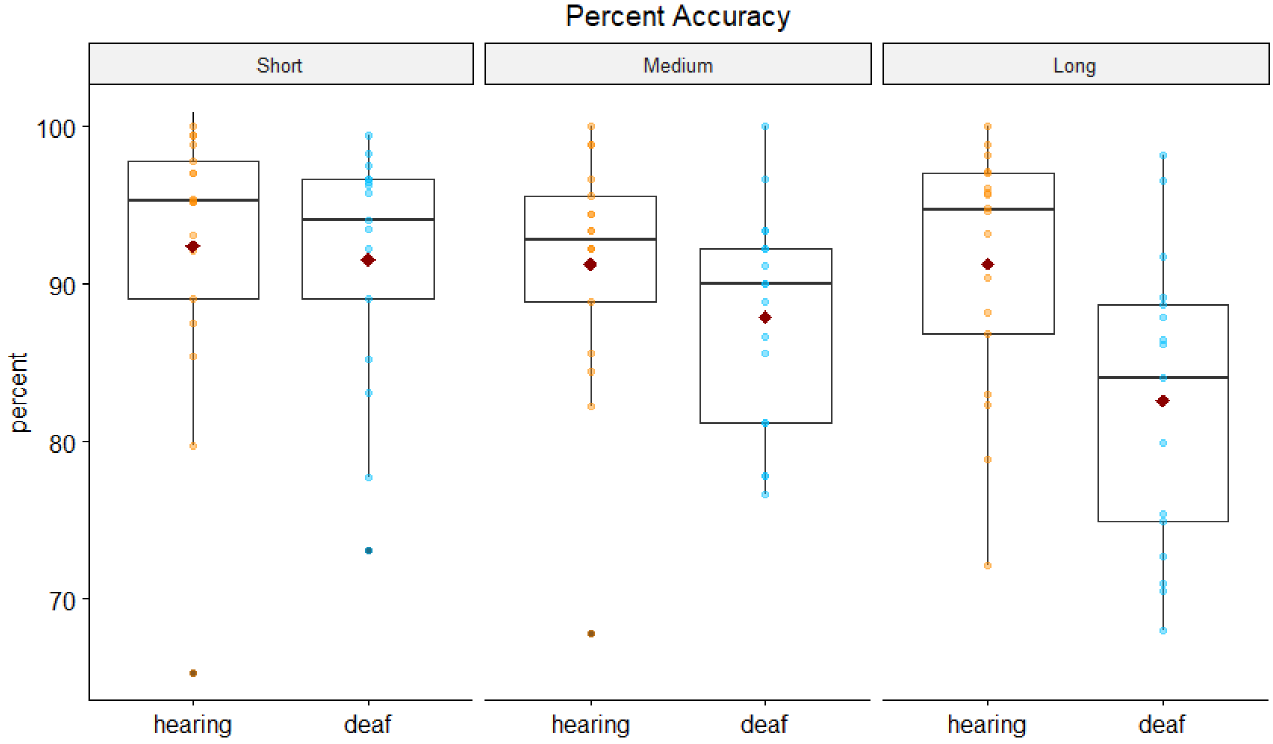
Notes: Horizontal lines indicate medians; red rhombuses indicate means.

Accuracy. Accuracy mean for each condition and group are reported in Table 3.7 and plotted (per SOA condition) in Figure 3.2. Accuracy data were analysed using a 2 × 3 × 3 mixed ANOVA. Age was included as a covariate. There was a statistically significant difference between group means $F(1, 32) = 4.14$, $p = .05$, $\eta_p^2 = .09$. Mauchly's test indicated that the assumption of sphericity was violated for local predictive context ($\chi^2(2) = 10.56$, $p = .005$), and for the interaction between local and global predictive contexts ($\chi^2(9) = 21.91$, $p = .009$), therefore the degrees of freedom were corrected using Greenhouse-Geisser estimate ($\varepsilon = .78$ and $\varepsilon = .75$ respectively). The global predictive context did not interact with group $F(1.78, 56.92) = .54$, $p = .57$, $\eta_p^2 = .02$, while a significant local predictive context x group interaction emerged $F(1.55, 49.66) = 6.73$, $p = .005$, $\eta_p^2 = .17$. All other main effects and interactions were non-significant $F \leq 1.55$, $p \geq .22$, $\eta_p^2 \leq .04$. The task was accessible for all ages, in fact, we did not find a significant correlation between Δ accuracy (average differences in accuracy between long and short SOA of all blocks) and age $r_s = .18$, $p = .30$.

Table 3.7. Means and Standard Deviations for Accuracy (percentage).

		Condition								
		Short-Biased			Uniform			Long-Biased		
		short	medium	long	short	medium	long	short	medium	long
Group	Deaf	89.76 (8.07)	85.29 (9.58)	81.37 (16.54)	91.77 (7.37)	90.00 (6.66)	82.35 (9.11)	93.14 (11.87)	88.43 (8.43)	83.99 (8.38)
	Hearing	92.70 (6.71)	88.52 (9.16)	91.67 (10.31)	91.85 (8.65)	91.67 (9.02)	91.11 (8.93)	92.59 (14.26)	93.52 (7.18)	91.05 (8.62)

Figure 3.2. Percent Accuracy per SOA condition (local context).



Notes: Horizontal lines indicate medians; red rhombuses indicate means.

Δ accuracy was also not significantly correlated with the duration of hearing compensation $r_s = .14$, $p = .59$, nor with other tasks' scores (correlations between Δ accuracy and other tasks are displayed in Table 3.8).

Table 3.8. Correlations.

	Δ Accuracy	Digit Span Forward	Digit Span Backward	Formulated Sentences
Δ Accuracy	-			
Digit Span Forward	-.27	-		
Digit Span Backward	-.16	.79***	-	
Formulated Sentences	.003	.58***	.68***	-

Notes: Correlations scores refer to Spearman's rho.
* *p* < .05, ** *p* < .01, *** *p* < .001, unflagged values are *ns*.

3.4 DISCUSSION

The auditory scaffolding hypothesis suggests that linguistic variability showed by deaf and hard-of-hearing children might depend on a deficit in their implicit learning skills (Conway et al., 2009). In the previous chapter, I described the investigation of implicit sequence learning in deaf (study A) and hearing (study B) children. The aim of the studies described in chapter 2 was the investigation of implicit sequence learning variability based on altered sensory experience (i.e. lack of auditory stimulation) and development (i.e. age). The results of the two studies suggest that implicit and explicit sequence learning are two separate processes, and both take place during learning. Both deaf and hearing children seem to use these processes, however, their efficiency might differ. Unfortunately, due to some limitations related with the paradigm used (see the introduction of this Chapter in section 3.1), it was not possible to draw clear-cut conclusions about the effect of auditory deprivation on implicit learning.

The aim of the study described in this chapter was to gather more evidence that can contribute to the discussion concerning the auditory scaffolding hypothesis by the investigation of dynamic implicit learning of temporal regularities in cochlear implanted deaf children. In order to reach this goal, we used an experimental task that can be used as an assessment tool for implicit learning. By using temporally distributed stimuli that appear on the same location on the screen, this task avoids the risk of unwanted confounding results ensuing from the interference of the explicit processes of working memory, namely verbal recoding, verbal rehearsal, and visuospatial working memory. Temporal regularities are distributed on two levels, local and global, as the manipulation of the stimulus-onset-asynchrony (SOA) requires the adaptation of the behavioural responses throughout the task, allowing the investigation of the ability to process and learn implicit regularities.

The results obtained show similar reaction times between deaf children with cochlear implants and normal hearing children. The ability of the two groups of children to adapt their response time to the small changes in the presentation rates of the stimuli throughout the task was comparable. In other words, both groups were able to implicitly process the small local differences in the presentation rate and implicitly learn the embedded regularities of each block’s global predictive context, optimising their responses during the task. Performance at this task was unrelated to hearing history as also suggested by correlational analyses.

As the results of the first studies (chapter II), also these results are therefore not supporting the auditory scaffolding hypothesis (Conway et al., 2009) since children with cochlear implants who participated in our study do not seem to have a deficit in implicit learning of regularities. Although it remains possible that children who endure a longer period without language and/or auditory access might demonstrate impaired implicit sequence learning, our results are consistent with the growing body of literature showing that implicit learning is not impaired by a lack of auditory stimulation (Arfé et al., 2017; Giustolisi & Emmorey, 2019; Hall et al., 2017; Klein et al., 2018; von Koss Torkildsen et al., 2018).

Given that children with cochlear implants scored significantly behind the normal hearing children in the verbal tasks that involved explicit processing and knowledge (verbal rehearsal and elaboration for digit span forward and backwards, and linguistic skills for the formulated sentences task, respectively) these results suggest that implicit learning is independent of explicit learning and not significantly affected by poor auditory input. Strong and significant negative correlations between RTs and age suggest that children’s target detection speed (ability to respond fast to the target) progressively increases with age. This result is consistent with the developmental trend in cognitive processing speed that is found in literature and that results in exponentially faster reaction times over age, during childhood and adolescence (Akshoomoff, 2002; Hale, 1990). In our study, reaction times showed the classical “foreperiod effect” (Niemi and Naatanen, 1981; Los, Knol, & Boers, 2001) and were faster in the long SOA condition for both groups if compared with short and medium SOA, due to the increased perceived probability of target appearance over time, once the short and the medium SOA limits were passed.

Our data also show an effect of participants' "response readiness" (Näätänen, 1971) according to which the duration of the intervals between the warning stimulus and the imperative stimulus, as well as the intertrial variability, affect the participant's state of nonspecific preparation to respond at the moment the imperative stimulus is presented (Los, Knol, & Boers, 2001). A high level of response readiness enables the participant to exert a smaller effort to reach the level of motor activation required for the successful initiation of a response (Näätänen, 1971), meaning faster reaction times.

Even if there was no difference between groups for the reaction times, adapting the response speed to the task requirements was detrimental for cochlear implanted deaf children's accuracy in the long SOA condition. We did not find this result for hearing children, who could consistently maintain the same level of accuracy throughout the task. In other words, the performance of deaf children with cochlear implants was more affected by the local conditional probability of target occurrence (foreperiod effect) compared to normal hearing children. However, this was not due to a poor response readiness in this group of deaf children; in fact, we registered generally faster response times in comparison with the normal hearing children.

This result is not consistent with a previous study that found slower RTs in children with cochlear implants compared to normal hearing children, in which this result was interpreted as indicative of poor sequential processing, rather than sequential learning (Klein et al., 2018). Other studies involving people with early deafness without prostheses or implants found that simple reaction times (detection) for visual stimuli are faster than in the normal hearing (e.g., Pavani & Bottari, 2012). It has been hypothesised that faster reactivity to the visual events in deaf individuals may primarily serve the purpose of triggering exploratory behaviour and detecting and reacting to discontinuities in order to orient the responses failing the auditory system. However, since our participants do have access to sound, this question remains open for future research.

We argue that the struggle to control response readiness, overriding a planned or already initiated action, might depend on weak inhibitory control in cochlear implants users and hard-of-hearing children (Bari & Robbins, 2013). This is consistent with other studies that found poorer executive functions in deaf and hard-of-hearing children (Beer, Kronenberger, Castellanos, Colson, Henning, & Pisoni, 2014), even after controlling for non-verbal intelligence and speed of processing (Botting, Jones, Marshall, Denmark, Atkinson, Morgan, 2017).

Study limitations and future directions. Unfortunately, we did not include any assessment of executive functions in the study protocol before starting the data collection. This represents a study limit because we did not have an independent measure of inhibition skills nor could control for children's switching skills. It could be possible that those profoundly deaf children with cochlear implants who were better at switching adapted better to the inherent variations of the task, getting better performance. This hypothesis requires to be further investigated in future studies in which we suggest including an assessment of executive functions, inhibitory control in particular.

3.5 CONCLUSIONS

Overall, our results do not support the hypothesis that a lack of auditory stimulation affects implicit learning or processing of sequential or temporal regularities. Deaf and typically hearing children participating in our study show comparable abilities to implicitly process and learn the regularities embedded in our task. Although we cannot be sure that this data can be extended to all children with profound deafness, it is interesting that is being replicated in various studies involving cochlear implants users.

Given the importance of implicit sequence learning ability for many aspects of linguistic development, it is good that it is independent of the hearing status. This also suggests, however, that the great variability in language outcomes consistently found in many studies with deaf children with cochlear implants cannot be explained by an implicit learning or implicit processing deficit in this population, and its causes need to be further investigated.

Our results suggest that other neurocognitive functions, such as inhibitory control, might have a role mediating implicit learning of regularities and the execution of an explicit response. This hypothesis should be considered for investigation in future studies involving deaf participants.

Despite the important contribution of the studies that have investigated implicit sequence learning in the deaf people with cochlear implants, it is necessary to do keep investigating the various cognitive processes and their possible interactions to explain the great linguistic variability that is observed in this population after receiving cochlear implantation. This could contribute to setting more suitable conditions to support deaf people to obtain the best language and learning outcomes.

OVERALL CONCLUSIONS OF PART I

In the first part of this manuscript, I described the theoretical frame of this PhD project (Chapter I) and the two studies (Chapter II and Chapter III) that represent the theoretical foundations on which our intervention project is based. The aim of this part was to explore implicit and explicit sequence learning processes involved in language acquisition taking into account the auditory scaffolding hypothesis.

In chapter II, we involved a group of deaf children with cochlear implants and a large sample of hearing children in order to explore the effects of auditory experience and age on implicit sequence learning. The task was based on the artificial grammar learning paradigm. If the auditory scaffolding hypothesis is right, then deaf children should perform worse than hearing children in the sequence learning task because of their reduced auditory experience, and their performance should be correlated with linguistic outcomes. Furthermore, if implicit learning is developmentally variant, the performance of typically developing children at the implicit sequence learning task should get better with age. Our results suggest that as soon as children start using explicit learning processes efficiently, implicit sequence learning processes seem masked and are harder to be detected. The two processes are independent and seem to be used by both cochlear implanted deaf children and typically hearing children in order to process and maintain sequential information.

In chapter III, we aim to gather complementary evidence regarding the relation between auditory deprivation and implicit learning of regularities in deaf children with cochlear implants, avoiding confounding results with explicit factors. The task is based on the simple reaction times paradigm. Our results suggest that our young deaf and typically hearing participants show comparable abilities to implicitly process and learn temporal regularities of visual inputs when the involvement of explicit sequence learning factors is minimised. A lack of auditory stimulation does not seem to affect general implicit learning or processing abilities for sequential or temporal regularities.

In sum, our results are not consistent with the *auditory scaffolding hypothesis* proposed by Conway and colleagues (2009). Our overall findings suggest that sequence learning includes both implicit and explicit learning processes, and whilst receiving poor auditory stimulation have a direct effect on the ability to actively manipulate verbal inputs using explicit learning processes, it does not seem to affect implicit learning processes.

This does not mean, however, that implicit learning processes could or should be ignored in rehabilitation practice. Given the importance of implicit sequence learning ability for many aspects of linguistic development and its interaction with explicit learning processes, both these aspects must be taken into account when training is planned. For this reason, we propose a serious game-based training aiming to improve both implicit and explicit sequence learning processes. This represents a cutting-edge approach to the training of cognitive abilities related to language that could help all the children that are struggling with sequence learning (Arciuli & von KossTorkildsen, 2012). The development and user experience assessments of this tool are described in the following part of this manuscript.

PART II

The Game Development and Evaluation, and the User Experience Assessment (UXA) described in Part II of this thesis (Chapter IV and Chapter V) contributed to a conference paper published within the proceedings of the 13th edition of the "CHITALY", the Biannual Conference of the Italian SIGCHI Chapter (Padua, September 2019). The paper has been resulting from the collaboration of the following authors: Ornella Mich (Bruno Kessler Foundation), Ambra Fastelli (University of Padua & Bruno Kessler Foundation), Elisa Armellini (Bruno Kessler Foundation), Barbara Arfé (University of Padua).

For this part, I contributed as follows: I discussed the design of the study and the mini-games with the other authors; I created the evaluation protocol used in the data collection; I carried out the data collection with the deaf children with cochlear implants and the hearing children, I also co-supervised (with Barbara Arfé) the master student who collected children with dyslexia's data; I summarised the results of the evaluation under the supervision of Barbara Arfé; I contributed to writing and reviewing the paper.

CHAPTER IV

THE DESIGN OF SELEDE: A SERIOUS GAME FOR SEQUENCE LEARNING TRAINING

4.1 INTRODUCTION TO SERIOUS GAMES FOR COGNITIVE TRAINING

The concept of “*serious gam*e” refers to game-based learning or to games that possess a higher non-entertainment purpose (e.g. for rehabilitation) beyond being fun and enjoyable. They are usually based on video-games console technologies (e.g. computers, tablets, smartphones) and their use is applied to several fields: healthcare, military, public sector, training, politics, religion, art, etc. (Laamarti, Eid, & Saddik, 2014; Susi, Johannesson, & Backlund, 2007). Serious games take advantage of the boost of motivation given by the challenging, enjoyable, and rewarding nature of games (Greitzer, Kuchar & Huston, 2007; Linehan, Kirman, Lawson & Chan, 2011) in order to support education or rehabilitation of the user. For example, serious games can support the development or the training of technical, social, cognitive, perceptual or motor skills, promote the acquisition of knowledge, or abet behavioural and affective/motivational modifications (e.g. confidence, self-efficacy, attitudes, preferences, dispositions) or physiological change (Connolly, Boyle, MacArthur, Hainey & Boyle, 2012; Garris, Ahlers & Driskell, 2002; Susi, Johannesson & Backlund, 2007).

The most popular examples of serious games aiming to train cognitive skills that are available in the commercial sector, are Lumosity[1], MentalUp[2], Einstein Brain Trainer HD[3], Brainturk Lite[4], Peak[5], Brain Wars[6] and Cogmed Working Memory Training[7]. In particular, Cogmed includes several serious brain training games, specifically for improving the information-processing speed and the efficiency in memory, attention and problem-solving.

Cogmed Working Memory Training is a training program based on several serious games to train cognitive processes such as working memory (WM). Its use is supposed to create cascading

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[1] www.lumosity.com
[2] www.mentalup.net
[3] www.bbg-entertainment.com/games/
[4] www.brainturk.com
[5] www.peak.net.
[6] https://play.google.com/store/apps/details?id=jp.co.translimit.brainwars&hl=it
[7] https://www.cogmed.com/category/color-bar/program/training-products.

beneficial effects on cognitive functionality and behaviour. The game has three versions including similar tasks yet with different interfaces depending on the final users: *Cogmed JM* for pre-schoolers, *Cogmed RM* for school-aged children, and *Cogmed QM* for adults. The exercises are meant to train working memory at the optimal level of difficulty, so the game complexity is adapting to the user's performance. The games can run on all platforms and operating systems and comprise of auditory tasks (e.g. remember sequences of letters), visuospatial tasks (e.g. remember the position of a series of floating asteroids), or a combination of the two (e.g. associate a visual stimulus with a certain letter). The full training requires 25 sessions lasting 35-40 minutes over five weeks of time. Cogmed RM is designed for children with typical development, however, Kronenberger, Pisoni, Henning, Colson, and Hazzard (2011) used it to train working memory in nine deaf children with cochlear implants aged 7-15 years. General improvements in working memory and language skills were recorded at the end of the training. Children's performance on most exercises improved, yet the follow-ups indicated that the magnitude of working memory improvement was slightly reduced after one month, and more substantially after six months.

These findings suggest that training based on serious games has the potential to improve explicit learning processes like working memory, and that may produce benefit on some aspects of memory and language learning in deaf children with cochlear implants.

Research suggests that the integrative training of explicit and implicit processes focused on both these core aspects of language development could target linguistic skills using a wider approach. These novel language interventions could be beneficial for deaf children who still present language delays after receiving cochlear implants, arguably boosting their sequence learning abilities and improving language development (Deocampo, Smith, Kronenberger, Pisoni, & Conway, 2018) and literacy abilities (Giustolisi & Emmorey, 2019). However, this kind of training is not yet available.

In this chapter, I describe the design, development, and user's experience assessment of SELEDE (SEquence LEarning for DEaf children): a digital serious-game that consists of three novel mini-games (SELEDE's logo is portrayed in Figure 4.1). SELEDE is designed to train implicit and explicit sequence learning processes in deaf children with cochlear implants who are attending the last years of kindergarten or primary school.

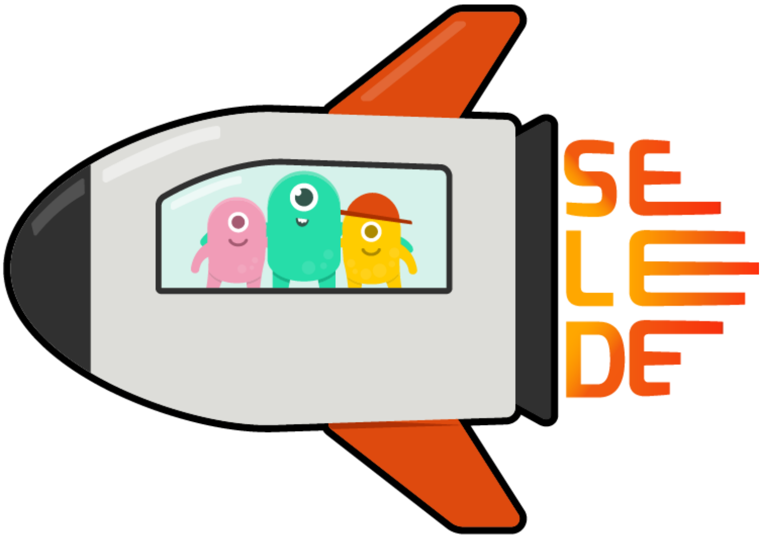


Figure 4.1. Logo of SELEDE.

4.2 IMPLICIT AND EXPLICIT SEQUENCE LEARNING PROCESSES

As described in Part I of this manuscript, language learning is a complex task that involves both implicit and explicit learning processes. Implicit sequence learning refers to the process of implicitly extracting, elaborating, and learning frequently occurring patterns in temporal or sequential stimuli. It is a domain-general mechanism that operates across domains and applies to the elaboration of regularities of sequences in different modalities from an early age. For example, within the first week after birth, neonates are able to process and discriminate visual sequences (Bulf, Johnson, & Valenza, 2011), and automatically extract statistical properties of the speech input from a continuous stream of syllables (Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009). It is a primary learning process that happens spontaneously and without awareness as a consequence of mere exposure to the stimuli (Batterink, Reber, Neville, & Paller, 2015).

At a young age, language acquisition mostly relies on implicit learning of recurrent linguistic regularities. Implicit sequence processes contribute the acquisition of many aspects of spoken language, from phoneme discrimination that allows word segmentation, to the elaboration of statistical regularities in mappings orthographic forms, and to the processing of frequent co-occurrences between words that contribute to lexical-semantic networks (Saffran, 2003). They also contribute to reading (for reviews: Arciuli, 2018; Sawi & Rueckl, 2019) in languages with deep (e.g., English; Arciuli & Simpson, 2012) and semi-transparent (e.g., Norwegian; von Koss Torkildsen, Arciuli, & Wie, 2019) orthographies.

Implicit learning differentiates from explicit learning, which involves active mnemonic strategies and explicit processes of elaboration of the stimuli. Verbal working memory is the fundamental explicit mechanism for speech and language processing and learning, so that better working memory skills are closely linked to improvement in speech and language skills with age (Pickering & Gathercole, 2001; Pisoni, Conway, Kronenberger, Henning, Anaya, 2010). Verbal working memory relies on active mnemonic strategies to maintain information through the use of verbal encoding and verbal repetition (i.e. subvocal verbal rehearsal). Verbal rehearsal relies on the phonological encoding of both verbal and non-verbal material and the strengthening of phonological memory traces, through repetition, to prevent them from rapid decay (Baddeley, 1986). Usually, this strategy is not spontaneously employed by typically developing young children before 6 or 7 years of age (Gathercole, 1998), while deaf and hard-of-hearing children start using it about 3-4 years later (Bebko & McKinnon, 1990) and are less efficient (Bebko, LaCasse, Turk, & Oyen, 1992; Hall & Bavelier, 2010; Harris & Moreno, 2004).

4.2.1 IMPLICIT SEQUENCE LEARNING ASSESSMENT

To our best knowledge, there is not yet a standardised task for the systematic assessment of implicit sequence learning. However, tasks used in research for this purpose usually have the three following characteristics:

1. Participants are exposed to a rule-governed environment. Learning conditions must be incidental, meaning that the participant must not be aware of the underlying structure of the task nor of its purpose of measuring SL. In order to limit the involvement of explicit processes (e.g. verbal rehearsal), the right task design is fundamental. Factors like stimuli presentation rate (Arciuli, Torkildsen, Stevens & Simpson, 2014; Bertels, Destrebecqz & Franco, 2015), stimuli nameability (Gremp, Deocampo, Walk, & Conway, 2019), and instructions delivery (von Koss Torkildsen, Arciuli, Haukedal, & Wie, 2018) that may prompt explicit strategies to perform the task and affect the results, presumably by favouring the acquisition of explicit knowledge (Bertels, Destrebecqz, & Franco, 2015);
2. Measures of participants' performance should track the learning process. The most prominent tasks in the extant literature are based on two paradigms, the Artificial Grammar Learning (AGL) and the Serial Reaction Time (SRT). The AGL tasks are serial recall tasks in which participants are exposed to sequences of stimuli and need to recall them straight after each sequence presentation. Each stimulus is covertly generated by an underlying grammar. The task comprises of two seamlessly integrated phases: the learning phase and the test phase. All sequences of the learning phase follow the same grammar (set of succession rules), whereas, the novel sequences in the test phase can be either generated according to the trained grammar or an untrained grammar. The better recall of the sequences based on trained grammar is considered as a measure of implicit learning. In SRT tasks, participants are instructed to respond to a target as fast as possible (usually a visual stimulus appearing on a monitor) by pressing a button. Targets can be presented either in a repeated order (sequence blocks) or in random order (random blocks). Reduced reaction times across successive sequence blocks compared with the reaction times when a random block is introduced is considered as a measure of implicit learning;

3. The participants' awareness of the knowledge they have acquired during the task is assessed at the end of the session. Participants should not be able to explicitly report any knowledge to the research team.

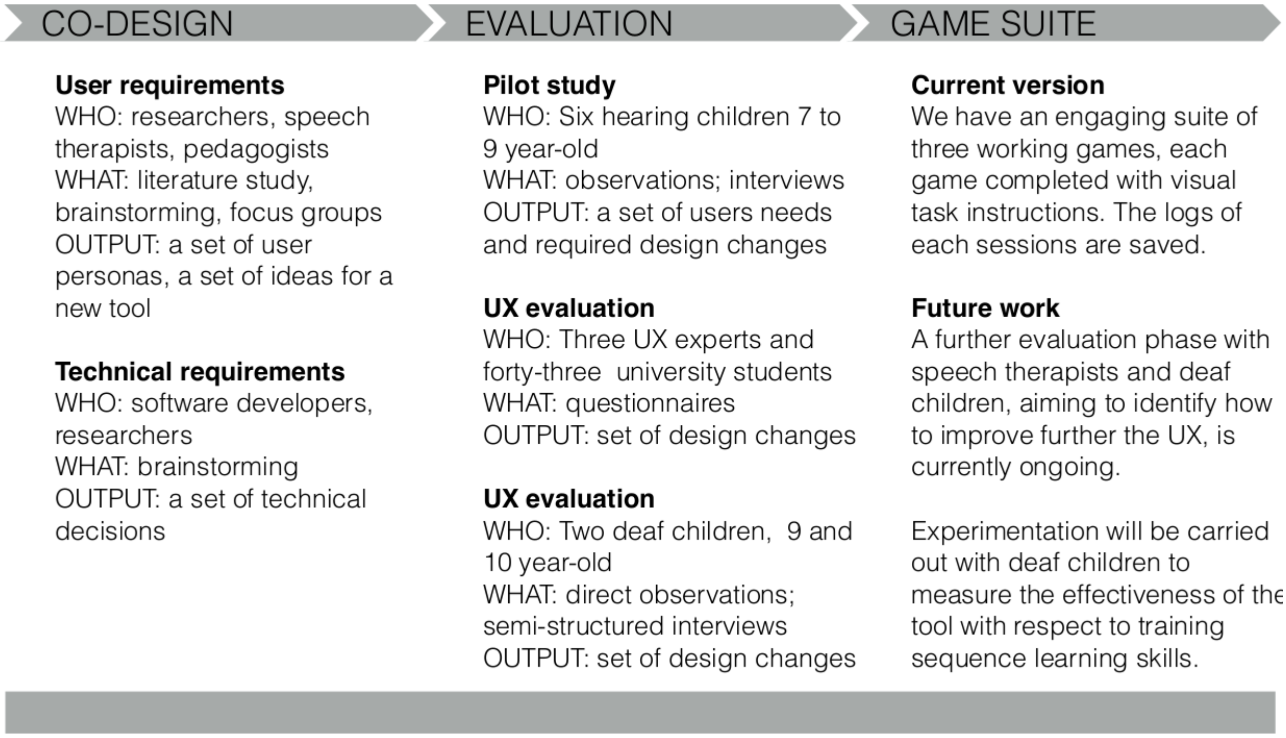
4.2.2 EXPLICIT SEQUENCE LEARNING ASSESSMENT

On the contrary, there are plenty of standardised tasks designed to assess explicit learning of different kinds of sequences: haptic, visuospatial or auditory (either linguistic or non-linguistic). Usually, in the tasks employed in research for this purpose, participants are presented several series of stimuli and are explicitly instructed to recall and/or repeat the sequences immediately after their presentation. These tasks generally involve the implementation of strategies that are consciously used in order to remember the sequences. A classic example is the digit span forward task, which requires the simple reproduction of sequences of digits. Participants usually rehearse the digits in their minds in order to hold the stimuli in their working memory for long enough to accomplish the task. Since the task requires no further manipulation of the stimuli, it is considered to reflect explicit working memory processes, namely the verbal rehearsal (for verbally codable items). Tasks like the digit span backwards, that requires to recall the sequences of stimuli in the opposite order to that followed during the presentation, require manipulation of the stimuli together with the simultaneous retention are considered to reflect verbal working memory executive elaboration.

4.3 SEQUENCE LEARNING TRAINING: SELEDE

Here we propose a prototype for a serious game for sequence learning training in deaf children with cochlear implants (SELEDE) specifically designed to train both implicit and explicit aspects of sequence learning. SELEDE was designed with a *co-design* approach (Norman, 2013), which is a methodology actively involving all stakeholders related to the target (e.g. researchers, designers, end-users and practitioners) during the entire design process (see Table 4.1). This approach is inserted in an iterative process alternating implementation, re-design and evaluation phases, and favours the creation of products and services that are usable and better meet the users' needs (Norman, 2013).

Table 4.1. A summary of the SELEDE design and evaluation steps.



CO-DESIGN	EVALUATION	GAME SUITE
User requirements WHO: researchers, speech therapists, pedagogists WHAT: literature study, brainstorming, focus groups OUTPUT: a set of user personas, a set of ideas for a new tool	**Pilot study** WHO: Six hearing children 7 to 9 year-old WHAT: observations; interviews OUTPUT: a set of users needs and required design changes	**Current version** We have an engaging suite of three working games, each game completed with visual task instructions. The logs of each sessions are saved.
Technical requirements WHO: software developers, researchers WHAT: brainstorming OUTPUT: a set of technical decisions	**UX evaluation** WHO: Three UX experts and forty-three university students WHAT: questionnaires OUTPUT: set of design changes	**Future work** A further evaluation phase with speech therapists and deaf children, aiming to identify how to improve further the UX, is currently ongoing.
	UX evaluation WHO: Two deaf children, 9 and 10 year-old WHAT: direct observations; semi-structured interviews OUTPUT: set of design changes	Experimentation will be carried out with deaf children to measure the effectiveness of the tool with respect to training sequence learning skills.

The SELEDE serious game is composed of three mini-games that can be used by any child, but are specially designed for children with hearing loss, for example, instructions are visual and there is a limited use of language (written inputs only include titles and the sign *"do you wish to continue?"* after a pause). The problem space and the characteristics of our end-users (deaf children with cochlear implants) were analysed through our studies (Part I of this manuscript) and through the creation of five player-personas and scenarios referring to 5 to 11 years-old deaf children with cochlear implants (Armellini, 2017). The aim of the creation of these personas is to imagine problematic scenarios in which the users meet an issue that could impede them to interact with the game interface (i.e. to play) which consequently also prevents them to fully engage in the training and enjoy the games. For example, one of the personas is Alessandro, a five-year-old boy who is unable to read and who do not like games in which the instructions involve written text.

Based on this preliminary phase, a complete list of requirements, both *functional* and *non-functional*, was compiled.

4.4 REQUIREMENTS

4.4.1 FUNCTIONAL REQUIREMENTS

As Salen, Tekinbaş, and Zimmerman (2004) wrote: *“Games are as complex as any other form of designed culture; to fully appreciate them means understanding them from multiple perspectives”* (page 14). The “functional requirements” correspond to the game functions, that is what the game is supposed to do. The general game requirements that follow (section 4.5.1.1) apply to all games and are partially implemented in SELEDE. In addition, given the aim of SELEDE, our serious game should present specific requirements related to the cognitive process that are the focus of the training, namely the sequence learning abilities. These are referred to as sequence learning training requirements (section 4.5.1.2).

4.4.1.1 GAME REQUIREMENTS

A game should allow the players to have fun and experience a sense of enjoyment and self-fulfilment (Vorderer, Hartmann, & Klimmt, 2003). All these aspects are supporting the player’s motivation, that is the real thruster of the game, so the system should cultivate, sustain, and increase it (Garris, Ahlers, & Driskell, 2002; Loftus & Loftus, 1983). Keeping the game at an optimal level of challenge, that is slightly higher than the player’s current performance so that achieving the goal seems possible but not too easy, is very important (Loftus & Loftus, 1983). This is linked to Vygotsky’s concept of zone of proximal development, that was defined as: *“the distance between the actual developmental level as determined by independent problem solving and the level of potential* *development as determined through problem-solving under adult guidance, or in collaboration with more capable peers"* (Vygotsky, 1978), with the difference that, in this case, the achievement of a certain level of skill should be scaffolded by the game. In order to accomplish that, the game's difficulty should not remain at the same level of difficulty throughout the gameplay but should progressively require a slightly higher effort from the player and automatically adapt to the player's progress (Greitzer, Kuchar, & Huston, 2007).

Other factors that promote motivation are precise initial instructions, self-evident goals, positive feedback, and a reward system. An initial clear-cut instruction phase before starting the game is essential. The rules and the mechanics of the game should be easy to understand so that the player will know how to interact with the interface (Linehan, Kirman, Lawson, & Chan, 2011). Also, goals should be clear since the very beginning of the game in order to captivate the player's attention. Goals are clear when they are explicit to the player, who is aware of what s/he should achieve (Greitzer, Kuchar, & Huston, 2007; Garris, Ahlers, & Driskell, 2002; Yusoff, Crowder, Gilbert, & Wills, 2009).

The positive feedback is preferable to a negative (unpleasant) feedback, especially for children, because encourage them to persist in their efforts and diminish the risk of task-related frustration or decreased feeling of competence (Burgers, Eden, van Engelenburg, & Buningh, 2015). For example, many games include celebration sounds or the collection of prizes (i.e. coins) as positive signals corresponding to the player's goal-targeted actions, focusing on what the player achieved rather than on the errors. It can be very important for a positive, steady, and fluid interaction between the player and the interface of the game, allowing the immediate awareness of the actions' consequences.

Finally, the reward system supports the player's engagement and successful behaviours within a narrative frame (Greitzer, Kuchar, & Huston, 2007). The feedback works as a positive reinforcement in the general reward system, that supports the player's motivation by giving rewards and bonuses during and/or at the end of the playing session. For example, the coins collected during the gameplay could contribute to the customisation of the avatar (i.e., buying clothes or accessories). Indeed, customisation is known to be an important aspect that strengthens the players' motivation and immersion in the game (Linehan, Kirman, Lawson, & Chan, 2011).

4.4.1.2 SEQUENCE LEARNING TRAINING REQUIREMENTS

SELEDE aims to train implicit and explicit sequence learning abilities. Multiple examples of explicit learning training are available to the public (see section 4.1), and recent results of published studies suggest that include the training of implicit learning processes could help to support linguistic skills development on a wider approach (Deocampo, Smith, Kronenberger, Pisoni, & Conway, 2018; Giustolisi & Emmorey, 2019). If sequence learning can be improved through exercise, training both explicit and implicit aspects of sequence learning could potentially result in a winning approach, boosting the cognitive processes related to language learning, and to stimulate all those children who show difficulties in processing sequences; not only children with deafness, but also children with autism, dyslexia or specific language impairment (Arciuli & von KossTorkildsen, 2012). To the best of our knowledge, there is no such training yet available to the public.

Given the novelty of this approach, the serious game's structure is inspired to the main characteristics of the paradigms that are typically adopted for implicit and explicit sequence learning assessments (see sections 4.2.1 and 4.2.2).

4.5 NON-FUNCTIONAL REQUIREMENTS

The "non-functional requirements" refer to constraints that are external to the tool and influence the design and the subsequent development of the interface. They include those specific to (a) deaf children with cochlear implants, (b) context of use, and (c) data.

a) Our primary target users are deaf children with pre-lingual severe-to-profound bilateral hearing loss, wearing at least one cochlear implant. Our users should be attending the last years of kindergarten or primary school. We decided to concentrate our attention to this age range because research studies and our results (Chapter 2) suggest that some developmental changes are occurring around this age. With the progressive development of explicit sequence learning strategies, the involvement of implicit learning processes and their interaction also seems to change, so this might represent a sensitive developmental stage. Moreover, empowering learning mechanisms in deaf children at this age seems crucial in order to prevent learning difficulties and their relevant consequences on language learning and literacy (i.e. reading and writing skills).

Given the young age of the children, and poor verbal working memory skills and language problems often associated with pre-lingual hearing loss, the first requirement is that written verbal instructions are limited. If any, they should make use of simple syntactic structures, and be supported by visual and non-verbal information as much as possible (Frost, Armstrong, Soegelman, & Christiansen, 2015; Ormel, Gijsel, Hermans, Bosman, Knoors, & Verhoeven, 2010). To favour children's focus of attention on the screen, visual messages should be characterised by large elements and bright colours. Unnecessary and potentially distracting animations should not be introduced. Lastly, background music and excessive use of auditory stimuli are not advised in order to avoid overwhelming auditory stimulation and consequent processing fatigue (Kramer, Kapteyn, & Houtgast, 2006).

b) Considering the context of use (as known as environmental requirements), the serious game should run on a small touchscreen device on landscape orientation. It should be easy for children to interact with the game with their hands, with nice touch-interactions and a wide playable area. The games' interface should be suitable for being used in different ways (e.g. being held or placed on a flat surface) and allow the child to play as s/he finds most comfortable (Neumann & Neumann, 2014). Small touch-screen devices allow children to directly interact with the screen by their touch, which is an easier and more direct way of interaction modality for young digital-native children rather than using a keyboard or a mouse (Haugen, 1998; Scaife & Bond, 1991). Furthermore, due to their accessible costs, reduced size, and lightweight, small devices are widely used, easily portable, and adaptable to different settings (Cooper, Reimann, & Cronin, 2007).

c) In relation to data requirements, it would be useful to save the player's progress within the different games. That would allow the players to not lose their achievements, keeping their motivation high, and permit to monitor the progress, directly by the children or by the adults interested in checking the training results. Finally, the serious game should preferably work and save data offline in order to be independent of the internet data network.

4.6 SELEDE PROTOTYPE

4.6.1 THE INITIAL CONCEPT

This paragraph describes the initial concept that was the foundation of the development of SELEDE prototype. SELEDE was conceived as a serious-game-based training consisting of three mini-games: *Avoid the Asteroids, Run and Jump*, and *Complete the Sequence*. The mini-games design should follow the principles and methods of the "interaction design" (Cooper, Reimann, & Cronin, 2007; Rogers, Sharp, & Preece, 2011) and the "serious games design" (Garris, Ahlers, & Driskell, 2002; Greitzer, Kuchar, & Huston, 2007; Linehan, Kirman, Lawson, & Chan, 2011; Yusoff, Crowder, Gilbert, & Wills, 2009). As both implicit and explicit learning skills are the targets of SELEDE intervention, the mini-games were devised to train implicit sequence learning alone or combined with explicit learning (i.e. training explicit strategies in support of sequence learning, namely verbal rehearsal).

The structure of the tasks for implicit learning training should be based on common paradigms for implicit learning assessment (i.e. artificial grammar learning and reaction time tasks). However, some factors could be manipulated in order to favour the overlapping use of explicit strategies for data processing and elaboration. For example, use of verbal recoding and rehearsal of the sequences could be supported by presenting the name of the stimuli verbally (by a recorded voice imbedded in the game) simultaneously with their visual presentation, or by manipulating the presentation rate (slowing down to 800ms or more) (Bertels, Destrebecqz, & Franco, 2015).

Each of SELEDE's mini-game should comprise the following key components: (a) clear initial instructions and goals; (b) adaptive challenge to the optimal level; (c) positive feedback, (d) reward system, (e) technical requirements.

(a) *Instructions and goals.* Before each game, an initial level should offer the player the chance to become familiar with the tasks. Instructions of each game must be visually presented by using eye-catching elements (e.g., bright arrows) and simple animations. Instructions should not involve written text. Goals should be clear.

(b) *Adaptive levels.* The mini-games should include different levels of increasing difficulty that adapt to the player's performance. In regards of SELEDE mini-games, difficulty can be defined by: the sequences length (i.e. sequences can be between three and six elements), inter-stimulus interval (i.e longer or shorter) and the presence or absence of additional verbal or visual hints (in order to focus the training on implicit learning only or on the combination of implicit and explicit learning conditions). The stimuli can be visual, auditory or both, with different level of abstractions. For example, visual stimuli could be abstract and not easy to be named (e.g. unfamiliar symbols) or refer to concrete objects that can be easily be named (e.g. animals). Following the same concept, auditory stimuli could be unpronounceable sounds, syllables, or names (i.e. animal names).

(c) *Feedback.* The feedback system should consist of the collection of coins throughout the game. Additional coins could be given the end of each level on the base on the player's performance. In case of a bad performance, the player should receive a reduced number of coins compared with the coins s/he could have received with optimal performance.

(d) *Reward.* The overall reward system should be based on positive feedback and customisation, meaning that the coins collected while playing with the mini-games should contribute to the personalisation of the player's avatar.

(e) *Technical Requirements*. SELEDE should be implemented using Phaser, a desktop and mobile HTML5 framework that allow the serious game to be used with any touch-screen device. The location of the command buttons that move the avatar should be personalised (on the bottom-left or bottom-right locations of the screen) based on the player's dominant hand. The games should be fluid enough to be played, therefore, they should run at a speed of 50-60 frames per second (fps). Also, the possibility to take a break and pause the games without losing any data should be granted. It should be possible for the player to create and login to a personal account so that more than one player can play with the serious game without interfering with other players' data. Each player should be able to recover personal data through the personal account after logging out or switching off the device.

4.7 IMPLEMENTATION OF SELEDE MINI-GAMES

The SELEDE mini-games are 2D platformer games (Boutros, 2006; Smith, Cha, & Whitehead, 2008) whose protagonists are a group of little and friendly aliens, involved in various adventures. All the mini-game assets have been created by Kenney[9],[8]who has made a portion of the asset packages available to the public and downloadable from the internet under the licence *CC0 1.0 Universal*. They were then modified as needed by Armellini, a Bruno Kessler Foundation developer (Armellini, 2017).

A home page containing the link to the three games appears once the serious game is launched (Figure 4.2).

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[9] https://kenney.itch.io/

Figure 4.2. SELEDE's homepage screen.

4.7.1 GAME 1 - RUN AND JUMP

In *Run and Jump*, a little pink alien runs on the ground of a planet jumping over wooden crates piled one on top of the other, forming obstacles of different heights. As for Avoid the Asteroids, this game is an endless runner game in which the avatar moves forward independently. The player can only avoid the obstacles by controlling the "jump" action (depicted as an arrow pointing up) that is at the bottom-right corner of the screen. The power (height) of the jump depends on the pressing time (milliseconds) of the jump button. After releasing the button, the avatar starts descending towards the ground. An initial short instructions level uses simple visual animations to show the player how to interact with the avatar and familiarize with the command (Figure 4.3).

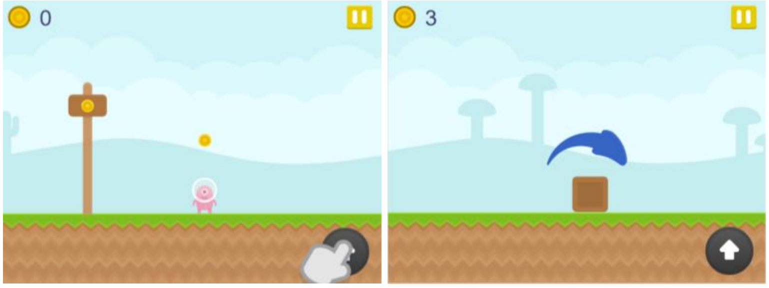

Figure 4.3. Run and Jump instructions level. From the left: the player is instructed to press the “up” button to make the avatar jump and collect the coin; the blue arrow indicates the goal of the game (to overcome the obstacles).

Obstacles differ in heights and consist of one, two, or three piled cranes (Figure 4.4). Any collision with the cranes equals to an unsuccessful jump. Coins can be collected throughout the game. No sounds or music are used in this game. The pattern of the obstacle heights follows a statistical regularity, on the model of the artificial grammar learning paradigm. Also, given that the player’s responses are temporally distributed, and the reaction times reflect the performance, the game also shares the characteristics of serial reaction time tasks. Quick reactions at the right power will allow to successfully overcome the obstacles. Since the obstacles appear on the screen one at a time, the player cannot anticipate the response and must rely on implicit expectations to predict when and how long to press the jump button. Higher accuracy and faster reaction times will indicate that the player has implicitly learnt the underlying regularity of the obstacles. The game environment is simple, featuring only the jump button (commands) and the head-up display (HUD) showing the number of coins collected.

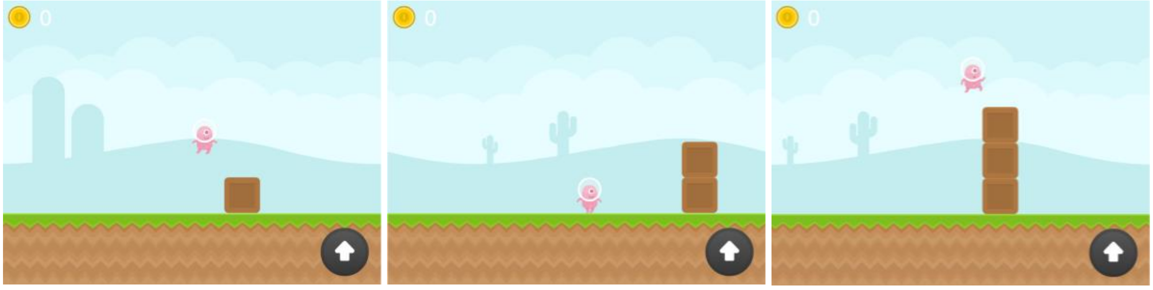

Figure 4.4. Run and Jump screenshots: examples of the obstacles’ different heights.

A reward screen appears at the end of each level (Figure 4.5) showing the number of coins collected during the gameplay. Their amount depends on the player's performance but cannot be zero. If the player overcame ≥50% of the obstacles, a bigger version of the avatar will appear in the upper part of the screen and praise the player by smiling and performing an enthusiastic victory dance. Otherwise, the avatar would show a neutral expression without performing any animation. This final screen also includes two commands: a green button (depicting a check symbol) that allow the player to continue playing, and a red button (depicting the symbol of a house) that redirect the player to the home screen.

Figure 4.5. Run and Jump reward screen.

4.7.2 GAME 2 - AVOID THE ASTEROIDS

In *Avoid the Asteroids*, the avatar is a purple alien driving a spherical spaceship across the universe. The player must assure the spaceship a safe passage through walls of asteroids by crossing the openings. These can be located at three different heights (i.e., upper, middle or bottom part of the wall/screen). This game is modelled on the endless runner game genre (e.g. Flappy Bird), therefore the spaceship independently moves forward, however, the player can control its position by pressing and holding the "up" and "down" buttons (depicted as arrows) at the bottom left corner of the screen (Figure 4.6). Any collision with the walls equals to unsuccessful passage. Coins can be collected throughout the gameplay. No sounds or music are present in this game. A short instructions level is proposed at the beginning of the game. It shows the player how to interact with the avatar through simple visual animations and allow the familiarization with the commands. The game environment includes the up and down buttons (commands) and the HUD showing the number of coins

Figure 4.6. Avoid the Asteroids screenshots: different heights of the walls' openings.

Similarly to Run and Jump, the pattern of the openings' heights follows a statistical regularity, and the reaction times of the player's responses reflect the performance. Quick reactions in the right direction will increase the possibility of a successful passage between the two blocks of asteroids. Since the openings appear one at a time on the screen, the player cannot prepare ahead of time and must rely on implicit expectations to predict in which direction s/he should drive the avatar. Higher accuracy and faster reaction times will indicate that the player has implicitly learnt the underlying regularity (grammar) which rules the openings' order of appearance (the grammar is summarized in Table 4.2). Differently from Run and Jump, Avoid the Asteroids requires the player to move the avatar in two directions (up and down), so it adds some visuospatial variability in addition to the temporality of the responses.

Table 4.2. Artificial grammar generating the sequence of openings and coins. Two openings of the same type (same height) cannot happen consequently. After a centre-opening, the ones at the bottom or at the top have an equal probability to follow. The bottom-opening can only be followed by a top-opening. The top-opening can either precede the centre-opening or a row of coins. Only the centre-opening can come after the row of coins.

	centre	bottom	Top	coins
centre	0	0.5	0.5	0
bottom	0	0	1.0	0
top	0.5	0	0	0.5
coins	1.0	0	0	0

At the end of each level, a reward screen appears and shows the number of coins whose amount depends on the player's performance (always in a positive number). If the player successfully passed half or more of the total number of openings, a smiling and dancing version of the avatar will appear in the upper part of the screen. Otherwise, the avatar would show a neutral expression without any additional animation. Also, the green button (check) and the red button (home) are shown in order to permit the player to keep playing or return to the home screen (Figure 4.7).

Figure 4.7. Avoid the Asteroids final reward screen.

4.7.3 GAME 3. COMPLETE THE SEQUENCE

The initial version of *Complete the Sequence* involved two characters, a boy and a girl dressed as farmers, who are desperate because their animals have escaped from the stable. As a matter of consistency with the other mini-games, the two human characters have been subsequently substituted by a yellow alien (Figure 4.8).

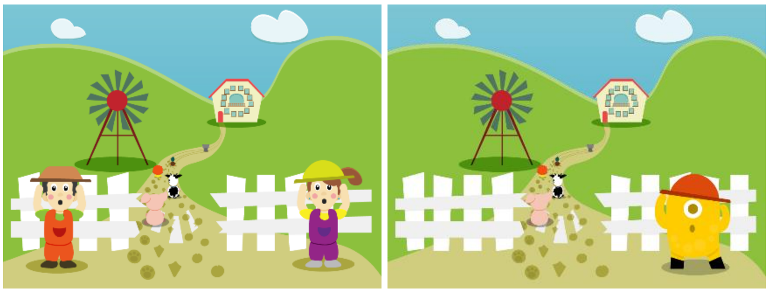

Figure 4.8. From the left: the two human characters of the first version of *Complete the Sequence*, and the yellow alien of the final version.

In this game, twelve animals form a circle around a central balcony, in which sequences of animals are presented one by one. Sequences can span from 3 up to 6 items (animals) and are progressively longer accordingly with the game progression and the increasing level of difficulty. The succession rules follow an artificial grammar. This is the only game involving a combination of visual and auditory inputs. In fact, the name of each animal is produced by the device's speakers together with its visual presentation. The player's attention is captured to the target animal by a short animation (i.e. the glass window in front of the target animal briefly disappear). After the presentation of the sequence, the animals disappear from the central balcony. Shortly after, the sequence is presented again but one or more animals are missing (never more than the 50%) and replaced by black dotted ovals containing a question mark. The player is required to tap on the missing animals in order to complete the sequence (Figure 4.9).

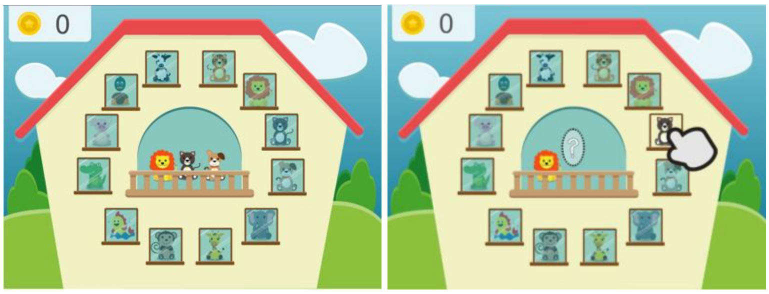

Figure 4.9. Screenshots of the prototype version of *Complete the Sequence*.

Using auditory inputs should promote the execution of explicit strategies. The game involves easily nameable items (animals) and the verbal recoding is facilitated by hearing the name of the animals during the initial presentation. During the initial instruction level, players are invited to pay attention to the sounds by visual instruction (Figure 4.10). This should also support verbal rehearsal. However, children are not asked to remember the whole sequence, since that would stress their working memory abilities. Instead, children are asked to simply retrieve the missing pieces. A future implementation could involve the memorisation of the entire sequence for those children who are performing well.

Figure 4.10. Visual instruction indicating to pay attention to the sounds produced by the device. From the left: characters of the first and the second version of *Complete the Sequence*.

Coins are earned for every correct response and their number is displayed in the HUD on the top left of the screen. The final reward screen shows a pile of the gathered coins.

4.8 DIFFERENCES BETWEEN THE INITIAL CONCEPT AND THE PROTOTYPE

Thanks to the great teamwork behind the design and the development of the software, the current prototype includes some of the functionalities that were initially planned. It also includes some implementations whose need emerged during the user experience assessment. However, it does not cover all the features that were part of the initial concept. Further implementations are expected to be incorporated in the near future.

With regards to what described in the initial concept (section 4.7.1), the mini-games in current SELEDE prototype:

- include clear (visual) instructions and goals at the beginning of each game;
- rely on positive feedback;
- allow to pause the games during the gameplay;
- involve a simple reward system.

However, future implementations should include:

- Some software improvements in order to make SELEDE adaptive to the player's performance so that it can provide an optimal level of challenge. The player could select the initial level (e.g. easy/medium/difficult) and then the game could automatically adapt its difficulty based on the rate of success of each level.
- Allowing the players to create and keep a personal account (i.e. a login access system with requested username and password). The association between the saved game's data and a specific player would allow more than one player to use the same device to interact with SELEDE and would permit the customisation of the games' level of difficulty intended for each player. Some personal data could also be requested during the creation of a new account (chronological age, for example) to facilitate the customization of the difficulty level of the

mini-games. The login access system would also contribute to the protection of the players' data.

- Some technical improvements that would allow the personalisation of the location of the command buttons that move the avatar. In fact, having the commands on the opposite side of the dominant hand could represent a disadvantage for some children.
- Recording the data on the device so that stopping the game or switch off the device would not mean losing the playing scores and data.
- Improving the reward system based on the player's performance in order to include the possibility of customisation (e.g. by using the coins to unlock some features to personalise the avatar or by receiving badges based on the achievements).
- Implementing an informative feedback system within the mini-games in order to facilitate the player to better understand the game's objectives (e.g. the player could lose a coin every time an obstacle is touched – once the coins are finished, the player could be invited to start the game again, perhaps lowering the level of difficulty).
- Some other additional implementations would also result beneficial for the games' use. For example, the given time to respond in *Complete the Sequence* could be customised based on the player's average response time so that the game would not be perceived as "too slow" or "too fast" by the children. Also, the correspondence between the time of pressure of the jump command and the avatar's jump in *Run and Jump* should be improved or possibly made adaptable. The avatar "floating time" should be reduced so that the jump would be sharper and there would be a faster fall during the descent.

CHAPTER V

USER EXPERIENCE (UX) ASSESSMENT AND EVALUATION OF SELEDE: A SERIOUS GAME TO TRAIN SEQUENCE LEARNING DESIGNED FOR DEAF CHILDREN WITH COCHLEAR IMPLANTS

5.1 WHAT IS THE USABILITY?

The International Organization for Standardization (ISO) for Ergonomics of Human-Computer interaction (ISO 9241-11) defines usability as follows: *"the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use"*.

A good user interface needs to meet the following usability characteristics:

1. It should be easy for the users to become familiar with the interface and competent in using it from the first interaction.
2. It should be easy for users to understand the objective of the game and understand how to achieve them.
3. It should be easy for the users to recall the user interface, and how to use it on subsequent interactions.

In order to assess if an interface meets the usability characteristics, it is necessary to assess a design's usability throughout the development process, from prototypes to the final deliverable. The UX assessment is fundamental since the usability is what determines an interface's success with the final users. For this reason, we developed a UX assessment plan for our serious game.

5.2 PROCEDURES FOR THE UX ASSESSMENT OF SELEDE

5.2.1 UX ASSESSMENT AIMS

The UX assessment had two aims: (1) to assess the usability of the games (viz. evaluate the quality of the interaction between the user and the games); and (2) to assess the user's experience (viz. evaluate the user's perception of the games in terms of motivation and fun).

5.2.2 SELEDE UX ASSESSMENT: CHILDREN PROTOCOL AND HEURISTICS

A UX assessment specific for the evaluation of our serious game with children with poor linguistic skills was developed following the five fundamental heuristics for usability drawn up by Nielsen (1993):

a. Learnability (how a software's usage is easy to learn);
b. Efficiency (how software is efficient in reaching its goals);
c. Memorability (how software's instructions are easy to remember);
d. Errors (how frequent are the errors made by the user while using the software);
e. Satisfaction (how satisfied is the user about the software).

The UX assessment protocol included the following steps, in this order (see appendix A):

1. A behaviour checklist based on the experimenter's observations while the user is playing covering the five heuristics (Nielsen, 1993)
2. A questionnaire inspired to the System Usability Scale (Italian version; Borsci, Federici, & Lauriola, 2009)
3. A semi-structured interview (audio-recorded)
4. A drawing with coloured markers

Although its apparent complexity, the application of this protocol requires about 30 minutes per child. The assessment consists of a playing session and a qualitative assessment. The first part of the assessment consists of behavioural observation during a playing session. Our behavioural observation includes time recording and behavioural sampling. Specific child's behaviours and the length of the interaction with the game are reported on the checklist. The advantage of behavioural observation is that it allows to observe and evaluate non-verbal behaviours. The disadvantage is that there is no control over extraneous contextual variables that can influence the data collection, such as an event that could capture the child's attention leaving the experimenter not sure about the interpretation of this drop of motivation. This technique could also cause slight discomfort in introvert children since they can feel at the centre of attention. In order to ease this feeling, the playing session can be done in a group with the children playing with their individual devices. Each participant is given a device on which the homepage of the serious game is already loaded and is observed while s/he starts and plays with the three games, one at a time, following the preferred order. No instructions or help is given unless explicitly asked by the child. If the child seeks for help, this is reported on the experimenter's form together with the amount of support needed to overcome the problem (from a minimal intervention, like a simple non-verbal encouragement such as a smile, to a maximum intervention, in which a practical explanation or demonstration is required). Children are usually self-motivated by curiosity to try all the games without the necessity of being invited by the experimenter. During the playing session, an evaluator is assigned to each child and directly observes the child-game interaction in order to fill the behaviour observation checklist. Children are free to play with each game as long as they prefer. The time spent on each game is recorded on the form by the experimenter. As a matter of time, the playing session lasts a maximum of fifteen minutes, then the children are invited to perform the qualitative assessment with their individual experimenter. In order to limit the effects of group thinking and facilitate the rise of an independent opinion, these parts of the assessment (step 2, 3, and 4 listed above) are preferably done individually in a quiet room.

The second step of the assessment is the questionnaire containing 14 statements designed to test the general appreciation of the serious game (e.g. *"Task instructions were easy to understand", "I like the game's colours"*). The participant is asked to express his/her opinion on the statements by these verbal instructions supported by a practical demonstration given by the experimenter:

> *"I am going to tell you some phrases and you will have to point out your response using this bar. You will point this green square (happy face) if what I said is very true for you, this square (light green square) if you think it is a little true but not so much, this square (neutral face) if you do not know, this square (orange square) if what I said is a bit false, or this red square (sad face) if it is very false for you."*

Each child is required to show his/her level of agreement with each statement by pointing their index finger on a five-point rating scale (Likert, 1932). The response scale consists of a table with five consecutive squares progressively coloured from red, to yellow, to green, containing an upset face (on the red square), a neutral face (on the yellow square), and a happy face (on the green square). Colours and faces were chosen to symbolise the agreement/disagreement with the statements. Faces were selected out of a standardised task for emotion recognition (Albanese & Molina, 2008) and the gender of the face displayed matched the gender of the child to facilitate the recognition. A copy of the coloured rating scale is available in the attachment (see appendix B).

The semi-structured interview is composed of 6 appreciation questions and is audio-recorded. In semi-structured interviews, the interviewer proposes a series of questions that serve as guidelines and serve to stay focused on a given topic, while still allowing a certain degree of flexibility, that is one of the advantages of this procedure together with the possibility of establishing a direct relationship with the child. However, this also set a risk related to the experimental effect, meaning that the peculiar interaction between the interviewer and the interviewee could high the probability that the respondent will provide socially desirable answers. In fact, asking direct questions can arise the risk of obtaining responses biased by social desirability. This phenomenon occurs when the participants who are being observed implement behaviours or give responses that they consider socially acceptable. In this case, for example, children could abstain from giving negative answers (e.g. *"I didn't like this game"* or *"This game was too difficult for me"*). The effect of social desirability is frequently observed in the field of research and could lead to a distortion of the obtained data (Tommasi & Busonera, 2010). Using indirect questions is a strategy used to avoid answers biased by social desirability (Fisher, 1993). For this reason, three out of six questions are indirect, meaning that the child is required to evaluate the game from the point of view of a younger child (i.e. *"Piero/Giulia is a younger child that will try these games tomorrow. Do you think s/he will be able to play with them? If not, why?"*). Asking the children to imagine a younger thus more vulnerable child serves the purpose of lowering their standards and facilitate the production of a critic review. The audio-recording allows the data of the respondents to be stored in order to be transcribed and eventually interpreted after the session.

Finally, children have the chance to express their ideas about the game with a drawing. They are asked to draw how they would like the game to be different. Although this little task might not be very informative for the purpose of the UX assessment, it is a good tool for allowing children with very poor expressive language skills to express their personal opinion and feel acknowledged.

At the end of the session, each child received a personalised diploma as a reward for his/her participation.

5.2.3 SELEDE UX ASSESSMENT: ADULTS PROTOCOL

A UX assessment protocol was designed in order to investigate some aspects of the games with adults. In this protocol, adult evaluators are asked to play individually with the three mini-games comprising the serious game without any time-constraint and to respond to seven questions for each of the three games. Each question targets one of the core aspects of the user interface assessment:

1. First time user: “Is the application still easily useable by first-time visitors?”;
2. Contrast: *“Is the interface easily usable also in the case of poor light conditions?”;*
3. Use of colours: *“Is colour used consistently?”;*
4. Labels: *“Is clear descriptive language used for buttons and navigation elements?”;*
5. Feedback: *“Does the state of objects change visually to provide feedback to user actions?”;*
6. Physical constraints: *“Does the interface respect users with physical constraints?”;*
7. Screen size: *“Does an application respond effectively to the visitor’s screen size?”*.

Answers were later collected and analysed in order to discover the games’ problems. Participation was entirely voluntary, and participants did not receive any reward beyond our gratitude.

5.3 SELEDE EVALUATION AND REIMPLEMENTATION

As anticipated, the final version of the serious game is the result of an iterative process, comprising three phases. The first phase consisted of a three-round assessment that involved different groups of evaluators: typically hearing children, typically hearing adults and gaming experts, and deaf children with cochlear implants, respectively. Each of these assessments allowed the identification of specific problems concerning the games and led to the second phase: the implementations of the games resulted from the resolution of the problems identified during the first phase. The third phase regards the UX assessment of the implemented version of the serious game.

5.3.1 FIRST UX ASSESSMENT OF SELEDE

5.3.1.1 ASSESSMENT NR. 1: TYPICALLY HEARING CHILDREN

Right after the initial implementation, a first pilot study has been carried out in order to perform a simple evaluation of the games. This study took place during an event organised to promote new technologies in young children. Some of the children attending the event participated in the UX assessment. Participation was entirely voluntary, and the children were accompanied by at least one parent who gave consent for their participation. Participants were six hearing children ranging from 7 to 9 years of age, including two 7-year-old girls, two 8-year-old girls and two 9-year-old boys. All the participants tried one or two of the first prototypes of the three mini-games and received a diploma as a reward for their participation. The assessment followed the protocol described in section 5.2.2 above. The overall evaluation revealed that the children enjoyed and found motivating two games out of three (*Run and Jump* and *Avoid the Asteroids*) whereas they found the first prototype of *Complete the sequence* unappealing due to its infantile graphical aspect and to the instructions that were considered not straightforward and uneasy to understand. The interview analysis revealed that this difficulty originated from lack of clear embedded instructions and from the non-chronicity between the two presentations of the sequence: one accompanied by the sound of the animals' names and one without.

5.3.1.2 ASSESSMENT NR. 2: TYPICALLY HEARING ADULTS AND GAMING EXPERTS

The second prototype of the serious game has been submitted to the evaluation of three UX experts and 43 master students attending the class of Educational Technologies (36 female students and 7 male students). Participation was voluntary. Candidates were asked for their consent before participating and did not receive any benefit for their participation. The assessment followed the protocol described in section 5.2.3 above. From the analysis of the collected answers, *Run and Jump* and *Avoid the asteroids* resulted easily usable, whereas several problems have been individuated in the game *Complete the sequence*: for example, several participants reported difficulties to understand the game's goal and playing procedure, colours were often opaque, and the feedback was judged not useful.

5.3.1.3 ASSESSMENT NR. 3: DEAF CHILDREN WITH COCHLEAR IMPLANTS

After evaluations 1 and 2 and the subsequent implementations, the serious game was tested with a small sample of deaf children with cochlear implants. Children were recruited with the help of a speech and language therapist in a health service in the area of Trento. Participants were two boys aged 9 and 10-year-old. Inclusion criteria were the following: onset of profound bilateral hearing loss before hearing loss (90 dB or greater) before the age of 2 with no additional cognitive, motor, or sensory impairment, cochlear implantation by age 4, use of at least one cochlear implant for a minimum of 3 years, and Italian as native or dominant language. Families received an informed consent form to return filled and signed in order to allow their children to take part in the research. Children were also asked for their consent immediately before participating in the assessment session. The UX assessment followed the protocol for children described above in section 5.2.2. The UX evaluation was accomplished without any problems and revealed some small bugs in *Run and Jump* that was nevertheless highly appreciated as well as *Avoid the Asteroids*. The evaluation highlighted some issues concerning *Complete the sequence,* judged as having the less straightforward goal and playing rules.

5.3.2 SELEDE REIMPLEMENTATION

The preliminary UX assessments described above were crucial for identifying the problems in the usability of the serious game. Based on the results of that first phase, some aspects of the three mini-games were fixed or reimplemented. This paragraph contains a summary of these implementations.

Based on this first UX test, the graphic interface of the task's instructions and the reward screen in *Run and Jump* and *Avoid the Asteroids* were revised and enhanced. For example, the reward screen displayed a single coin in the first version of the games. This was changed to a big pile of coins (4 coins) when the child obtains a good result or a small pile of coins (2 coins) when the result can be improved (Image 5.1). This was implemented in order to enhance motivation.

Image 5.1. From the left: an example of reward screen for the first version of the games; reward screen for the second version of the games (for poor results); reward screen for the second version of the games (for good results).

Given the results of the UX assessment, we implemented a new version of *Complete the Sequence* which was completely redesigned (Image 5.2). The narrative of the first part of this game was changed and a small story (entirely visually presented) was added. In the second version, two farmers (a boy and a girl) appear on the screen once the game is launched. The fence of their farm is broken, and all the animals had run away. The child is invited by visual instructions to pay attention to the sequence of animals and click on the missing one. Each animal constituting the sequence is either visually presented (in one version of the game) or combined with the sound of its name. Following the suggestion of the audiologist, the audios (animals names) have been changed for better clarity and to ensure the standardisation of the auditory input: a standardised female voice from a dictionary library is used instead of the recorded voice of a female speech and language therapist employed in the older version.

Image 5.2. From the left: Screen of *Complete the Sequence* before and after the reimplementation.

5.3.3 FINAL UX ASSESSMENT OF SELEDE

5.3.3.1 EVALUATION NR. 4: TYPICALLY HEARING CHILDREN WITH DYSLEXIA

For the UX assessment of the ultimate version of the game, we recruited five Italian children with a diagnosis of Dyslexia (4 males and 1 female). Given that the diagnosis of dyslexia is not usually given in Italy before the child ends the second year of primary school, participants were aged 8 to 11 years. Children had Italian as their first language and were recruited in a health service with the help of a speech and language therapist. We included children comorbidity with other learning disorders, expressive language disorders, or attention-deficit/hyperactivity disorders. However, intellectual disabilities, hearing loss or motor disorders constituted a reason for exclusion. Before the assessment, families received an informed consent form that they had to fill and sign before their children could take part in the research. Children were ultimately asked for their consent to participate immediately before the assessment session. The protocol for the assessment followed what described in section 5.2.2. Children were met individually on the occasion of one of their appointments for speech and language therapy. The UX assessment was performed by trained a master student in the presence of the speech and language therapist. A tablet Samsung Galaxy Tab S2, with display resolution set on 2048x1536 and processor 1.8 GHz + 1.4 GHz octa-core was used for the assessment. The UX assessment revealed a clear preference of the children for *Run and Jump* and *Avoid the Asteroids*, however, they were sometimes criticised for being too "slow". Nevertheless, *Complete the Sequence* did not receive good feedback from the children involved, who judged it too infantile and more appropriate for younger children. Despite the reimplementation, this last game was perceived as having a complicated goal, and not clear playing rules.

5.3.3.2 EVALUATION NR. 5: DEAF CHILDREN WITH COCHLEAR IMPLANTS

Given the results of the UX evaluation involving children with Dyslexia (section 5.6.1), we decided to involve young children with hearing loss in the UX evaluation of the second version of the game. Children were recruited at a health service in the north-east of Italy, with the support of speech and language therapists. Considering that our serious game must be suitable for all deaf children with cochlear implants and given that this group is characterised by a great overall variability in their hearing loss and hearing compensation history, as well as family and therapy conditions, and individual traits, we decided to apply less strict inclusion criteria compared to the previous assessment involving deaf children with cochlear implants (section 5.3.1.3). Inclusion criteria included: onset of profound bilateral hearing loss before hearing loss (90 dB or greater) before the age of 3, no additional sensory impairment, children with progressive hearing loss were included as long as they received a hearing compensation by the age of 3 and/or cochlear implantation by the age of 4, use of at least one cochlear implant for a minimum of 2 years, and Italian as native or dominant language. Families were contacted by their speech and language therapists and received an informed consent form that they had to return filled and signed if they agreed their children to take part in the research. Children were also asked for oral consent right before participating in the UX assessment. The UX assessment took place in the room used for speech and language therapy during a routine appointment, in the presence of the speech and language therapist. The protocol is the one for children described above in section 5.2.2. Participants were six profoundly deaf children (two males) aged from 4 to 9 years (mean age = 6,04; SD = 1,62). All children wore cochlear implants (two monolateral, two bilateral, and two with a hearing aid in the counterpart). Two children were diagnosed with dyspraxia, one with motor delay, one with hyperkinetic disorder, and one with language delay in addition to profound deafness. All children received oral education, except for the child diagnosed with language delay who used signs supported oral language. The same device previously used with dyslexic children was used for the assessment: tablet Samsung Galaxy Tab S2, with display resolution set on 2048x1536 and processor 1.8 GHz + 1.4 GHz octa-core. The assessment procedure was carried out successfully, however, three children needed adults' support to understand the instructions of *Complete the Sequence*. Once again, the UX assessment revealed preference of the children for *Run and Jump* and *Avoid the Asteroids*, apart from one child who preferred *Complete the Sequence.* One of the oldest children criticised the games for being too "slow" while two of the younger children complained that they could not respond fast enough for playing with *Complete Sequence* or their answers were not recorded, instead of the message *"Do you want to continue?"* kept appearing. The majority of the children asked to play with *Run and Jump* and *Avoid the Asteroids* more than once, however they showed a slight sign of frustration for the repetitiveness of the games, that did not appear to become more challenging with the use. Furthermore, the speech and language therapists expressed their concern about the inability to personalise the side of the command buttons. In fact, having the commands on the opposite side of the dominant hand could represent a disadvantage for some children.

5.4 CONCLUSIONS

The UX assessment was very useful in order to offer a product with the best chances of being welcomed by the users, and that would also optimize the possibilities of obtaining good results from the training. The UX assessment consisted of five evaluations. First, we involved a small group of normal hearing children. This first evaluation has enabled us to have some insight into the main problems with the initial prototype. The second round of evaluation involved normal hearing adults and experts in software development that gave their opinion about some core aspects of the user interface (section 5.3.1.2) and contributed to identify and correct technical issues with the mini-games, respectively. The third evaluation involved two profoundly deaf children with cochlear implants. These participants followed strict inclusion criteria (as described in section 5.3.1.3), for consistency with the inclusion criteria that were used the studies described in Chapters II and III. The results of this evaluation, together with the first two, contributed to the reimplementation of some aspects of the mini-games *Run and Jump* and Avoid the Asteroids, and to the complete redesign of the user interface of *Complete the Sequence* (section 5.5). This second version of the mini-games that are part of SELEDE was then submitted to the second cycle of UX assessment, involving normal hearing children with dyslexia, and deaf and hard-of-hearing children. Given that we want to propose SELEDE to the public, we decided to include children with a wider range of characteristics and comorbidities (sections 5.6.1 and 5.6.2) in this phase. If we compare the feedback from the first cycle of UX assessment with the second cycle, results suggest that the reimplementation was effective for increasing the enjoyment and the engagement of the children towards the games. It is noteworthy that the UX assessment did not reveal any specific problem or issue related to the specific condition of the children who were playing. Whether the children were normal hearing with typical development or dyslexia or were deaf with cochlear implants, we did not report any specific differences in the issues observed in each group. Despite the fact that the UX assessment was performed with a small number of children, this indicates that SELEDE is likely to be suitable for being used with children with different personal characteristics. Both boys and girls rated SELEDE as overall enjoyable. Two mini-games, *Run and Jump* and *Avoid the Asteroids* were considered intuitive and received the deepest appreciation. However, some issues were still present. In particular, older children did not find SELEDE to be challenging enough to be at the optimal level of difficulty. On the other hand, some of the younger children struggled to understand the rules and goals of *Complete the Sequence* that was rated as the least intuitive.

GENERAL CONCLUSIONS AND FUTURE WORK

Experiencing auditory deprivation during early childhood affects adversely children's ability to process and acquire spoken languages. Deaf and hard-of-hearing children are therefore at risk of language delays. If compared with hearing peers, deaf children with cochlear implants are reported having poorer speech perception (Pisoni & Cleary, 2003), reduced articulation speed (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003), poorer expressive and receptive syntactic skills (Harris, Kronenberger, Gao, Hoen, Miyamoto, & Pisoni, 2013), and poorer reading skills (Geers, 2003). However, large individual differences in language outcomes that are typically found in deaf children following cochlear implantation (Pisoni et al., 1999), and a considerable amount of this variability remains unexplained (Geers, 2002, 2006).

The *auditory scaffolding hypothesis* suggests that poor oral language and literacy outcomes in deaf and hard-of-hearing children it might be partially explained by deficits in implicit learning processes (Conway et al., 2009). These processes allow the implicit detection and elaboration of distributional statistical regularities that are recurring in inbound information without intention to learn nor awareness and are crucial for language development (Saffran & Kirkham, 2018; Romberg & Saffran, 2010). According to this hypothesis, the perception and elaboration of sound build *"an auditory scaffolding for* (the elaboration of) *time and serial order"*. Consequently, *"under conditions of auditory deprivation, this auditory scaffolding is absent, resulting in neural reorganization and a disturbance to cognitive sequencing abilities"* (Conway et al., 2009, p.275).

In this thesis, we investigated sequence learning abilities in deaf children with cochlear implants aged between 5 and 11 years old to develop a serious game-based training. The aim of the first part of this doctoral research project was to explore implicit and explicit sequence learning processes, taking into account the auditory scaffolding hypothesis. The overarching purpose of this work was to gather information about the processes underlying language development in this population and provide evidence for the development of a training aiming to improve both implicit and explicit sequence learning processes related to language acquisition.

Starting from the theoretical framework based on the auditory scaffolding hypothesis (Conway et al., 2009), in chapter II we explored the implicit sequence learning variability based on sensory experience (i.e. deafness) and development (i.e. age). The implicit learning task was based on the artificial learning grammar paradigm, following the research protocol created by Conway and colleagues (2011). The results led to interesting findings. If experiencing reduced auditory stimulation is detrimental for implicit sequence learning skills, as stated by the auditory scaffolding hypothesis, then deaf children should have performed worse than hearing children in the sequence learning task, and their performance should have been correlated with the linguistic outcomes. Also, if implicit learning variates with the development, differences in typically developing children's performance at different age should have been observed. Our results suggest that implicit and explicit sequence learning processes are independent and both cochlear implanted deaf children and typically hearing children seem to use them to process and maintain sequential information. As soon as children start using explicit learning processes efficiently, implicit sequence learning processes seem masked and are harder to be detected.

Although leading to interesting results, tasks based on the artificial learning grammar paradigm - as the one we and Conway et al. (2011) employed - have been criticised for not providing strong evidence for reliable group differences, and for being at risk of confounding results due the interference of explicit factors, that would make these tasks not very reliable for the assessment of implicit learning (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017).

In chapter III, we investigate dynamic implicit learning in deaf children with cochlear implants (aged 5 to 11) using a simple reaction time task that was designed to limit the interference of the explicit processes of working memory and avoid confounding results. The task relies on temporal regularities instead of sequences to avoid the possibility that the participants could engage in verbal recoding and verbal rehearsal. The temporal regularities used in our task are distributed on two levels, local and global, in order to assess the participants' ability to implicitly process and integrate different levels of information. This task allows the investigation of implicit learning on a higher level of complexity, by assessing the ability to implicitly process and learn regularities and to adapt the behavioural responses accordingly. Deaf and typically hearing children who participated in the study showed comparable abilities to implicitly process and learn the regularities embedded the task. Although we cannot be sure that this data can be extended to all children with profound deafness, it is interesting that our results are consistent with various studies involving cochlear implants users.

Overall, the results of the studies illustrated in the first part of this manuscript do not support the hypothesis that a lack of auditory stimulation affects implicit learning or processing of sequential or temporal regularities. This does not mean, however, that implicit learning processes could or should be ignored in rehabilitation practice. Both implicit and explicit sequence learning processes take part (and probably interact) to support language development. It is therefore important to consider both these aspects to offer an overarching training.

The second part of this research project was dedicated to the design, the development, and the user experience assessment of a training for implicit and explicit sequence learning processes. SELEDE (SErious game for sequence LEarning training in DEaf children) is a serious game-based training specifically designed to train both implicit and explicit aspects of sequence learning.

In chapter IV, are described the co-design approach and the iterative process that was alternating implementation, re-design and evaluation phases to create a product that meets the users' needs. The concept of "*serious gam*e" refers to game-based training that integrates the fun and enjoyable characteristics of games with a serious non-entertainment purpose (e.g. for rehabilitation or education). SELEDE consists of three mini-games: *Avoid the Asteroids, Run and Jump*, and *Complete the Sequence*. The structure behind the mini-games is based on paradigms used for implicit learning assessment (i.e. artificial grammar learning and reaction time tasks). The games expose the user to regularities to train implicit sequence learning alone, or they support the use of explicit sequence learning strategies (i.g. verbal rehearsal) to combine the use of the different processes.

SELEDE has been subjected to a cycle user experience assessment (UX) to assess the design's usability of the mini-games throughout the development process, from prototypes to the final deliverable version. The UX assessment is fundamental since the usability is what determines an interface's success with the final users and can enhance the chances of successful outcomes of the training.

The iterative process alternating two UX assessment phases partitioned by and a phase of re-design and implementation is described in chapter V. The UX assessments followed different protocols, one for adults and one for children, created ad-hoc for the evaluation of SELEDE. The first cycle of assessment included three evaluations involving adults (normal-hearing adults and experts in software development), typically hearing children, and deaf children with cochlear implants, respectively. This phase provided information that was useful to the re-design of *Complete the Sequence* and the implementation of some aspects of *Run and Jump* and *Avoid the Asteroids*. The new version of the games was then subject to the second cycle of UX assessment involving normally hearing children with dyslexia and deaf and hard-of-hearing children.

Overall, the UX assessment results suggest that some of the fundamental requirements of the game design (section 4.4) were failed. In particular, the most important future implementations should regard the possibility to make the mini-games adaptive to the player's performance achieved during the gameplay, to allow some personalisation to the player's preference (e.g. the side of the commands), to improve the reward system (e.g. unlocking features to personalise the avatar or receiving medals based on the achievements), and create an access system based on username and password that would allow to record score data on the device and to protect the player's account.

After these implementations, an evaluation of the training efficacy will be necessary to assess the effectiveness of this tool for training sequence learning abilities in deaf children with cochlear implants and evaluate the size of eventual secondary effects of this training on the children's linguistic outcomes. If the effects of the training will be observed, the findings will be informative at a theoretical level because they will suggest that implicit and explicit sequence learning skills can be trained and improved. They will also be very important for rehabilitation practice because they will represent a validation of this new tool. This represents a cutting-edge approach to the training of cognitive abilities related to language that could be useful for deaf children that are struggling with language development after receiving cochlear implantation using a mean that is generally captivating and very appreciated by children: a videogame. In addition, this training can be used by children with normal hearing too and could be of help to other clinical children who are struggling with sequence learning.

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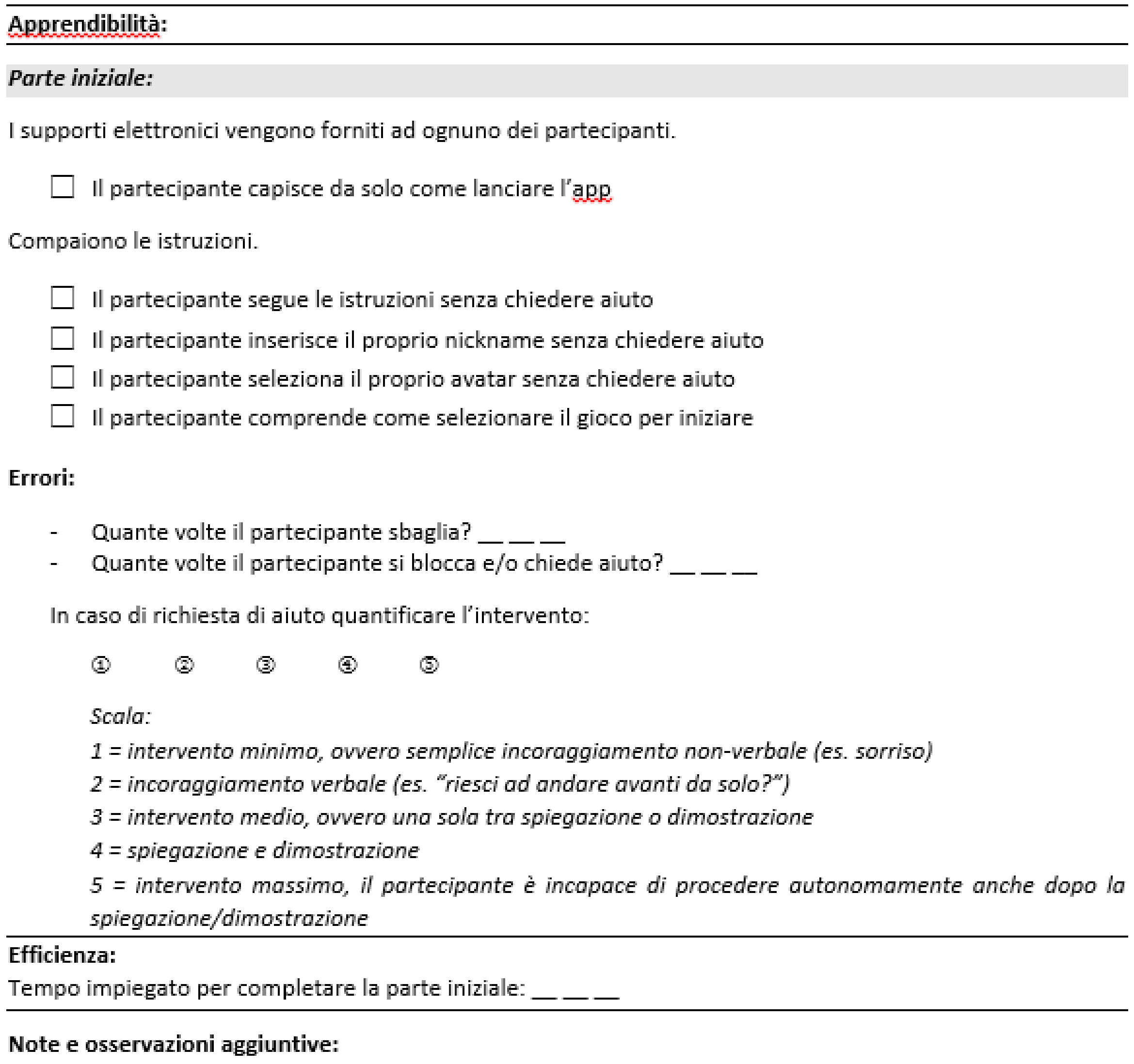
APPENDICES

APPENDIX A: UX ASSESSMENT FORM

Observation Checklist



Apprendibilità:

Parte iniziale:

I supporti elettronici vengono forniti ad ognuno dei partecipanti.

☐ Il partecipante capisce da solo come lanciare l'app

Compaiono le istruzioni.

☐ Il partecipante segue le istruzioni senza chiedere aiuto
☐ Il partecipante inserisce il proprio nickname senza chiedere aiuto
☐ Il partecipante seleziona il proprio avatar senza chiedere aiuto
☐ Il partecipante comprende come selezionare il gioco per iniziare

Errori:

- Quante volte il partecipante sbaglia? __ __ __
- Quante volte il partecipante si blocca e/o chiede aiuto? __ __ __

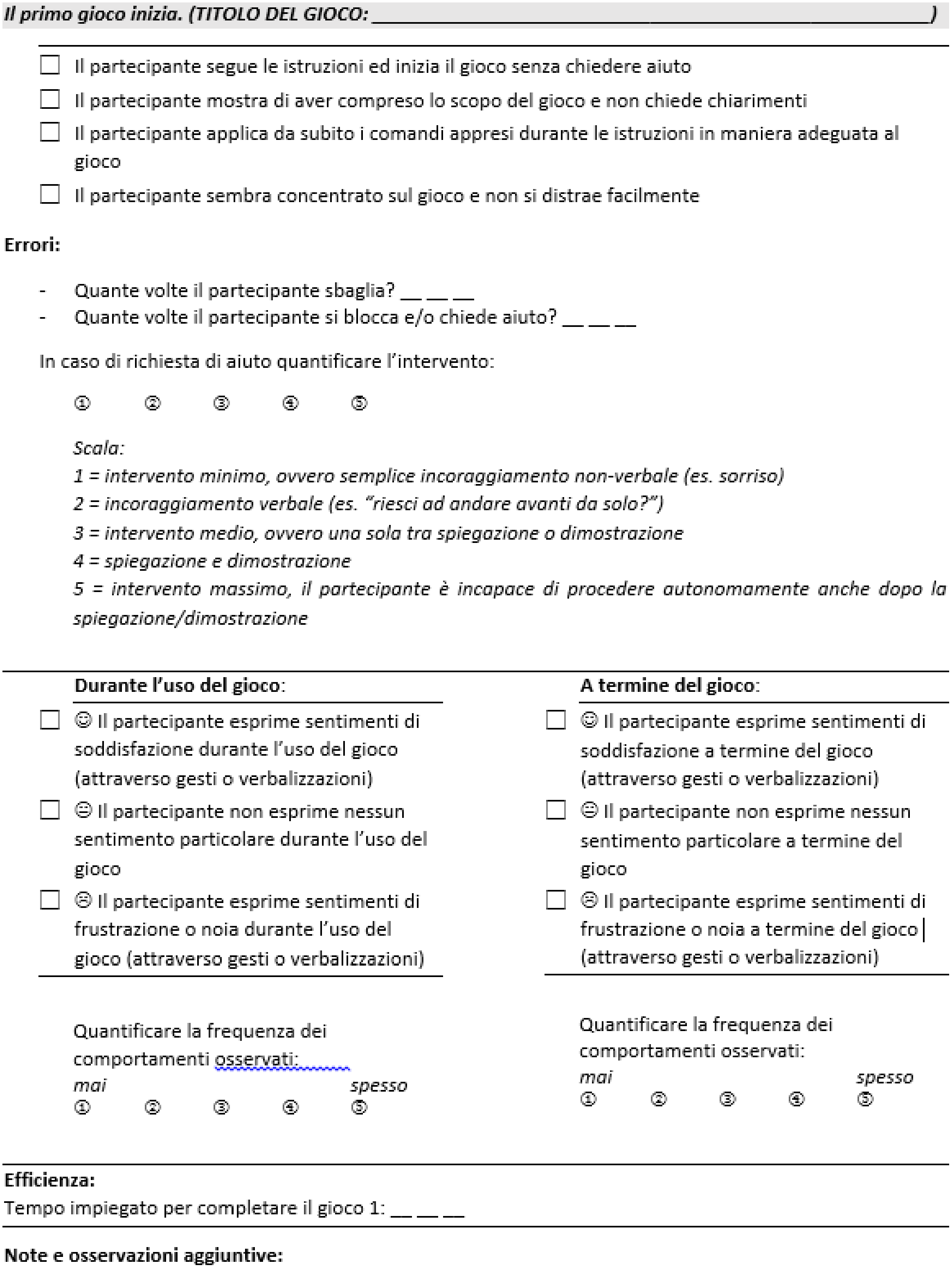
In caso di richiesta di aiuto quantificare l'intervento:

① ② ③ ④ ⑤

Scala:
1 = intervento minimo, ovvero semplice incoraggiamento non-verbale (es. sorriso)
2 = incoraggiamento verbale (es. "riesci ad andare avanti da solo?")
3 = intervento medio, ovvero una sola tra spiegazione o dimostrazione
4 = spiegazione e dimostrazione
5 = intervento massimo, il partecipante è incapace di procedere autonomamente anche dopo la spiegazione/dimostrazione

Efficienza:
Tempo impiegato per completare la parte iniziale: __ __ __

Note e osservazioni aggiuntive:



Il primo gioco inizia. (TITOLO DEL GIOCO: ______________________________)

☐ Il partecipante segue le istruzioni ed inizia il gioco senza chiedere aiuto
☐ Il partecipante mostra di aver compreso lo scopo del gioco e non chiede chiarimenti
☐ Il partecipante applica da subito i comandi appresi durante le istruzioni in maniera adeguata al gioco
☐ Il partecipante sembra concentrato sul gioco e non si distrae facilmente

Errori:

- Quante volte il partecipante sbaglia? __ __ __
- Quante volte il partecipante si blocca e/o chiede aiuto? __ __ __

In caso di richiesta di aiuto quantificare l'intervento:

① ② ③ ④ ⑤

Scala:
1 = intervento minimo, ovvero semplice incoraggiamento non-verbale (es. sorriso)
2 = incoraggiamento verbale (es. "riesci ad andare avanti da solo?")
3 = intervento medio, ovvero una sola tra spiegazione o dimostrazione
4 = spiegazione e dimostrazione
5 = intervento massimo, il partecipante è incapace di procedere autonomamente anche dopo la spiegazione/dimostrazione

Durante l'uso del gioco:	**A termine del gioco**:
☐ ☺ Il partecipante esprime sentimenti di soddisfazione durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☺ Il partecipante esprime sentimenti di soddisfazione a termine del gioco (attraverso gesti o verbalizzazioni)
☐ 😐 Il partecipante non esprime nessun sentimento particolare durante l'uso del gioco	☐ 😐 Il partecipante non esprime nessun sentimento particolare a termine del gioco
☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia a termine del gioco (attraverso gesti o verbalizzazioni)
Quantificare la frequenza dei comportamenti osservati: *mai* ... *spesso* ① ② ③ ④ ⑤	Quantificare la frequenza dei comportamenti osservati: *mai* ... *spesso* ① ② ③ ④ ⑤

Efficienza:
Tempo impiegato per completare il gioco 1: __ __ __

Note e osservazioni aggiuntive:

Il secondo gioco inizia. (TITOLO DEL GIOCO: ____)

☐ Il partecipante segue le istruzioni ed inizia il gioco senza chiedere aiuto
☐ Il partecipante mostra di aver compreso lo scopo del gioco e non chiede chiarimenti
☐ Il partecipante applica da subito i comandi appresi durante le istruzioni in maniera adeguata al gioco
☐ Il partecipante sembra concentrato sul gioco e non si distrae facilmente

Errori:

- Quante volte il partecipante sbaglia? __ __ __
- Quante volte il partecipante si blocca e/o chiede aiuto? __ __ __

In caso di richiesta di aiuto quantificare l'intervento:

① ② ③ ④ ⑤

Scala:
1 = intervento minimo, ovvero semplice incoraggiamento non-verbale (es. sorriso)
2 = incoraggiamento verbale (es. "riesci ad andare avanti da solo?")
3 = intervento medio, ovvero una sola tra spiegazione o dimostrazione
4 = spiegazione e dimostrazione
5 = intervento massimo, il partecipante è incapace di procedere autonomamente anche dopo la spiegazione/dimostrazione

Durante l'uso del gioco:	**A termine del gioco**:
☐ ☺ Il partecipante esprime sentimenti di soddisfazione durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☺ Il partecipante esprime sentimenti di soddisfazione a termine del gioco (attraverso gesti o verbalizzazioni)
☐ 😐 Il partecipante non esprime nessun sentimento particolare durante l'uso del gioco	☐ 😐 Il partecipante non esprime nessun sentimento particolare a termine del gioco
☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia a termine del gioco (attraverso gesti o verbalizzazioni)
Quantificare la frequenza dei comportamenti osservati: *mai* *spesso* ① ② ③ ④ ⑤	Quantificare la frequenza dei comportamenti osservati: *mai* *spesso* ① ② ③ ④ ⑤

Efficienza:
Tempo impiegato per completare il gioco 2: __ __ __

Note e osservazioni aggiuntive:

Il terzo gioco inizia. (TITOLO DEL GIOCO: ____)

☐ Il partecipante segue le istruzioni ed inizia il gioco senza chiedere aiuto

☐ Il partecipante mostra di aver compreso lo scopo del gioco e non chiede chiarimenti

☐ Il partecipante applica da subito i comandi appresi durante le istruzioni in maniera adeguata al gioco

☐ Il partecipante sembra concentrato sul gioco e non si distrae facilmente

Errori:

- Quante volte il partecipante sbaglia? __ __ __
- Quante volte il partecipante si blocca e/o chiede aiuto? __ __ __

In caso di richiesta di aiuto quantificare l'intervento:

① ② ③ ④ ⑤

Scala:
1 = intervento minimo, ovvero semplice incoraggiamento non-verbale (es. sorriso)
2 = incoraggiamento verbale (es. "riesci ad andare avanti da solo?")
3 = intervento medio, ovvero una sola tra spiegazione o dimostrazione
4 = spiegazione e dimostrazione
5 = intervento massimo, il partecipante è incapace di procedere autonomamente anche dopo la spiegazione/dimostrazione

Durante l'uso del gioco:	**A termine del gioco**:
☐ ☺ Il partecipante esprime sentimenti di soddisfazione durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☺ Il partecipante esprime sentimenti di soddisfazione a termine del gioco (attraverso gesti o verbalizzazioni)
☐ 😐 Il partecipante non esprime nessun sentimento particolare durante l'uso del gioco	☐ 😐 Il partecipante non esprime nessun sentimento particolare a termine del gioco
☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia durante l'uso del gioco (attraverso gesti o verbalizzazioni)	☐ ☹ Il partecipante esprime sentimenti di frustrazione o noia a termine del gioco (attraverso gesti o verbalizzazioni)
Quantificare la frequenza dei comportamenti osservati: *mai* *spesso* ① ② ③ ④ ⑤	Quantificare la frequenza dei comportamenti osservati: *mai* *spesso* ① ② ③ ④ ⑤

Efficienza:
Tempo impiegato per completare il gioco 3: __ __ __

Note e osservazioni aggiuntive:

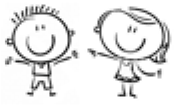
Efficienza:
Tempo totale impiegato per completare tutte le parti: __ __ __

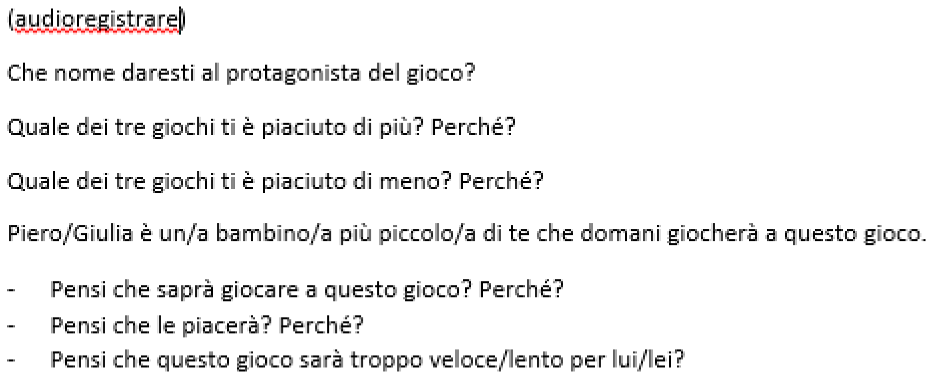
Questionnaire

La risposta del/la bambino/a è fornita muovendo un cursore/indicando con il dito la propria posizione su una barra di gradimento a cinque punti su cui sono riportate tre espressioni facciali estratte dal Test di Comprensione delle Emozioni (TEC; Albanese & Molina, 2008), ovvero espressione triste, neutra, e felice. Al partecipante viene chiesto di esprimere la propria opinione rispetto alle affermazioni dello sperimentatore. "Adesso io ti dirò delle frasi e tu dovrai indicarmi su questa barra se che quello che ho detto è tanto vero per te (faccia felice), se è un po' vero ma non tanto (zona verde chiaro), se non lo sai (faccia neutra), se è un po' falso (zona arancione), o se è proprio tanto falso per te (faccia triste).

Soddisfazione:					
	Per niente vero				Molto vero
	☹		😐		☺
Le istruzioni del gioco erano facili da capire.	1	2	3	4	5
L'obiettivo del gioco era spiegato chiaramente.	1	2	3	4	5
Era facile capire come arrivare alla fine del gioco.	1	2	3	4	5
Mi piaceva raccogliere le monetine durante il gioco.	1	2	3	4	5
Mi piacciono i suoni che ci sono nel gioco.	1	2	3	4	5
Mi piacciono i colori che ci sono nel gioco.	1	2	3	4	5
Mi piace il personaggio del gioco.	1	2	3	4	5
Era facile guidare il personaggio del gioco.	1	2	3	4	5
Il gioco era divertente.	1	2	3	4	5
Mi sono annoiato/a durante il gioco.	1	2	3	4	5
Mi piacerebbe provare altri giochi simili a quello che ho provato oggi.	1	2	3	4	5
Se avessi questo gioco a casa ci giocherei spesso.	1	2	3	4	5
Vorrei invitare i miei amici a provare questo gioco.	1	2	3	4	5
In generale il gioco era facile da usare.	1	2	3	4	5

Semi-structured Interview





(audioregistrare)

Che nome daresti al protagonista del gioco?

Quale dei tre giochi ti è piaciuto di più? Perché?

Quale dei tre giochi ti è piaciuto di meno? Perché?

Piero/Giulia è un/a bambino/a più piccolo/a di te che domani giocherà a questo gioco.

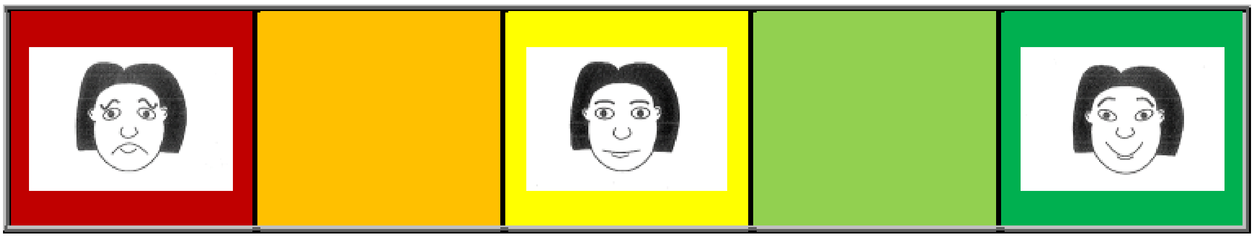
- Pensi che saprà giocare a questo gioco? Perché?
- Pensi che le piacerà? Perché?
- Pensi che questo gioco sarà troppo veloce/lento per lui/lei?

Drawing

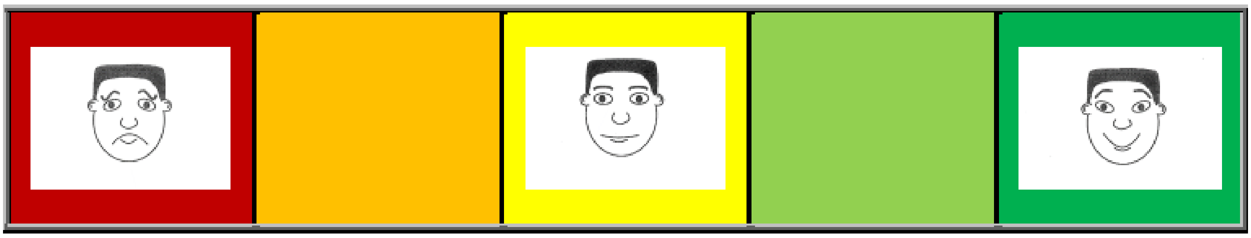
Grazie per i tuoi suggerimenti! Fai un disegno dei miglioramenti che vorresti vedere nel gioco/di come cambieresti il gioco/immagini il gioco.

APPENDIX B: FIVE-POINT RATING SCALE (LIKERT)

Female version



Male version



Images source: Test di Comprensione delle Emozioni (TEC; Albanese & Molina, 2008)