FEDERAL UNIVERSITY OF CEARÁ
COMPUTER SCIENCE DEPARTMENT
GRADUATE PROGRAM IN COMPUTER SCIENCE

TICIANNE DE GOIS RIBEIRO DARIN

USABILITY SCAFFOLDING FOR EVALUATING MULTIMODAL VIDEO GAMES FOR LEARNERS WHO ARE BLIND

FORTALEZA
2018

TICIANNE DE GOIS RIBEIRO DARIN

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Thesis submitted to Master and PhD in Computer Science (MDCC/UFC), in partial fulfillment of the requirements for the degree of Doctor in Computer Science. Concentration Area: Human-Computer Interaction.

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FORTALEZA

2018

Dados Internacionais de Catalogação na Publicação
Universidade Federal do Ceará
Biblioteca Universitária
Gerada automaticamente pelo módulo Catalog, mediante os dados fornecidos pelo(a) autor(a)

D233u Darin, Ticianne.
Usability Scaffolding for Evaluating Multimodal Video Games for Learners who are Blind / Ticianne Darin. – 2018.
257 f. : il. color.

Tese (doutorado) – Universidade Federal do Ceará, Centro de Ciências, Programa de Pós-Graduação em Ciência da Computação , Fortaleza, 2018.
Orientação: Profa. Dra. Rossana Maria de Castro Andrade.
Coorientação: Prof. Dr. Jaime Sánchez Hernán Illabaca.

1. Multimodal interaction. 2. Usability Evaluation. 3. People who are blind. I. Título.
CDD 005

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Tese apresentada ao Curso de Doutorado em Ciência da Computação do Programa de Mestrado e Doutorado em Ciência da Computação, como requisito parcial à obtenção do título de doutor em Ciência da Computação. Área de concentração: Interação Humano-Computador.

Aprovada em: ____/_____/______

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To my beloved father, my hero, my backbone, my mentor, and my inspiration. It was not God's will that you would see me finish this work. But you were the one who taught me to love knowledge. I will carry your life lessons in my heart forever and use them until the day we meet again, in the glory of the resurrection.

ACKNOWLEDGEMENTS

First and above all, I praise God, the Almighty for providing me this opportunity and granting me the strength and capability to undertake this research study and to persevere and complete it satisfactorily. This thesis appears in its current form due to the assistance and guidance of several people. I would like to pay special thankfulness and appreciation to the persons below who made my research successful and assisted me in this journey.

I would like to express my gratitude to my esteemed advisor, prof. Dr. Rossana Andrade - in whom I have found a teacher and a friend - for the trust and opportunities, for accepting me as a Ph.D student, and for teaching me so much more than academic curriculum. I learned inspiring life lessons from your advices, your loyalty, and your untiring dedication to the University and to your students. Thank you for being a pillar of support to me, for your heartfelt encouragement, thoughtful guidance, critical comments, and correction of the thesis.

I also want to express my deep thanks to my co-advisor prof. Dr. Jaime Sánchez, to whom I have an intellectual debt for the insightful conversations, discussions, and ideas. Thank you for sharing with me your knowledge and aspiration for greatness. I am immensely grateful for your support and patient feedback during the whole period of the research, and for the careful guidance, great experiences, and priceless suggestions in my quest for knowledge.

I extend my thanks to the members of the committee, Prof. Dr. Elizabeth Furtado, Prof. Dr. Letícia Leite, Prof. Dr. Lotfi Merabet, and Prof. Dr. Windson Carvalho for kindly sharing your time and knowledge, accepting to review and comment this thesis. My special thanks to Prof. Dr. Windson Carvalho for first encouraging me to pursue a Ph.D. degree, and also to Prof. Dr. Mauro Pequeno for being really supportive.

I am deeply grateful to my lovely husband Daniel, who has been a constant source of love, support and encouragement during the challenges in my pursuit of Ph.D degree and in life. I greatly value his warmly dedication and appreciate his belief in me. Thank you for always being understanding and for being around every time I thought that it was impossible to continue. I am truly thankful for having you in my life.

I would also like to express my heartfelt appreciation to my family, especially my mom and dad - Jaqueline and Ivaldo - who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. Special thanks to my brother Thiago, my grandma Marilza, and my aunt/sister Tita for their love and support. I also deeply thank my parents-in-law, Evandro and Solange, and my sister-in-law Danielle who fondly encouraged me during all these years.

It’s my fortune to gratefully acknowledge the support of my two dearest friends, who have, in their own ways, kept me going on my path to success, assisting me as per their abilities, in whatever manner possible and for ensuring that good times kept flowing: Raquel, for her prayers, her sincerely supportive words and for her such tender care in every detail of my life; and Nayana for being my "What! You too? I thought that no one but myself...”, and for standing by my side with determination in every single step of this journey, literally being my hands if she had to! I also extend my gratitude to my persons: Rute, Bruno and Belmondo for being always beside me during the happy and hard moments to push me and motivate me. Although the carousel never stops turning, it has been an honor to ride with you.

I also thank my school colleagues who have helped make my learning a unique and stimulating experience. I have also had the support and encouragement of my colleagues of Virtual University Institute, among which I especially thank Cadu and Ney for their friendly support, Rafael for the invaluable help with statistical analysis, and Alysson for the constant fellowship, sharing with me the ups and downs of this journey and bringing so many moments of enjoyment in the process. I owe a very important debt to all the non-teaching staff of GREat that have helped me, and thanks are due to all of them for their silent - but precious - contributions, in particular Jana, Dari and Chris, who have been so helpful and cooperative in giving their support at all times to help me achieve my goal.

I appreciate the generous support received from Matías Pardo and Exequiel Cifuentes in the execution of this research. I am particularly grateful for the assistance given by Paulina Castillo in the user tests. Thank you so much, Paulina, for the help and sympathetic attitude! I have greatly benefited from the collaboration of Hellen Keller and Santa Lucia Schools for children who are blind, and from the researchers that kindly answered to my expert opinion survey. I also extend my appreciation to Alexandra Elbakyan for the inestimable sharing of scientific papers.

And lastly, I thank the financial support received from Brazil LGE – Project Mobile, Tool & CAS with FCPC administration (Law 8248/1991) during my years of research. The development of this Doctoral Thesis is part of the Research Project of the National Fund for Science and Technology, Fondecyt-Chile # 1150898, "*Knowing with Multimodal Interfaces in Blind Learners*", as well as being part of the Basal Funds for Centers of Excellence, FB0003, CONICYT-Chile.

Technology may change rapidly, but people change slowly. Principles and lessons that come from an understanding of people remain true forever.

- Don Norman

RESUMO

Videogames multimodais sérios baseados em estímulos sonoros e hápticos têm sido usados para ajudar a desenvolver habilidades e estimular a melhoria cognitiva em alunos cegos. Nesse cenário, a presença de problemas de usabilidade durante interação com o jogo pode comprometer o desenvolvimento e o aprimoramento de habilidades cognitivas. Manter o foco em problemas de usabilidade, e não na aprendizagem, seria frustrante e indesejável. Assim, realizar uma avaliação de usabilidade precisa é um passo necessário para ajudar os alunos que são cegos na construção de habilidades cognitivas enquanto jogam videogames multimodais. No entanto, a avaliação nesse contexto necessita de pesquisa em relação a quais aspectos do jogo devem ser avaliados e como proceder com a avaliação. Para estabelecer diretrizes para a avaliação da usabilidade nessa área, evitando cenários em que esta dependa apenas da experiência individual do avaliador, a identificação de princípios de avaliação é necessária.
Assim, o principal objetivo deste trabalho é gerar *scaffolding* para orientar pesquisadores e profissionais na escolha e combinação de métodos de avaliação de usabilidade para avaliar tais jogos em contextos de uso específicos, dadas as características dos usuários-alvo e as modalidades de interação do jogo. Para tanto, são propostos princípios para avaliação de usabilidade (PLUMB), dois instrumentos para auxiliar na identificação de problemas de usabilidade (SLUP e CLUE) e um modelo descritivo para orientar a escolha de métodos e as etapas de avaliação de usabilidade neste contexto. A validação da proposta inclui experimentos envolvendo alunos cegos jogando tais videogames, além da avaliação de especialistas na área. Nossa expectativa é que os futuros videogames multimodais criados para melhorar a cognição de alunos cegos levem em consideração suas habilidades e deficiências amplamente diferentes, fornecendo interfaces de jogo usáveis e prazerosas, beneficiando-se de nossas descobertas.

Palavras-chave: Interfaces audio hapticas. Métodos de avaliação de usabilidade. Jogos digitais multimodais.

ABSTRACT

Serious multimodal video games based on audio and haptics have been used to help developing new skills and to stimulate cognitive improvement for learners who are blind. In this scenario, the presence of usability issues in the gaming interaction can jeopardize the development and enhancement of the target cognitive skills, once focusing on usability issues rather than on learning would be frustrating and undesirable. Administering an accurate usability evaluation is hence a necessary step towards assisting learners who are blind in the construction of cognitive skills while playing video games. Nevertheless, the usability evaluation of serious multimodal video games for learners who are blind lacks reasoning, in regard to what game aspects to evaluate and how to proceed with the assessment. To avoid scenarios where usability evaluation relies on individual experience and expertise, the identification of evaluation principles to assess the usability of these games is a necessary step, which also helps to establish guidance for usability evaluation in this field. Hence, the main goal of this work is to provide scaffolding to guide researchers and practitioners to employ the most appropriate combination of Usability Evaluation Methods (UEMs) to assess such games in particular usage contexts, given the characteristics of the target users and game interaction modalities. To achieve that, the present work proposes principles for usability evaluation (PLUMB), two instruments to support identification of usability problems (SLUP and CLUE), and a descriptive model to guide the choice of UEMs and the steps of usability evaluation in this field. The validation of the proposal includes experiments involving learners who are blind playing video games and evaluation by experts in the field. Our expectation is that forthcoming multimodal video games designed to improve cognition of learners who are blind take into consideration their broadly different abilities and disabilities and provide them with usable and pleasurable gaming interfaces, benefiting of our findings.

Keywords: Audio haptic interfaces. Usability evaluation methods. Multimodal video games.

FIGURES LIST

TABLES LIST

LIST OF ABBREVIATIONS AND ACRONYMS

ACM	Association for Computing Machinery
AINIDIU	Agente Inteligente para Ninos con Discapacidad Visual
AMITUDE	Application, Modalities, Interaction, Task, User, Device and Environment
BPMN	Business Process Model Notation
CARE	Complementarity, Assignment, Redundancy and Equivalence
CASE	Concurrent, Alternate, Synergistic and Exclusive
CLUE	Checklist for Usability Evaluation of Multimodal Games for Children who are Blind
DNA	Deoxyribonucleic acid
DOM	Document Object Model
EC	Exclusion Criteria
EMG	Electromyography
ETA	Electronic Travel Aids
EUQ	End User and Facilitator Questionnaire for Software Usability
GBL	Game-Based Learning
GDD	Game Design Document
GPS	Global Positioning System
GSR/EDA	Galvanic Skin Response/Electrodermal Activity
GUI	Graphic User Interface
HCI	Human-Computer Interaction
HEQ	Heuristic Evaluation Questionnaire
HEV	Heuristic Evaluation of the Video game
HR	Heart Rate
IC	Inclusion Criteria
ICIDH	International Classification of Impairments, Disabilities and Handicaps
IDE	Integrated Development Environment
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
IUE	Initial Usability Evaluation
MIS	Multimodal Interaction Space
MMOG	Massively Multi-player Online Game
MVE	Multi-sensory Virtual Environment

O&M	Orientation and Mobility
OQU	Open Question Usability Questionnaire
PLUMB	PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind
QUIM	Quality in Use Integrated Map
SDK	Software Development Kit
SLR	Systematic Literature Review
SLUP	Standard List of Usability Problems
SUBC	Software Usability for Blind Children Questionnaire
SUE	Software Usability Elements Questionnaire
TAP	Think Aloud Protocol
TTS	Text-to-speech
UEM	Usability Evaluation Method
UI	User Interface
UX	User Experience
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
VT	Videotrainer
WIMP	Window, Icons, Menu and Pointer
XML	Extensible Markup Language

SUMMARY

1. INTRODUCTION

The present Chapter introduces the research topic studied in this work: usability evaluation of multimodal video games for cognitive development of learners who are blind. Moreover, it summarizes the approach followed to investigate and answer the raised research questions.

Section 1.1 contextualizes this study. Section 1.2 discusses the motivation behind the development of this work. Section 1.3 presents the research problem that was studied. Section 1.4 shows the hypothesis tested in the present work. Section 1.5 describes the main questions that guided this research. Section 1.6 declares the purpose and expected outcomes of this study. Section 1.7 details the followed methodology. Section 1.8 stablishes the scope and delimitations of this work. Section 1.9 presents the structure of the next sections of this document.

1.1 Contextualization

Cognition is the key to human life. People's actions, behavior, and understanding of the world is deeply connected with how they construct their worldview and explain the causes, mechanisms, and relationships between things and situations (NORMAN, 2013). In human cognition, the process whereby people structure concepts of the surrounding world is connected to abstracting principles and articulating generalizations based on a person's impressions and perceptions of the world (CHESS & HASSIBI, 2013). This process culminates in the formation of mental models, which are mental representations of the physical world (JOHNSON-LAIRD, 1983; VELDHUYZEN & STASSEN, 1976), and cognitive constructs that explain human behavior (KEMPTON, 1986; WICKENS, 1984). These mental models of the world allow humans to manipulate an internal representation of an external domain expressed in some private language, determining how they transform their intentions into actions to interact with the world (FODOR, 1975 APUD JULKA 2010; NORMAN, 2013).

The maturity and the proper development of the previously mentioned mental conceptualizations determines someone's ability to solve problems, understand reality, and interact with their surroundings (CHESS & HASSIBI, 2013). Humans build up abstract concepts by integrating experiences from different sensory modalities (UNGAR, 2000), being the optical channels responsible for collecting most of the information required for forging mental representations of the surrounding world (LAHAV & MIODUSER, 2008).

Therefore, in the absence or reduction of visual information, the ability to conceptualize the environment as well as to establish relations among distinct objects is negatively affected, because a person needs to gather contextual information about his surroundings to assemble a mental representation of the world (LOOMIS, KLATZKY & GOLLEDGE, 2001). Consequently, the development of cognitive skills requiring some level of abstraction represents a challenge for people who are legally blind[1], especially in the case of children, who have difficulty in making inferences and forming concepts that are mostly forged by the extensive use of visual cues (CHESS & HASSIBI, 2013).

For this reason, children with visual disabilities[2] have more difficulties in accessing information, learning and putting basic operations into practice, as well as in solving problems when compared to their sighted peers (KULYUKIN et al., 2004). One fact behind these issues is that children who are blind cannot fully perceive anything at once; instead, everything has to be constructed through either direct experience or some auxiliary aids (SPENCER et al., 1992). As the collection of environmental information in people who are blind is based on sensory channels different from sight, the integration of this information is distinct when creating mental representations of the environment. Only when engaged in these types of activities children who are blind will be able to forge the cognitive concepts that connect them to the external world (CHESS & HASSIBI, 2013). For example, learning the environment using touch means having to rely on sequential observations and building a mental image from its components and not from the whole (FIELDER, BEST, & BAX 1993; GOUZMAN & KOZULIN, 2000).

This sequential information capture coming from the sense of touch opposes to the identification by sight, which allows sighted people to identify objects and space more quickly. However, Nunes and Lomônaco (2008) point out that the perception of space and objects by people who are blind occurs by joining tactile, kinesthetic, and auditory sensations

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[1] By “legally blind”, this work means people with central visual acuity of 20/200 or less in the better eye with the use of a correcting lens. The terms legally blind, blind, visually impaired, person with visual loss and person with visual disabilities are used indistinctly throughout the present text.

[2] This work employs "Person first language" (Coalition for Tennesseans with Disabilities 1992, 1994; PACER Center 1989) when referring to individuals with disabilities. The goal of using this writing style is to create a positive view of people with disabilities, instead of insensitive portrayals that stereotype and discriminate them. In this style of communication, the person is put before the disability, for example, "a person who is blind" rather than "a blind person". The use of this language places the focus on the individual rather than on his or her disability. At the same time, by following "person first language" guidelines, we do not refer to a person's disability unless it is relevant; we avoid negative or sensational descriptions of a person's disability (such as, "suffers from blindness"); and we avoid statements that qualify the person with a disability (such as "even though this child is blind, he is very intelligent").

allied to mental experiences already experienced by them. It means that the lack of vision, by itself, is not an impediment to cognitive development, but requires different forms of interaction and learning for the construction of knowledge and the development of skills like Orientation and Mobility (O&M). O&M involve a set of techniques to provide the concepts, skills, and tools necessary for individuals who are blind to move efficiently throughout the environment (HATTON, 2014) including, for example, safely navigating a set of stairs, moving around their home, schools, workplaces, and communities, crossing streets, accessing public transportation and determining locations (FIGURE 1).

Figure 1 – O&M specialists teaching children who are blind some of the concepts and techniques necessary for safe navigation.

Source: Central Association for the Blind and Visually Impaired (2017)

Since acquiring and reasoning about abstract concepts is difficult for children who are blind, diverse daily life situations that require the use of some general domain skills become more difficult, including tempo-spatial orientation, and learning specific domain content, like graphics and algebraic expressions (SÁNCHEZ & SÁENZ, 2005). Learning Mathematics, for instance, can be very complex for children who are blind, because of their usually poor abstraction skills that create a barrier for various mathematical concepts and culminate in demotivation for learning (EBENEZER, ADAIKALARAJ & GAJALAKSHMI, 2014). For these learners, geometry and spatial sense has to be taught by means of concrete hands-on experiences, using adapted instruments equivalent as those shown in Figure 2.

Biology can also be difficult for them to learn due to the abstraction innate to the studied concepts, such as in the case of Genetics, associated to the impossibility of doing a direct observation of natural phenomena (SÁNCHEZ & AGUAYO, 2008). In fact, students with visual disabilities hardly learn Sciences by practicing, and diverse adaptation is necessary for the teaching methodology to help students who are blind construct the necessary cognitive concepts to carry on experiments and reach their potential in science (KUMAR, RAMASAMY & STEFANICH, 2001).

Easy tasks that require spatial representation in the daily routine of children who are blind, like obstacle avoidance and route selection, are also frequently more complex due to the absence of sight (KOLB & WHISHAW, 2006). Actually, navigation and wayfinding, particularly in unknown indoor scenarios, have been a long-standing research challenge in this field (BHOWMICK & HAZARIA, 2017). For example, it is common that people who are blind choose a certain route based on safety concerns, instead of on route efficiency, considering the reduced risk of tripping or bumping into something, although the distance may be longer (PRESSL & WIESER, 2006). This experience is far more complex in an unfamiliar or public environment (KULYUKIN et al., 2004), where traditional aids would present limitations when facing obstacles like escalators and revolving doors, causing difficulties in guiding a person to choose the best possible route to a given destination (SÁNCHEZ & ELIAS, 2007).

Figure 2 – Giant Textured Beads with Pattern Matching Cards, varying in color, shape, and texture, including Pattern Matching Cards and Sorting Trays. This product helps teachers and parents working with young students in preschool, kindergarten, and early elementary grades who have visual impairments and blindness.

Source: American Printing House for the Blind, Inc. (2014)

Several aids and techniques have been developed aiming to help children and adults who are blind to overcome difficulties caused by the lack of sight: O&M techniques to help them navigate efficiently; Braille techniques for reading and writing; and the representation of images and graphics in tactile maps. Despite the helpful assistance the mentioned techniques provide, it is further necessary to help these people improve cognitive skills that require abstraction, especially while learning (CHESS & HASSIBI 2013; SPENCER et al., 1992).

Young learners[3] with functional or total blindness rely on the use of non-visual stimuli to help them acquire information from a real-world object or environment to construct a cognitive image that will allow them to interact with a target. They naturally use a combination of modalities to interact with their surroundings and to construct cognitive concepts about it (TURNBULL, 1995; COX & DYKES, 2001). Based on this fact, there is scientific evidence that multimodal computational interfaces based on audio and haptic stimuli, like the one shown in Figure 3, can enhance learning and cognitive skills in individuals who are blind (LAHAV & MIODUSER, 2008; LAHAV et al., 2008; SÁNCHEZ & TADRES, 2010, PINCINALI et. al, 2014, LAHAV et al., 2018).

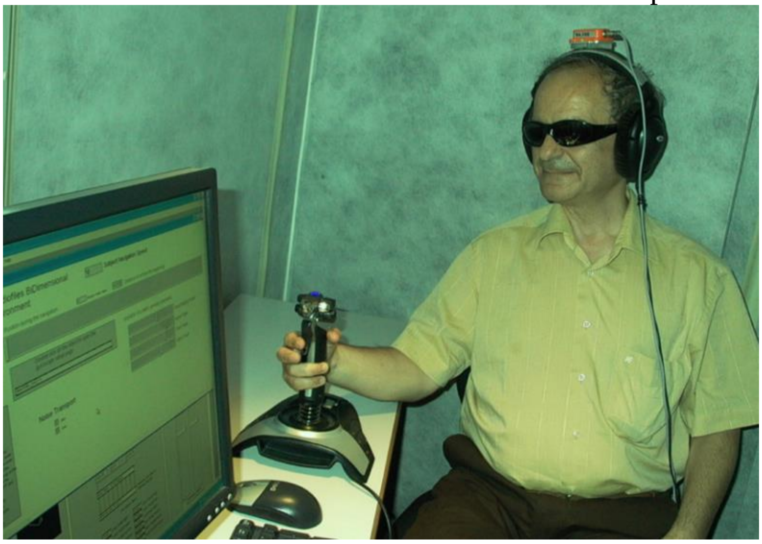
Serious multimodal games based on audio and haptics are attractive teaching tools, especially in the case of children with visual disabilities. These games can be used to teach them new skills and to stimulate cognitive improvement, because they provide a deeply engaging virtual environment in which the children experience situations that would be unreachable in their everyday lives (CHENG et al., 2015; CHENG & ANNETTA, 2012).

The research literature presents evidence that serious multimodal video games based on audio and haptic inputs have great potential to help people who are blind to develop new skills (CONNORS et al., 2014), learn academic curriculum (FERREIRA & CAVACO, 2014, AHMETOVIC et al., 2017), and even to improve and enhance cognitive skills. Among these skills are navigation (CONNORS et al., 2014, ALLAIN et al., 2015), construction of cognitive maps (LAHAV & MIODUSER, 2008), abstract and geometrical thinking (FERREIRA & CAVACO, 2014; LUMBRERAS & SÁNCHEZ, 1999), and collaboration and sociability (SÁNCHEZ et al., 2003; TANHUA-PIIROINEN, PASTO, RAISAMO, & SALLNÄS, 2008). In this type of video games, the multimodality plays a crucial role for children who are blind to acquire non-visual stimuli during interaction (RAISAMO et al., 2006; SÁNCHEZ, LUMBRERAS & CERNUZZI, 2001). since children and young students

[3] "Young learner" is a generic term that encompasses a wide range of learners as a group that shares commonly accepted needs and rights as children but differ greatly as learners in terms of their physical, psychological, social, emotional, conceptual, and cognitive development, as well as their development of literacy (ELLIS, 2013). In this work, the term "young learners who are blind" is employed to refer to legally blind literate children and adolescents attending from 2nd grade (Elementary School) to 12th grade (senior High School), in the context of acquiring skills or knowledge. The terms young learners who are blind, learners who are blind and children who are blind are used indistinctly throughout the present document.

with functional or total blindness naturally use a combination of modalities to learn and to interact with their surroundings (COX & DYKES, 2001; TURNBULL, 1995).

Figure 3 – Individual who is blind performing virtual navigation using a joystick (haptic input) and wearing headphones (audio output) equipped with orientation sensor. In this setup, the interactive exploration of virtual acoustic room simulations can provide sufficient information for the construction of coherent spatial mental maps



Source: Pincinali et al. (2014)

When real-life surroundings are represented using virtual environments, it is possible to create training applications that allow a person who is blind to interact with elements in a simulated environment during navigation (SÁNCHEZ et al., 2009, 2010a). Various virtual environments have been designed to train people who are blind and to assist them in the development of O&M skills (LAHAV & MIODUSER, 2008; LUMBRERAS & SÁNCHEZ, 1999; SÁNCHEZ et al., 2009; LAHAV, SCHLOERB & SRINIVASAN, 2015; MAIDENBAUM & AMEDI 2015; LAHAV et al. 2017).

These environments have also been presented as video games, combining the development of orientation and mobility skills with challenging and fun purposes, especially when aimed at children (SÁNCHEZ, SÁENZ, & GARRIDO, 2010; MERABET et al. 2012; CONNORS et al., 2014; ALLAIN et al. 2015; CUTURI, 2016). Video games, when integrated with virtual training environments, represent a valuable tool for the development of various abilities, particularly O&M skills (SQUIRE, 2003; STEINKUEHLER, 2004).

In fact, these video games constitute a specific type of multimodal applications, i.e., they process two or more combined user input modes in a coordinated manner with multimedia system output (OVIATT, 2002). However, they make use of multimodal gaming technology for purposes other than mere entertainment or "fun", focusing on the attainment of a serious goal, so they can be classified as serious games (SUSI, JOHANNESSON, & BACKLUND, 2007; SENDBERG, MARIS, GEUS, 2011). These video games incorporate a series of fundamentally sound learning principles strongly endorsed by modern research in cognitive sciences (GEE, 2003).

Consequently, they encourage the fostering of diverse kinds of specific mental skills in people with multiple types of disabilities (SÁNCHEZ & OLIVARES, 2011; DURKIN et al., 2013; CHENG et al., 2015). This later helps learners to virtually transfer this knowledge to a real environment and, ultimately, to everyday life (CONNORS et al., 2014; PINCINALI et. al, 2014; LAHAV et al., 2018), as shown in Figure 4.

In this work, the focus is mainly on this type of multimodal video game, although the analysis performed can be expanded for video games meant to enhance and improve multiple types of cognitive skills.

Figure 4 – A young learner who is blind interacting with a multimodal video game on a tablet to develop skills related to geometry, at Santa Lucia School for children who are blind. The details show cognitive tasks performed after learning from the video game.

Source: Photograph taken by the author, in Santiago (Chile), February, 2015.

It is important to highlight that the development and enhancement of the target cognitive skills depend on the capacity of the game to represent abstract information by associating the interaction modalities with significant interface elements and perceivable feedback (LAHAV & MIODUSER, 2008; SÁNCHEZ & SÁENZ, 2010). Consequently, the game modalities must afford a precise interpretation of the information conveyed, as well as to support a comfortable and pleasant interaction. If multimodal video games fail to combine the controls and feedback to represent abstract information in an adequate modality, learners who are blind could misinterpret the game elements and goals, therefore facing interaction problems with the game interface that will distract them from learning (ARDITO et al., 2006; SÁNCHEZ, SAÉNZ & GARRIDO, 2010; BERNSEN & DYBKJÆR, 2009).

Hence, such games ought to have a carefully designed multimodal interaction, achieved when researchers and practitioners consider that learners who are blind have different abilities and disabilities, and may need individual support at various levels to learn new skills (RAISAMO et al., 2006; PAGLIANO, 2001).

1.2 Motivation

Although multimodal systems are expected to produce better ways of interacting with various systems using natural modalities of interaction (NIGAY & COUTAZ, 1993), it is still difficult to build usable and effective multimodal systems (CHANG & BOURGUET, 2008; ALIBAY, KAVAKLI, CHARDONNET, & BAIG, 2017). In addition to the inherent challenges of evaluating multimodal systems, critical issues are frequently neglected during the evaluation of multimodal video games for learners who are blind, such as the audience's limitations, and whether the offered modalities support the target cognitive skills (SÁNCHEZ, DARIN & ANDRADE, 2015). Even though usability evaluation is the most frequent type of quality assessment in this context, the lack of a proper and trustable evaluation is a recurrent situation in the development of such video games (DARIN, SÁNCHEZ & ANDRADE, 2015).

Researchers and practitioners often choose to carry out informal usability evaluations due to either time or team issues, or even unfamiliarity with specific usability evaluation instruments and methods (TORRENTE et al., 2009; GUERRERO & LINCOLN, 2012). When usability evaluations do not consider the combination of multimodal inputs, the users' visual disabilities, and the addressed cognitive skills, an important part of the context of use is left out. In this scenario, a drawback is that simply applying ad-hoc questionnaires or interviews after a gameplay session is no guarantee of meeting the user's needs, neither the cognitive requirements of the game.

The role of usability evaluation in this context should be guaranteeing that the multimodal interaction could harmoniously integrate the game modalities with the user preferences, context, and game features (CHILANA, WOBBROCK, & KO, 2010). In addition, it aims to ensure an easy and pleasant multimodal interaction and to prevent interaction issues when using the multimodal interface. Otherwise, children can feel bewildered, tired and inattentive, which negatively affects the learning of cognitive skills while playing (GONZÁLEZ et al., 2011), and possibly lead them to become frustrated, focusing on usability issues rather than on learning the content (ARDITO et al., 2006).

Since one cannot assume that all individuals with visual disabilities are identical – especially in different contexts and with specific cognitive development purposes – evaluators have to identify whenever is necessary to change or extend the interactive modalities and whether the customization options fit the actual user needs (BERNSEN & DYBKJÆR, 2009; FORBRIG et al., 2011). During the evaluation, the types of game modalities should also be analyzed because it could make a considerable difference to usability, from the perspective of learners who are blind, whether a piece of abstract information has been represented in one or another modality (SÁNCHEZ & OLIVARES, 2011; BERNSEN & DYBKJÆR, 2009).

There are specific issues that differentiate multimodal usability evaluation from the evaluation of traditional user interfaces (BERNSEN & DYBKJÆR, 2009), notably in the context of children who are blind (RAISAMO et al., 2006). Considering this difference, conventional Usability Evaluation Methods (UEMs) (HARTSON, ANDRE & WILLIGES, 2003) may not disclose most of the issues that recurrently affect the game interaction of users who are blind. General usability guidelines and methods usually claim to be valid for all application types, but they tend to result in an evaluation biased towards GUI-based systems (BERNSEN & DYBKJÆR, 2009).

Research literature shows comparisons of general UEMs applied in several areas (BOWMAN, GABBARD & HIX, 2002; HARTSON, ANDRE & WILLIGES 2003; DUH, TAN & CHEN 2006; EDWARDS & BENEDYK, 2008; MIAO et al., 2016) and the viability of using the same UEM in diverse domains has been argued (CHILANA, WOBBROCK & KO, 2010; FORBRIG et al., 2011). In the case of people who are blind, it is necessary to take into consideration that traditional UEMs are designed for users without disabilities (CHANDRASHEKAR, 2006). Apart from that, specific issues differentiate multimodal usability evaluation from the evaluation of traditional user interfaces, such as GUIs (BERNSEN & DYBKJÆR, 2009), because usability depends on the context (NEWMAN & TAYLOR, 1999) and is fashioned according to the interaction between tools, problems, and people (NAUR, 1985).

Considering the target users' specificities is necessary for the HCI evaluation of any system (SHNEIDERMAN & PLAISANT, 2005). However, it is a more sensitive matter when evaluating applications for cognitive enhancement of learners who are blind, because of their different contexts, disabilities and specific cognitive development purposes (ESPINOZA, SÁNCHEZ & CAMPOS, 2014; SÁNCHEZ & SAÉNZ, 2006; BERNSEN & DYBKJÆR, 2009). Besides, evaluating multimodal applications involving children with visual disabilities requires specific attention, principally considering the game constant interaction and the need for game modalities that actually afford a precise interpretation of the information conveyed, given the absence of sight (RAISAMO et al., 2006; BELLOTTI, BERTA & DE GLORIA, 2010; BERNSEN & DYBKJÆR, 2009).

The importance of reasoning about multimodal usability in the context of video games for cognitive enhancement of children who are blind resides in the need of gaming interfaces free of unnecessary complexities during the interaction. It is necessary to avoid that the effectiveness of the usability evaluation is jeopardized by the use of inappropriate usability methods and the neglecting of critical issues. These issues include the nature of the audience's limitations, and if the game modalities support and enhance the target cognitive skills. This is an exceptionally relevant issue considering that users who interact for learning generally behave differently from general users, as they do not possess domain expertise, are heterogeneous (including their learning styles), and may not be intrinsically motivated (QUINTANA et al., 2013).

Usable and pleasant multimodal video games could influence the lives of children who are blind by helping them in developing skills that allow them to be more independent in their everyday lives and better integrated and included into society.

1.3 Research Problem

The facts discussed above demonstrate that evaluating video games usability in the context of cognitive enhancement of learners who are blind requires UEM adaptation to ensure that usability evaluation instruments and methods administered disclose most of the issues that affect the game interaction of the target users. In this regard, identifying evaluation principles to assess the usability of multimodal video games for learners who are blind is a necessary step towards establishing guidance for usability evaluation in this field.

Nowadays, however, there is not a consistent proposition on which UEMs are suitable in these circumstances, so the selection of methods usually relies on individual experience and expertise. The usability evaluation of serious multimodal video games for learners who are blind lacks reasoning, regarding to what game aspects to evaluate and how to proceed with the assessment. Such gap is demonstrated by the fact that, frequently, studies evaluating usability of multimodal games and virtual environments involving people who are blind follow broadly different procedures, even when they have very similar goals and setups (DARIN, SÁNCHEZ & ANDRADE, 2015). Consequently, video games can be developed for learners who are blind relying on unconfirmed assumptions about ease of use, learnability, and interaction, for not performing usability evaluation involving potential users (TORRENTE et al., 2009; GUERRERO & LINCOLN, 2012; TREWIN, HANSON, LAFF & CAVENDER, 2008).

In addition to that, to the best of our knowledge, few works are addressing usability evaluation of multimodal games for learners who are blind. As discussed in Chapter 3, there are related works that analyze the usability evaluation of multiple types of interfaces for blind users. They illustrate the need for reasoning about the administration of UEMs to fit better the context of people who are blind. None of them, however, focuses on the following research problem addressed in this work:

> *How to conduct usability onsite evaluation of multimodal video games based on audio and haptics, designed for enhancing and improving cognition in learners who are blind, employing UEMs adequate to the users' individualities and to the evaluation goals?*

1.4 Research Hypothesis

In this study, a two-tailed non-directional[4] experimental hypothesis is tested to investigate the research problem:

During onsite usability evaluation involving learners who are blind playing multimodal video games for cognitive development, Usability Evaluation Methods (UEMs) effectiveness differ significantly for disclosing specific types of usability issues directly associated with the interaction modalities.

1.5 Research Questions

The adequate conduction of usability onsite evaluation begins in the planning phase, when choosing a proper combination of UEMs and identifying usage context and users' characteristics. However, planning a usability user test to identify relevant issues on multimodal video games for learners who are blind is not a trivial task. To help overcome the lack of guidance about planning and conducting usability evaluation involving users in this context, this research aims to answer the following questions:

RQ1. What are the main interface and interaction characteristics of multimodal video games for cognitive development of learners who are blind?

RQ2. What are the main principles that should be followed to evaluate multimodal video games based on audio and haptics for learners who are blind?

RQ3. Given a set of the most used UEMs when field-testing games for learners who are blind, what types of usability issues can each of them disclose?

RQ4. During field tests involving multimodal games for learners who are blind, how can UEMs be combined to evaluate interaction modalities?

[4] A two-tailed non-directional alternative hypothesis does not state the direction of the difference, it indicates only that a difference exists (SALKIND, 2010).

1.6 Objectives and Outcomes

Many studies have been reporting usability evaluation involving users who are blind. However, since the approaches are not focused on multimodal games for learners who are blind, they can miss usability issues that affect the game interaction and the fostering of target cognitive skills in these users.

For that reason, the main goal of this work is to provide a scaffolding[5] to guide researchers and practitioners to employ the most appropriate combination of Usability Evaluation Methods (UEMs) to assess such games, given the characteristics of the target users, the game cognitive tasks, and the interaction modalities.

To achieve that, investigation about the characteristics of multimodal games the and use of UEMs during usability field studies involving the use of video games for cognitive development of learners who are blind is necessary. Hence, the following steps led to the accomplishment of this thesis goal:

(i) Classify the features and characteristics of multimodal video games and environments for cognitive development of children who are blind;

(ii) Describe principles to conduct usability evaluation in this field, considering the specificities of the target users and multimodal interaction;

(iii) List and compare the usability issues raised by different UEMs while testing such multimodal video games, involving real potential users, identifying the advantages and drawbacks of each UEM usually employed during onsite usability evaluation, considering the multimodal aspects of the games;

(iv) Describe structured, practical guidance on usability evaluation of multimodal video games for cognitive development of children who are blind, aiming to help practitioners and researchers to effectively apply and combine UEMs in this context.

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[5] By scaffolding, this work means offering clarity and structure to help conducting research while giving the researcher freedom to construct new insights to organize and support the investigation (MCKENZIE, 1999). A scaffolding is produced from accumulated knowledge in a field and provides clear directions for research, clarifies its purpose, reduces uncertainty, surprise and disappointment, and delivers efficiency to the research (MCKENZIE, 1999).

Consequently, when putting together the discussions and the research main outcomes, this work provide scaffolding to guide researchers and practitioners in the administration of UEMs while considering the learners' characteristics and the game interaction modalities. In addition to the discussions raised by each of these outcomes, the usability evaluation scaffolding (FIGURE 5) comprises:

(i) An initial classification scheme of the interface and interaction features existing in multimodal video games and environments for cognitive development of children who are blind;

(ii) A set of principles for usability evaluation of interfaces and interaction of multimodal video games for enhancing and improving cognition of learners who are blind;

(iii) A structured list containing, usability issues related to the multimodal gaming interaction, users' gameplay behavior, and users' characteristics.

(iv) A usability evaluation instrument to support the identification of the most relevant interface and interaction issues when young people who are blind are playing multimodal video games for cognitive purposes.

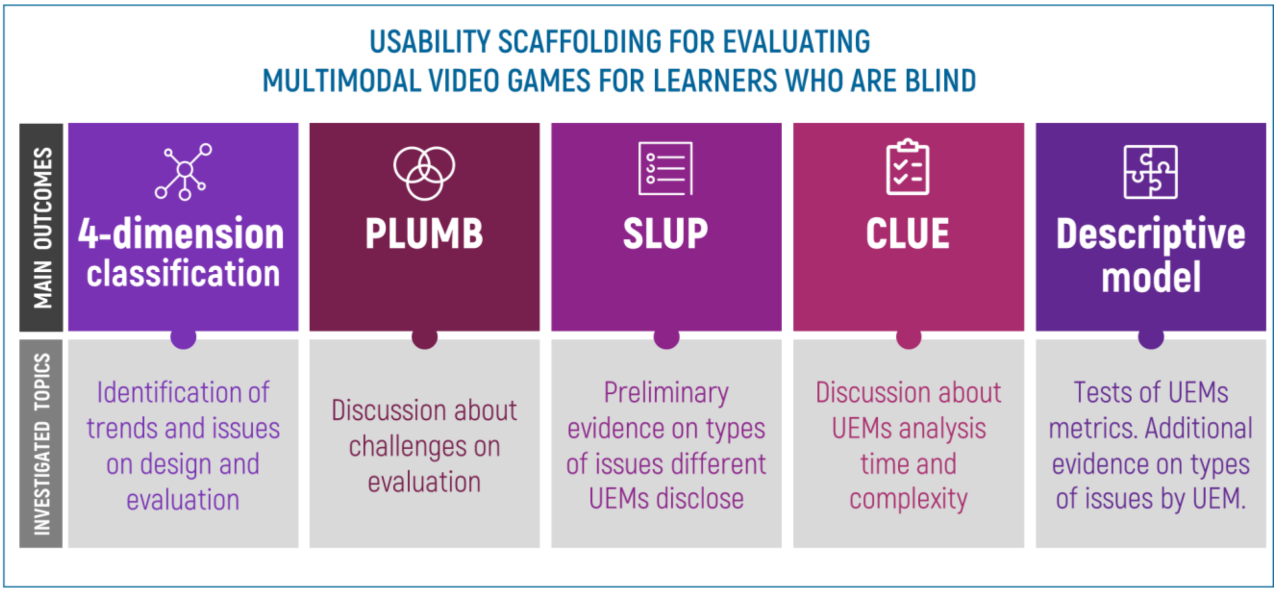
(v) A descriptive model[6] to systematize the main findings and to provide a "tool for thought", i.e., a context for reasoning about how to use and combine UEMs in usability evaluation in this field, given the context, the target users characteristics and the multimodal video game aspects to be evaluated.

The usability scaffolding assembles the knowledge produced and acquired in this work. It will be relevant in different spheres and contexts of society. On one hand, specialized Institutes and Schools can use the principles and instruments for learners who are blind, helping teachers and instructors to evaluate multimodal video games for children who are blind, and to identify whether a game is helping children instead of creating a barrier to their learning and cognition. They can also provide support to research groups and interested practitioners in performing usability evaluations capable of disclosing the most relevant issues related to the interface and interaction with multimodal games designed for cognitive purposes of children who are blind. On the other hand, the descriptive model could serve as the basis for planning usability evaluations in this context, guiding the choice of a

[6] A model represented by a verbal and graphic articulation of categories and identifiable features, with the ultimate goal of providing a tool for studying and thinking about a subject in a specific context (MACKENZIE, 2003).

combination of UEM and evaluation instruments that best suit the evaluation of the multimodal elements of a video game in a given context, while covering the specific characteristics of the target users who are blind.

Figure 5 – Summary of the knowledge produced in this work, composing the core of the usability scaffolding for evaluating multimodal video games for learners who are blind. The key contributions are shown in the top. Each of them is connected to knowledge gathered and produced during their development, represented by the squares in the bottom.



Source: produced by the author

Therefore, based on this thesis findings, there is an expectation that forthcoming multimodal video games designed to improve cognition of learners who are blind take into consideration their broadly different abilities and disabilities and provide them with usable and pleasurable gaming interfaces. Better-designed multimodal video games for cognitive purposes can affect the lives of children who are blind by helping them in developing and enhancing cognitive skills, which allow them to be more independent in their everyday lives and better integrated and included into society.

1.7 Research Methodology

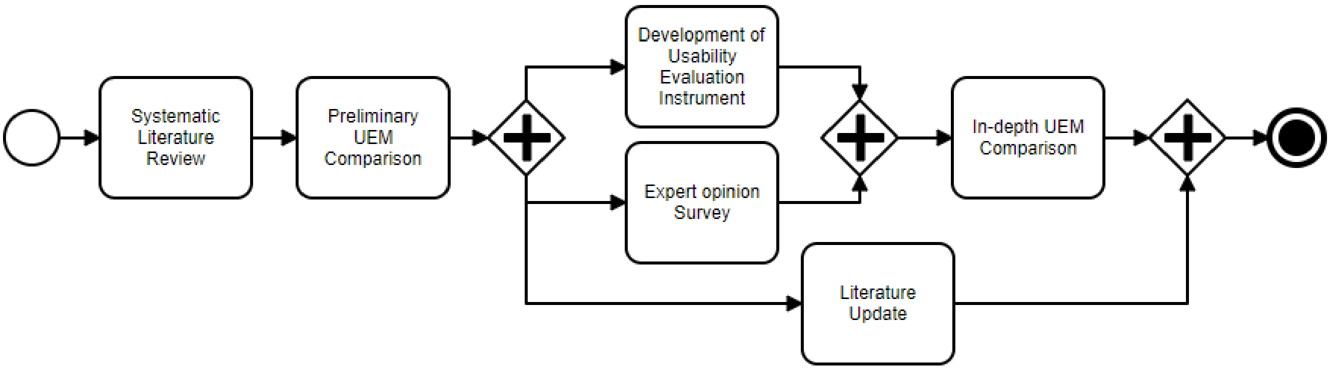
The research presented in this work was conducted according to a 6-step methodology, which is shown in Figure 6, established based upon the research objectives. Overall, it consisted in an empirical research, emphasizing systematic observations of the interactions between a sample of learners who are legally blind and a set of multimodal video games.

The core steps of this research aim to compare the use of UEMs in this context (Step 2: Preliminary UEM Comparison and Step 6: In-Depth UEM Comparison).

Seeking to answer the proposed research questions (See Section 1.3), this work compares UEMs following the approach proposed by Hartson, Andre & Williges (2003), which qualifies the present research as a "UEM comparison study". According to the authors, a UEM comparison study is any empirical summative evaluation that compares performance (by any measure) among UEMs.

As a result, the core steps of this research examine and record the quality of interaction rather than quantifiable human performance, and focuses on the usability methods and evaluation instruments instead of the participants' performance per se. For this reason, the user-related measurements gathered use categorical data or simple counts of phenomena (MACKENZIE, 2012, MACKENZIE & CASTELLUCCI, 2016), while the UEMs are compared based on effectiveness of the methods to disclose usability problems (HARTSON, ANDRE & WILLIGES, 2003).

Figure 6 – Overview of the research methodology adopted in this work



Source: produced by the author, using Business Process Model Notation (BPMN)

Each of these steps followed a specific methodology, according to the goals they support. Detailed explanation about the methodology applied to each of the research steps, in addition to their respective outcomes, are discussed in Chapters 4 to 6. A detailed version of Figure 6 is shown in Appendix A, depicting the inputs and outputs of each research step.

Each step is summarized as follows to provide the reader with an overview of the research methodology followed in this work:

- ***Step 1: Systematic literature review.*** A systematic review approach (KITCHENHAM & CHARTERS, 2007; PETERSE, FELDT, MUJTABA & MATTSSON, 2008) was conducted to review existing primary studies in-depth, describing their results according to the following research questions: (i) the strategies that have been used for the design of multimodal games for blind learners to enhance cognition; (ii) the strategies to evaluate usability and quality of such video games; and (iii) the technologies that have been used for their development. The analysis comprised 25 papers describing 21 distinct applications: 17 multimodal games and four multimodal navigation virtual environments.

  This research step addresses the investigation of *the main interface and interaction characteristics of multimodal video games for cognitive development of children who are blind (RQ1).*

- ***Step 2: Preliminary UEM Comparison.*** To investigate how different UEMs can raise usability issues, first, the usability evaluation reports of five target multimodal video games were analyzed based on Hartson and colleagues' (2003) methodology for comparing usability evaluation methods. The selected video games had been previously identified in the Literature Review. After this, four evaluators conducted usability test sessions with six children who are legally blind in real environment, employing the observation method together with a Think-Aloud Protocol (RAISAMO et al., 2006), followed by a semi-structured interview (KANTNER, SOVA & ROSENBAUM, 2003), and the Software Usability for Blind Children Questionnaire (SUBC) (SÁNCHEZ, 2003). Such methods were identified in the Literature Review and administered according to the users' needs.

  This research step partially addresses the investigation of *what types of usability issues each UEM can disclose, given a set of the most used UEMs when field-testing games for learners who are blind (RQ3).* It also addresses an initial analysis of *UEMs combination to evaluate interaction modalities during field tests involving multimodal games for learners who are blind (RQ4).*

- ***Step 3: Development of Usability Evaluation Instrument.*** Based on the key issues that impact the interaction of children who are blind with multimodal video games discovered during Step 2, an observational checklist was proposed and validated, following Stufflebeam's (2000) guidelines for developing evaluation checklists (DARIN, ANDRADE & SÁNCHEZ, 2018). This instrument was designed to assist researchers and practitioners in studies on the usability evaluation field, addressing multiple aspects of gameplay and multimodality, including audio, graphics, and haptics.

  This research step partially addresses the investigation of *what types of usability issues each UEM can disclose, given a set of the most used UEMs when field-testing games for learners who are blind (RQ3).*

- ***Step 4: Expert Opinion Survey.*** To deepen the understanding related to the evaluation in this field, international researchers in the usability area were surveyed, using an Expert Opinion Survey (ARMSTRONG, 2001). From the analysis of the experts' answers, insights on their recent research work were obtained, as well as challenges related to usability evaluation of multimodal video games for learners who are blind.

  This research step addresses the identification of *the main principles that should be followed to evaluate multimodal video games based on audio and haptics for learners who are blind (RQ2)*

- ***Step 5: Literature Update.*** In parallel with Steps 3, 4 and 5 the literature initially gathered in Step 1 was continuously updated once a month, until April 2018, including new references related to adaptation of UEMs for people who are blind, as well as new multimodal video games for the development of cognitive skills in these users. The literature update was not based on a specific systematic approach but consisted of a continuous process of consistently searching for papers citing the previously identified papers; as well as papers more recently published using the same keywords in the search string already used in the literature review. For that reason, there is no further description of this step in the next Chapters of this work. The papers obtained during the literature update were mainly used as theoretical background and related work.

- ***Step 6: Second UEM Comparison.*** In this step, the aim was to test the research hypothesis, expanding the evaluations made in Step 2 to comprise different multimodal games and a larger user sample, following a formal UEM comparison approach. A comparative single-factor within-subject experiment design was used to assess the significance of UEMs effectiveness at three treatments. Interaction data was collected from twenty independent onsite user evaluations, using observation together with a think-aloud protocol, field notes, semi-structured interview and the checklist proposed in Step 3. Half the users took part in the evaluations playing a role-playing desktop game, while the other half played a puzzle game for tablet. Following the approach discussed by Harston, Andre & Williges (2003), the list of usability issues produced by each UEM were compared. Then, UEM performance metrics were calculated for each of the UEM under comparison and statistical tests determined whether there was a significant difference among them.

  This research step addresses the investigation of *what types of usability issues each UEM can disclose, given a set of the most used UEMs when field-testing games for learners who are blind (RQ3).* It also addresses a detailed analysis of *UEMs combination to evaluate interaction modalities during field tests involving multimodal games for learners who are blind (RQ4).*

1.8 Scope and Delimitations

The coverage of this study is the analysis of empirical Usability Evaluation Methods employed when evaluating multimodal video games designed for developing and enhancing cognitive skills in learners who are blind. This study focuses on applying existing UEMs and analyzing their use and results in the context mentioned before. The aim of this scope is to guide and support researchers and practitioners in the planning and conduction of usability field studies involving learners who are blind.

This study does not cover analytical methods or the ones for inspection usability evaluation, which are performed by experts without the participation of end users. The evaluation of cognitive impact of multimodal video games does not belong to the scope of this work either. Likewise, the evaluation of quality of use criteria other than usability, such as accessibility and user experience, and the evaluation of measures of engagement and interaction, such as flow and user control, are out of this work scope.

1.9 Document Organization

This chapter presented the issues motivating the investigation of Usability Evaluation Methods applied during usability field studies involving young learners who are blind, playing video games for cognitive development. The remainder of the document is organized as follows:

Chapter 2 discusses the main topics of the theoretical background related to this doctoral thesis, establishing a basis for understanding the challenges and solutions proposed in this work: multimodal interfaces, cognitive development of learners who are blind, multimodal video games for learners who are blind, usability evaluation, and evaluation of multimodal video games for learners who are blind.

Chapter 3 presents a bibliographic review comprising work related to existing research on the design and evaluation of multimodal applications for people who are blind. Regarding the essence of this thesis proposal, chapter 3 presents works that analyze the usability of specific types of multimodal interface, and the adaptation of the usability evaluation process with people who are blind.

Chapter 4 presents the results obtained from the systematic literature review (Step 1), which include a 4-dimension classification, describing the interface and interaction characteristics of multimodal video games for the cognition of people who are blind, in addition to the identification of the trends and issues on the design and evaluation of these games.

Chapter 5 analyzes the outcomes from the preliminary comparison between the most used UEMs (Step 2) previously identified in the systematic literature review, which encompasses the Standard List of Usability Problems (SLUP) and preliminary evidence about the types of usability issues disclosed by different UEMs. Chapter 5 also presents the development of a usability evaluation instrument (Step 3), which is the CheckList for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE). Finally, this chapter presents the results of the Expert Opinion Survey (Step 4) which consists in the PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind

(PLUMB), in addition to the identification of the main challenges in the practical evaluation of these games.

Chapter 6 describes the results obtained by the in-depth UEMs comparison (Step 6), which include the research hypothesis testing, based on the calculus of UEMs performance metrics, evidence on UEMs effectiveness regarding the different dimensions of multimodal interaction, and the descriptive model that reunites and summarizes all the previously validated findings.

Chapter 7 presents the conclusions of this thesis and synthesizes the limitations and future work. In addition, this chapter lists the publications resulting from this research.

1.10 Guide to Readers

This thesis has two main parts. The first part describes the theoretical basis for the development and evaluation of multimodal video games for learners who are blind, as well as how the research literature has been approaching these themes (respectively, Chapter 2 and Chapter 3). The second part of the thesis presents the main contributions, which are the classification scheme (Chapter 4), the structured list of usability problems (Chapter 5), the checklist for observation studies (Chapter 5), the principles for guiding evaluation (Chapter 5), and the descriptive model (Chapter 6).

A reader who is familiar with usability concepts and with the development and evaluation of multimodal video games for cognitive development of learners who are blind can skip the first part and go directly to the contribution topics.

Yet another way to read this thesis for those who are interested in practical guidance for evaluating video games in this context is going directly to Chapter 5 and then Chapter 6. Eventually, the remaining chapters can be brought into play when more details are necessary.

2. THEORETICAL BACKGROUND

This chapter presents a conceptual discussion of the relevant research areas necessary to establish a basis for understanding the challenges and solutions proposed in this work. Section 2.1 presents definitions, characteristics, and models regarding multimodal interfaces. Section 2.2 shows an overview of the impact of serious video games in education and cognitive improvement. Section 2.3 discusses the challenges of cognitive development of learners who are blind. Section 2.4 introduces the interface and interaction characterization of multimodal video games for learners who are blind. Section 2.5 shows definitions related to usability evaluation and its related concepts. Section 2.6 presents the current approaches to evaluation of multimodal video games for learners who are blind. Finally, Section 2.7 brings some final considerations for the theoretical background presented.

2.1 Multimodal Interfaces and Interaction

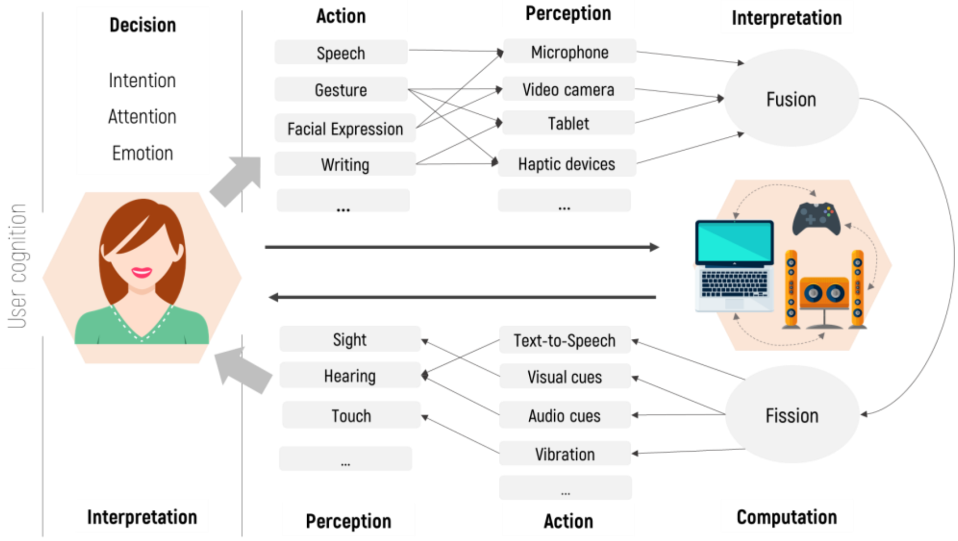
Multimodal interfaces have evolved in a complex way regarding technological resources and interaction possibilities that can be offered, in consequence of processing multiple combined user input modes in a coordinated manner with the multimedia output (OVIATT, 2003). According to Coutaz and Caelen (1991), a computer system is multimodal if it supports human modalities like gesture, written or spoken natural language, being equipped with hardware to acquire and render multimodal expressions in “real time”, i.e., with a response time compatible with the user’s expectations. It must also be able to choose the appropriate modality for outputs and to understand multimodal input expressions.

Multimodal interfaces are a class of interfaces that aim to recognize naturally occurring forms of human language and behavior, and which incorporate one or more recognition-based technologies and different from standard WIMP GUIs (graphical user interfaces based on windows, icons, menus, and a pointing device, typically a mouse). This difference is highlighted by the emphasis on using richer and more natural ways of communication, such as speech or gestures, and more generally all the five senses (DUMAS, LALANNE & OVIATT, 2009).

Multimodal interfaces should dynamically adapt to the needs and abilities of different users, as well as different contexts of use, by leveraging complementary and supplementary modalities according to changes in task and context (REEVES et al. 2004). They can also be seen as post-WIMP interfaces (VAM DAM, 1997), when they contain at least one interaction technique not dependent on classical 2D widgets like menus and icons, possibly involving senses in parallel, natural language communication, and multiple users.

It is generally accepted that the multimodal interaction definition is built upon Norman's action cycle (NORMAN, 1988), using established findings on human-machine multimodal communication to orchestrate the fusion of multimodal inputs and the fission of multimodal outputs (FIGURE 7), resulting in an adequate outcome to the users, according to their context of use, and personal preferences and characteristics (DUMAS, LALANNE & OVIATT, 2009).

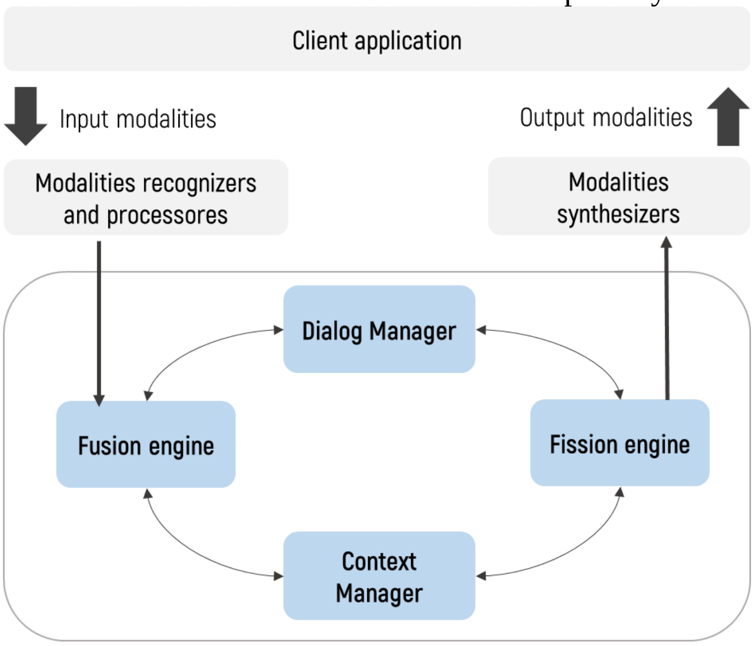
Figure 7 – A representation of multimodal HCI interaction loop



Source: Adapted from Dumas, B., Lalanne, D., & Oviatt, S. (2009).

The architecture of multimodal applications (FIGURE 8) is generically represented by four components responsible for handling the multimodal integration: a fusion engine, a dialog manager, a fission engine, and a context manager (DUMAS, LALANNE & OVIATT, 2009). During the multimodal interaction, initially, the input modalities are identified by recognizers and processors, which output their results to the fusion engine and extract meaning from a set of different input modalities. The meaning extraction occurs at data, feature and decision level, and then the fusion engine communicates the input interpretation to the human-computer dialog manager. The dialog manager is responsible for the identification of the current dialog state, the transition to execute, the action to communicate to a given client application, and the message to return to the fission component. The fission engine is finally in charge of returning a message to the user by the agency of the most suitable modality or a combination of modalities, considering the user profile, the type of task, and usage context. For this purpose, the context manager communicates any changes in the environment to the three other components, in order to adapt their interpretations.

Figure 8 – Generic architecture of a multimodal human-computer system



Source: Adapted from Dumas, B., Lalanne, D., & Oviatt, S. (2009).

Multimodal interfaces have applicability in diverse areas due to the range of possibilities brought by the combination of interaction modalities. An interaction modality can be seen as a communication channel related to the human senses or form of expression (BONGERS & VAN DER VEER, 2007), describing an interaction technique that utilizes a particular combination of user abilities and device capabilities (TURK, 2014). The combination of the aforementioned input and output channels and modes, in addition to the output modality selection based on context and user needs, turns the modeling of a multimodal application into a complex task (DUMAS, LALANNE & OVIATT, 2009). As a result, researchers have put much effort in describing and modeling multimodal applications from both physical and conceptual points of view.

Considering the physical dimension of multimodal systems, the World Wide Web Consortium proposed a Multimodal Interaction Framework, emphasizing the interpretation and inner system layers (LARSON & RAMAN, 2003). Under a different perspective, the CASE model (NIGAY & COUTAZ, 1993) describes four techniques to combine modalities at the integration engine level. However, as in the present work multimodal usability is considered from a human-centered perspective[7], conceptual descriptions of the multimodal interaction are discussed further than physical descriptions. Conceptual descriptions of the multimodal interaction can provide valuable insights on the human aspects that should be considered during the usability evaluation of multimodal interfaces.

In the remainder of this section, approaches that describe the multiple facets of the multimodal interaction are briefly discussed, considering how different modalities combinations and choices may affect the users' behavior towards the application. It is important to highlight that these aspects are not only relevant to the design of multimodal applications but also essential to plan and carry out an adequate multimodal usability evaluation.

2.1.1 CARE Properties

Coutaz et al. (1995) proposed the CARE properties (complementarity, assignment, redundancy, and equivalence) as a straightforward way of characterizing the features of the multimodal interaction that occur between the techniques available in a multimodal user interface. The CARE properties focus on the possibilities of modality combination at the user level. They can also be used to assess multimodal interfaces, considering the fusion and fission of information during the interaction. Each CARE property is represented in a formal expression based on state, goal, modality, and temporal relationship, and has a counterpart in CARE-like user properties.

- The complementarity property addresses the situation in which multiple complementary modalities must be used to carry out a user task in the system, i.e., none of the available modalities can lead the user to achieve a goal, if used individually.
- The assignment property indicates the presence of a specific modality that must necessarily be used to execute a given task in the system.
- The redundancy property expresses that, although multiple modalities can be used to achieve a goal in the system, if used individually each one of them has the same expressive power and can lead to the same outcome.

[7] Approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques (ISO 9241-210:2010).

- The equivalence property implies that users can choose among multiple modalities to execute a task in the system, in opposition to Assignment, but they use one modality at a time.

According to the authors, physical, social, cognitive and environmental circumstances, as well as personal preferences, affect the user's choice of modalities during the interaction. Therefore, the authors also identify a set of four U-preferences, which are user behavior patterns based on the CARE properties definition. The U-preferences consist in: U-complementarity, the user's preference in using various modalities for different aspects of the same task; U-assignment, when only one modality is acceptable to users, or when they show a strong preference for a specific modality; U-redundancy, the user's preference to employ more than one modality to convey the same piece of information; and U-equivalence, when the user prefers a particular subset of the system modalities, but arbitrarily chooses among them. The essential requirement on the design a multimodal system is that its properties must meet the user's U-preferences.

2.1.2 Multimodal Interaction Space (MIS)

Bongers & Van der Veer (2007) introduced the Multimodal Interaction Space (MIS), a theoretical framework to describe multimodal interactions, focusing on the space where the interaction occurs, in a human-centered approach. MIS is a descriptive framework for interaction styles and comprises levels, modes, and sensory modalities, but do not include physical interfaces of input and output modalities.

According to this approach, a multimodal interaction can be described in multiple layers, considering the user's goal and intention, the formulation of tasks and subtasks, and finally the execution of said actions in the interface where the user receives physical feedback and evaluates the outcome. Therefore, the multimodal interaction as described in MIS can comply with different levels: goal, task, semantic, syntactic, lexical, alphabetical, and physical.

MIS also describes the human input modalities involved in the interaction and its relation to the user's perception and proprioperception, stating that interaction can be based on addressing visual, auditory, tactual, olfactory, gustatory, temperature, nociception, and vestibular senses. In addition, conforming to MIS, multimodal interactions can take place in several modes, whose description reflects the human output modalities mainly used by someone to influence the environment and communicate with other people, whether supported by technology or not. Thus, the modes can assume different meanings for the users depending on the context they appear in the interaction. MIS categorizes modes as symbolic, para-linguistic, involuntary, subconscious, and continuous.

The interactions between people and technological environments can be analyzed and assembled in the MIS descriptive model of levels, modes and modalities, not only by classifying the current interaction styles but also by considering the interaction possibilities in the design space.

2.1.3 AMITUDE Model of Use

Based on an empirical study of multimodal usability, Bernsen (2010) proposed AMITUDE (BERNSEN & DYBKJAER, 2009), a conceptual development-for-usability framework to express a model of use of the system under development, based on seven interaction aspects: application type, interaction, task or domain, user, environment of use, modalities, and device. According to the authors, each aspect addressed by AMITUDE must be taken into account when developing for usability.

Therefore, while designing a multimodal application, practitioners and researchers should provide detailed description of the application target users, the tasks the application will support, the modalities and respective devices involved, as well as the environment in which the tasks will be carried on, and how each one of these aspects can affect the usability during user interaction. In this regard, usability implies the relationship of fitting a multimodal application to people guaranteeing, for example, that the target users will accept using a specific modality to carry out a specific task while interacting with the application under development in a particular usage environment.

The author defines modality as a way of representing information in a certain medium and describe modalities as a triple <medium–carrier–sensor>, foreseeing that different modalities can be represented in the same medium. He considers modalities across three types of media (graphics, sound, and touch) and classifies them into linguistic or nonlinguistic, analog or nonanalog, arbitrary or nonarbitrary, and static or dynamic (BERNSEN, 1993), later identifying eight common relations among different modalities (TABLE 1).

Table 1. The most common relations between different modalities.

1. Type of relation	2. What it does	3. Co-ordination	4. Aimed at user groups
Complementarity	Several modalities necessary to express a single communicative act	Tight	Same
Addition	Add up different expressiveness of different modalities to express more information	Loose	Same or different
Redundancy	Express partly the same information in different modalities	Tight	Same or different
Elaboration	Express partly the same information in different modalities	Tight Loose	Same or different
Alternative	Express roughly the same information in different modalities	Loose None	Same or different
Stand-in	Fail to express the same information in a less apt modality	None	Same or different
Substitution	Replace more apt modality/modalities by less apt one(s) to express the same information	None	Special
Conflict	The human system cannot handle modality addition	Tight	None

Source: Bernsen & Dybkjaer, 2009

Based on their modality taxonomy and on the relations identified among different modalities, Bernsen and Dybkjaer (2009) established a list of modality combinations that have been massively tested and proved their usability with, primarily, large groups of ordinary, non-specialist users. The short list proposed by the authors of well-established stand-alone modalities and modality combinations of established usability follows:

1. Dynamic graphic images input, as in camera surveillance.
2. Spoken discourse input, as in microphone surveillance.
3. Static graphic text and (1D, 2D or 3D) images output, as in books and web sites.
4. Static haptic text and (1D, 2D or 3D) images output, as in books and haptic device displays for the blind.
5. Static graphic text, keywords and maps, graphs or diagrams (compositional or conceptual) output, as in data graphics.
6. Dynamic graphic text and (2D or 3D) images output, spoken discourse, acoustic images and non-speech sound output, as in subtitled movies.
7. Haptic keyword, pointing and simple notation input, graphics output, as in simple search engines.
8. Haptic pointing and simple notation input, static and dynamic graphics output, non-speech acoustics output, as in many computer games.

9. Spoken discourse input/output, as in conversation over the phone.
10. Dynamic graphics image input/output, as in fun movement games for children.
11. Haptic body action input, dynamic graphic image output, as in virtual reality surgery training.
12. Spoken discourse input, graphic (3D) or haptic (2D) pointing gesture input, static or dynamic graphics output, as in pointing to, and talking about, visible images, text or math notation.
13. Spoken discourse input/output, haptic (2D/3D) pointing gesture and body action input, static haptic and graphic image output, as when the doctor examines the sprained ankle with his hands and asks if "this" hurts.
14. Situated dynamic natural input/output communication, including audiovisual spoken discourse, visual facial expression, gesture and body action, haptic gesture and body action, as in a brawl at the pub.
15. Situated dynamic natural input/output communication, including visual sign language discourse, facial expression, gesture and body action, haptic gesture and body action, as in a happy communion at the pub

The list shows examples of various non-interactive input-only or output-only modalities and modality combinations (1–6), followed by paradigms of interaction (7–15), some of which only exist in human–human interaction so far. The authors propose that, if it works between people and it could be emulated, in essence, by a system, it will also work between humans and systems, in a multimodal interaction.

The importance of considering modalities in different configurations and granularities reside in the fact that the usability – and hence the user's comprehension and ability to properly interact – can be profoundly affected by which modality is chosen to represent each type of abstract information. This statement should be even more carefully considered when developing multimodal interaction for users with special needs.

Thus, the AMITUDE modality analysis aims to help multimodal application designers making a usable choice of modalities, in agreement with the user's physical, social and cognitive characteristics, the context of use, the type of information to be exchanged in the task, the user's goals, and so forth. The modalities that provide the user with the best degree of usability are those able to express the information to be exchanged between user and system, as aptly as possible.

2.2 Serious Video Games for Cognitive Improvement

Serious video games have the purpose of going beyond entertainment, aiming to induce players to learn a content or skill, possibly while having fun (MICHAEL & CHEN, 2006). Serious video games usually are used for training, advertising, simulation, and education, and are designed to run on computational devices or video game consoles (SUSI, JOHANNESSON & BACKLUND, 2007). However, because serious video games are tools to support a specific type of learning, not only the gameplay aspects but also the pedagogical dimension must be considered during their design (GROSS, 2016).

Serious video games and virtual simulation environments allow learners to experience situations that are unfeasible in the real world for diverse reasons, like safety, cost, time, and human limitations (SQUIRE & JENKINS, 2003; CORTI, 2006). Consequently, they help improving people's performance in a variety of tasks and skills. Over the years, researchers have consistently demonstrated that serious video games can promote learning (SUSI, JOHANNESSON & BACKLUND, 2007; DURKIN, BOYLE, HUNTER & CONTI-RAMSDEN, 2015) and showed that serious games can be used for diverse types of cognitive improvement (BOOT *et al*., 2008; BALLESTEROS *et al*., 2017; PARONG *et al.,* 2017).

According to Mitchell and Savill-Smith (2004), among the various skills that serious video games support are: learning and recollection capabilities, psychomotor skills, visual selective attention, analytical and spatial skills, and strategic skills. These video games can also enhance perceptual, attentional, and cognitive abilities in an engaging and entertaining way (BOOT *et al*., 2008). Other examples of cognitive improvements are thinking and reasoning (LIU, CHENG & HUANG, 2011), attention (GREEN, LI, & BAVELIER, 2010), creativity (JACKSON *et al*., 2012), problem solving (SHUTE, VENTURA & KE, 2015), and spatial skills (SHUTE & VENTURA, 2015; XIAO *et al*., 2018).

Researchers have also demonstrated that playing serious games repeatedly can generate self-efficacy, and consequently lead to behavioral change related to the individual's acquired knowledge and skills (TANES, 2017). Despite the debates about positive and negative impact of digital games, there is enough empirical evidence to support the benefits of video and computer games for learners in several aspects, including cognitive, motivational, social and emotional dimensions (GE & IFENTHALER, 2017).

In this context, serious games can assume roles in several areas. For instance, pedagogical purposes, by providing learning activities; acting as instructional tools; fomenting learners' assessments (CHENG *et al*., 2015); measuring learning (BAKHUYS, VISSCHEDIJK & OPRINS, 2017); and for cognitive rehabilitation (ROCHA *et al*., 2016; ELAKLOUK & ZIN, 2018), by fostering specific mental skills in people with multiple kinds of special needs (SÁNCHEZ & OLIVARES, 2011; DURKIN *et al*., 2013; VASALOU, KHALED, HOLMES & GOOCH, 2017).

Both types of serious video games are further discussed in the remainder of this section, although the present work focuses on serious video games for developing cognitive skills, especially those related to orientation and mobility, due to the high relevance of this type of skill for people who are blind.

2.2.1 Serious Video Games in Education

The development of serious video games to support learning has increased in recent years due to its effectiveness as learning material (BACKLUND & HENDRIX, 2013), and its positive impact on learning and engagement (CONNOLLY *et al*. 2012; PARASKEVA *et al*. 2010). The type of serious games specifically used for education is denominated Educational Games (BACKLUND & HENDRIX, 2013) and they are used for stimulating the learning of content subject matters (FERREIRA & CAVACO, 2014; SÁNCHEZ, FLORES & SÁEZ, 2008). Multiple research has been conducted towards analyzing the use of serious games to improve learners' cognition and to help to develop various types of skills. In this regard, some literature reviews by Conolly *et al*. (2012), Cheng *et al*. (2015) and Boyle *et al*. (2016) are briefly discussed in the following.

Conolly and his colleagues carried out a systematic literature review, analyzing empirical evidence of computer and serious video games, concerning the potential positive impact of gaming on young players aged 14 years or above, especially with respect to learning, skill enhancement, and engagement. They identified 129 papers reporting empirical evidence about the impacts and outcomes of computer games and serious games concerning learning and engagement, and they developed a multidimensional approach to categorizing games. Their findings show that games are incorporated into learning specifically addressing curricular goals in the classroom, reporting that students generally enjoyed or felt motivated by the use of game-based approaches.

In the same study, the authors discuss the impact of 13 games on perceptual and cognitive skills. Although most of these games were focused on entertainment, they presented evidence that players of digital entertainment games demonstrate increased attentional and visual perceptual when compared with non-game players (GREEN & BAVELIER, 2006; TERLECKI & NEWCOMBE, 2005). They also report serious video games capable of extending players' memory and problem-solving capabilities (BOOT, KRAMER, SIMONS, FABIANI & GRATTON, 2008), as well as improving performance on working memory, addition, auditory perception and selective attention tasks (VOWELS, SHANTEAU, CROW, & MILLER'S, 2009), supporting decision-making (DAMMERS, 2004), and reasoning skills (STEINKUEHLER & DUNCAN, 2008).

There is also indication of the impact of playing video games on the acquisition of motor skills (HOGLE, WIDMANN, UDE, HARDY & FOWLER, 2008; ORVIS, HORN, & BELANISH, 2008), behavior change (JOURILES *et al*., 2008; DAVIDOVITCH, PARUSH & SHTUB, 2008), and socials skills (ASSMANN & GALLENKAMP, 2009). The authors discuss that the most common outcomes in these games were knowledge acquisition and content understanding, which were usually found in games for learning, affective and motivational outcomes, even when they were primarily dedicated to entertainment. Table 2 summarizes the video games related to knowledge acquisition and cognitive skills analyzed by Conolly *et al*. (2012).

Cheng *et al*. (2015) systematically reviewed 53 empirical studies on the use of serious games in science education from 2002 to 2013, analyzing the game pedagogy and research method applied. According to the authors, the significant research trends identified include a crescent interest in the use of serious games in science education and the prevalence of adventure/role-playing games in this area. As summarized in Table 3 and Table 4, the games are usually computer-based and have knowledge construction as major learning goal, followed by problem-solving abilities.

Furthermore, their results show that most of the analyzed games address Physics and Biology learning and often incorporate the concept of interdisciplinary learning. However, few studies explicitly introduced the educational theoretical foundations for using serious games in science education or the instructional strategies coupled with the use of serious games. Most of the studies used quantitative research designs and focused on investigating the effectiveness of serious games from the perspective of cognitive outcomes.

Table 2 – Games with outcomes related to knowledge acquisition, content understanding, and perceptual and cognitive skills

Authors	*Objectives of the study*
	Knowledge acquisition and content understanding
Cameron and Dwyer (2005)	To explore whether: (1) presenting material in a game format helps students to learn; (2) different instructional effects (embedded questions and feedback) help to make games more effective; (3) students with different learning styles (field dependent and field independent) learn differently.
Yip and Kwan (2006)	To examine the usefulness of online games in vocabulary learning for undergraduate students.
Miller and Hegelheimer (2006)	To determine whether the popular authentic simulation, the SIMs, can be adapted to enhance vocabulary learning through supporting materials.
Felicia and Pitt (2007)	To examine whether learning outcomes of educational games could be improved if the content was tailored to suit players' personalities and learning styles.
Yaman *et al*. (2008)	To find out to what extent computer simulations incorporating different kinds of instructional support (worked examples or problem tasks) had positive effects on situational subject interest. To evaluate the interactions between learners' interests and the instructional support with regard to the learning results (factual knowledge and understanding).
Nte and Stephens (2008)	To develop a computer game that explains the statistical concept of normal distribution
	Perceptual and cognitive skills
Boot *et al*. (2008)	To determine whether (1) perceptual benefits of playing video games are restricted to visual and attentional tasks or whether improvements might be broader and evident in spatial processing, spatial memory, executive control, and reasoning tasks; (2) video games practice could produce these gains in non-gamers.
Steinkuehler and Duncan (2008)	To examine the scientific habits of mind and dispositions that characterize online discussion forums of the massively multi-player online game (MMOG) World of Warcraft
Stefanidis *et al*. (2005)	To explore whether laparoscopic skill retention is improved using Virtual Reality (VR) and Videotrainer (VT).
Feng *et al*. (2007)	Study 1: To examine differences in spatial attention between males and females and video game players and non–players; study 2: to examine differences in spatial attention and cognition between males and females following 10hr practice with an action or non action game

Source: Adapted from Conolly *et al*. (2012).

Table 3 – Game learning goals in the serious games related studies published from 2002 to 2013

Game learning goals	2002–2006	2007–2011	2012–2013	Total
Knowledge construction	4	21	18	43
Problem-solving ability	3	8	1	12
Collaboration skills	0	2	0	2

Source: Cheng *et al*. (2015).

Table 4 – Game vehicle of the serious games used in the reviewed studies from 2002 to 2013

Game vehicle	2002–2006	2007–2011	2012–2013	Total
Computer	4	17	18	39
Mobile device	0	3	1	4
Video console	0	5	1	6

Source: Cheng *et al*. (2015).

While investigating game-based learning (GBL) to identify gaming trends in GBL for engagement and academic learning, Abdul Jabbar and Felicia (2015) performed a systematic literature review and analyzed 91 papers coming from 10 databases. The authors addressed the lack of empirical evidence on the impact of game design on learning outcomes, identifying how the design of game-based activities affect learning and engagement. Therefore, they developed a set of general recommendations for GBL instructional design.

Their findings illustrate the impact of key gaming features in GBL at both cognitive and emotional levels. They also identified gaming trends and several key drivers of engagement created by the gaming features embedded within GBL, as well as external factors that influence on engagement and learning. They summarize the findings of their research in five main points:

1. Most research shows that gaming provides opportunities for players to have something to gain from the gameplay.
2. GBL helps students to develop skills and knowledge and strengthens their ability to handle the learning experiences provided by the games.
3. By reviewing the gaming elements that produce enjoyment and motivation, it becomes clearer what makes students engaged and disengaged with gameplay and learning. This can be demonstrated by players acting as enthusiastic, confident, and strategic learners to access and understand content and to achieve their goals, triggered and supported by multiple elements.
4. Most critically, in the GBL context, engagement is related to students' cognitive and emotional involvement in the gameplay.
5. There is a thin line between the ability, motivation, and enjoyment, which encourage students to go beyond the requirements to meet extended goals.

Going beyond the previous findings, Nadolny, Alaswad, Culver and Wang (2017) analyzed the selection and implementation of game mechanics in 27 courses from middle school to higher education designed with GBL, using a survey with teachers in 5 different countries. Their goal was to identify what game mechanics are most appropriate and effective for learners at different academic levels.

Regarding the game elements used at each educational level, according to the survey results, high school and college teachers selected points, quests, instant feedback, and academic rewards with the highest frequency. On the other hand, middle school teachers included quests, instant feedback, competition, and adaptive release items most often in their course. Academic grades motivate students at different developmental levels, and this is reflected in the choices made by teachers when choosing game elements.

The authors also pointed that, although all of these elements were used in some way by the group of surveyed teachers, the way in which students were motivated by these game elements was not consistent. Some found success with badges or rewards and competition, while others did not (Table 5). The game elements that motivated students the most included quests, instant feedback, academic rewards, adaptive release items, and points. This highlights the individual nature of GBL and the importance of context in determining game elements.

Heintz and Law (2018) investigated how the choice of game type influences the success of digital educational games, where success is defined as significant domain-specific knowledge gain (learning outcome) with positive player experience. The comparison of different game types is based on the previously developed Game Elements-Attributes Model (GEAM), show in Figure 9, and a Game Genre Map, which summarize game features and their relations.

The authors conducted two independent empirical studies with 280 university students, in the domain of learning computer programming skills. Study 1 compared three digital educational games of the mini-game genre, differing in a single GEAM attribute: time pressure vs. puzzle solving, and abstract vs. realistic settings. Study 2 compared DEGs of different genres, a Mini-game leaning toward the Action genre and an Adventure game. These games varied by multiple attributes (e.g., Challenges: time pressure vs. puzzle, Goals: static vs. various, Actions: no character vs. character).

For both studies, the authors found significant differences in learning outcomes, for Study 2 also in some of the player experience dimensions. Finally, the authors introduced GEAM (FIGURE 9) as a promising framework for games user research. According to the experiments results, GEAM proved to be a valuable framework for designing and evaluating DEGs as well as formulating hypothesis and explanations on the impact of differences in certain game elements between games.

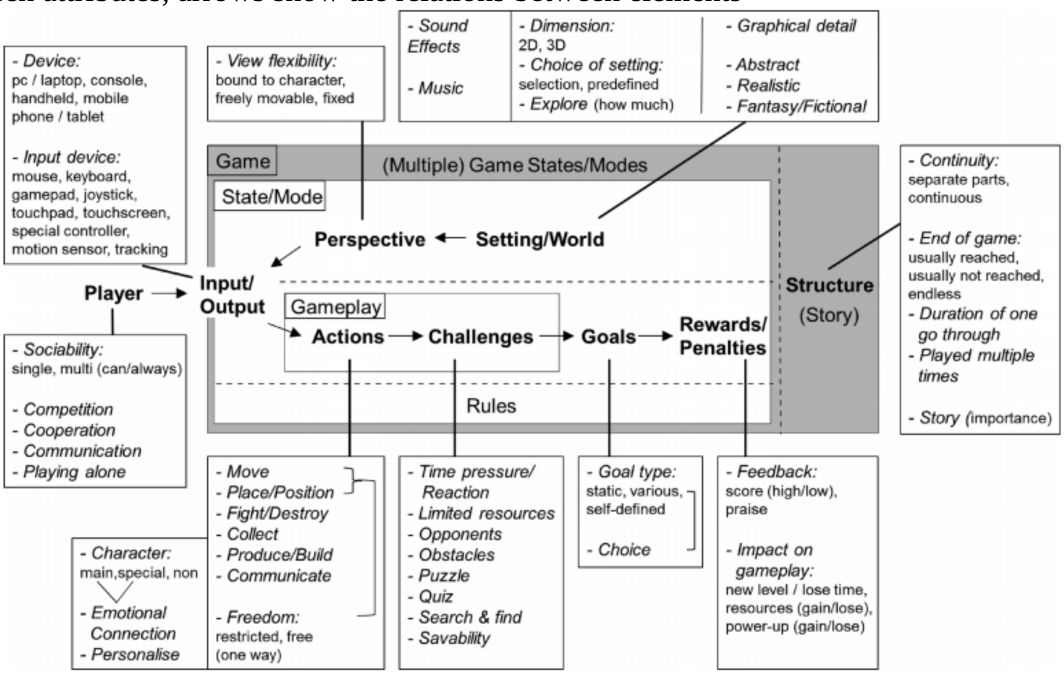
Given the large diversity of digital educational game types, more collaborative effort of the research community is needed to find conclusive answers and deeper insights into the issue of how to successfully combine game elements to achieve an educational purpose (HEINTZ & LAW, 2018).

Table 5 – Student motivation and game elements

#	Question	Positively	Neutral	Negatively	Total Responses
1	Badges	57.89%	42.11%	0.00%	19
2	Leaderboard	72.22%	27.78%	0.00%	18
3	Rewards: academic (extra points, bonus items)	79.17%	20.83%	0.00%	24
4	Rewards: non-academic (candy, prizes)	61.54%	38.46%	0.00%	13
5	Quests	80.00%	20.00%	0.00%	25
6	Boss Level	66.67%	33.33%	0.00%	15
7	Points	75.00%	25.00%	0.00%	24
8	Instant feedback	82.61%	17.39%	0.00%	23
9	Unlock / adaptive release items	76.47%	17.65%	5.88%	17
10	Competitive tasks	63.16%	36.84%	0.00%	19

Source: Nadolny, Alaswad, Culver & Wang (2017).

Figure 9 – Game Elements-Attributes Model (GEAM). Lines in boxes show dependencies between attributes, arrows show the relations between elements



Source: Heintz and Law (2018)

2.2.2 Serious Video Games for People with Disabilities

Multiple research has been discussing the positive effects of serious video games on health-promoting and clinical outcomes (DESMET *et al*., 2014; MUSCIO, 2015; STERKENBURG & VACARU, 2018; CANO *et al*., 2018), demonstrating the feasibility of translating traditional evidence-based interventions into computer gaming formats to exploit game features for therapeutic change (FLEMING *et al.,* 2017). The therapeutic capacity of video games has been verified in several contexts, including physiotherapy and occupational therapy, cognitive rehabilitation, and pain management for various groups of people, such as stroke patients, people with brain injuries, people with autism, and people who are blind or deaf (GRIFFITHS *et al*., 2013).

In this context, the possibility of training skills and transfer them to a variety of tasks is highly appealing (BAILY & PEARSON, 2007; PARONG *et al.*, 2017). Consequently, researchers have been proposing video games to challenge the sensory, cognitive, and social dimensions of young people with mental and developmental disorders (GAYLORD-ROSS, 1984; DURKIN, 2010;), and to develop skills in people with physical and sensory disabilities (BARTSCHERER & DOLE, 2005; SANCHEZ, SAENZ & RIPOLL, 2009).

Durkin *et al*. (2013) reviewed the emerging literature on the use of entertainment and serious video games by children with special educational needs, including individuals with physical and/or sensory impairments (e.g., motor difficulties, hearing, sight), and individuals with cognitive and learning difficulties. The authors consider the implications of peoples' disabilities for gameplay, outlining the challenges and attractions that these games present to young people with exceptional characteristics and needs.

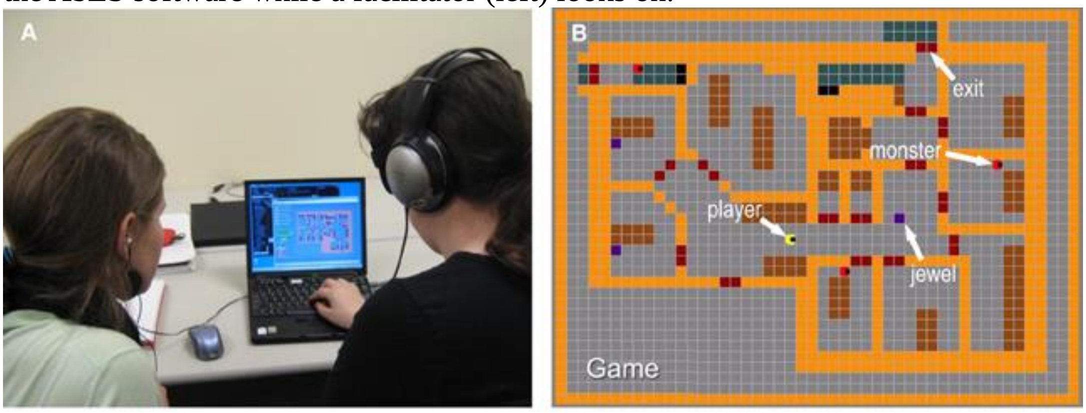
The results suggest that the difficulties during game interaction will vary according to a person's condition. According to the authors, while children with motor or visual disabilities encounter challenges in the physical manipulation of most games (SANDLUND, MCDONOUGH, & HOGER-ROSS, 2009), children with cognitive disabilities struggle learning the game rules, mastering play options, and determining which actions are appropriate in response to different types of game feedback (YUAN, FOLMER & HARRIS, 2011).

Although video games are not always positive or necessary for people with disabilities, they bring clear benefits for some individuals at some stages (DURKIN, 2010). Even though training skills in this context is challenging, there is initial evidence that playing video games can foster brain plasticity and learning in people with disabilities (BAILY &

PEARSON, 2007; MERABET & SÁNCHEZ, 2009; CONNORS, CHRASTIL, SÁNCHEZ, & MERABET, 2014). Illustrating this fact, Sanchez *et al*. (2009) presented the design, development, and evaluation of Audio-Based Environments Simulator (AbES) aiming to enable a user who is blind to navigate through a virtual representation of a real space, to train orientation and mobility skills (FIGURE 10).

The authors incorporated AbES within a neuroimaging environment to study changes and adaptations at the brain level, regarding the development of navigation skills. The results showed that the interaction with AbES leads to selective task activation of specific brain areas, identifying areas of the brain in action specifically related to navigating through a virtual environment (CONNORS, CHRASTIL, SÁNCHEZ, & MERABET, 2014). The implication of this result is that this kind of virtual environment is highly efficient as a testing, training and rehabilitation platform for learning and navigation.

Figure 10 - Virtual rendering of an existing two-story building (for simplicity, only the first floor is shown) represented in the AbES software used. A blind participant is interacting with the AbES software while a facilitator (left) looks on.



Source: Connors, Chrastil, Sánchez, & Merabet (2014).

On the one hand, video games designed to address a specific problem or to teach a certain skill to groups of people with special needs have been achieving considerable success (GRIFFITHS, 2002; HAINEY *et al*., 2016;). On the other hand, there has been an increasing effort towards making regular video games accessible to distinct groups of people. According to Torrente *et al*. (2012), there are holistic approaches that encourage the consideration of the needs of different profiles of users during the game design, facilitating the posterior inclusion of accessibility features to cater for the demands of multiple users.

The video game Access Invaders (GRAMMENOS, 2006), for example, is a game developed under the ‘‘design for all’’ paradigm and supports multiple types of impairments. It offers a one-switch control allowing access to players with motor disabilities, in addition to synthetic speech, audio cues and the ability to increase the size of game objects allowing access to players with visual disabilities (YUAN, FOLMER & HARRIS 2011; SAVIDIS & STEPHANIDIS, 2004).

Nevertheless, Torrente *et al*. (2012) also state that accessibility in video games is usually addressed individually, by either developing video games for a specific community of users with disabilities or by adapting the original game title and characteristics to meet the needs of a user profile. The games Haptic Sudoku (GUTSCHMIDT, SCHIEWE & ZINKE, 2010), Terraformers (WESTIN, 2004) and AudioDoom (SÁNCHEZ & LUMBRERAS, 1998) are examples of the first group, while Blind Hero (YUAN & FOLMER, 2008) and RockVibe: RockBand® (ALLMAN *et al*., 2009) represent the second group.

This trend is also confirmed in the study conducted by Yu *et al*. (2011), in which from 35 analyzed video games, only 3 followed a holistic design approach. The adaptation of video games aiming to include people with disabilities frequently occurs by analyzing the problems that players with disabilities are facing when playing (TABLE 6) and providing alternative ways of interaction for the target disabled users (BIERRE *et al*., 2005).

Table 6 - Common Problems for Disabled Gamers

Problem	**Reason**
Inability to follow a storyline	• No subtext available, story is advanced by cut scenes. (Auditory) • Story is very complex and difficult to follow. (Cognitive)
Unable to complete a puzzle or task	• Vital clues given in cut scenes with no text available. (Auditory) • All clues are given as text. (Visual) • Requires precise timing with controller. (Mobility) • Requires the ability to position a cursor accurately (Mobility)
Unable to determine how game is played	• Lack of a tutorial mode • Poor documentation • Documentation written at too high a level for intended audience
Inability to use adaptive hardware	• Game only supports limited set of devices
Player's character gets killed/injured repeatedly in game	• Not recognizing audio clues. (Auditory) • No indication of dangerous situation • Inability to respond quickly with controller (Mobility) • Unable to alter game speed. (Mobility)

Source: Bierre *et al*. (2005).

Video games ought to be developed considering how multiple types of disabilities impact on gameplay. In this regard, Bierre *et al*. (2005) analyzed the types of disability affecting a person's ability to play video games, which are organized into Visual, Auditory, Mobility, and Cognitive, discussing possibilities to overcome the difficulties while gaming for different disabilities. According to the authors, a gamer with disabilities can be included in any number of these groups (BIERRE *et al*., 2005).

In a similar effort but in a more extensive way, Yuan *et al*. (2010) present the state-of-the-art of research and practice in game accessibility identifying how disability affects a player's ability to play video games; and the strategies commonly implemented to make games accessible. Table 7 compile the findings on those two research studies, showing the usual strategy to allow game access for people with different types of disabilities.

Table 7 – Strategies usually applied to allow game access for people with different types of disabilities

DISABILITY TYPE	**DISABILITY DESCRIPTION** *International Classification of Impairments, Disabilities and Handicaps (ICIDH) and the writing guidelines for technology and people with disabilities:*	**STRATEGIES FOR GAME ACCESSIBILITY** *According to Bierre et al. (2005) and Yuan et al. (2010)*
Visual Disability	Encompass conditions that affect vision resulting in a certain degree of vision loss. Include low vision, partially sightness, legal blindness, complete blindness and color blindness.	• Replace visuals with audio (speech, audio cues, sonification) • Replace visuals with haptics • Enhance visuals • Allow gaming based solely on auditory cues, speech, and haptic feedback
Auditory Disability	Refers to complete or partial loss of the ability to hear from one or both ears. The level of impairment can be mild to profound. Deafness refers to the complete loss of ability to hear and recognize environmental sounds from one or both ears	• Replace audio with text (subtitles, closed caption) • Replace audio with non-text (visual cues, sound radar, signing) • The impact regarding the game context relies mainly on the dialogues and all types of game sounds and music carrying contextual information
Motor Disability	Regards a loss or limitation of function in muscle control or movement or a limitation in mobility. Can either be caused by physical injury, illness, genetics, and aging, ranging in severity from limitations of stamina to paralysis.	• Remove part of the original interaction • Automate part of the original interaction • Use a context sensitive scanning mechanism changes depending on the state of the game • Use a context-agnostic scanning mechanism is the same throughout the game.
Cognitive Disability	Refers to a mental and psychological disorder ranging from mental retardation developed during childhood to memory loss and senility as a result of aging. Their main characteristics are impairments in social interaction, communication, restricted interests and repetitive behavior.	• Reduce time constraints • Reduce the amount of stimuli • Reduce inputs

Source: adapted from Bierre *et al*. (2005) and Yuan *et al*. (2010).

Westin *et al*. (2011) present a literature study of the advances in game accessibility research, based upon 38 published papers between 2005 and 2010, describing games simultaneously accessible by several groups of people with disabilities; as well as games or interaction techniques targeted to people with a specific disability. The authors listed video games addressing visual, hearing, and motor disabilities. Based on the analysis of papers, they concluded that the use of haptics as complimentary feedback to sound is the prevalent approach in the development of video games targeting people with visual disabilities (SEPCHAT, 2006; GUTSCHMIDT *et al*., 2010).

Other useful approaches identified for this audience include adapting the graphics, using speech and sound effects, and multimodal presentation of game information (GUTSCHMIDT *et al*., 2010; SEPCHAT, 2006; MORELLI *et al*., 2010). This analysis further indicates that accessibility for hearing disabilities is one of the easiest to implement, being mainly based on presenting alternative text and visuals on the screen (WESTIN, 2010). Despite that, the authors observed that many games do not include closed captioning or even dialogue subtitling. Regarding motor disabilities, accessibility features employed in video games are usually achieved by allowing a remap of controllers, and the modification of the response speed.

Many challenges have been raised in the literature regarding the design and the evaluation of video games for people with disabilities. Some of them are the need for more video games developed for players with cognitive disabilities (WESTIN *et al*., 2011; YUAN, FOLMER & HARRIS, 2011), the need for using universal design approaches instead of adapting video games for specific user profiles (TORRENTE *et al*., 2012; YUAN, FOLMER & HARRIS, 2011), and the use of multimodality to provide access to video games (WESTIN *et al*., 2011; YUAN, FOLMER & HARRIS, 2011). These challenges stand out as they repeatedly occur in diverse literature research.

Specifically, in the case of players with visual impairments, Grabski *et al*. (2016) outlined methods and guidelines to help compensate the lack of visual orientation in virtual 3D environments for players who are blind, which can help to optimize accessible games and make existing games accessible. The authors suggested guidelines for future developments of games for people with visual impairments, which helps to include further these people into society. They conducted a user study, showing that the use of haptic device and the acoustic feedback have a positive effect on the players’ environmental awareness. According to their results, contextual tactile feedback, such as the usage of wind to simulate the speed, helps users who are blind in their orientation in virtual 3D environments.

Jaramillo-Alcázar and Luján-Mora (2017) compilated and analyzed accessibility guidelines for the development of video games for people with visual impairments. They proposed a categorization of guidelines that can be used to analyze the level of accessibility of a serious video game, verifying: touch and multi-touch features, alternative buttons, high contrast, colorblind options and speed settings.

Araujo *et al*. (2017) analyzed six sets of guidelines for general accessibility in digital games, identifying a number of inconsistencies among them. To help filling this gap, the authors determined a set of 10 minimal requirements to the design and development of mobile audio games, in the form of simple considerations and design decisions addressing game mechanics. The recommendations aim to benefit the majority of players and are easy to implement if taken into account since the Game Design Document (GDD) creation. Table 8 summarizes the set of proposed recommendations, detailing their goals and straightforward verification questions.

Despite the advances in serious video games for people with disabilities, further research are still needed to respond to the diverse user needs and preferences in their rapidly changing environments, addressing faster iterations, rapid testing, non-traditional collaborations, user-centered approaches (FLEMING *et al*,. 2017).

Table 8 – Recommendations for accessibility of mobile audio games for players who are blind

RECOMMENDATION	DESCRIPTION	GOAL	VERIFICATION QUESTIONS
R1 - Game level and speed adjustments	The game should allow players to choose between a wide range of challenges and speed.	People might benefit from slower and easier versions to adjust the game, adapting it to their needs	• Does the game allow these settings to be changed? • If yes, can the title be adjusted to a mode in which is much harder to fail or to be hit?
R2 - Free exploration and tutorial modes	The game should offer a way in which the player can explore the game without failures. Another possibility includes a tutorial mode that explains how to play the title.	This game feature helps in the understanding, control adjustment, skill development and to offer a fun way for those who interact with the standard game while playing alone	• Is the game free exploration mode easy to enable? • Does it have attractive commands to catch the player's attention? • Are players free to try the game and learn on their own pace?
R3 - High contrast interfaces	The game should offer high contrast color schemes. Essential items and the menu selection must follow the same approach. In addition, the game should allow background deactivation in 2D/3D games.	It increases the visibility of text items that are important for players who are visually impaired	• First, the tester should run the game on a low-resolution computer screen. Is it possible to read and navigate by its menu or is it too difficult? • If it is hard to navigate, the game is not following this recommendation correctly.
R4 - Friendly design for people with color blindness	Game developers should avoid color combinations that are hard or impossible for a person with color blindness to distinguish.	The goal is to allow access to information in all color shapes and also offer alternative configurations to transmit the meaning of the color combination	• How is the color information in the display? • Are only two colors being used to give options? • Is there a color palette showing all colors in a way that allows people who are color-blind to change it?
R5 - Accessible menu	Game interface customization should be easy to access by people who are blind.	For a game with a complex interface, the goal is to provide a simplified interface that shows only the most common used controls.	• Do the players face difficulties during navigation through the menu? • Is there a way to access most of the game functions in 3 menu options or less?
R6 - Standard presentation of texts	Game messages and labels should be compatible with screen readers. Gamers should be able to use simple gestures to access the majority of the text messages, which should be read by the screen readers.	Users with visual impairment will be able to identify and understand texts presented in the game	• Use a screen reader provided by the mobile operational system or one that is compatible with it. • Are the items and descriptions read correctly by the tool?
R7 - Speech-generating features	This recommendation is a derivation of R6. The main idea is to use text-to-speech technologies to improve the user immersion.	It allows users with visual impairment situate themselves in the game dialogues and the sequence of narrative texts.	• Navigate through the game with a personal with no visual impairment and another one with visual impairment. • Does the navigation of all control combinations properly return visual and hearing feedback for both users?
R8 - Accessibility resources easily found	Gamers should access and understand, in the first contact with the game, where the accessibility features are.	The goal is to permit players to know that they are capable of enjoying the game before purchasing the title or start playing.	• Is there a way to check quickly the accessibility features, options and requirements of the game right in the first contact with the title?
R9 - Game tutorials and help	Developers should hierarchize game tutorial and helps to guide the gamer through the help items, providing feedback.	Following R9, the game provides the players with objective indicators assisting the players in situations of bewilderment.	• Is the player forced to read long information passages? • Can the player properly continue with the game through fast orientation?
R10 – Orientation	Players should be able to use the physical keyboard or the touchscreen to guide the avatar in many directions and receive feedback about its direction.	To guide specific avatar movements and receive orientation feedback.	• Is there a way to offer the player to be guided based on the cardinal points, for example?

Source: Araújo *et al*. (2017)

2.3 Cognitive Development of Learners who are Blind

People construct cognitive concepts by integrating experiences from different sensory modalities (UNGAR, 2000), relying mainly on the visual channels, which are responsible for collecting most of the information required for forging mental representations of the surrounding world (LAHAV & MIODUSER, 2008). It means that, in the absence or reduction of visual capabilities, a person's ability to conceptualize the environment is affected, because gathering contextual information about the surroundings is necessary to assemble a mental representation of the world (LOOMIS, KLATZKY, & GOLLEDGE, 2001).

However, the dominant channel of the information acquiring for people who are blind is auditory, followed by tactile and kinesthetic (GOUZMAN & KOZULIN, 2000). Consequently, the development of cognitive skills requiring some level of abstraction represents a challenge for people who are blind. According to Gouzman and Kozulin (2000), there are three main cognitive problems faced by learners who are blind:

1. Visual perception occurs simultaneously, but the tactile perception takes place progressively, as they touch an object, which causes the narrowing of their perceptual field.
2. Usually, during the process of concept formation in learners who are blind, one out of two extremes prevail: either extremely abstract verbal notions that have little support in the learners' experience, or extremely concrete tactile images of quotidian life objects that possess little potential for generalization. Because of this situation, everyday concepts that possess some level of generality are under-represented in the learners' cognitive repertory.
3. The cognitive tools used by sighted students remain underdeveloped in the blind learners because the predominant methods of education for the blind almost entirely exclude two-dimensional schematic representations of objects and processes, like diagrams, charts, plans, and maps.

Developing cognitive skills is particularly more challenging in the case of children who are blind because they are still learning things and experiencing events that are recognized and understood at a different level (RAISAMO et al., 2006). Children with visual disabilities have more difficulties in accessing information, learning and putting basic operations into practice, as well as in solving problems when compared to their sighted peers (KULYUKIN, 2004). They have difficulty in making inferences and forming abstract concepts, which are mostly forged by the extensive use of visual cues in fully sighted children (CHESS & HASSIBI, 2013).

For children who are blind, every concept needs to be constructed before it can be perceived, either via direct experience or using some auxiliary aids (HERSH & JOHNSON, 2008). Auxiliary aids are equivalent to nonvisual access to computer interfaces and printed materials, mostly focusing on object recognition, mobility, and navigation (HERSH & JOHNSON, 2008; YE et al., 2014; GRUSSENMEYER & FOLMER 2017; BHOWMICK & HAZARIKA, 2017). These aids can help to forge the cognitive concepts to connect them to the external world (CHESS & HASSIBI, 2013).

When applied in educational approaches (FIGURE 11), they usually emphasize the integration of learners who are blind into the regular classroom, relying on the auditory channel for learning, supported by educative materials in Braille (GOUZMAN & KOZULIN, 2000), as shown in Figure 11. Although these technologies are necessary for such children's learning, they do not provide a total solution to their educational needs (SÁNCHEZ et al., 2013).

Figure 11. A boy who is blind in a math class handling an auxiliary aid to work on fractions, using segments of wood in various sizes that are labeled both in marker and with braille tape, at Texas School for the Blind and Visually Impaired.

Source: Perkins School for the Blind e-Learning

Besides cognitive skills related to curricular learning, navigation throughout unfamiliar spaces is another key issue related to cognitive skills of children who are blind. It usually consists of a more complicated task when compared to sighted persons, since visual information is essential for spatial processing and its lack directly influences the development of locomotor skills (PRESSL & WIESER, 2006; NAKAMURA, 1997; RIESER et al., 1986; CUTURI et al., 2016).

Consequently, they have a very different understanding of navigation tasks and could have trouble in activities that demand Orientation and Mobility (O&M) skills (WILLIAMS et al., 2014; SAARELA 2015). The core of O&M principles relies on providing individuals who are blind with the concepts, skills, and tools necessary to move efficiently over the environment (HATTON, 2014).

In the field of O&M techniques, the terms orientation, navigation, and wayfinding have been defined under diverse perspectives (LONG & HILL, 1997). Particularly, orientation is usually associated to the development of conscience regarding a person's distance and direction relative to something perceived in the surroundings, while keeping track of spatial relationships as they change during locomotion (BLASCH, WELSH & WIENER, 1997). Considering the psychological dimension of orientation, it can be understood as the process that a person experiences when familiarizing with a new setting, in a way that the movement becomes independent of memory cues, like maps, and eventually it becomes usual (VANDENBOS, 2007).

On the one hand, navigation involves the planning of travel over the environment, updating position and orientation during travel, and, in the event of becoming lost, reorienting and establishing travel toward the destination (GOLLEDGE, 1999). On the other hand, wayfinding refers to purposeful movement to a specific destination that is distal and, thus, cannot be perceived directly by the traveler, including, but not restricted to, the act of avoiding obstacles while moving over the environment (GOLLEDGE, 1999).

Different solutions have been developed to help support O&M for people who are blind – electronic travel aids (ETA), 3D models, and haptic and tactile maps –, by allowing the acquisition of contextual information from the environment, diminishing anxiety and concerns while travelling (SAARELA, 2015; BROCK, 2013; PAPADOPOULOS, BAROUTI & KOUSTRIAVA, 2017; STRUMILLO et al, 2018). The EyeSynth (FIGURE 12) is an example of a commercial approach to aid people who are blind in mobility and navigation.

EyeSynth is an audiovisual system consisting of a pair of glasses connected to a microcomputer. The system records the surrounding environment in three dimensions. Then, the collected data is converted into abstract audio, which interprets open spaces, shapes and obstacles, and is transmitted via cochlear nerve for a person who is blind, so the ears are free to listen.

Figure 12. EyeSynth equipment and scheme of tracking mode, where the glasses only capture the central, front view. The user has to sweep left and right, in a similar way as when using a cane.

Source: EyeSynth Project

While this type of solution helps to overcome limitations of conventional aids when facing obstacles in unfamiliar environments (e.g., escalators and revolving doors), they frequently focus on sensory substitution or alternative perception devices. These turn visual cues into non-visual indications, instead of helping people who are blind to develop their orientation skills and mobility techniques (SANCHEZ & ELÍAS 2007; KHOO & ZHU 2016).

However, to navigate efficiently, people with visual disabilities, notably children, must develop O&M skills based on an appropriate mental representation of the surroundings, mapping the possible paths for navigating these spaces (LAHAV & MIODUSER, 2000). To achieve this, they need to be able to detect items and places and to keep a trail of the relationships between the objects within an environment (LOOMIS, KLATZKY & GOLLEDGE, 2001). The process of assembling this mental representation, or mental model, provides a person with an internal representation of the external world, as perceived by the sensory systems while gathering information about the surroundings (GRECA & MOREIRA, 2000).

Mental models of the world serve as a personal framework for reasoning, decision-making, and behavior (JONES et al., 2011). Most of the environmental information necessary for this mental mapping is gathered by the visual channel, combined with a personal interpretation of the figurative information perceived (LYNCH, 1960; BISHOP, 1989).

In the lack of vision, receiving information via complementary sensors collaborates with the creation of an adequate mental representation of the environment (LAHAV & MIODUSER, 2000; SÁNCHEZ & SAÉNZ, 2010; MERABET & SÁNCHEZ, 2009). Consequently, to acquire spatial information and assemble a mental model of the surroundings, people who are blind need non-visual stimuli to perceive the environment, relying on alternative sources of environmental feedback, corresponding to sounds and textures (SÁNCHEZ & TADRES, 2010).

In this sense, virtual environments have been designed to create interactive virtual environments interfaces for people who are blind, particularly children, and have continuously proved to be an effective approach to enhancing and improving diverse types of cognitive skills (LAHAV & MIODUSER, 2000; LAHAV & MIODUSER, 2005; SÁNCHEZ & SAÉNZ, 2006; LAHAV & MIODUSER, 2008; MERABET & SÁNCHEZ, 2009; SCHINAZI, THRASH, & CHEBAT, 2016; MERABET & SÁNCHEZ, 2016; LAHAV et al., 2017).

2.4 Multimodal Video Games for Cognitive Improvement of Learners Who Are Blind

Multimodal serious games are particularly attractive interactive interfaces to teach learners who are blind new skills and to stimulate cognitive improvement. These games provide learners with a genuinely engaging virtual environment in which they undergo situations that would be unreachable in their everyday life (CHENG, 2012).

Receiving information in a multimodal way enables learners who are blind to interact with real and virtual environments mainly using audio- and haptic-based interfaces. These interfaces are capable of enhancing learning and cognition in this audience (TURK, 2014), by stimulating the utilization of general cognitive processes: tempo-spatial orientation, abstract memory and haptic perception (SJOSTROM, 2001; SÁNCHEZ & SAÉNZ, 2007).

Several studies have shown that multimodal gaming interfaces can be used to enhance learning and cognition in children who are blind, including collaboration, logical reasoning, navigation, and spatial cognition (YUAN, 2009; LAHAV & MIODUSER, 2008; SÁNCHEZ & AGUAYO, 2008; SÁNCHEZ et al., 2003; SIMÕES & CAVACO, 2014; BALAN, MOLDOVEANU & MOLDOVEANU, 2015; AHMETOVIC et al., 2017). These video games are capable of increase young people's motivation and engagement with learning (KLOPFER & YOON, 2005; SÁNCHEZ, 2008), promote high-order learning (STEINKUEHLER, 2008), enhance students' cooperation (MCDONALD & HANNAFIN, 2003), as well as social (PELLEGRINI, BLATCHFORD & KENTARO, 2004), and science skills (SÁNCHEZ & FLORES, 2005; SÁNCHEZ & AGUAYO, 2008).

Multimodal applications are especially useful when one of the user's senses is absent because the modalities provide alternative ways of interaction that suit people's capabilities, making the interaction a more efficient, pleasurable, fun, or natural process

(BONGERS & VAN DER VEER, 2007). Specifically in the case of people who cannot rely on their vision to obtain information to interact with their surroundings, a multimodal interface offers them non-visual stimuli to perceive the environments with which they are interacting in a richer way, avoiding the execution of simple tasks with extra complexity (ESPINOZA, SÁNCHEZ & CAMPOS, 2014).

Furthermore, given the growing popularity of video games (DEDE, 2009), serious multimodal video games contribute significantly to the development of various cognitive abilities in both sighted and visually disabled learners, including O&M skills (SÁNCHEZ & ELIAS, 2007; SÁNCHEZ & ESPINOZA, 2011; YUAN, 2009; YUAN & FOLMER, 2008; CONNOLLY et al., 2012; CONNORS, 2014; BOYLE et al., 2016). With the use of multimodal virtual environments and serious video games, it is possible for people who are blind to become familiar with real-life, strange, closed spaces before actually physically navigating them. This is possible by interacting with spatialized sound and audio-based interfaces (SÁNCHEZ & ELÍAS, 2007; SÁNCHEZ et al., 2009, 2010a; PICINALI, AFONSO, DENIS, & KATZ, 2014; MERABET & SÁNCHEZ, 2016), and with haptic-based interfaces (SÁNCHEZ & ESPINOZA, 2011; SÁNCHEZ & MASCARÓ, 2011; SÁNCHEZ et al., 2010; KOUKOURIKOS & PAPADOPOULOS, 2015; LAHAV et al., 2017). In virtue of multimodal interaction, the users receive information from the virtual environment that facilitates their navigation within the correspondent spaces in the real world, because the virtual experiences enhance one’s orientation and mobility skills (LAHAV & MIODUSER, 2008, 2008a; SÁNCHEZ & ESPINOZA, 2011).

In the remainder of this section, the crucial features related to the interaction, interface and cognitive aspects involved in the design and evaluation of multimodal gaming interfaces for learners who are blind are discussed. The data was gathered from a systematic literature review (DARIN, SÁNCHEZ & ANDRADE, 2015) following the steps proposed in the systematic review approach (KITCHENHAM & CHARTERS, 2007; PETERSEN, FELDT, MUJTABA & MATTSSON, 2008), in which were analyzed 25 papers describing 21 distinct applications: 17 multimodal games and 4 multimodal navigation virtual environment. The data was later updated using a 15-questions online questionnaire, emailed to the authors of the previously analyzed studies. Further details on the methodology and outcomes of the literature review and are given in Chapter 4.

2.4.1 Characterization of Interaction

Overall, the results showed that the crucial features that characterize the multimodal interaction in multimodal gaming interfaces in this context are Audio, Adaptation, Interaction Mode and Feedback, along with the cognitive aspects meant to be stimulated (DARIN, SÁNCHEZ & ANDRADE, 2015), in consonance with a motivating story (ALLAIN et al., 2015). Table 9 summarizes the multiple dimensions of the interface and interaction dimensions of multimodal games for learners who are blind, showing the diversity of interaction input modes and their associated feedback, as well as the possible types of audio and graphics interfaces.

Table 9 – Interface and interaction features on multimodal video games for learners who are blind

Interaction mode	Feedback type	Audio Cues	Visual Cues	Interface Customization	
Pointing devices	Tactile	Spoken audio	Bidimensional	**Graphical Elements**	**Aural Elements**
Keyboard	Kinesthetic	Speech synthesis	Tridimensional	Size	Speed
Natural language	Aural	Iconic sounds		Contrast	Intensity
Force feedback devices	Visual	Spatialized sounds		Color	
Touchscreen		Stereo sounds		Scheme	
Directional pads		Abstract earcons			
Specific-purpose devices					

Source: produced by author

Typically, video games for learners with visual disabilities provide input to the application by using a combination of mouse, keyboard, natural language, force feedback devices, touchscreen (with or without a stylus), directional pad, or specific devices, designed for a particular application (DARIN, SÁNCHEZ & ANDRADE, 2015). The application input devices determine the style of interaction available in the application. It also influences the type of feedback that the application provides to an interaction, which can be a combination of haptic (kinesthetic and tactile), aural and visual cues.

The keyboard is the prevalent input device in games developed for desktop paradigm, associated with the aural and visual output (TORRENTE et al., 2014; TORRENTE et al., 2009; SÁNCHEZ, GARRIDO & SAÉNZ, 2010). The keyboard is a low-cost, accessible and straightforward device, but it provides no sense of touch or volume during the interaction. Nevertheless, for learners who are blind, it is a desirable feature in a navigation context to provide nonvisual stimuli that help to perceive the physical characteristics of the environment.

Force feedback devices enhance the perception of people who are blind allowing them to acquire information via haptic perception, which is a combination of tactile and kinesthetic feedback (OAKLEY et al., 2000). Tactile feedback allows information to be perceived by the skin, while kinesthetic feedback provides information using muscles and tendons (BALLESTEROS, 1993). Force feedback devices measure the positions and contact forces of the user’s hand, displaying contact forces and positions to the user (SÁNCHEZ, 2012), even without visual clues.

Applications using haptic devices allow manual interactions with the multimedia environment using touch (SÁNCHEZ & AGUAYO, 2008; SÁNCHEZ, 2012; LAHAV & MIODUSER, 2008). They allow users to explore the environment to extract information from the tactile feedback, as well as to manipulate and modify the environment, via the kinesthetic feedback (HAMAM, EID & SADDIK, 2013). Multimodal applications use various devices to allow the function of haptic feedback – gamepads and joysticks – and force feedback devices (FIGURE 13). The applications that use gamepads and touch screen focus on the tactile feedback, providing sensations of vibration, pressure, touch, and texture. The tactile feedback allows the user to perceive contact force, the geometry of an object and temperature.

The games that utilize joystick provide kinesthetic sensation, dealing with forces resulting from position and velocity of the hand motion and simulating the force and torque (HAMAM, EID & SADDIK, 2013). Specialized joysticks, like 3D touch controllers, usually combine tactile and kinesthetic, providing haptic feedback. Among them, the force feedback devices usually have an alternative interaction mode, normally a keyboard (FIGURE 13b). It assures the availability of the game, even when force feedback is unavailable. Some force feedback devices, similar to the Novint Falcon, have a high cost. However, lower cost devices have also been utilized: OWL joystick, Wiimote, and SideWinder joystick.

The use of mouse and touchscreen with stylus configures a style of interaction that uses a directional pointer to select items on a display screen (LUMBRERAS & SÁNCHEZ, 1999; TORRENTE et al., 2009; TREWIN et al., 2008). Due to the visual limitation of the target audience, these are the less common interaction modes in this type of games. However, they occur when main target users are partially sighted. The use of mouse relates to sound feedback while the use of stylus also provides tactile feedback.

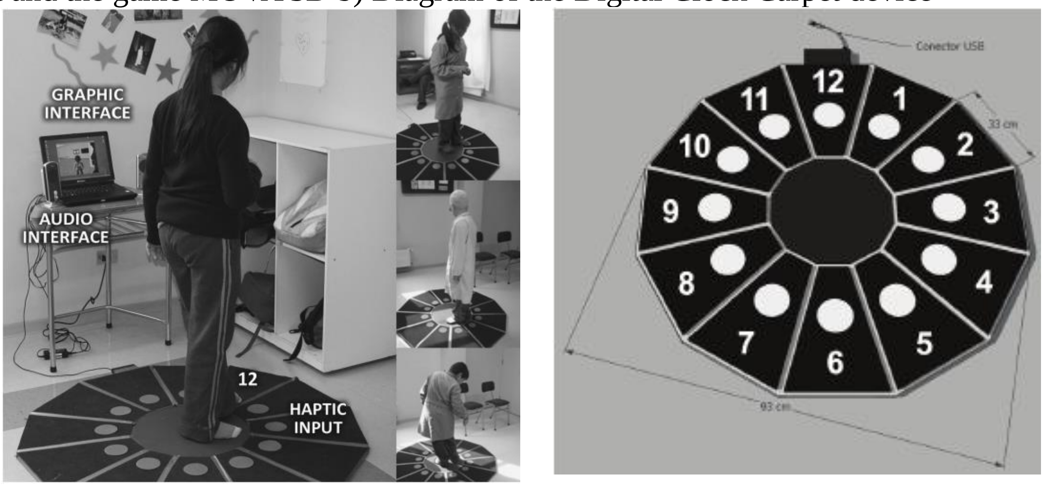
The interaction based on natural language is related to aural feedback and is usually associated with keyboard interaction (TORRENTE et al., 2014; TORRENTE et al., 2009). Some applications use directional pad, a type of four-way directional control with one button on each point, which is found on most console gamepads. Interaction with directional pad can also occur in mobile applications, with visual and aural feedback (SÁNCHEZ & AGUAYO, 2008).

Figure 13 – Children with visual disabilities interacting with multimodal video games using a) Xbox joystick, with aural, haptic and visual feedback; and b) force feedback device and keyboard, with aural and haptic feedback.

Sources: Photograph taken by the author and archive of Centro de Computación y Comunicación para la Construcción del Conocimiento (C5). Santiago (Chile).

Another option is the development of specific haptic devices to allow for the interaction of the users who are blind with the multimodal video game (FIGURE 14). For instance, the Digital Clock Carpet (SÁNCHEZ, SAÉNZ & GARRIDO, 2010) is a device based on a usual cane and a simple digital carpet that inform the user about directions to a destination point, based on the hour system. In this particular case, the feedback is both aural and haptic, but adapting a device to interaction and feedback specific to the context of a multimodal video game brings a number of new possibilities.

Figure 14 – a) Children with visual disabilities interacting with the Digital Clock Carpet and the game MOVA 3D b) Diagram of the Digital Clock Carpet device



Source: Sánchez, Saénz & Ripoll (2009).

2.4.2 Characterization of Interface

Multimodal gaming interfaces can support adjustments related to the graphic interface including the size, color or contrast of the graphical elements; or to the audio interface, addressing the speed and intensity of the sounds. The resizing relates mainly to text elements, which can be resized with no loss of content or functionality. The high contrast is to provide enough contrast between the content and its background so that people with low vision can read it. The use of colorblind safe colors is to assure the interface presents the visual elements in color combinations that are perceivable by people with any colorblindness. The customization of sounds includes the possibility of volume control and the option to adjust voice levels and TTS speed.

The Graphical User Interface (GUI) is a vastly utilized feature in this kind of applications, allowing the user to interact with graphical elements employing direct manipulation. Some applications allow the users to choose to navigate exclusively via sound, by using a graphic interface for configuration only (SÁNCHEZ, 2012; SÁNCHEZ & SAÉNZ, 2010). The reason some video games usually dispose of a GUI, despite the visual disability of the main audience, is to increase the interaction options for users with visual loss. The graphics on the interface can be either 2D or 3D combined with icons, images, and text. The association of said elements helps to fill some gaps in the interaction.

For instance, children with visual loss have difficulties recognizing specific 2D icons and not always associating them with the designed actions, so the use of 3D icons helps to increase the fidelity of the representation (SÁNCHEZ & SAÉNZ, 2006). Besides, when a video game disposes of a graphical interface, a facilitator can support the interaction with the video game, observing the navigation and the cognitive aspects (SÁNCHEZ, CAMPOS & ESPINOZA, 2014).

Although the graphics are substantial features to the interfaces of multimodal video games, the essential interface feature is the Audio (CAVACO et al., 2016). These applications always use at least one aural interface element. The combination of two or more aural elements, among iconic sounds, spoken audio, spatialized sounds, speech synthesis, stereo sound and abstract earcons is frequent, principally between iconic and spatialized sound, in 3D environments (SÁNCHEZ & MASCARÓ, 2011; SÁNCHEZ, 2012; LAHAV et al., 2008; LAHAV, SCHLOERB & SRINIVASAN, 2013; SIMÕES & CAVACO, 2014;).

Iconic sounds are specific sounds associated with each available object and action in the environment. Every time the user executes a specific action or interacts with a particular object, the corresponding representative sound is heard – for example, distinct sounds of steps for different kinds of floors. Spatialized or 3D sounds are stereo sounds that are digitally processed to appear to come from particular locations in the three-dimensional space, aiming to simulate the acoustic experienced by a listener within a specific environment, hence providing a higher degree of immersion in the video game (SÁNCHEZ, SAÉNZ & RIPOLL, 2009; CAVACO, SIMÕES & SILVA, 2015). A 3D sound navigable environment can serve as an aural representation of the space and surrounding entities, helping the players who are blind to assemble a mental image of an environment (LUMBRERAS & SÁNCHEZ, 1999).

Spoken audio refers to the use of sentences, pre-recorded in a human voice, usually describing the game status or relevant information about the actions and objects. Speech synthesis, on the other hand, is the artificial creation of the human voice. Stereo sounds consist in the mixing of two channels of sound recorded in two separate sources, with the distinction of left and right channels. This type of sounds provides information regarding the nature and location of objects, using intuitive associations (e.g., the sound of flowing water representing a fountain). Abstract earcons use music/tones to represent different objects. They refer to the use of sounds unrelated to the elements they represent. The use of abstract earcons requires the user to learn with what the sounds are associated. However, it is possible to represent a much wider range of concepts with abstract earcons than by using iconic sounds (DULYAN & EDMONDS, 2010).

2.4.3 Cognitive Aspects

Multimodal video games and virtual environments designed to enhance cognition of learners who are blind meticulously combine the Interaction and Interface features, not only for entertainment but also for learning and stimulating cognitive processes (SÁNCHEZ, SAÉNZ & GARRIDO, 2010; SIMÕES & CAVACO, 2014; CONNORS et al., 2014; BALAN, MOLDOVEANU & MOLDOVEANU 2015; MERABET & SÁNCHEZ, 2016; LAHAV et al., 2017).

These video games aim to develop specific target cognitive skills, but usually stimulate secondary skills during the gameplay. The cognitive skills usually fostered by multimodal games targeting learners who are blind are the development of mental models, spatial structures and orientation and mobility, mental mapping, academic curriculum learning, problem-solving and social collaboration.

Mental models are constructs that explain human behavior and the internal mechanisms that allow people to understand, explain, and predict the behavior of objects and systems (ROUSE & MORRIS, 1986). The improvement of mental models involves the user adopting and restructuring a mental model of spatial dimensions, based on aural and haptic cues after interacting with a video game (SÁNCHEZ, 2012; LAHAV et al., 2017). The adequate orchestration between audio and haptics also helps the learner who is blind to build up a specific model of a fantasy world (TREWIN et al., 2008) and of how a game works (MCCRINDLE & SYMONS, 2000).

Mental maps are mental representations of the space being navigated and its defining features, e.g., overall structure, spatial components, landmarks, dimensions, and relative positions (LAHAV & MIODUSER, 2008). The cognitive mapping involves the ability to learn a route and to review it from memory, including all aspects of coding, processing and retrieving information about the environment (BLADES et al., 2002; GOLLEDGE, 1999). Having a mental map of space is fundamental to the efficient development of Orientation and Mobility skills (SÁNCHEZ, SAÉNZ & GARRIDO, 2010), which consist of a set of techniques that helps children and adults who are visually impaired to develop and master the concepts and competencies necessary to be able to move safely and efficiently within their world. While navigating the video game environment, people who are blind can perceive the aural and haptic elements and use them as references for orientation and mobility (SÁNCHEZ, 2012).

Cognitive spatial structures relate to spatial and temporal reference frames, implying the connection between visual and haptic space (FREKSA, 1997). The spatial properties include location, size, distance, direction, separation and connection, shape, pattern, and movement. Humans acquire spatial knowledge and beliefs directly via sensorimotor systems that operate as they move about the world (SMELSER & BALTES, 2001). While navigating in multimodal environments, players who are blind acquire spatial knowledge indirectly with the help of maps and images, tridimensional audio and graphics models, and the language (CONNORS et al., 2014; MERABET & SÁNCHEZ, 2016).

The development of social collaboration skills involves supporting the execution of collaborative tasks necessary to achieve the main goal (SOUTE & MARKOPOULOS, 2007). These skills facilitate school integration of learners who are blind through team interaction with a video game, while teaching specific subjects – Science, for instance – or by encouraging competition and concentration skills (SÁNCHEZ & SÁENZ, 2009). On the other hand, it is also possible to enhance collaboration by providing tools to the learner who is blind to minimize disadvantages in comparison with sighted learners, while improving a cognitive mutual skill, like abstract memory (SÁNCHEZ et al., 2003).

Problem-solving skills are usually associated with the game motivating story. Approaches for developing these skills in multimodal games for learners who are blind include searching, investigation, mobilization, localization, and designing strategies (SÁNCHEZ & SAENZ, 2005), and by using clues that are provided to the students during their interaction and investigation throughout the video game (SÁNCHEZ & SÁENZ, 2009).

Finally, the use of video games to support teaching of academic curriculum can foster learning and cognition. This is possible by using audio and haptics to highlight abstract aspects that are usually difficult for learners who are blind to acquire in multiple disciplines related to literacy and sciences. For example, using audio to allow children to learn and develop the concept of number (EBENEZER, ADAIKALARAJ & GAJALAKSHMI, 2014), and fostering learning and practice of mathematical concepts: positional value, sequences, additive decomposition, multiplication, and division (SÁNCHEZ & FLORES, 2005). Another strategy used in these types of games is providing learners with virtual simulators, which emulate what sighted students could observe adopting the application of the scientific method, using proper feedbacks (SÁNCHEZ, FLORES & SAÉNZ, 2008).

The combinations and choices of different modalities affect the users' behavior towards the game and determine how learning takes place and how cognitive processes are stimulated. For instance, audio and visual cues coordinated with haptic elements distributed in a virtual navigational environment serve as references for orientation and mobility, as well as to help learners who are blind adopting and restructuring a mental model of spatial dimensions.

The diverse types of audio cues represent spatially and surrounding properties including location, size, distance, direction, separation and connection, shape, pattern, and movement; or be associated with each available object and action in the environment. For that reason, the multimodal interaction provided by the game interface must adequate the use of modalities to the cognitive game goals, along with the game story, while offering the learner with the proper interaction mode to develop the desired skills in a certain usage context.

2.5 Usability Evaluation

Usability evaluation methods are thoroughly documented in the Human-Computer Interaction research and practitioner literature (SHACKEL, 1991; DIX et al., 1993; NIELSEN, 1994; WIXON & WILSON, 1997; ABRAN et al., 2003; HORNBAEK, 2006; BEVAN, CARTER & HARKER, 2015; ISO 9126; ISO 14598; ISO 9241; ISO 13407), as they are a basis to determine whether an interactive system is usable and understandable. In this Section, basic concepts related to the definition of usability and usability problems are discussed, as well as the types and uses of usability evaluation methods.

2.5.1 Usability

Usability can be appointed as a core term in human-computer interaction (HORNBAEK, 2006). The term "usability" may refer to various concepts – execution time, performance, user satisfaction, and learnability taken together –, since it has not been defined homogeneously, either by the researchers or by the standardization bodies (ABRAN et al., 2003). Intending to explain the meaning of this term, usability has been defined as "the capability to be used by humans easily and effectively" (SHACKEL, 1991, p. 24); as "quality in use" (BEVAN, 1995, p. 350), and as 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" (ISO, 1998, p. 2).

The International Organization for Standardization (ISO) has developed different standards on usability, in which the software usability properties vary, depending on the target audiences of the software system, resulting in usability definitions from different points of view for each of these audiences. In this context, two major viewpoints categories are distinguished: product-oriented standards (ISO 9126 and ISO 14598) and process-oriented standards (ISO 9241 and ISO 13407) (ABRAN et al., 2003).

The standard ISO 9126 (1991, p. 9), for example, defines usability as "a set of attributes that bears on the effort needed for use and on the individual assessment of such use, by a stated or implied set of users." In this standard, usability is one of the six defined software quality characteristics, besides functionalities, reliability, effectiveness, maintainability, and portability. ISO 9126 is currently incorporated into ISO/IEC 25000 (2005), which is a quality model for systems in general, that specifies the usability as a quality characteristic and lists software measures to evaluate it. According to this standard, usability is "the capability of the software product to be understood, learned and liked by the user, when used under specified conditions" (ISO / IEC 25000, 2005, p. 4).

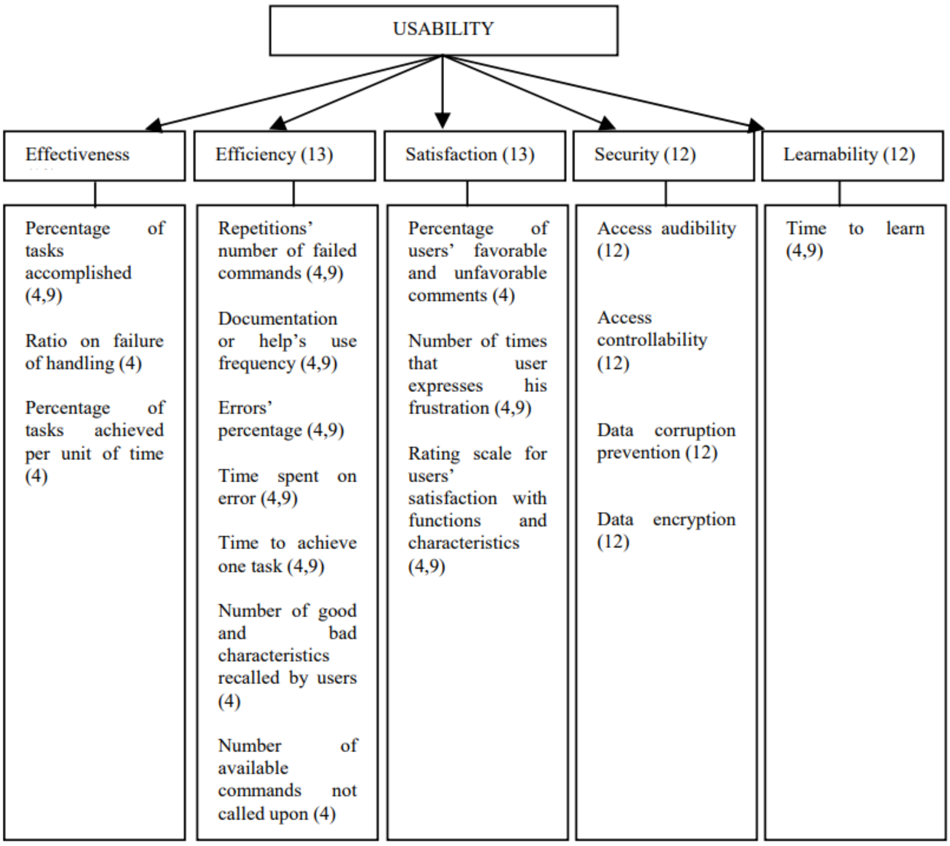
The standard ISO 9241-11 (1998, p.8), however, defines usability stating that "a software is usable when it allows the user to execute his task effectively, efficiently and with satisfaction in the specified context of use". According to this standard, the measuring of system usability must consider three attributes: (i) effectiveness, related to how well the users achieve their goals using the system; (ii) efficiency, regarding what resources are consumed in order to achieve users' goals; and (iii) satisfaction, which analyzes how the users feel about their use of the system (WIXON & WILSON, 1997). ISO 9241 is the only normative model that specifically addresses usability and it is generally adopted by experts in Human-Computer Interaction (ABRAN et al., 2003).

Abran and colleagues (2003) proposed a consolidated and normative model for the evaluation of software usability from the individual ISO models, addressing some of the limitations in each one. According to the authors, a more comprehensive model of usability should include both process-related and product-related usability characteristics, as the two viewpoints on usability are complementary. Their Consolidated Usability Model uses ISO 9241-11 as a baseline and integrates into this standard other relevant usability characteristics from both 9126 and other sources: learnability and security.

The three-layer structure of ISO 9126 (characteristics, sub-characteristics, and measures) was used to complete the Consolidated Model of Usability, describing relevant candidate measures which were proposed and analyzed by authors (FIGURE 15). The resulting usability model proposes 18 specific measures comprising effectiveness, efficiency, satisfaction, security and learnability, based on the strengths and weaknesses of the two analyzed standards.

The standards mentioned above are used to support user interface development in multiple ways: to specify details of the appearance and behavior of the user interface; to provide guidance on user interface design; and to provide criteria for the evaluation of user interfaces (BEVAN, 2001).

Figure 15 – Consolidated and Normative Usability Model, constructed based on measures from ISO 9241-11 and ISO 9126



Source: Abran et al. (2003)

In another perspective, HCI researchers have proposed their own usability models, often including other characteristics for usability, like learnability (ABRAN et al., 2003). Often, groups of authors propose usability models based on the same set of usability characteristics. However, they differ as to the levels of the proposed measures to use for these characteristics. For example, Dix et al. (1993) and Nielsen (1994) both defined a usability model based on effectiveness, efficiency, satisfaction, and learnability, but while Dix and colleagues proposed 14 usability measures, Nielsen proposed a set of 9 usability measures. Shneiderman and Plaisant (2005) identified five usability measures: time to learn, speed of performance, rate of errors by users, retention over time, and subjective satisfaction, respectively related to the five attributes they use to characterize usability: learnability, effectiveness, tolerance for errors, memorization, and satisfaction.

Seffah et al. (2006) developed the QUIM model of usability, which was synthesized from existing work and incorporates more than 127 specific measures in 10 factors, including – in addition to the ISO aspects – safety, trustfulness, and accessibility, among others. The main contribution of this type of work seems to be its detailed look at the meaning of the usability construct and its implications for how to measure usability (HORNBAEK & LAW, 2007).

Hornbaek (2006) conducted a review of usability measures used in HCI and listed more than 54 types of measures. This fact indicates that, in practice, choosing among usability measures is a challenging task, in particular considering the discussion on whether they actually measure usability, if they cover usability broadly, how they are reasoned about, and if they meet recommendations on how to measure usability (HORNBAEK, 2006; HORNBAEK & LAW, 2007). According to the authors, in the same way that a standard definition of usability is unfeasible, there is not a unique way of measuring the usability of a system. Among the challenges faced by researchers and practitioners, it is important to highlight the need to understand the relation between objective and subjective measures of usability (HORNBAEK, 2006), because, as interestingly remarked by Bevan (2001), no interactive system has intrinsic usability by itself, but only an ability to be used in a particular context of use.

Aiming to retain the basic concept of usability and to add further levels of understanding about usability considering what the HCI community had learned about usability since 1998, ISO 9241-11 (1998) was revised originating ISO 9241-210 (2010). The revised version defines usability as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use".

Two main changes were proposed in the revised version of ISO 9241-11 (BEVAN, CARTER & HARKER, 2015). First, the inclusion of the concept of user experience, clarifying that the satisfaction component of usability includes aspects of user experience. In addition to highlighting the importance of the individual user's emotional experience, ISO 9241-210 explains that although environments are considered as part of the context of use, user interactions with a specific environment or component of the environment can be considered in terms of the usability of an environment.

Second, it is now appreciated that there is more to usability evaluation than measurement. It means that effectiveness, efficiency, and satisfaction represent the intended outcomes of interaction, but that their measurement does not represent the only way of evaluating usability. The revised version also applies the concept of usability equally to "products, systems, and services" instead of "products" only.

2.5.2 Usability and User Experience

Although evaluating the user experience of multimodal games is out of the scope of this work, a discussion about this concept is welcome to situate properly the focus of the present research. Bevan, Carter and Harker (2015) discuss that a source of confusion when discussing usability and user experience (UX) is the increasingly widespread use of the term user experience to refer to an overall view of all aspects of the user's interaction with a system, product or service, instead of its original meaning that emphasized the importance of emotional experience. According to the authors, this use of the term user experience is closer to the concept of usability in ISO 9241-210, which explicitly includes the personal factors for individuals.

ISO 9241-210 (2010, p.3) defines user experience as a "person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service". Consequently, user experience focuses on the experience of an individual in contrast with the view provided by usability comprehending effectiveness, efficiency and satisfaction as representing the collective responses of a group of users.

While usability typically deals with goals shared by a group of users, user experience is about individual goals, which include personal motivations like needs to communicate personal identity and to provoke pleasant memories in users (BEVAN, CARTER & HARKER, 2015). Thus, usability is concerned with the observed effectiveness, efficiency and satisfaction of target users – measured during interaction – while user experience focuses on the user's preferences, perceptions, and emotions, as well as physical and psychological responses that occur before, during and after use.

Although UX is primarily about the actual experience of usage, this is difficult to measure directly. The measurable consequences are the user's performance, satisfaction with achieving pragmatic and hedonic goals, and pleasure (BEVAN, 2008).

According to a systematic review analyzing UX measurement and evaluation in 45 studies, Maia and Furtado (2014) highlighted that the main metrics used in UX evaluation are related to user satisfaction (4.55%), application use (18.18%), efficiency/effectiveness (36.36%) and feelings/emotions (40.91%). The authors observed that the metrics related to user satisfaction are usually measured in the form of scales of 5 to 7 points and are informed by the own user. Meanwhile, metrics based on feelings and emotions are usually measured with the help of devices attached to the user's body, with emphasis on measurement of blood pressure and pupil diameter. They also found that application usage metrics identify how the application-under-evaluation is being used, including, for example: number of visits per user per week and time spent on a page. Finally, efficiency and effectiveness metrics are those that measure the percentage of tasks performed correctly by the user.

In a posterior study (MAIA & FURTADO, 2016), the authors further investigated the use of psychophysiological measures present in 14 of the previously analyzed studies. They found that multiple psychophysiological signals (e.g., Galvanic Skin Response/Electrodermal Activity (GSR/EDA), respiration, Heart Rate (HR), and Electromyography (EMG)), are used to measure the following states of user (emotional or not): arousal (35%), emotional state (26%), pleasure/likeability (9%), valence (9%), frustration/fear (9%), and, with only one study (4%), mental effort, attention, and relaxation.

Despite the established standards that define usability (ISO 9241-11) and UX (ISO 9241-210), there is a growing discussion about a scientific definition of usability and UX and no consensus has been achieved so far (RAJANEN et al., 2017). In a research examining the views of UX professionals on the definitions of usability and user experience between countries and within different socio-cultural groups, Rajanen et al. (2017) found that usability appears to be an established concept in all researched countries, particularly using ISO 9241-11 definition. However, the authors pointed a tendency of UX professionals to diverge systematically when defining UX, according to their socio-cultural conditions. For example, their results showed that UX professionals in Finland and France incline more towards the definition highlighting the experiential qualities, when compared to Turkey and Malaysia who incline towards the definition reflecting the ease of use, utility, attractiveness, and degree of usage.

Ten years ago, Law et al. (2008) remarked that it is an intriguing phenomenon that the notion of UX had been widely disseminated and speedily accepted in the HCI community, however, without it being explicitly defined or well understood. More recently, Rajanen et al. (2017) showed that the lack of a shared definition is still a reality and causes diverse misunderstandings, especially regarding the relation between usability and UX.

For Bevan (2009) that confusion, in part, is due to the ambivalence as to whether usability is part of user experience brought by the notes that accompany the definition of user experience in ISO 9241-210: “User experience includes all the users’ emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviors and accomplishments that occur before, during and after use” (ISO 9241-210, 2010, p.3). If user experience includes all behavior, it presumably includes the user’s effectiveness and efficiency (BEVAN, 2009), which would be consistent with the methods nominated by many people in industry who appear to have subsumed usability within user experience (KETOLA & ROTO, 2008; ROTO, OBRIST, VÄÄNÄNEN-VAINIO-MATTILA, 2009).

On the other hand, researchers working in the field consider user experience to be entirely subjective (BEVAN, 2009), e.g. "The objective measures such as task execution time and the number of clicks or errors are not valid measures for UX, but we need to understand how the user feels about the system" (ROTO, OBRIST, VÄÄNÄNEN-VAINIO-MATTILA, 2009, p.1). Consequently, user experience can be either conceptualized as (i) an elaboration of the satisfaction component of usability (BEVAN, 2009a); (ii) distinct from usability, which has a historical emphasis on user performance (ROTO, OBRIST, VÄÄNÄNEN-VAINIO-MATTILA, 2009); and (iii) an umbrella term for all the user's perceptions and responses, whether measured subjectively or objectively (ISO 9241-210, 2010).

Regardless of the terminology, the scope of UX comprises two main objectives: optimizing human performance and optimizing user satisfaction by achieving both pragmatic and hedonic goals (BEVAN, 2009; HASSENZAHL, 2003; HASSENZAHL, 2007). According to Bevan (2009), the methods for optimizing user satisfaction achieving both pragmatic and hedonic goals are categorized as: (i) methods of evaluation and design for the hedonic goals of stimulation, identification and evocation, and associated emotional responses; (ii) methods of evaluation and design for users' perception of achievement of pragmatic goals associated with task success; and (iii) methods that support the design of users' experience.

Measures of system usability and UX are dependent on product attributes that support different aspects of user experience, as shown in Table 10. Consequently, the choice of what methods to use to support both types of UX goals aforementioned will depend on the specific product and design objectives.

Table 10 - Factors contributing to system usability and UX

<table>
<tr><th>Quality characteristic</th><th>UX</th><th>Functionality</th><th>User interface usability</th><th>Learnability</th><th>Accessibility</th><th>Safety</th></tr>
<tr><td>Product attributes</td><td>Aesthetic attributes</td><td>Appropriate functions</td><td>Good UI design (easy to use)</td><td>Learnability attributes</td><td>Technical accessibility</td><td>Safe and secure design</td></tr>
<tr><td>UX pragmatic do goals</td><td colspan="6">To be effective and efficient</td></tr>
<tr><td>UX hedonic be goals</td><td colspan="6">Stimulation, identification and evocation</td></tr>
<tr><td>UX: actual experience</td><td>Visceral</td><td colspan="5">Experience of interaction</td></tr>
<tr><td>Usability (= performance in use measures)</td><td colspan="3">Effectiveness and Productivity in use:
effective task completion and efficient use of time</td><td>Learnability in use: effective and efficient to learn</td><td>Accessibility in use: effective and efficient with disabilities</td><td>Safety in use: occurrence of unintended consequences</td></tr>
<tr><td rowspan="2">Measures of UX consequences</td><td colspan="6">Satisfaction in use:
satisfaction with achieving pragmatic and hedonic goals</td></tr>
<tr><td>Pleasure</td><td colspan="4">Likability and Comfort</td><td>Trust</td></tr>
</table>

Source: Bevan et al. (2008)

2.5.3 Usability and Accessibility

As in the case of user experience, evaluating the accessibility of multimodal games is also out of the scope of this work. However, in this subsection a brief discussion about accessibility and usability is presented, aiming to clarify the distinction between the two types of evaluation. Accessibility is a term for which there is a range of definitions. In the literature, different ways can be found of defining accessibility and its relation with usability (BILLI et al., 2010). For example, ISO/IEC Guide 71 (2001, p.4) defines Accessible Design as “design focused on principles of extending standard design to people with some type of performance limitation to maximize the number of potential customers who can readily use a product, building or service”.

ISO 9241-171 (2006) and 9241-20 (2006), however, define accessibility in a very different way. The first describes accessibility as “usability of a product, service, environment or facility by people with the widest range of capabilities”, introducing a tight connection with usability. This definition is a way of conceptualizing accessibility as simply usability for the maximum possible set of specified users accommodated; this fits within the universal design or design for all philosophy (PETRIE & BEVAN, 2009). The second adds that “the concept of accessibility addresses the full range of user capabilities and is not limited to users who are formally recognized as having a disability”; and “the usability-orientated concept of accessibility aims to achieve levels of effectiveness, efficiency, and satisfaction that are as high as possible considering the specified context of use, while paying particular attention to the full range of capabilities within the user population”.

Wegge and Zimmermann (2007) explain that this mixture of the concepts of accessibility and usability probably occur for historical reasons and highlight how impressive it is that, even within the same standardization organization, incompatible definitions are used. However, accessibility is not usability, and a well-constructed usable interface is not necessarily accessible – and vice versa (POWLIK & KARSHMER, 2002). Although accessibility is the key requirement to allow people with limitations to interact with a system, it is only a first step to assure a satisfactory and efficient usage (BILLI et al., 2010). On the other hand, usability cannot be considered as encompassing all the possible problems encountered by every user.

Even when Shneiderman (2000; 2003) proposes the concept of ‘‘universal usability’’ as a term to encompass both accessibility and usability, he observes that access is not enough to ensure successful usage. Similarly, Shneiderman established a different ranking of accessibility in comparison with usability: accessibility is a first but not sufficient requirement to achieve universal usability (BILLI et al., 2010).

In the present work, usage problems are investigated for a specific target audience: learners who are blind. Although some authors consider that any problem that affects people with performance limitations can be seen as an accessibility problem (PETRIE & KHEIR, 2007), the differentiation of concepts proposed by Wegge and Zimmermann (2007) is adopted in this work, as explained as follows.

Wegge and Zimmermann (2007) clarify the differences between the two types of evaluation: (i) Accessibility evaluation involves representatives for each group providing feedback on whether the system supports their specific disability type, if the product fits their mental model, if it is interoperable with the assistive devices they commonly use, and if the product supports certain compensation strategies they have learned to cope with their impairment; (ii) Usability evaluation requires the definition of the usage types by different contexts of use. These contexts are either based on the type or role of the user, or the specific setting (e.g., organizational characteristics and user physical condition) in which the task is carried.

For the authors, usability evaluation focuses on the support for a context of use and fit with the mental model, but also for compatibility with general learning or problem-solving strategies of the users, while executing given tasks. In the present work, the focus is on usability because the cognitive improvement of the target users depends on the correct execution of the game cognitive tasks during users' interaction with the multimodal interface.

2.5.4 Usability Problems

Before performing any usability evaluation, researchers need to clarify what exactly they consider a usability problem, to avoid including irrelevant problems, as well as excluding actual problems or relevant aspects of a problem (MANAKHOV & IVANOV, 2016). A consistent definition of usability problem should meet the following requirement: include all HCI phenomena, distinguish usability problems from problems in general, distinguish a problem and its cause, imply a relational position on usability, and distinguish a problem and a recommendation (MANAKHOV & IVANOV, 2016).

In this work, Manakhov and Ivanov's (2016, p. 3146) definition of usability problem was adopted: "a set of negative phenomena, such as user's inability to reach his/her goal, inefficient interaction and/or user's dissatisfaction, caused by a combination of user interface design factors and factors of usage context". In this definition, negative phenomena are divided into effectiveness, efficiency, and satisfaction, intentionally avoiding defining usability phenomena in terms of quantity (e.g., task completion time, level of negative emotions) rather than quality. Said definition was chosen because, compared to previous ones (e.g., MACK & MONTANIZ, 1994; KAHN & PRAIL, 1994; NIELSEN & MACK, 1994; LAVERY et al., 1997; RUBIN & CHISNELL, 2008), it meets the requirements mentioned before, and leads to the examination of a combination of factors that cause a usability problem, in addition to the resulting effect.

Usability problems can be identified both in systematic inspections and during field tests, by experts and users. Although users can report about half the problems as trained usability evaluators, and even point potential solutions, they are not substitutes for professional usability evaluators (CASTILLO, HARTSON & DIX, 1998). When reporting usability problems, an individual problem report can be seen as a way to describe the causal relation between the negative phenomena and a combination of factors (MANAKHOV & IVANOV, 2016). According to the relational position on usability (COCKTON, 2013), the cause of a usability problem is a combination of factors coming from the user interface design and a context of use.

In a usability evaluation report, a usability problem should be characterized using name, clear description and usually a severity rating, which can be based on a scale (e.g., 1-5 and 1-7). They can be also assigned according to predefined criteria, including whether the problem prevents task completion, causes a significant delay or frustration, has a relatively minor effect on task performance, or is just a user suggestion (DUMAS & REDISH, 1999; RUBIN & CHISNELL, 2008).

Studies aiming to compare usability evaluation methods in a specific context – which is the case in this work – are required to match usability problems descriptions to determine whether they are similar or not. According to a study conducted by Hornbaek & Frokjaer (2008), aiming to compare reliability of matching techniques, the ones usually applied for this purpose are (i) the similarity of solutions to the problems; (ii) a prioritization effort for the owner of the application tested; (iii) a model proposed by Lavery, Cockton & Atkinson (1997); and (iv) the User Action Framework (ANDRE, HARTSON, BELZ, & MCCREARY, 2001).

In the present work, Lavery, Cockton & Atkinson's (1997) model to report and match usability problems will be used, taking advantage of structured reporting of problems, thereby making explicit how problems are different (HORNBAEK & FROKJAER, 2008). In this model, the levels of matching similarity are high, ranging from 85% to 96%, and evaluators are reportedly satisfied with grouping results, presenting fewer difficulties in interpreting the model execution (HORNBAEK & FROKJAER, 2008). The model proposed by Lavery and colleagues (1997) suggests that descriptions of usability problems have four components: a cause (e.g., a design fault), a breakdown (e.g., the user misinterprets feedback), a behavioral outcome (e.g., the user's task failed), and a design change (e.g., modification of a feature).

The specified components are used as the basis for determining which problems match, as suggested by Hornbaek & Frokjaer (2008). According to their procedure, a straightforward application of Lavery *et al*'s model to the matching activity is to analyze the problems of similarity in degrees, depending on the number of components in which they match. For every group of problems, this degree will go from 0 (no overlap in any component) to 4 (overlap concerning the problems' cause, breakdown, outcome, and design changes). Thus, the analysis of the usability problems descriptions helps evaluators determine the extent to which the descriptions agree, helping to separate four aspects of a problem description. The notion of similarity to be used within these aspects is left, however, for the matcher to determine (HORBAEK & FROKJAER, 2008).

2.5.5 Usability Evaluation Methods

In the context of this work, the term usability evaluation method (UEM) is taken from the definition adopted by Hartson, Andre & Williges (2003, p. 149): “any method or technique used to perform usability evaluation, with emphasis on formative usability evaluation (i.e., usability evaluation/testing used to improve usability) of an interaction design at any stage of its development”. According to the authors, this broad definition includes field and lab-based usability testing with users, heuristic and other expert-based usability inspection methods, model-based analytic methods, all kinds of expert evaluation, and remote evaluation of interactive software after deployment in the field.

For Hartson and his colleagues, regardless of the method, the goal of all UEMs is, essentially, to produce descriptions of usability problems observed or detected in the interaction design, for analysis and redesign. Consequently, every method capable of producing a list of potential usability problems as its output, when applied to interactive design, is a Usability Evaluation Method.

Evaluation methods can be understood under two basic approaches: formative evaluation, which is performed during development and aims to improve a design; and summative evaluation, which is done after development with the goal of assessing a design (SCRIVEN, 1967). In the context of usability, while formative evaluation is used to find usability problems, in order to fix them and improve an interaction design, summative evaluation is used to assess and/or compare the level of usability achieved in an interaction design (HARTSON, ANDRE & WILLIGES, 2003). UEMs are used to perform formative usability evaluation of interaction designs, and formal experimental design is used to perform summative evaluation (HARTSON, ANDRE & WILLIGES, 2003).

Usability Evaluation Methods are usually divided into analytical/inspection methods, performed by experts without end users, and empirical/test methods, which involve end users (HOLZINGER, 2005). Every usability evaluation method, either empirical (test-based) or analytical (inspection based), is susceptible to instrumentation bias, equivalent to systematic judgment errors about existence and severity of usability problems (GRAY & SALZMAN, 1998). To diminish these threats, usability studies should be based on a clear theoretical assumption, regarding a definition of usability problem to specify the evaluation scope and the usability problem report format (MANAKHOV & IVANOV, 2016).

Usability inspection methods are used to identify usability problems and improve the usability of an interface design by checking it against established standards. These methods include heuristic evaluation, cognitive walkthroughs, and action analysis (HOLZINGER, 2005). Among these, heuristic evaluation is the most common informal method. It involves having usability specialists judging whether each dialogue or other interactive element follows established usability principles (NIELSEN, 1994).

Test-based usability evaluation is the most fundamental and indispensable usability method, because it provides direct information about how people use the target systems and their exact problems with a specific interface (HOLZINGER, 2005). In the present work, the focus is on this type of methods, since the proposal is to consider the user characteristics and context of use while evaluating multimodal video games for children who are blind. There are several methods for testing usability with end users, the most common being thinking aloud, field observation, and questionnaires (HOLZINGER, 2005).

Each of the empirical and analytical usability evaluation methods has advantages and disadvantages that need to be considered according to the context of use, the design phase in which the evaluation is conducted, and the available resources for evaluation. Table 11 compares the aspects of techniques that involve inspection and test methods.

The comparison shows that inspection methods are generally cheaper and easier to apply. The inspection methods require no users and no special equipment, while test methods not only require equipment, but also a usually high number of users. However, some test methods, like field observation, are adequate to final product testing since these methods outcome real impressions, problems and opportunities for improvement. Even though test methods are generally more expensive and time-consuming, they provide a better insight on end-user characteristics and usage context specificities.

Table 11 – Comparison of usability evaluation methods

	Inspection Methods			Test Methods		
	Heuristic Evaluation	Cognitive Walkthrough	Action Analysis	Thinking Aloud	Field Observation	Questionnaires
Applicably in Phase	all	all	design	design	final testing	all
Required Time	low	medium	high	high	medium	low
Needed Users	none	none	none	3+	20+	30+
Required Evaluators	3+	3+	1-2	1	1+	1
Required Equipment	low	low	low	high	medium	low
Required Expertise	medium	high	high	medium	high	low
Intrusive	no	no	no	yes	yes	no
Comparison of Usability Evaluation Techniques						

Source: Holzinger (2005).

2.6 Evaluation of Multimodal Video Games for Learners who are Blind

In order to assure the quality of multimodal video games with cognitive enhancement purposes, it is necessary to perform not only usability evaluations but also to assess the impact of the video game on the development of the target cognitive skills in learners who are blind. Although this work focuses on the usability aspects of multimodal games, both types of evaluation are discussed in the remainder of this section.

2.6.1 Instruments and procedures for usability evaluation

There is currently no particular model or methodology for the cognitive impact and usability evaluation of this type of multimodal games (DARIN, ANDRADE & SÁNCHEZ, 2015). However, it is possible to observe the most used instruments and procedures for cognitive impact evaluation, as well as the traditional HCI evaluation methods applied in usability assessment.

For the usability evaluation, diverse types of instruments are usually administered: Specialized Questionnaires, Common Questionnaires, and Likert-based Surveys. The specialized questionnaires are validated and reusable instruments prevailing in formal evaluations. They consist of some context-specific statements for which the users can define the degree of fulfillment on a scale. The specialized questionnaires identified are the Software Usability for Blind Children Questionnaire (SUBC) (SÁNCHEZ, 2003a); the End User and Facilitator Questionnaire for Software Usability (EUQ) (SÁNCHEZ, 2003b); the Software Usability Elements Questionnaire (SUE), which quantifies the degree to which the sounds of an application are recognizable; the Open Question Usability Questionnaire (OQU); and the Initial Usability Evaluation (IUE).[8]

The common questionnaires and the Likert-based surveys are developed and used circumstantially to evaluate a given video game and consist of a set of factual, opinion, and attitude questions. In both cases, the authors themselves create the instruments and they do not disclose the validation process neither show the instrument itself. The surveys are mainly based on the context of the application and can be applied either in person (ESPINOZA, SÁNCHEZ & CAMPOS, 2014) or via email (TORRENTE et al., 2014).

The typical activities executed during the usability evaluation of the multimodal games and environments analyzed are traditional UEM: Observation, Interviews, and Heuristics Evaluation. The observation is direct and involves an investigator viewing users as they use the application and taking notes on usability aspects (LUMBRERAS & SÁNCHEZ, 1999). The interviews are semi-structured and occur after the user interacts with the application. The questions intend to establish the subject's previous experience, identify aspects of the interface that were helpful or problematic, and prompt for suggestions on improving the experience (DULYAN & EDMONDS, 2010). In the heuristic evaluation, usability experts inspect the application's interface and compare it with usability principles in a checklist. For example, the Heuristic Evaluation of the Video game (HEV), based on Shneiderman's golden rules and Nielsen's usability heuristics, and the Heuristic Evaluation Questionnaire (HEQ) (SÁNCHEZ, SAÉNZ & GARRIDO, 2010). The usability evaluations analyzed often combine UEMs and questionnaires.

The effectiveness of the instruments and methods administered during the usability evaluation of multimodal games for learners who are blind depends on whether they can reveal the relevant issues related to the key features of the game interaction and interface characterization. Usually, when researchers address usability evaluations in this field, they

[8] No citations were found on the literature for the following instruments: SUE, IUE and OQU. Although they are mentioned in some papers, they are not referenced, probably because they were developed and used inside the same research group (Dr. Jaime Sanchez and coauthors).

just describe the diverse evaluation processes carried out in specific situations, conducting different procedures for usability evaluation in studies with similar goals (LUMBRERAS & SÁNCHEZ, 1999; MCCRINDLE & SYMONS, 2000; LAHAV & MIODUSER, 2008; SÁNCHEZ & AGUAYO, 2008; SÁNCHEZ, 2012; CAVACO, SIMÕES & SILVA, 2015).

This fact underlines the lack of reasoning on which and how to evaluate specific aspects of the multimodal interaction for people who are blind. Moreover, some studies make unconfirmed assumptions about usability as they, for multiple reasons, do not discuss the usability evaluation of video games for developing cognitive skills in people who are blind (TREWIN et al., 2008; TORRENTE et al., 2009; GUERRERO & LINCON, 2012; SIMÕES & CAVACO, 2014; FERREIRA & CAVACO, 2014; ALLAIN et al., 2015).

Considering the lack of guidance for usability evaluation of multimodal gaming interfaces for learners who are blind, there is no basis to compare usability methods in this context and to decide which UEM is more suitable to each situation. Besides, when researchers omit the usability evaluation process during the development of these games, they cannot just assume that users will develop cognitive skills by interacting with the developed video game. Users could have difficulties in learning the right way to interact, and also become fatigued, confused, or frustrated, focusing on the usability issues rather than on cognitive and learning skills (GONZÁLEZ et al., 2001; ARDITO et al., 2006). Consequently, identifying and fixing real usability issues on the design of multimodal video games for learners who are blind plays a crucial role in the acquisition of cognitive skills for these users.

2.6.2. Instruments and procedures for cognitive impact evaluation

Regarding the cognitive impact evaluation of multimodal video games for children who are blind, the literature review showed that the instruments most commonly used are Logs, Checklists, Questionnaires and Modeling Kits (DARIN, SÁNCHEZ & ANDRADE, 2015). These four evaluation instruments can be utilized to analyze the improvement of any of the cognitive skills discussed in Section 2.3.3, throughout the assessment’s activities, combined with observation and interviews.

The goal of cognitive impact evaluation is to collect data that will allow an investigator to observe, compare, analyze and measure the skills and the development of the subjects. The typical activities identified relates to the research structure of the quasi-experimental design of non-equivalent groups (CAMPELL, STANLEY & CAGE, 1963), considering experimental and control groups and a two-sample test analysis (also known as pretest-posttest design). The basic premise behind the pretest–posttest design involves obtaining a pretest measure of the outcome of interest prior to administering a treatment, followed by a posttest on the same measure after treatment occurs. Pretest–posttest designs are employed in both experimental and quasi-experimental research and can be used with or without control groups (SALKIND, 2010).

The four typical activities identified are pretest, training tasks, cognitive tasks, and posttest, performed in this order. The pretest involves the users executing an activity under observation so that an investigator can establish the subjects' initial skills (SÁNCHEZ, 2012; SÁNCHEZ & SÁENZ, 2010). The training tasks refer to the entrance skills that users need to have developed before using the video game (SÁNCHEZ & MASCARÓ, 2011). Because of the training tasks, the user can be familiar with the gameplay (SÁNCHEZ et al., 2010). The cognitive tasks focus on developing the specific desired skills based on the software interface (SÁNCHEZ & MASCARÓ, 2011).

During the utilization of the video game, each targeted cognitive skill is worked on to strengthen the development of these skills in learners by using the video game. Once the cognitive tasks are completed, the posttest takes place, to determine whether there were any cognitive gains after using the video games (SÁNCHEZ & MASCARÓ, 2011; LUMBRERAS & SÁNCHEZ, 1999). In the posttest, each subject is also asked to model, in an adequate way, the learned skills. The representation can be either a graphic or physical model, a verbal description, a test or another suitable approach. Besides, the representation data can be gathered from, for example, logs and in-depth or structured interviews. All the generated data is analyzed and compared with the pretest and cognitive tasks data, determining possible gains and the cognitive impact of the application.

Cognitive impact evaluation is crucial to estimate the level of knowledge of learners who are blind before and after an intervention using a video game, helping researchers to determine whether they are actually helping to develop the learners' intellect (SÁNCHEZ, ESPINOZA, DE BORBA CAMPOS & MERABET, 2013). However, the literature has not been systematically approaching this topic yet. For that reason, the development of strategies or models to conduct cognitive impact evaluation with learners who are blind is an opportunity to help researchers and practitioners in analyzing the several dimensions of cognitive development for specific cognitive skills.

2.7 Final Considerations

The purpose of multimodal applications is to deal with the problems of the human-computer interaction, employing the adaptation of a computational device to the user's needs (ALBA, 2006). First, approaches that describe the multiple facets of the multimodal interaction are discussed in this chapter, considering how different modalities combinations and choices affect the users' behavior towards the application. The main cognitive problems faced by learners who are blind are also discussed and how multimodal video games enhance learning and cognition in this target audience, using audio- and haptic-based interfaces.

In addition, the key features of the interaction in multimodal gaming interfaces for learners who are blind were presented, according to a bibliographic review, discussing interaction inputs and outputs, feedback, audio, customization, and game cognitive aspects. It was considered how multimodal video games designed to enhance cognition of learners who are blind should combine the interaction and interface features, not only for entertainment but also for learning and enhancing cognitive processes.

Finally, concepts, instruments and methods for performing usability and cognitive impact evaluation were presented, as well as the challenges in the evaluation of multimodal games for learners who are blind. As discussed in this chapter, the literature highlights the relevance of evaluating the usability of multimodal applications by considering their modalities, as well as the user context, characteristics, and limitations. Employing usability evaluation methods regardless of the usage context and the users' limitations and goals is a contradiction with the definition of usability. Thus, research on usability evaluation involving learners who are blind playing multimodal games is necessary to help to produce usable and pleasant multimodal video games capable of impacting their lives by supporting the development of skills that will allow them to be more independent and better integrated into society.

3. RELATED WORK

This chapter synthesizes the literature work related to existing research on the design and evaluation of multimodal applications for people who are blind, gathered from the literature. Section 3.1 presents video games developed for improving and enhancing cognitive skills in people who are blind or helping them in the execution of everyday activities. Section 3.2 shows work that analyze the usability of specific types of multimodal interfaces and suggest improvements for the evaluation process with people who are blind, in addition to the studies that propose to adapt UEMs to fit better the context of individuals who are blind. Finally, Section 3.3 presents some considerations about the related work discussed in this chapter.

3.1 Video Games and Virtual Environments for the Development of Cognitive Skills in People who are Blind

For people who are blind, the absence of sight often hinders multiple daily life situations that require reasoning based on abstract cognitive concepts, because the absence or reduction of visual information creates a barrier to the development of cognitive skills requiring abstraction (CHESS & HASSIBI, 2013; LOOMIS, KLATZKY & GOLLEDGE, 2001). In this sense, various research initiatives have targeted to approach and reduce this problem with the main goal of supporting people who are blind during the process of learning skills.

In the remainder of this section, some of the recent efforts towards using serious video games based on audio and haptics to help people with visual disabilities to develop cognitive skills relevant to their everyday life are presented, such as problem-solving, orientation and mobility, collaboration, spatial structures and mental mapping. The deepest focus is on games aiming to develop orientation and mobility skills, as most of the video games proposed for enhancing and improving cognition of people who are blind are designed with this purpose.

Although the work presented in this section do not propose any solutions for usability evaluation per se, they develop and evaluate multimodal videogames for blind learners. This topic is deeply tied in the present research because it shows practical attempts to solve a problem similar to the one addressed in this work.

3.1.1 Problem Solving and Collaboration

Video games for people who are blind addressing problem solving involve navigating and interacting, while solving tasks, challenges, and issues, optionally associated with learning curricular competencies. In this category, AudioNature (SÁNCHEZ, FLORES & SÁENZ, 2008) is an audio-based virtual simulator for science learning implemented in a mobile device (pocketPC) platform. The game presents an ecosystem that has been somehow altered and challenges learners to return it to normality by interactive tasks and problem solving.

The AudioNature graphic interface was designed with high color contrasts and it comprises a maximum of five components at a time, distributed on the pocketPC's screen. Interaction occurs by means of the touchscreen and the available buttons, combined with audio feedback (FIGURE 16). The usability evaluation conducted with AudioNature showed that the interaction between users and the mobile device via sound feedback support was a good combination to aid in the learning of science for these users, and the ones with residual sight attributed higher scores in their game evaluation. The cognitive impact evaluation showed that children learned biology concepts and performed problem-solving tasks correctly.

Figure 16 – Learners who are blind and with visual residues playing AudioNature

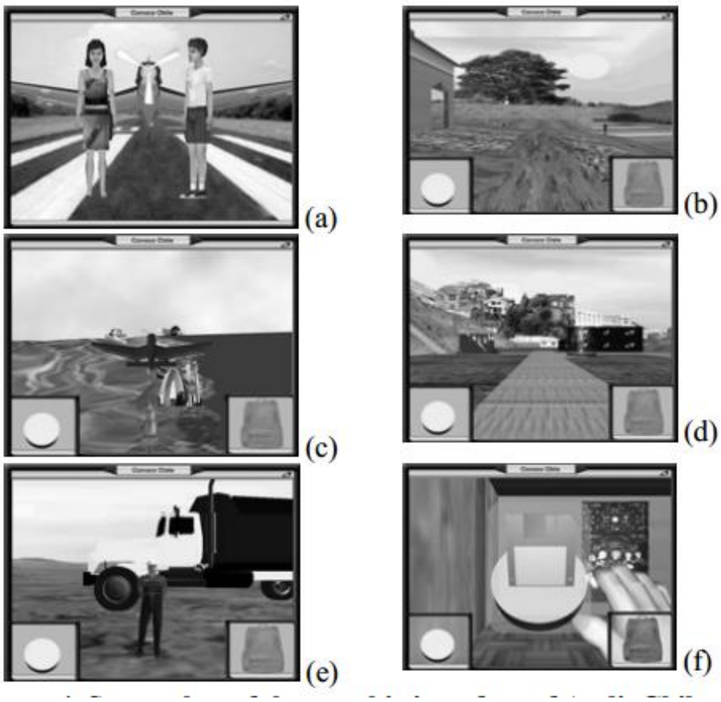
Source: Sanchéz, Flores, and Saéz (2008).

Problem-solving skills can also be developed simultaneously with collaboration skills, what is proposed in AudioGene (SÁNCHEZ & AGUAYO, 2008), a mobile virtual gaming world including certain genetics concepts: DNA, mutation, genotype, phenotype, and gene. The game story is based on a tree of life that has certain characteristics and is dying, so the player is challenged to replace the tree by another one with the same characteristics using a combination of seeds that will result in a similar tree. During the process of finding the seeds, the players have to evolve their characters' skills in a way that each player solves a specific mission of the game, but the mission is only solved when all players properly combine their skills.

Meanwhile, game-controlled characters also teach the users about contents concerning genetics in virtue of dialogs that are triggered as the user approaches them. AudioGene has a graphic and audio interface, which is composed of two types of sounds. The first one is used for spatial orientation and it consists in using sound clues. The second one is for learning contents about genetics using pre-recorded sentences. The evaluation showed that children were highly motivated by the game story and interaction and that AudioGene supported interaction and integration between sighted children and children who are blind.

AudioChile (SÁNCHEZ *et al.*, 2009) is a computer-based video game oriented towards developing not only problem-solving skills but also orientation and mobility skills in children who are blind. AudioChile (FIGURE 17) allows players to navigate virtual environments based on cities and other places in Chile, by using 3D sound to get a better spatiality and immersion. Relevant geographic information is provided by hidden cues that allow users to visit and know aspects of the geography and traditions of Chile.

Figure 17 – Screenshot of the graphic interface of AudioChile: (a) Character menu; (b) Chiloé; (c) Travel; (d) Valparaíso; (e) Chuquicamata, and (f) Option menu (save game)



Source: Sánchez *et al*. (2009).

To travel between zones, players must attain certain objectives that help them in futures tasks, in a navigable virtual world delimited by labyrinths that allow mobility and freedom to the character within certain parameters. The usability evaluation conducted indicated that the children correctly interacted with the game by using the keyboard, and rightly associated the game sound with the different information they conveyed. Due to the quality of graphics, children with visual loss showed greater motivation to play than children who are blind.

AINIDIU (*Agente Inteligente para Niños con Discapacidad Visual* – Intelligent Agent for Children with Visual Disability) acts as a computer assistant in training skills with children with visual disabilities and special needs (Guerrero & Lincon, 2012). AINIDIU provides challenges and gives children the opportunity to explore and discover, and it provides interaction for children who are blind with a voice synthesizer and a screen reader. The authors do not describe the game evaluation process.

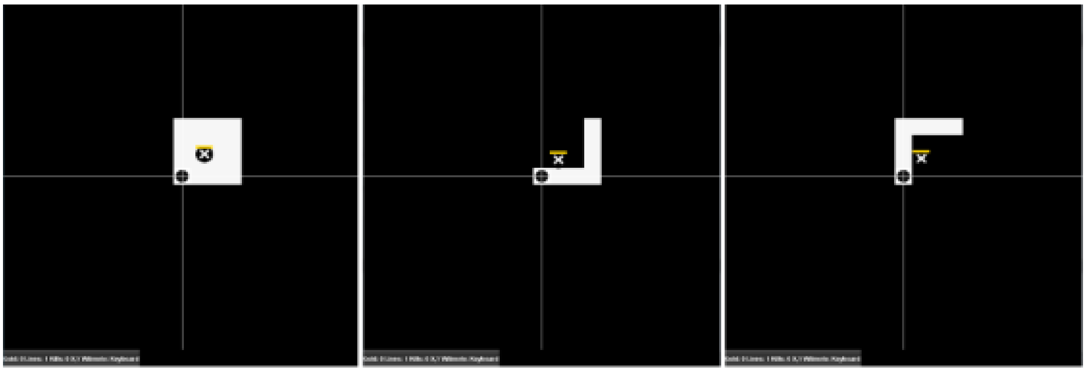
Moll and Pysander (2013) designed and evaluated two haptic and visual applications for learning geometrical concepts in group work in primary school. The aim was to support collaborative learning among sighted pupils and the ones who are visually impaired. The first application is a static flattened 3D environment that supports learning to distinguish between angles by means of a 3D haptic device providing touch feedback. The second application is a dynamic 3D environment that supports learning of spatial geometry. The scene is a room with a box containing geometrical objects, which pupils pick up and move them around.

The applications were evaluated in four schools with groups of two sighted pupils and one pupil who is visually impaired, and the results showed that the support for the children who are visually impaired and for collaboration was satisfying. According to the authors, verbal communication was crucial for the work process and haptic guiding substituted communication about direction to some extent. The study extended prior work in the areas of assistive technology and multimodal communication by evaluating functions for joint haptic manipulation in the setting of group work in primary school.

Espinosa, Sánchez, and Campos (2014) proposed a game based on the tower defense metaphor, which allows learners to interpret and associate points on a Cartesian plane. While solving the task of arriving at the ending point of the enemy’s trajectory first and installing their own tower to attack the enemy, the players gradually generate a mental map of their paths, directionalities, and the association of enemy’s coordinates to attack them. Players interact with the game by using a Wiimote control, which allows them to execute actions like moving on the game map, obtaining clues, and installing towers within the game. The game presents a high contrast graphic interface, as shown in Figure 18.

The game interface is based on audio, which provides all of the information related to carrying out actions and the status of the game, and also based on haptics, responsible for feedback associated with movements. In the usability evaluation carried out, players expressed a clear level of acceptance regarding how fun the game is, the game elements, the mechanisms for providing information, and the use of the controls, which was seen as easy to use and helpful to move around in the game. A cognitive impact evaluation demonstrated that the players had an increased total efficiency when performing the cognitive tasks, indicating that the video game allows users to construct gradually a mental map while solving problems in the game.

Figure 18 – Interface of the tower defense game, showing three possible ways of navigation



Source: Espinoza, Sánchez, and Campos (2014)

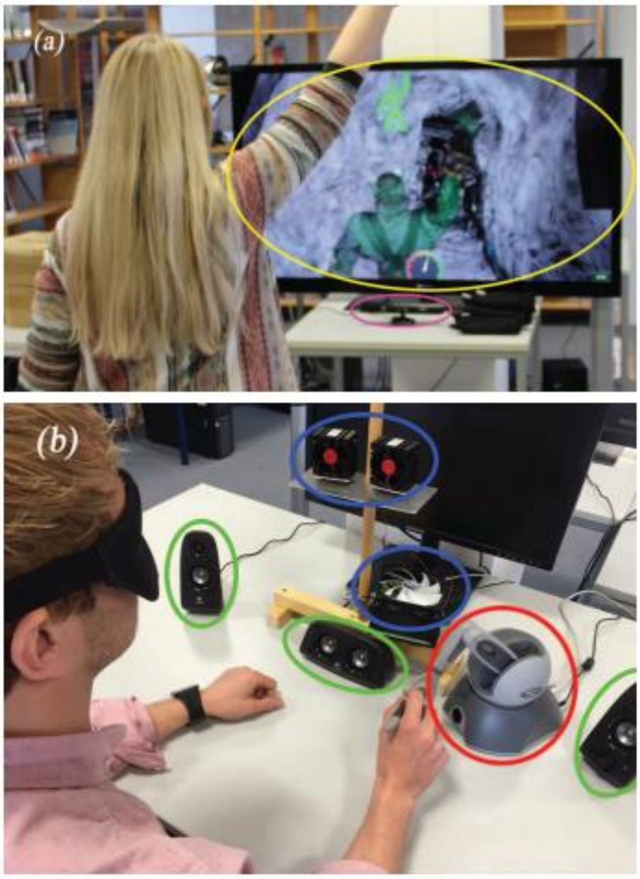
Grabski *et al*. (2016) presented an accessible game that allows a fair competition between sighted people and people who are blind in a shared virtual 3D environment. The game uses an asymmetric setup that allows touchless interaction via Kinect, for the sighted player, and haptic, wind, and surround audio feedback, for the player who is blind (FIGURE 19). They evaluated the game in an in-the-wild study.

The results showed that the proposed setup was capable to provide a mutually fun game experience while maintaining a fair winning chance for both players, increasing the real-world interaction between sighted and blind peers. The basic game idea is a virtual variation of the classic trap game. The sighted player tries to escape, while the player who is blind tries to catch them. The sighted player digs a tunnel to escape by using their whole body as a controller to move the ground. Their movements are tracked by a Kinect (see Figure 19a, pink ellipse) and they receive visual feedback on a large stereoscopic screen.

As crouching on the ground would reduce the tunnel size, the game design introduced another challenge: it periodically displays full body poses on the screen that have to be struck by the sighted player, otherwise their speed will be reduced. Meanwhile, the player who is blind controls an avatar in ego-perspective that flies inside the tunnel, which is created by the escaping opponent, and tries to catch them.

The blind player's avatar is controlled by a haptic device that gives feedback on collisions with the tunnel walls (see Figure 19b, red circle). Furthermore, a common 5.1 surround system (Figure 19b, green ellipses) provides audible feedback: the player hears the noises produced by the sighted player during their digging and they can trigger a sonar signal that indicates the middle of the tunnel. An in-house developed speed-controlled wind simulator (Figure 19b, blue ellipses) provides additional feedback on the acceleration to the player who is blind. Additionally, the player who is blind is equipped with the opportunity to increase their speed, by using a button on the haptic device that triggers a boost, which lasts for a few seconds. The game is over when the player who is blind touches the sighted player, or the sighted player escapes.

Figure 19 – Game setup for (a) the sighted and (b) the player who is blind



Source: Grabski *et al*. (2016)

An interesting result of their experiments is the usage of different orientation and navigation patterns, which all lead to a similar success in playing the game and in a similar rating of the game experience. However, their results showed that the most important sensory input for players who are blind to determine their orientation within the environment remains the sound. They showed that 3D sound in combination with abstract sound features, like sonar or voice-over, have a significantly positive effect on self-orientation. More sophisticated audio, e.g. using the image source method or ray tracing, can increase the positive effect on self-orientation. Thus, they point out that realistic audio feedback should have a higher priority in the game development processes.

3.1.2 Orientation and Mobility (O&M) and Mental Mapping

The approaches used in virtual environments and video games for developing O&M skills and mental mapping have been generally audio-based, taking advantage of the use of auditory cues to encourage people who are blind to perceive sounds. Consequently, they can interpret these sounds, converting them into guidelines for orientation in a space, enabling them to locate objects of interest, in the same way as a sighted person (CROSSAN & BREWSTER, 2006).

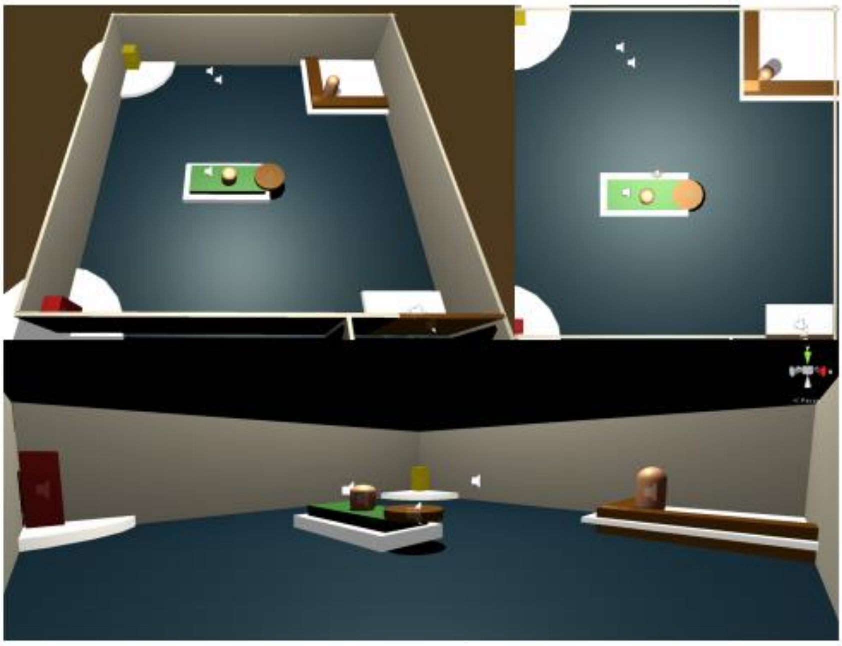
Diverse video games for cognitive development of people who are blind address Orientation and Mobility (O&M), comprising some of the biggest problems that people who are blind have when moving around: determining their position in the surroundings, conscious of which direction they are facing; and keeping track of information on important objects in the environment (HUB *et al*., 2004).

Usually, video games that support O&M skills in learners who are blind also support the construction of mental maps of the virtual space navigated using the integration of audio and haptic components. The creation of mental maps is a way of understanding the spatial representation that people with visual disabilities make of the physical surroundings they navigate (SANABRIA, 2007).

In this sense, Pincinali *et al*. (2014) used spatial auditory feedback to assist people who are blind as they virtually navigated an unknown environment, represented by a 3D architectural acoustic model from a real environment, using a pair of oriented headphones and a joystick. Balan *et al*. (2014) developed a navigational 3D audio-based game, where people who are blind can perform route-navigational tasks under different conditions, with the purpose of training and testing their orientation and mobility skills, relying exclusively on the perception of 3D audio cues.

Jäger & Hadjakos (2017) proposed “Fire in Neptune”, an audio-only first-person adventure game, in which players who are blind move freely in a virtual space using the mouse to control the viewing direction and keyboard to move (FIGURE 20). The game supports auditory navigation in a virtual acoustic environment without visual feedback, for the development of mental maps. A 3D environment was used for development only and it is not shown to the players.

Figure 20 – The layout of “Fire in Neptune”. The 3D environment was used for development only and it is not shown to the users of the audio game.



Source: Jäger & Hadjakos (2017)

Audio-based applications are also being developed for mobile devices with users who are blind as the target audience, such as a puzzle game in which the pieces with images originally used for puzzles are replaced with randomized musical patterns (CARVALHO *et al*., 2012).

Focusing on auditory feedback, Magnusson *et al*. (2011) proposed Blindfarm, a mobile game that uses both GPS and the compass sensor to help children with visual disabilities to learn paths that they must go through in their everyday lives. The players follow a path in the real world by listening to stereo vocalizations of virtual animals placed in specific locations in the virtual game environment. The virtual animals are previously placed in the game environment by adults who determine their location, according to the real-world path to be represented.

Simões & Cavaco (2014) proposed an immersive audio game aimed at implicitly teaching orientation skills to students with visual disabilities. The video game uses 3D spatialized audio to allow the training of audio localization skills and other localization concepts like front/back, left/right, close/far, in an entertaining environment.

Focusing on audio cues as the main stimulus to support O&M, AbES (SÁNCHEZ *et al*., 2009) supports the creation of video games that integrate virtual environments, focusing on the mental construction of real and fictitious environments by users who are blind navigating through virtual environments, using the keyboard of a computer to execute actions and receive audio feedback. AbES expands on the concept of the fictitious corridors used in its predecessor AudioDoom (LUMBRERAS & SÁNCHEZ, 1999), in order to generate an audio-based virtual representation of real environments, thus serving as a video game that allows for O&M training (SÁNCHEZ *et al*., 2009).

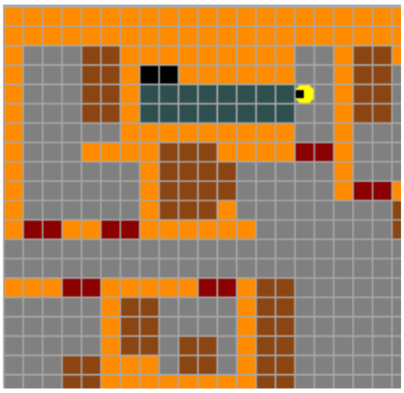
Connors *et al*. (2014) discuss a positive correlation between success in playing Audio-based Environment Simulator (AbES) (SÁNCHEZ *et al*., 2009a; SÁNCHEZ *et al*., 2010) and navigation task performance. AbES provides a virtual rendering of an existing physical building that can be explored using audio cues alone, focusing on the mental construction of both real-world and virtual environments, forming a virtual route in which a user can travel through the spaces by using the computer keyboard and audio feedback.

Specifically, the purpose of the AbES virtual environment is to allow for the "offline" survey of a given spatial layout prior to navigating in the corresponding physical environment represented. Using simple keystrokes, the player navigates through a target virtual environment acquiring contextually relevant spatial information in a manner that allows the individual to generate a mental representation of a building's layout.

AbES was developed under an action video game metaphor requiring the user to search for randomly hidden jewels, remove them from the building, and avoid monsters that are programmed to take away the jewels and hide them in new locations (FIGURE 21). Interacting with AbES in the context of a video game metaphor instead of using a structured path learning approach facilitates the learning and transfer of navigation skills when assessed in the target building represented in the game (MERABET *et al*., 2012).

In general, research using haptic interfaces for people with visual disabilities focus on building a cognitive map of haptically simulated environments (JAFARI, ADAMS & TAVAKOLI, 2016), to support the teaching and improvement of O&M skills, leading to the development of adequate cognitive maps (SÁNCHEZ, CAMPOS & ESPINOZA, 2014). In this sense, haptic interfaces have come to represent a significant contribution to the cognitive development of learners who are blind, providing the user with differing haptic sensations, and generating a higher degree of realism in the user's interaction with virtual environments (SÁNCHEZ, 2008). The use of force feedback joysticks has introduced a more realistic means of tactile sensory interaction that provides information including temperature, texture, and pressure, with real-time feedback.

Figure 21 - Partial screenshot of AbES labyrinth (left) and a child with visual loss playing AbES at Santa Lucia School for children who are blind (right)



Source: Snapshot and photograph taken by the author, in Santiago (Chile), December 2016.

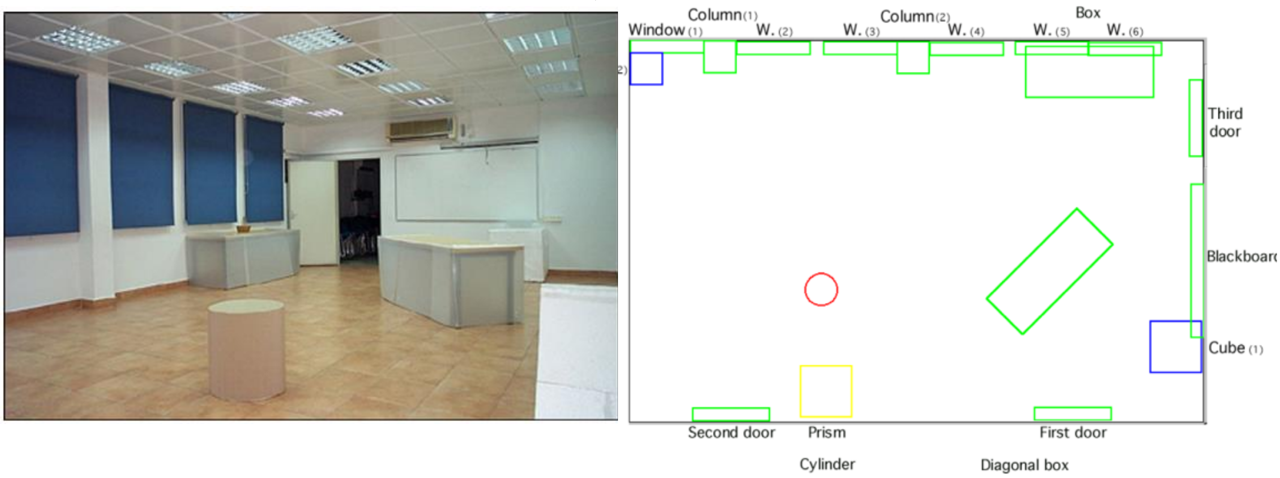
For example, with the use of Novint Falcon and Sensable Phantom, a learner who is blind can recognize surfaces, objects and graphics by just using the hands. This is possible because they are pointer devices that provide force feedback information in a way that users feel volume and force (LUTZ, 2006; WHITE, FITZPATRICK & MCALLISTER, 2008; SÁNCHEZ & ESPINOZA, 2011; SÁNCHEZ & MASCARÓ, 2011; YU & BREWSTER, 2002; TANAKA & PARKINSON, 2016; HANSEN *et al*., 2016). In this way, users receive haptic feedback, which allows them to recognize a diversity of objects, walls and hallways within virtual environments and video games (LAHAV & MIODUSER, 2004, 2008, 2008a; SÁNCHEZ & ESPINOZA, 2011; SÁNCHEZ & MASCARÓ, 2011; LAHAV *et al*., 2017).

Using this approach, BlindAid is a virtual system developed for O&M training of people with visual disabilities and allows interaction with different virtual components representing structures and objects, via auditory and haptic feedback, using Phantom (2010). BlindAind can be used as a training simulator for O&M, a diagnostic tool for O&M specialists to track and observe participants' spatial behavior, and a technique for advanced exploration of unknown spaces (LAHAV, SCHLOERB & SRINIVASAN 2009; LAHAV, SCHLOERB & SRINIVASAN, 2015).

In a previous work that provided the basis for the development of BlindAid, Lahav and Mioduser (2008) proposed and evaluated a Multi-sensory Virtual Environment (MVE), which supports the construction of efficient cognitive maps of unknown spaces. Since MVE models a real-world environment, first, a developer has to define the physical characteristics of the space to be navigated, by using an environment builder tool. The developer must also attribute haptic effects to all objects in the environment using the force feedback effects editor, as well as attach auditory feedback to the objects, by means of the audio feedback editor. After this, during the navigation in the MVE, the user faces forward and is allowed to move to the right, to the left, backward, or diagonally (always facing forward).

While "walking", the participants interact with the virtual spatial components, perceiving shape, dimensions, relative location of objects, and the structural configuration of the room. While the interaction takes place, users get haptic-feedback using a Force Feedback Joystick, in addition to audio feedback. After evaluating MVE with participants navigating either in only the MVE or in correspondence with the real space (FIGURE 22), the results showed evidence that working within the MVE provided a robust foundation for the participants' development of comprehensive cognitive maps of the unknown space.

Figure 22 - The real (simulated) environment and the representation of the virtual environment modeled in the evaluations of MVE

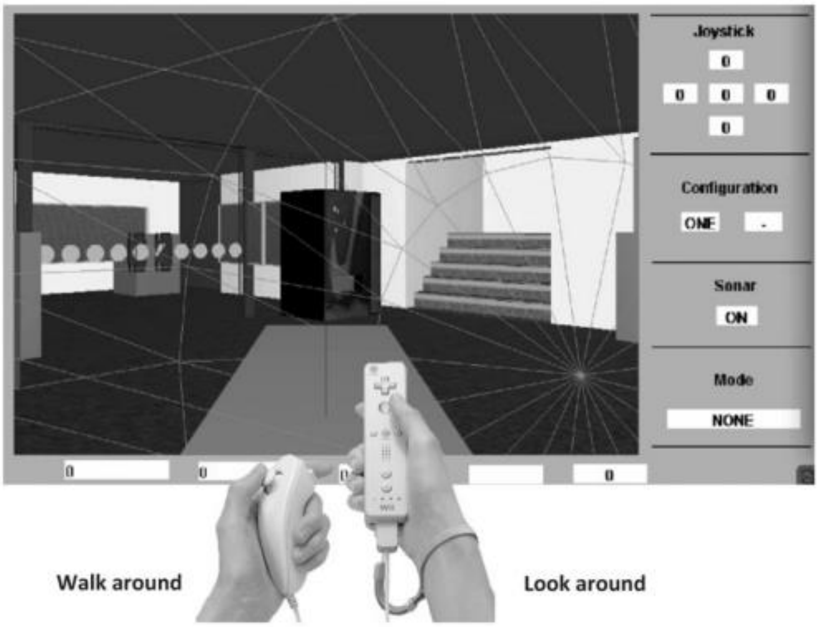


Source: Lahav and Mioduser's (2008).

A simple and low-cost way to detect the user's movement is to utilize the Wiimote controller of the Nintendo Wii console, and specifically there is evidence of a "finger-tracking" system by using the Wiimote (GLINERT & WYSE, 2007; WILLIAMS, 2010; CHEIRAN, NEDEL & PIMENTA, 2011; EVETT *et al.*, 2013). Research has also been done regarding the use of virtual environments that users who are blind explore by using Nintendo Wii devices, with audio and haptic feedback, facilitating and supporting the construction of cognitive maps and spatial strategies (EVETT *et al*., 2009; LAHAV *et al*., 2014).

Using a similar approach, Lahav and colleagues (2017) examined the ability of people who are blind to construct a mental map and perform orientation tasks in real space by using Nintendo Wii technologies to explore virtual environments (FIGURE 23). The participant explored new spaces by the agency of haptic and auditory feedback triggered by pointing or walking in the virtual environments and later constructed a mental map, which can be used to navigate in real space. The research methodology was implemented by using virtual environments exploration and orientation tasks in real spaces, with both qualitative and quantitative research methods.

Figure 23 - The virtual cane system using Wiimote and Nunchuk, and the graphic ser interface.



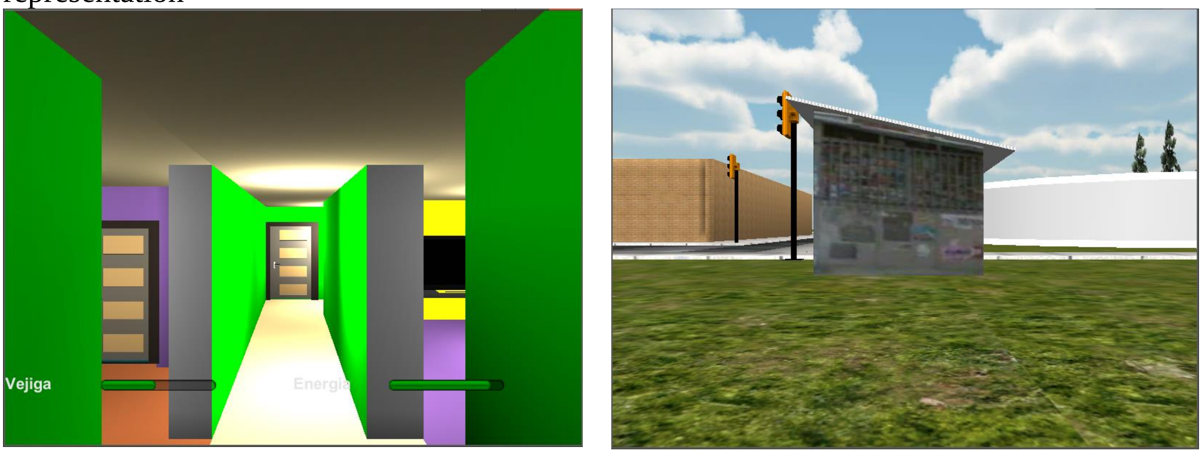
Source: Lahav *et al*. (2017).

During sessions, the participants were seated next to the computer to which the device was connected and held the Wiimote and the Nunchuck (forming a virtual cane system) in both of their hands to move it and get additional information about the objects' names and locations. They received this auditory feedback via stereo headphones. The results showed that the mode of exploration was radically new in orientation and mobility training; as a result, participants constructed mental maps that were based on the virtual environment map model. The authors discuss that the technology that enabled them to explore and collect spatial information in a way that does not exist in real space influenced the ability of the experimental group to construct a mental map based on the map model.

Combining the use of audio and haptics interfaces, AudioSIMS (SÁNCHEZ *et al*. 2015) is a social and strategy desktop video game for the simulation of an athlete's daily life, based on Electronic Arts' The Sims. The players personify a young man or woman who receives a special scholarship and lives in the Sports Campus C5IMS, a virtual space represented in 3D graphics (FIGURE 24). The athlete character then receives several tasks, and he/she must navigate an unknown place, so the players needs to orient themselves in the environment using the game compass and the environment's audio clues. The users interact with the game using an Xbox 360 joystick. The audio focuses on 3D sounds so that the players can associate the sounds emitted by objects to landmarks on the virtual environment.

AudioSIMS offers on-demand contextual information regarding location and objects, in addition to other built-in sounds representing touches, objects, and textures. The haptic component is presented with the Xbox 360 joystick, using vibration to represent collisions with objects in the game. According to the authors, the usability evaluation carried out indicates that players were amused with the game, but they declared they did not feel challenged. Besides, users who regularly use joysticks felt comfortable using the Xbox joystick in AudioSims.

Figure 24 – AudioSims graphic environment indoor (left) and outdoor (right) representation

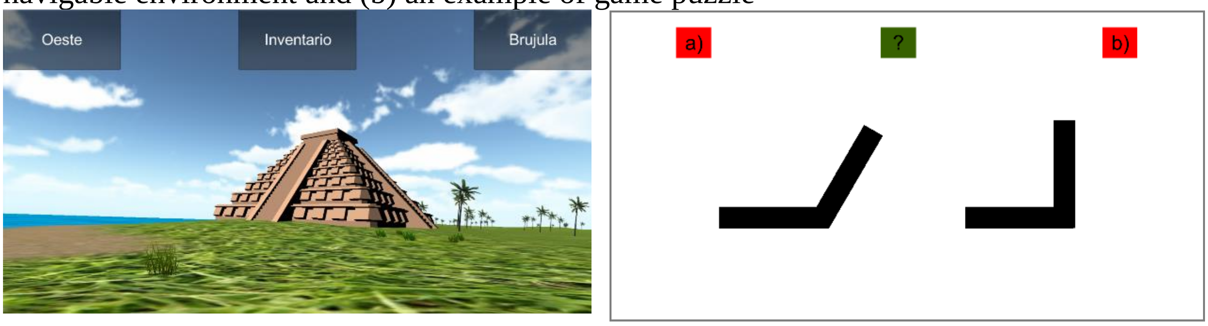


Source: Screenshots produced by the author.

Aiming to enhance cognitive skills related to mental mapping, spatial structure, and logical reasoning, AudioGeometry is a puzzle game for tablet, in which the player is the only survivor of a shipwreck, arriving at an unknown and dangerous Geometric Island from which he must exit. To achieve this, the player navigates the Island seeking to solve various geometric problems that aim to develop logical or mathematical thinking skills, in three levels of difficulty. The goal is that, starting with such tasks, players elaborate mental visualizations that stimulate the interpretation of mathematical concepts, and its later transference to daily life.

AudioGeometry presents a 3D graphic interface (for activities on the Island) and 2D graphic interface (for solving math problems), together with audio, visual and tactile feedback. The 3D graphic interface (FIGURE 25) consists of a view of the virtual island surroundings, where it is possible to distinguish the navigable zones of the Island, from a first-person perspective, i.e., having the player as a reference position. The puzzles interface (FIGURE 25b) uses high contrast colors and simple elements, focusing the player attention on the geometric problem, and clearly showing the option or action to be executed. This interface is especially aimed at players with low vision. Three different vibration frequencies were established to present figures and shapes on the screen, along with a particular vibration for specific gestures like moving or colliding during the exploration of the island. Besides the traditional tap and double tap, AudioGeometry provides a multi-touch interaction with the tablet, using specific on-screen gestures.

Figure 25 – AudioGeometry gaming graphic interfaces showing (a) the virtual navigable environment and (b) an example of game puzzle



Source: Snapshot taken by the author

3.2 Usability Evaluation of Applications Involving People who are Blind

The research literature has presented a diversity of sound proposals for evaluating serious games (MAYER *et al*., 2003; OLSEN, PROCCI & BOWERS, 2011; YÁÑEZ-GÓMEZ, CASCADO-CABALLERO & SEVILLANO, 2017) and multimodal interfaces (COUTAZ *et al*., 1995; DUMAS, SOLÓRZANO, & SIGNER, 2013). However, when carrying out a usability evaluation involving people who are blind, it is worth to consider that traditional Usability Evaluation Methods (UEM) are usually designed for users without disabilities (CHANDRASHEKAR, 2006).

The usability evaluation of these video games involving young learners who are blind can be further affected because they differ from adults with the same condition since they are still learning things and experiencing situations that are recognized and understood at a different level (RAISAMO *et al*., 2006). The conjunction of these facts indicates that evaluating usability in this context requires UEM adaptation to assure that usability evaluation instruments administered can disclose most of the issues that persistently affect game interaction of target users. This is necessary because their cognitive improvement according to the game design depends on the correct execution of the game cognitive tasks during learner's interaction with the multimodal interface

However, no research studies were found focusing on the adaptation and analysis of usability evaluation methods in the context of children who are blind playing multimodal serious video games for cognitive development. Identifying usability problems in serious multimodal video games designed for children who are blind matters because said issues make them focus on the problems, distracting them from learning cognitive skills when interacting with the video game. Hereafter, we discuss some related work that analyzes and compares diverse aspects related to the usability evaluation of several types of interfaces for people who are blind. They illustrate the need for reasoning about the administration of UEM to fit better the context and goals of people who are blind.

Fukuda *et al*. (2005) introduced two metrics related to information density for people who are blind in Web pages. Aiming to help Web authors or auditors in easily finding information usability problems, like inappropriate alternative text, the authors propose evaluating the Web usability measuring Navigability, i.e., how well structured the Web content is; and Listenability, which denotes how appropriate the alternative texts are. Both studies address the evaluation of the interaction between people with visual impairments and specific I/O modalities. However, gaming for cognitive improvement is out of their scope.

In an effort to improve usability evaluation that involves people who are blind, researchers have been proposing adaptation in the processes and UEM usually employed. Chandrashekar *et al*. (2006) observed usability testing sessions in which users employed the Talk Aloud Protocol (TAP) during the evaluation of websites using a screen reader, with four users who were blind and six users with visual disabilities. The sessions were recorded in audio. The results indicated that alternative training strategies are necessary for these users with total blindness to apply TAP successfully. In addition, users with this condition did not offer as many comments as the users with low vision, indicating that TAP may not be effective for a user with total blindness using a screen reader in websites.

Raisamo *et al*. (2006) discussed a procedure for testing usability with children with visual disabilities based on standard UEM refined with the knowledge and experience of the authors. The authors tested a multimodal system using haptic feedback devices, stereo sound, and visual feedback, using questionnaires, interviews, and observation methods in laboratory and field tests. They analyzed the data gathered from both types of tests, including children's videotaped interviews, video recordings and log files of the children's use of the program, and questionnaires.

As a result, the authors gave practical directions on how to consider the children's special testing requirements in different environments when conducting usability tests of multimodal applications for children with visual disabilities. The authors' advice for performing usability evaluations involving children who are blind include:

- To prioritize performing usability tests in a school where children attend for special education because it facilitates their participation in tests.
- To limit interviews to one or two specific themes so that the child will not get tired.
- To carefully avoid stating interviewers' own opinion of the issue in concern, and ask questions in a neutral way, since children often want to please their interviewer.
- To avoid laboratory testing despite its controlled and peaceful surroundings, because the traveling could exhaust a child who's expected to concentrate on a test and it also may be an inconvenience to the family
- To be careful not to "waste" actual test subjects in the pilot tests because the target population is too small.
- To provide verbal feedback during the test, covering the emotional aspects and attitudes of the supporting person.
- To make sure that child's posture is ergonomically valid, since usually computer equipment and furniture are made for adults, and children may not feel comfortable or get tired.

Leporini and Paternò (2008) argued that the evaluation of Web interfaces developed for users who are blind should consider the lack of page context, and information overload due to excessive sequential reading should be considered. Besides, the authors identified the main usability issues in Web interfaces for users who are blind, which are related to serialization of page content, lack of shortcuts and special commands for efficient navigation, and the difference between information conveyed via sound and visual cues.

Billi *et al*. (2010) proposed a unified methodology for evaluating usability and accessibility of mobile applications, pursuing universal access, i.e., it is not explicitly aimed at users who are blind but includes them. The methodology includes evaluation of criteria like ergonomics and minimalist design, ease of input/screen, and readability/glanceability. Accessibility and usability are evaluated using different approaches, depending on the type of assessment and the specific characteristics consequently involved.

Tomlinson (2016) conducted an exploratory pilot study using semi-structured interviews to explore perceptions related to accessibility and usability from the perspective of five adults with visual impairments, aiming to provide information for user-centered design practice. The authors focus their investigation on issues related to the use of screen readers to access Web content, resulting in factors like training and education, experience, and motivation for use.

Miao, Pham, Friebe and Weber (2016) investigated four usability methods involving people who are blind, partially sighted and sighted people, comprising local test, synchronous remote test, tactile paper prototyping and computer-based prototyping. The results showed that local tests were as efficient as synchronous remote tests, while tactile paper prototyping was comparable to computer-based prototyping, based on the number of usability problems uncovered by each approach in different categories.

The authors discussed the planning and conducting of these methods with people who are blind and gave recommendations for dealing with these problems from a technical and organizational point of view, which are summarized in Table 12. Although the recommendations are given for a specific test environment, they could easily be adapted for other types of usability evaluation involving people who are blind, especially regarding the organizational improvements.

Horton *et al*. (2017) analyzed 62 papers in a systematic literature review aiming to determine which hardware platforms are often used for assistive technologies for people who are blind in various domains and to investigate the nature of user studies conducted with assistive technologies for these individuals. The authors systematically examine the methodologies previously adopted to test the usability of assistive devices. As a result, they recommend characteristics for optimal assistive devices: being multimodal, adaptable, portable, and multitouch.

Likewise, they give general suggestions for structuring user studies, like testing devices with at least five users with visual impairments, employing user-centered design approaches, and including sighted blindfolded users as control groups. Although the authors give general suggestions and research insights on usability evaluation of tactile devices that are used in multimodal games, they do not cover the specific issues that children who are blind experience when interacting with a multimodal interface to improve cognition.

Table 12 – Recommendations for synchronous remote testing particularly with people who are blind and visually impaired

Technical improvements *Tool for remote testing*	**Organizational improvements** *Environment for remote testing*
It should be executable on each operating system with minimum configuration.	Extensive understanding of participants
Minimum effort should be required to install it	Minimizing security concerns and gaining trust.
It should be usable and accessible for people who are blind and visually impaired	Pilot tests with people who are blind or visually impaired but not with sighted people
The following functionalities should be available: - Internet speed test before transmitting the first data - Remote control. - Transmission and recording of the screen - Transmission and recording of Braille display, mouse, and keyboard signals.	Minimizing interference with privacy
All of the data should be transmitted in real time and saved for analysis afterward.	

Source: Miao Pham, Friebe and Weber (2016).

Seeking to understand better the non-functional software requirements that address the accessibility and usability challenges in computer gaming for users who are visually impaired, Chakraborty, Chakraborty, Dehlinger and Hritz (2017) performed an analytic review of interview transcripts and further demonstrated the utilization of qualitative analysis techniques within the information systems development and evaluation process. However, their outcome focuses on game design instead of evaluation. Additionally, they presented tangible advice for software engineers designing games for people with visual disabilities.

Aiming to offer a practical tool for assessing usability for users who are blind, Lee and Lee (2017) proposed a checklist to address the characteristics of the issues faced by users who are blind when using smartphone applications for learning. The checklist systematically integrates general principles for usability and accessibility and incorporates characteristics of touchscreen-based mobile devices, learning applications, and interaction patterns of the user who is blind.

Finally, Mori, Paternò and Santoro (2018) reported and initial investigation about usability problems that jeopardize the use of wearable vibrotactile feedback to support orientation for users who are blind in complex and unfamiliar buildings. To achieve that, they conducted experimental setups to test and analyze four wearable vibrotactile prototypes. They investigated the benefits and the usability problems of each solution. The main goal of their study is to reach a better understanding of the design aspects that make a vibrotactile solution usable. As a result, they give insights for developing cheap solutions that are easy to wear and maintain.

What many of the related work have in common is the proposal of practical tools and recommendations for usability evaluation of applications for people who are blind. These tools are usually easy to follow and understand, and they consider some of the specific characteristics of people who are blind during design and evaluation. They also discuss that further practical guidance and systematic reasoning is necessary towards helping researchers and practitioners to employ UEM properly when evaluating specific types of applications for people with visual disabilities.

3.3 Final Considerations

Identifying and fixing the relevant issues related to the usability of multimodal games designed for learners who are blind plays a crucial role in the acquiring of cognitive skills for these users. Nowadays, however, there is not a consistent guidance on how to choose UEMs and conduct usability evaluation in these circumstances.

In this chapter, first, a number of video games developed for improving and enhancing cognitive skills in people who are blind were described. They report usability evaluation including very different aspects of interaction even in similar games, which demonstrates that the selection of methods usually relies on individual experience and expertise. Among the usability issues these works evaluate are feedback for partially sighed and blind, interaction with game input device, game mechanisms to provide information, understanding of game sounds, motivation to play, and satisfaction with the game.

After this, the present chapter showed research work that analyzes the usability of specific kinds of interfaces for people who are blind and suggest improvements for the evaluation process to fit the need of the target audience was presented. The scenario portrayed by the related work shows that the approaches are not focused on multimodal games for learners who are blind. Consequently, they can miss usability issues that affect the game interaction and the fostering of target cognitive skills in these users. For that reason, in the next sections the results of this thesis research are presented, supporting usability for learners who are blind play multimodal games for cognitive enhancement.

4. IDENTIFICATION OF DIMENSIONS OF THE DESIGN AND EVALUATION OF GAMES FOR LEARNERS WHO ARE BLIND

This chapter describes the results obtained from the systematic literature review (Step 1) that addressed *RQ1(What are the main interface and interaction characteristics of multimodal video games for cognitive development of children who are blind?).* Section 4.1 describes the methodology followed to conduct the Systematic Literature Review. Section 4.2 presents the obtained results regarding approaches and technologies employed during the design and development of multimodal games for learners who are blind. Section 4.3 proposes a 4-dimension classification, assembled from the literature review results, that describes the interface and interaction characteristics of multimodal video games for the cognition of people who are blind as well as the usual types of evaluation conducted, and the cognitive skills addressed by those games. Finally, Section 4.4presents some final considerations.

4.1 Methodology

As the first step of the research methodology applied in this work, a bibliographic review was performed, based on the steps proposed in by the Systematic Literature Review (SLR) approach (KITCHENHAM & CHARTERS, 2007; PETERSEN *et al*., 2008). Later, the SLR findings were deepened using an Expert Opinion Survey that is further described in Chapter 5.

The SLR consists in a secondary study method that reviews existing primary studies in-depth and describes their results (PETERSEN et al., 2008). In this research approach, a set of search strings correspondent to the research questions is submitted to suitable sources. Then, the obtained papers are filtered according to a set of exclusion and inclusion criteria. The resulting papers are analyzed in order to answer the initial research questions. There are three main phases of a systematic review: planning, conducting and reporting the review (KITCHENHAM & CHARTERS, 2007). To support the realization of the three stages of the study, the tools StArt (FABBRI et al., 2012) and Mendeley (SINGH, 2010) are employed. Each of the three phases followed are detailed in the next subsections.

As Figure 26 illustrates, the systematic literature review conducted in this work was based on a research protocol and resulted in four main outcomes:

(i) A set of multimodal video games for cognitive development of learners who are blind;

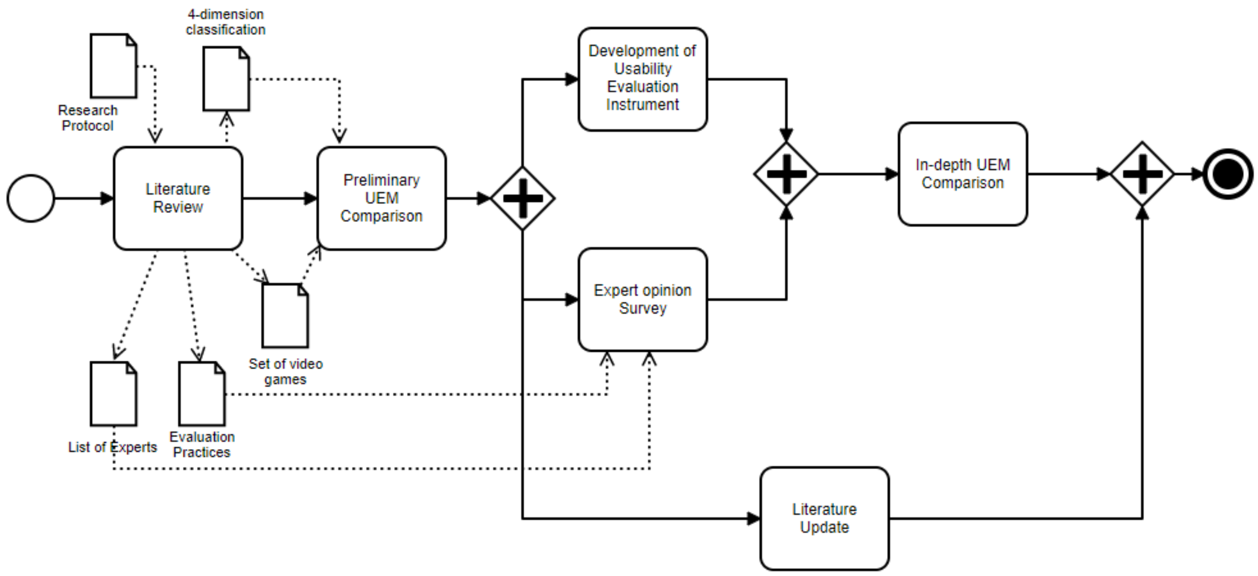
(ii) A 4-dimension classification based on identified characteristics related to interaction, interface cognition and evaluation of those games;

(iii) A list of researchers publishing in this field;

(iv) The main types of evaluation practices they employ.

Results (i) and (ii) were later used as input for the Preliminary UEM Comparison step, while results (iii) and (iv) served as input for the Expert Opinion Survey.

Figure 26 – Incomes and outcomes of the first step of the research methodology: Literature Review.



Source: produced by the author.

Throughout the conduction of the present research, the results obtained in the Literature Review were periodically revised to keep them up to date. The 4-dimension classification items and organization were first updated after the Expert Opinion Survey phase, and once again after the In-depth UEM Comparison phase.

The set of video games and the evaluation practices were continuously updated once a month, starting when the Expert Opinion Survey phase was going on until May 2018 (Literature Update phase). It included new references related to the adaptation of UEMs for learners who are blind, as well as new multimodal video games for the development of cognitive skills in these users. The most representative examples of games identified are presented as part of related work, in Sections 3.1 and 3.2 of this document. Regarding the evaluation practices, no new practices were identified besides those that had already been found.

4.1.1 Planning phase

According to Kitchenham (2007), the SLR planning phase most important activities are defining the research questions(s) that the systematic review will address and producing a review protocol to specify the basic review procedures. The review protocol is to be subject to an independent evaluation process.

Following these guidelines, the first step took during the planning phase in this research was the definition of a SLR protocol to guide the research objectives and clearly define the SLR research questions and sub questions, the query sources, and the selection methods. After the protocol definition, two independent researchers and two experts performed incremental reviews to the protocol.

The main research question defined coincides with the first research question of this work: *What are the main interface and interaction characteristics of multimodal video games for cognitive development of children who are blind?* The question focus relates to the identification of strategies and technologies in use for developing mental models, cognitive spatial structures, and navigation skills in learners who are blind when playing video games. The focus also relates to the verification of which are the approaches commonly used for usability evaluation and quality measurement in this context.

Once this topic is delimitated, the SLR goal is to discover how the literature is dealing with design, evaluation and technologies for these video games. To answer the main research question, the following sub questions were defined:

- Q1: What strategies have been used for the design of multimodal games for learners who are blind to enhance cognition?
- Q2: What strategies have been used to evaluate usability and quality of multimodal games for learners who are blind?
- Q3: What technologies have been used for the development of multimodal games for learners who are blind, to enhance cognition?

After the question definition, the following criteria to select the search sources were delimitated in the research protocol: (i) availability to consult and download published articles from conference publications, magazines or journals; (ii) presence of search mechanisms using keywords; (iii) relevance in the target research area; (iv) availability of papers in either English, Portuguese or Spanish.

According to these criteria, eight digital libraries were selected as sources: ACM Digital Library, Engineering Village, IEEE Xplore, Scopus, Science Direct, Springer Link, PubMed, and Web of Science.

The research protocol also defined a search string to translate the SLR research questions into an adequate format to submit to the digital sources. To create the search string, a set of keywords and synonyms was defined and refined after several pilot searches returning too many results with low relevance. The search string was refined by reviewing the data needed to answer each of the research questions, as well as the relevance of the results returned at each test of the string in the bases. This process was repeated with different combinations of keywords in each source base, until a suitable set of keywords and operators was found. Figure 27 presents the final search string submitted to the eight sources, addressing the research questions Q1, Q2 and Q3.

Figure 27 – Search string submitted to the eight selected sources.

```
(
      ((Evaluation AND (usability OR quality)) OR Design OR
      Development)
       AND
      (Serious AND (Videogame OR Game))
)
AND
(
           ("blind learners" OR (("eyes-free" OR "visually
           impaired" OR blind) AND ("education" OR "learning")))
      AND
           (Multimodal OR haptic OR audio OR auditory OR
           vibrotactile OR device OR "I/O" OR gadget OR
           technology)
      AND
           ("cognition" OR "Cognitive spatial structures" OR
           "Navigation Skills" OR "Mental map" OR "Walking
           Simulation")
)
```

Source: produced by the author.

After the definition of a search string, the SLR protocol also defined a set of selection criteria (TABLE 13) in order to filter suitable studies, according to the goals of the research. The set of selection criteria consists of four inclusion criteria (IC-1 to IC-4) and eleven exclusion criteria. The large set of exclusion criteria is due to the variety of knowledge fields that this research covers. Thereby, to restrict the scope of the study to a set of papers able to answer the research questions, seven exclusion criteria specific to the research field were applied (EC-S1 to EC-S7), in addition to the four general-purpose exclusion criteria (EC-G1 to EC-G4).

Table 13. Set of criteria used for the selection of papers

#ID	INCLUSION CRITERIA
IC-1	Studies presenting initiatives to evaluate multimodal videogame (including virtual environment) for learners who are blind;
IC-2	Studies presenting initiatives to develop multimodal videogame (including virtual environment) for learners who are blind;
IC-3	Presents results related to the impact of multimodal technology for enhancing cognition
IC-4	Studies presenting technologies to support multimodal videogames (including virtual environment)

#ID	EXCLUSION CRITERIA
EC-G1	Short paper publication (less than 4 pages);
EC-G2	Paper under review or not a paper, but course notes or other supplementary materials;
EC-G3	Paper published before 1995;
EC-G4	Secondary studies or surveys;
EC-S1	Studies describing videogames for any public other than learners who are blind;
EC-S2	Studies presenting initiatives to develop or to evaluate other multimodal software besides videogames or virtual navigational environments;
EC-S3	Studies describing no results related to cognitive impact for learners who are blind;
EC-S4	Studies describing evaluation or design of non-multimodal software;
EC-S5	Study validating specific assumption related to brain function, learning, navigation or gaming;
EC-S6	Studies related to cognition but not related to multimodal games for people who are blind;
EC-S7	Studies introducing or evaluating specific technologies for accessibility in general.

Source: produced by the author.

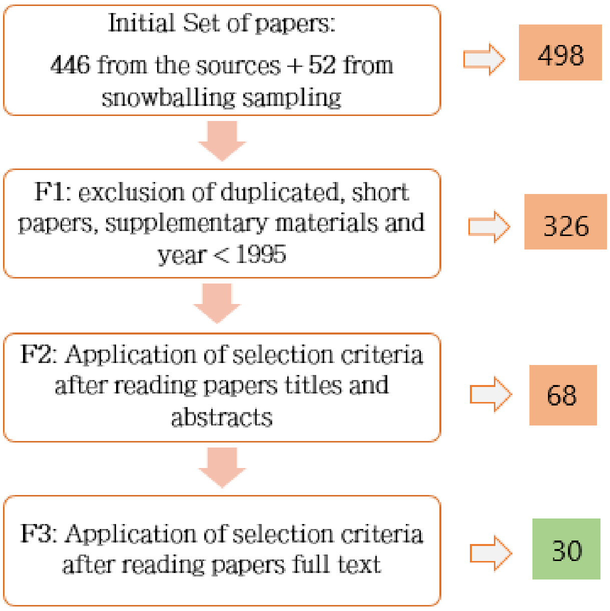
4.1.2 Conduction phase

In SLR, once the protocol has been agreed, the conduction phase takes place. It includes the selection of primary studies following the predefined selection criteria, the study quality assessment – which, in this work, used an adaptation of the Quality Checklists for Quantitative and Qualitative Studies proposed by Kitchenham (2007) –, data extraction, and data synthesis.

In this research, the selection of primary studies used the selection criteria listed in Table 13 and followed the process summarized in Figure 28. First, the search string depicted in Figure 27 was submitted to the eight selected query sources, addressing the research questions Q1, Q2, and Q3. This process resulted in an initial sample of 446 papers.

Then, the snowballing sampling (LEWIS-BECK, BRYMAN & LIAO, 2004) – a technique to use the reference list of a paper (backward snowballing) or the citations to the paper (forward snowballing) to identify additional papers – was applied. In this work, a backward snowballing to the secondary studies or surveys recovered is used. After the first iteration conducting backward snowballing, each paper is examined according to the inclusion criteria before deciding to use it in the analysis. This process resulted in a set of 52 papers added to the original sample. Thus, the total of papers obtained was 498.

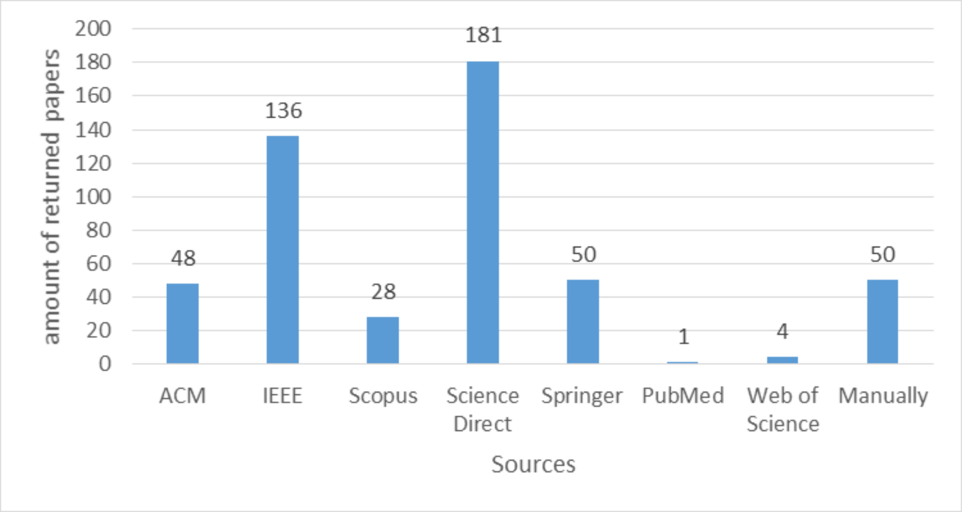
Figure 28 – Filtering process



Source: produced by the author.

From the initial 498 papers, there were 48 papers from ACM (9.6%), 136 from IEEE (27.3%), 28 from Scopus (5.6%), 181 from ScienceDirect (36.3%), 50 from Springer (10%), 4 papers from Web of Science (0.8%), 1 paper from Pubmed (0.2%) and 52 added manually (10.5%), as summarized in Figure 29. It is important to note that, although ScienceDirect had the higher number of papers, there were not many outcomes related to the target area. It happened because this source returned a vast number of articles related to cognition and/or people who are blind but from the medical point of view, which is out of the scope for this work.

Figure 29 – Amount of papers returned by sources



Source: produced by the author.

To choose the most suitable studies to answer the research questions, the papers were filtered according to the inclusion and exclusion criteria (FIGURE 28). The inclusion criteria helped in the selection of studies describing multimodal serious video games, some specific entertainment video games and virtual navigational environments, whose goal was to enhance cognition. They also helped selecting studies describing no application but introducing a model for the design or the evaluation of multimodal games or environments for people who are blind.

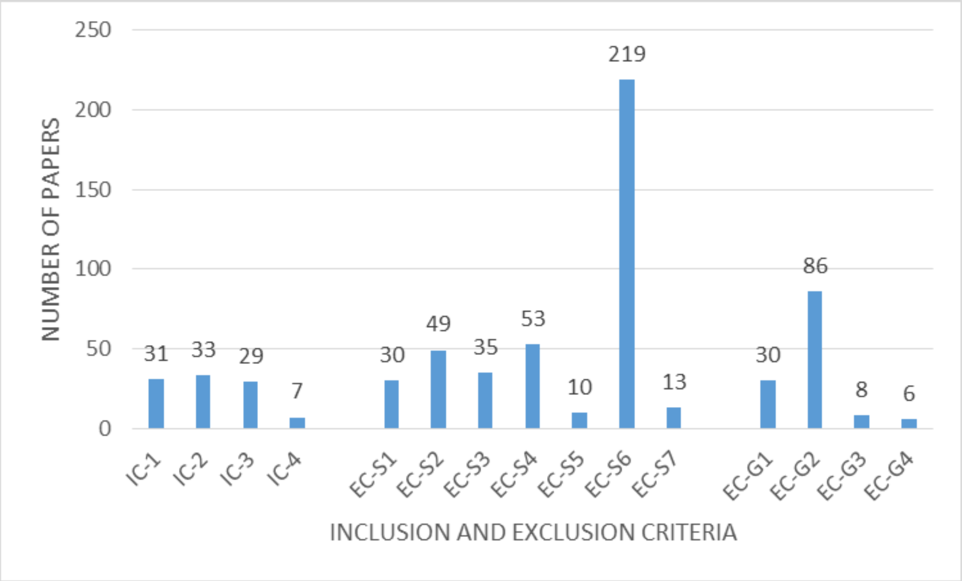
The exclusion criteria mainly helped eliminating papers proposing multimodal interactive interfaces to audiences other than learners who are blind. Besides, it also excluded those papers proposing games or applications for people who are blind unrelated to the development of mental models, navigational and similar cognitive skills. Figure 30 summarizes the amount of papers included and excluded by each selection criteria.

The filtering process for the selection of studies used three filters. The first filter (F1) consists of removing the duplicated and short papers (i.e., less than four pages) and secondary studies or those published before 1995. F1 excluded 172 papers (34.5%) so that 326 studies went to the second filter.

The second filter (F2) consists of the application of the specific exclusion criteria and the inclusion criteria, after reading the papers' title and abstract. F2 excluded 216 papers (43.4%) and included 68 papers (13.7%). These papers went to the third filter (F3), intending to refine the initially accepted set of studies.

F3 consisted of the examination of the full text of the 68 articles and the review of the assigned inclusion and exclusion criteria. In this phase, 19 papers were added manually, using a forward snowballing sampling. F3 eliminated 34 articles by exclusion criteria and four duplicated papers (7.6%) and included 30 papers (6%). Most of the papers eliminated were related to cognitive enhancement, but not to multimodal games for people who are blind.

Figure 30 - Classification of papers using selection criteria. Each paper is included or excluded based on one or more criteria.



Source: produced by the author.

The relevant papers obtained are from 1999 to 2014, being 80% of the papers from 2008 on. Among these, 25 papers described 21 distinct applications: 17 multimodal games and four multimodal navigation virtual environments. Some papers discussed the same applications, but from another point of view. The selected papers are listed in Table 14.

A data extraction form composed by 22 factors (e.g. application type, multimodal controls, interface characterization, types of evaluation conducted, steps of evaluation process, quality characteristics evaluated etc.) was designed to record accurately the information obtained from the primary studies selected. To reduce the opportunity for bias, the data extraction form was defined and piloted when the study protocol was defined. A test-retest process, where the researcher performs a second extraction from a random selection of primary studies, was used to check data extraction consistency.

Finally, after data was extracted, the data synthesis involved collating and summarizing the results of the included primary studies. The synthesis was mainly descriptive (non-quantitative). However, it was complemented with a quantitative summary.

Table 14. List of games and virtual environments in selected papers

GAME / ENVIRONMENT	PAPER
e-adventure	Torrente, J., Blanco, A., Moreno-Ger, P., Martinez-Ortiz, I., Fernandez-Manjon, B.: Implementing Accessibility in Educational Videogames with e-Adventure. In Proceedings of the 1st ACM International Workshop on Multimedia Technologies for Distance Learning. Pages 57-66. Beijing, China (2009)
AINIDIU	Guerrero, J., Lincon, J.: AINIDIU, CANDI, HELPMI: ICTs of a personal experience. Engineering Applications (WEA), 2012 Workshop on. Pages 1-7. Bogotá, Colômbia (2012)
e-Adventure / Case Study: "My First Day at Work"	Torrente, J., Blanco, Á. d., Serrano-Laguna, Á., Vallejo-Pinto, J. Á., Moreno-Ger, P., Fernán-dez-Manjón, B.: Towards a Low Cost Adaptation of Educational Games for People with Disa-bilities. Computer Science and Information Systems, Vol. 11, No. 1, 369–391 (2014)
MOVA3D	Sánchez, J., Saenz, M., Garrido, J.M. (2010). Usability of a multimodal video game to improve navigation skills for blind children. ACM Transactions on Accessible Computing. Proceedings of the 11th international ACM SIGACCESS conference on Computers end Accessibility. Pages 35-42.
AudioGene	Sánchez, J., Aguayo, F.: AudioGene: Mobile learning genetics through audio by blind learners. Learning to live in the knowledge society. IFIP 20th World Computer Congress, IFIP TC 3 ED-L2L Conference September, 2008. Pages 79-86. Milano, Italy (2008)
Audio Haptic Maze (AHM)	Sánchez, J.: Development of navigation skills through audio haptic videogaming in learners who are blind. In Proc. Software Development for Enhancing Accessibility and Fighting Info-exclusion (DSAI), pp. 102-110, Jul 2012. Douro, Portugal (2012)
Audio Space Invaders	Mccrindle, R. J., Symons, D.: Audio Space Invaders. In Proceedings of the Third International Conference on Disability, Virtual Reality and Associated Technologies. Pages 59-65 (2000)
AudioDoom	Lumbreras, M., Sánchez, J.: Interactive 3D Sound Hyperstories for Blind Children. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pages 318-325, May 1999. Pittsburgh, USA (1999)
multi-sensory VE modeling real spaces (no specific name)	Lahav, O. and Mioduser, D.: Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. International Journal on Human-Computer Studies, 66, pp. 23–35 (2008a)
AUXie	Dulyan, A., Edmonds, E.: AUXie: initial evaluation of a blind-accessible virtual museum tour. In Proceedings of the 22nd Australasian Computer-Human Interaction Conference. Pages 272-275. Brisbane, Australia (2010)
Tower Defense Game metaphor (no specific name)	Espinoza, M., Sánchez, J., Campos, M. B.: Videogaming Interaction for Mental Model Con-struction in Learners Who Are Blind. In Proceedings of 8th International Conference, UAHCI 2014, Held as Part of HCI International 2014, pages 525-536. Crete, Greece (2014)
Audiopolis	Sánchez, J., Mascaró, J.: Audiopolis, Navigation through a Virtual City Using Audio and Haptic Interfaces for People Who Are Blind. In Constantine Stephanidis (ed.), Proc. 15th Human-Computer Interaction International (HCII), pp. 362-371, Jul 2011. Orlando, Florida, USA. Springer-Verlag, Berlin/Heidelberg, Germany. Lecture Notes in Computer Science (2011)
Audio-based Environment Simulator(AbES)	Sánchez, J., Sáenz, M., Pascual-Leone, A., Merabet, L. B.. Enhancing Navigation Skills through Audio Gaming. In Proc. ACM Conference on Human Factors in Computing Systems (CHI), pp. 3991-3996, Apr 2010. Atlanta, GA, USA. (2010)
The Natomy's Journey Game	Sánchez, J., Sáenz, M.: Video Gaming for Blind Learners School Integration in Science Classes. In Tom Gros, Jan Gulliksen, Paula Kotzé, Lars Oestreicher, Philippe Palanque, Raquel Oliveira Prates, Marco Winckler (ed.), Proc. 12th IFIP TC13 Conference on Human-Computer Interac-tion (Interact), pp. 36-49, Aug 2009. Uppsala, Sweden. Springer-Verlag, Berlin/Heidelberg, Germany. Lecture Notes in Computer Science vol. 5726 (Part I) (2009)
AudioNature	Sánchez, J., Flores, H.: Virtual Mobile Science Learning for Blind People. Cyberpsychology & behavior: the impact of the Internet, multimedia and virtual reality on behavior and society, vol. 11, number 3 (2008)
AudioChile	Sánchez, J., Sáenz, M.: 3D sound interactive environments for blind children problem solving skills. Behaviour & IT. Vol. 25, issue 4, pages 367-378. From the 7h International ACM SIGACCESS Conference on Computers and Accessibility. Baltimore, USA (2006)
a multi-sensory virtual environment - MVE (no specific name)	Lahav, O. and Mioduser, D.: Construction of cognitive maps of unknown spaces using a multysensory virtual environment for people who are blind. Computers in Human Behavior 24(3), pp. 1139-1155 (2008)
AudioMetro	Sánchez, J., Sáenz, M.: Metro Navigation for the Blind. Computers and Education (CAE) 55(3):970-981, Jul 2010. Elsevier Science, Amsterdam, The Netherlands (2010)
AudioVida	Sánchez, J., Sáenz, M. (2006). Three-Dimensional Virtual Environments for Blind Children. CyberPsychology & Behavior. Vol. 9, issue 2, page 200.
Terraformers	Westin, T.: Game accessibility case study: Terraformers – a real-time 3D graphic game. In: Proceedings of the 5th International Conference on Disability, Virtual Reality and Associated Technologies, ICDVRAT 2004, Oxford, UK, pp. 95–100 (2004)
PowerUp	Trewin, S., Hanson, V. L., Laff, M. R., Cavender, A.: PowerUp: An Accessible Virtual World. In Proceedings of the 10th international ACM SIGACCESS conference on Computers and acces-sibility, pages 177-184. Halifax, Canada (2008)

Source: produced by the author.

4.2 Discussion of SLR Main Results

In this section, the main results obtained from data synthesis are described regarding models and processes for designing multimodal video games for cognitive development of children who are blind. In addition, the common practices and software technologies employed during the development of these games are discussed.

4.2.1 Models for Designing Multimodal Games for Learners who are Blind

The selected papers showed that there is not a widespread process for the design of this particular type of application. Most of the papers use some traditional software engineering process. However, given the specificities of this type of implementation and the limitations of the audience, several factors must be taken into consideration, such as the context of use and expected skills to be developed. The typical development cycles do not cover these aspects. Thus, most authors adapt a development process, according to the goals of the game under development.

Nevertheless, four papers (SÁNCHEZ et al., 2007; SÁNCHEZ & ESPINOZA, 2013; SÁNCHEZ et al., 2014; SÁNCHEZ et al., 2010) introduce models for the design and development of games for enhancing cognition of blind people. Each one addressing a particular context of use, audience and/or desired cognitive skill, which are discussed in the following.

Sánchez et al. (2010) introduce a model for the development of video game-based applications designed to assist the navigation of people who are blind. Sánchez et al. (2014) propose a model for video game development, which serves as a framework for designing games to help learners who are blind to construct mental maps. These maps are for the development of geometric-mathematical abilities and orientation and mobility (O&M) skills. The second process modifies the first one, improving and extending it in terms of the cognitive abilities implied by O&M and geometric thinking.

The study of Sánchez & Espinoza (2013) introduces a novel technique using concept maps for the design of serious video games, in Ejemovil Editor. The goal is that teachers would be able to define the storyline of the video game, incorporating the concepts that they want to teach in a structured way. The proposed process guides the teacher in transforming a conceptual map into a video game model.

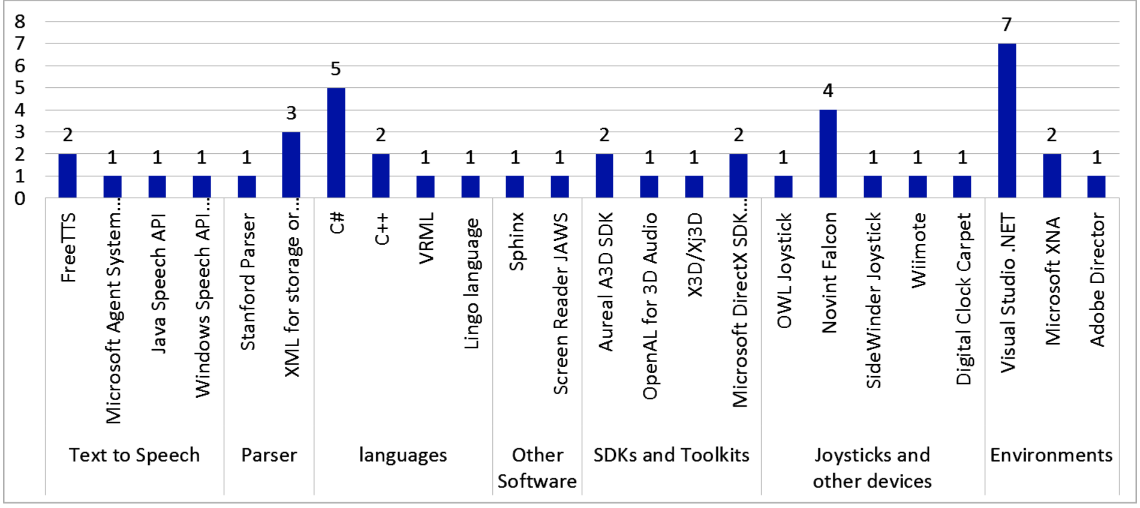
Finally, Sánchez (2007) presents a complete model for developing virtual learning environments for learners with visual disabilities. The model is cyclic and includes various steps and recommendations by discussing critical issues for conceptualization and implementation. The result is the input to generate a suitable user-adapted aural output.

4.2.2 Development of Multimodal Games and Environments for People who are Blind

Regarding the types of software and hardware technology used to develop these games, from the 25 papers that presented applications, four (16%) did not describe any of the technologies used in the development process. Among the articles that described the software or hardware technologies used during the development process, different levels of details were available. There were papers describing the programming environment, libraries and modules applied while other papers described only the hardware used for the interaction with the game. Figure 31 summarizes the software and hardware tools reportedly employed in the development of the video games and virtual environments analyzed.

The software and hardware tools and technologies reported were grouped into Development Environments, Software Development Kits (SDKs) and Toolkits, Programming Languages, and Parsers. Besides, there is another specific software utilized, joysticks and devices, and technologies related to Text to Speech. There were cases when the papers claimed that a game provided a specific functionality but did not describe the technology used to develop it.

Figure. 31 – Software and hardware tools and technologies reported in the development of multimodal games or environments



Source: produced by the author.

Concerning development environments, Visual Studio.NET was the most used one (seven applications); it is an Integrated Development Environment (IDE) developed for the .NET software framework. Another utilized environment was Microsoft XNA Framework + Game Studio (two applications). Microsoft XNA is a set of tools with a managed runtime environment that aims to facilitate video game development and management. XNA is also based on the .NET Framework. Both environments being based on the .NET framework explain the extensive use of the languages C# and C++, the use of XML for storage and the need for parsers, such as DOM and Stanford Parser. These results point that the .NET framework and its related technologies seem to offer better support for developing multimodal video games and environments. One application used Macromedia Director (currently Adobe Director); that is a multimedia application authoring platform, initially designed for conceiving animation sequences.

The papers showed a considerable variety of Software Development Kits (SDKs) and Toolkits related to spatialized audio. Two applications applied the Microsoft DirectX SDK library. It is a set of application programming interfaces (APIs) for the handle of tasks related to multimedia, principally game programming and video, on Microsoft platforms. These applications also used the Microsoft's DirectSound that provides diverse capabilities – for instance, adding effects to sound (e.g., reverb, echo, or flange) and positioning sounds in 3D space. Two applications used the Aural A3D SDK. It is similar to an improved DirectSound, featuring hardware accelerated 3D positional audio, providing three-dimensional sound quality to an ordinary pair of speakers. OpenAL for 3D Audio appears in one application and allows a developer to produce high-quality audio output, specifically the multichannel output of 3D arrangements of sound sources around a listener. In addition, one application utilized Xj3D, a Java toolkit to develop X3D applications. It displays the 3D modeling standard formats VRML97 and X3D.

The most-used programming languages identified are C# (five applications) and C++ (two applications), due to the significant use of the .NET framework. The one application that used Adobe Director also used Lingo, an object-oriented programming language, embedded into this environment. Besides, one application used the Virtual Reality Modeling Language (VRML). It is a file format for describing interactive 3D objects and worlds. Although this language is a standard (ISO/IEC 14772-1:1997), it is more common to develop these applications using the commercial frameworks support.

The functionality implemented using the wider range of technologies is speech synthesis. Two applications used FreeTTS, a speech synthesis system written in Java. Java

Speech API, Microsoft Agent System Module's text-to-speech function, and the Windows Speech API are present in one application each. Whether to use a Java-based or a Microsoft API depends on the development environment adopted.

The applications use various devices to allow the function of haptic feedback. Novint Falcon, a USB haptic device, is the most popular one (of four applications). It seems to exist an attempt to reduce the cost of a specialized haptic device. Joysticks and low-cost devices present in four video games: OWL joystick, Wiimote, SideWinder joystick and Digital Clock Carpet. The last device is based on a usual cane and a simple carpet, and it is specific to one application, but it could be reutilized. Among the 21 applications, there are only three (14.3%) designed for the mobile paradigm. It seems to be a quite unexplored area, since only few among these applications take advantage of the benefits that mobiles offer (GPS, sonar, and the sound compass, for instance).

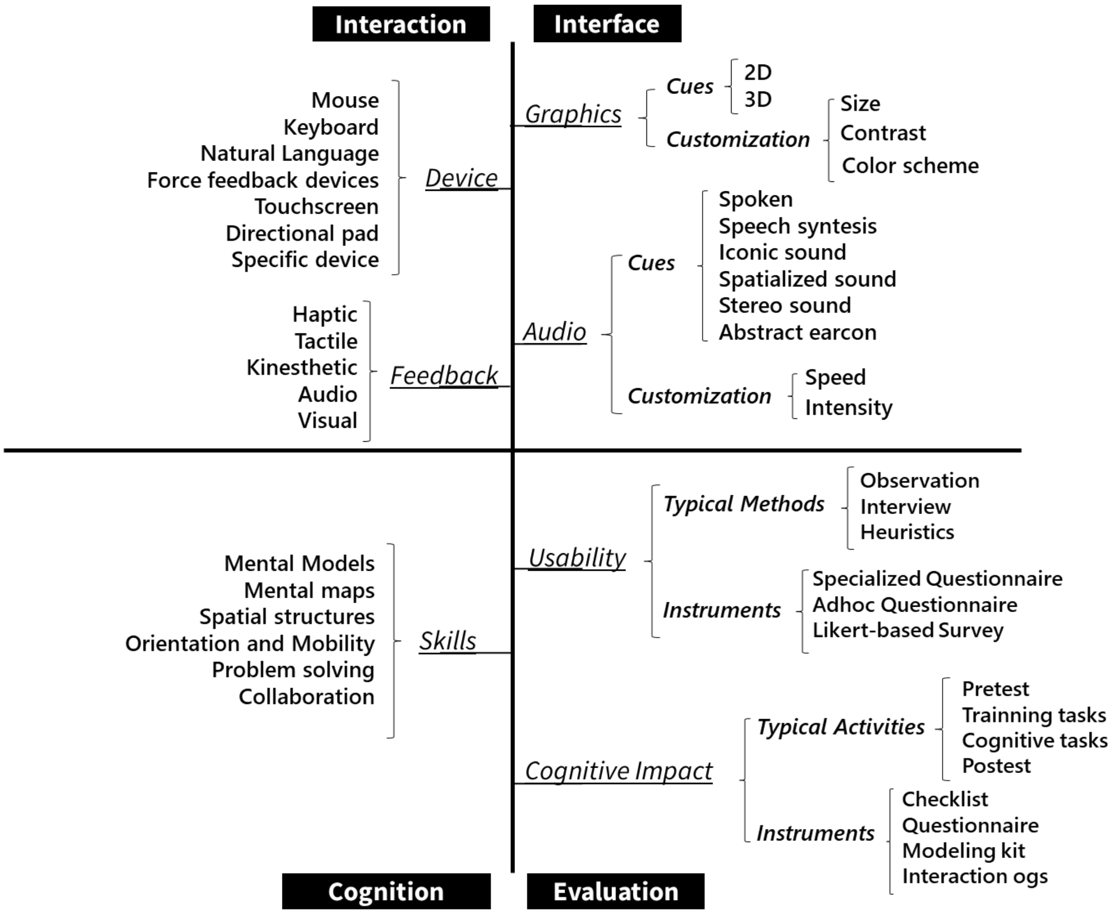
4.3 Dimensions of the Design and Evaluation of Multimodal Video Games for the Cognition of People Who Are Blind

During the Literature Review, trends were identified about the interface and interaction aspects of these games, together with the cognitive skills addressed and the types of evaluation usually conducted. From this information, a scheme was organized to describe the characteristics of multimodal video games and environments in four dimensions related to *interaction*, *interface*, *cognition*, and *evaluation*.

The *interface* and *interaction* dimensions are related to the game and environments design, the *cognition* dimension relates to the cognitive skills on which the game activities are focused, and the *evaluation* dimension comprises the commonly used methods, activities and instruments to conduct usability and cognitive impact evaluation in these games. It is important to highlight that, although there might be other relevant aspects, the features initially described in the 4-dimension scheme are those found on the analyzed papers.

The *audio customization*, however, was not initially identified in those papers. The *audio* feature was updated after the identification of these aspects during the second research step of this work methodology (preliminary UEM comparison), which is further discussed in Chapter 5. Figure 32 gives an overview of the identified aspects that comprise each dimension.

Figure 32 – Dimensions for the description of the key characteristics of the design and evaluation of multimodal video games for cognitive development of people who are blind



Source: Darin, Sánchez & Andrade (2015).

The *interface* dimension consists of two types of features: graphics and audio, and their respective types of cues and customization. The main features related to the *interaction* dimension are feedback and device. Furthermore, one can distinguish the games and environments by the type of skill they aim to improve in learners who are blind, which is addressed in the *cognition* dimension, which lists six types of cognitive skills that the game activities commonly aim to improve.

The dimensions that describe *interaction, interface,* and *cognition* aspects are mainly connected to the design of multimodal video games and environments for cognitive improvement of learners who are blind. Finally, the *evaluation* dimension comprises information about the types of evaluation usually conducted in the analyzed studies. Although only part of the applications carried out a proper evaluation, this process usually focuses on the interaction and interface features that are meaningful to the cognitive enhancement proposed. The evaluation concentrates on the aspects of usability and cognitive impact verification.

Even though no stablished model for usability evaluation of multimodal games and no formal standardization about the elements to evaluate were found, it was possible to identify the most used tools and methods. As so, the aspects described on *evaluation* dimension are usability and cognitive impact, both being according to the typical activities conducted and instruments applied.

The characterization of interaction and interface of multimodal video games for cognitive development of children who are blind, as well as the cognitive aspects and evaluation instruments usually employed to evaluate these games, were previously discussed in Chapter 2 of the present work. Hereafter, these aspects are further considered to demonstrate their relation to the proposed dimensions, and with the analyzed set of papers from the SLR.

4.3.1 Interaction Dimension

According to the information available in the analyzed studies describing video games and environments for learners who are blind, there are seven types of devices, which the user can interact, providing input to game. The chosen input device determines the style of interaction available in the application. It also influences the type of feedback that the application provides to an interaction. The *interaction device* aspect comprehends mouse, keyboard, natural language, force feedback devices, touchscreen (with or without a stylus), directional pad, and specific devices, designed for particular games. The *interaction feedback* aspect describes a form of modality response that is given immediately after the user action in the game or environment. It comprises five types of feedback: haptic, kinesthetic, tactile, aural or visual. Some applications combine two or more interaction devices and feedback types.

As summarized in Table 15, the analysis of the papers showed that the most common interaction pattern is the keyboard, used by 15 applications (71%) especially in those whose feedback is mainly aural. The second most used interaction form is the joystick, present in seven applications (33%). The joystick interaction always has an alternative interaction device, usually the keyboard. The interaction with joystick occurs in interfaces with 3D environments that commonly use some haptic feedback.

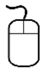
Two applications (9%) allows the use of mouse together with the keyboard and one claims the mouse as the primary interaction device. However, this application’s target audience is not totally formed of users who are blind. Although the natural language might be expected to be an easier and instinctive way to interact, only two games allow the user to give natural language commands. The reasons are not clear in the papers, but it can be due to it is not a trivial task to recognize and process the natural language accurately. Besides, users with visual disabilities who have any experience with technologies are used to utilizing the keyboard in other applications, what facilitates the interaction.

The keyboard requires no specific learning and allows direct interaction since it is a familiar input device, common to multiple systems and technologies. The interaction via keyboard is associated with an aural or visual feedback. The keyboard is a low-cost, accessible and straightforward device, but it provides no sense of touch or volume during the interaction. Nevertheless, it is a desirable feature in a navigation context to provide nonvisual stimuli that helps to perceive the environment physical characteristics.

Force feedback devices allow the haptic feedback (tactile and kinesthetic). These devices measure the positions and contact forces of the user’s hand, displaying contact forces and positions to the user, even without visual clues. In this way, it has been possible to establish two categories of perceptions used by people who are blind (BALLESTEROS, 1993): (i) Tactile Perception, which is information perceived exclusively by the skin, and (ii) Kinesthetic Perception, which is information provided by muscles and tendons. The combination of both concepts, in order to benefit a person who is blind regarding the acquisition of information, is called haptic perception (BALLESTEROS, 1993; OAKLEY *et al*., 2000).

The video games and environments using force feedback devices allow manual interactions with the multimedia environment using touch. It allows the user to explore the environment to extract information, by means of the tactile feedback and manipulation for modifying the environment, via the kinesthetic feedback (HAMAM, EID & SADDIK, 2013). They employ various devices to allow the function of haptic feedback. Gamepads and joysticks are the second most used interaction form, present in 33% of the studied applications.

Table 15 – Classification of the studied applications according to the *interaction* dimensions.

		INTERACTION									
		DEVICE							FEEDBACK		
									HAPTIC	AURAL	VISUAL
MULTIMODAL VIDEO GAME OR ENVIRONMENT	e-adventure (Torrente *et al*. 2009)	x		x						x	x
	AINIDIU (Guerrero & Lincon, 2012)		x	x						x	
	e-Adventure / Case Study: "My First Day at Work" (Torrente *et al*. 2014)		x							x	x
	MOVA3D (Sánchez, Sáenz & Garrido, 2010)		x					x	x	x	
	AudioGene (Sánchez & Aguayo, 2008)					x	x			x	
	Audio Haptic Maze (AHM) (Sánchez, 2012)		x		x				x	x	
	Audio Space Invaders (Mccrindle & Symons, 2000)		x		x				x	x	
	AudioDoom (Lumbreras & Sánchez, 1999)	x	x		x				x	x	
	Multi-Sensory Virtual Environment (Lahav & Mioduser, 2008a)				x				x	x	
	AUXie (Dulyan & Edmonds, 2010)		x							x	
	Tower Defense Game (Espinoza, Sánchez & Campos, 2014)				x				x	x	
	Audiopolis (Sánchez & Mascaró, 2011)		x		x				x	x	
	Audio-based Environment Simulator(AbES) (Sánchez *et al*., 2010)		x							x	
	The Natomy's Journey Game (Sánchez & Saénz, 2009)		x							x	
	AudioNature (Sánchez & Flores, 2008)					x				x	
	AudioChile (Sánchez & Sáenz, 2006)		x		x				x	x	
	Multi-sensory virtual environment (Lahav & Mioduser, 2008b)				x				x	x	
	AudioMetro (Sánchez & Sáenz, 2010)		x							x	
	AudioVida (Sánchez & Sáenz, 2006)		x							x	
	Terraformers (Westin, 2004)		x							x	
	PowerUp (Trewin *et al*., 2008)	x	x							x	

Source: produced by the author.

The applications that use gamepads focus on the tactile feedback, providing sensations of vibration, pressure, touch, and texture. The tactile feedback allows the user to perceive contact force, the geometry of an object and temperature (HAMAM, EID & SADDIK, 2013). The applications that utilize joystick provide kinesthetic sensation, dealing with forces resulting from position and velocity of the hand motion and simulating the force and torque (HAMAM, EID & SADDIK, 2013). Those applications that employ specialized joysticks (e.g., 3D touch controllers) usually combine tactile and kinesthetic, providing haptic feedback. The force feedback device always has an alternative interaction style, usually using the keyboard. It assures the availability of the game, even without the force feedback.

The use of mouse and touchscreen with stylus configures a style of interaction that uses a directional pointer to select items on a display screen. Due to the visual limitation of the audience, these are the less frequent interaction devices identified, targeting partially sighted users. The use of mouse relates to a sonorous-only feedback while the stylus also provides tactile feedback. The natural language is still an underutilized feature (found in two applications). The feedback to this type of interaction is aural. Unlike the mouse, a wide use of the natural language in this type of application was expected, as an easier and instinctive way to interact. However, the accurate and efficient recognition and processing of the human language is still a challenge in computer science.

A single application uses the directional pad, a four-way directional control with one button on each point, found on most video game console gamepads. In this context, the directional pad interaction occurs in a mobile application, and its feedback is aural. Another option is the development of specific devices to allow for the interaction of the users who are blind with the multimodal video game.

For instance, the Digital Clock Carpet (SÁNCHEZ, SÁENZ & GARRIDO, 2010) is a device based on a usual cane and a simple digital carpet that inform the user about directions to a destination point, based on the hour system. In this particular case, the feedback is both aural and haptic, but adapting a device to interaction and feedback specific to the context of a multimodal video game brings a bunch of new possibilities.

4.3.2 Interface Dimension

The interface aspects identified in the analyzed studies that influence most the design of the multimodal video games and environments are *graphics* and *audio*, each one comprising different types of cues and customization options (FIGURE 32).

As shown in Table 16, all the applications use at least one aural interface element, although most of the cases combine two or more aural elements. The prevailing combination is between iconic and spatialized sound, in 3D environments. Iconic sounds are the most common type of aural feedback, occurring in 16 applications (76%) followed by spatialized sounds, present in 11 (52%) applications. The spoken audio is more prevalent than the speech synthesis, what may cause more empathy to the interface. The first one occurs in 11 applications (52%) while the second appears in seven (33%). Twenty applications (95%) present a graphic interface in addition to the aural elements. The interfaces can be 2D or 3D graphics combined with images or text.

Contrary to what one could imagine, the results do not point to sound-only interfaces. Three of the applications (14%) allow users to navigate only by sound (no graphics mode) and use a graphic interface only for configuration. It happens because these interfaces aim to include not only users who are blind but also users who are visually impaired and sighted users, especially the teachers. However, only one interface assures that shows no relevant information in colors (for people who are color-blind).

Although some papers omitted this information, it is an essential issue to attempt, to ensure that this public will be able to use the interface correctly. Other essential features that demand more consideration are the customization of the elements size and the use of a high contrast mode. Only 9% of the applications allow the resize of interface elements and 23% of the applications offer a high contrast mode. Both of these functionalities should be typical in these applications since they are crucial to people with partial blindness.

In the analyzed papers, games and environments that support graphic customization were found, but none provided the possibility of audio customization, which can be done by the user or a tutor. A game can enable players to customize or make changes to the experience to meet their specific needs by configuring items around the interface to reflect the users' priorities and needs (SCHADE, 2016). Regarding customization, the game and environments interfaces can support the adjustment of the size, color or contrast of the graphical elements. The features include the resize of the elements, the possibility of choosing a high contrast mode and the presentation of relevant information in colorblind safe colors.

The resizing relates mainly to text elements, which can be resized with no loss of content or functionality. The high contrast is to provide enough contrast between the content and its background so that people with low vision can read it. The use of colorblind safe colors is to assure the interface presents the visual elements in color combinations that are perceivable by people with any colorblindness.

Table 16 – Classification of the studied applications according to the *interface* and *interface* dimensions.

		INTERFACE										
		AUDIO						GRAPHICS		CUSTOMIZATION		
		SPOKEN	SPEECH SYNT	ICONIC	SPATIALIZED	STEREO	ABSTRACT	2D	3D	SIZE	COLOR	CONTRAST
MULTIMODAL VIDEO GAME OR ENVIRONMENT	e-adventure (Torrente *et al*. 2009)	x	x					x				
	AINIDIU (Guerrero & Lincon, 2012)	x	x					x		x	x	
	e-Adventure / Case Study: "My First Day at Work" (Torrente *et al*. 2014)		x					x				
	MOVA3D (Sánchez, Sáenz & Garrido, 2010)			x	x				x			x
	AudioGene (Sánchez & Aguayo, 2008)	x		x	x			x				
	Audio Haptic Maze (AHM) (Sánchez, 2012)	x		x	x	x			x	*No graphics*		
	Audio Space Invaders (Mccrindle & Symons, 2000)	x		x	x			x				
	AudioDoom (Lumbreras & Sánchez, 1999)				x			x				
	Multi-Sensory Virtual Environment (Lahav & Mioduser, 2008a)			x					x			
	AUXie (Dulyan & Edmonds, 2010)	x	x				x		x			
	Tower Defense Game (Espinoza, Sánchez & Campos, 2014)	x		x	x	x		x				x
	Audiopolis (Sánchez & Mascaró, 2011)			x	x				x			x
	Audio-based Environment Simulator(AbES) (Sánchez *et al*., 2010)		x	x	x			x				
	The Natomy's Journey Game (Sánchez & Saénz, 2009)			x	x	x		x				
	AudioNature (Sánchez & Flores, 2008)	X	x	x				x				x
	AudioChile (Sánchez & Sáenz, 2006)			x	x	x			x			
	Multi-sensory virtual environment (Lahav & Mioduser, 2008b)	X		x				x				
	AudioMetro (Sánchez & Sáenz, 2010)	X		x		x		x		*No graphics*		
	AudioVida (Sánchez & Sáenz, 2006)			x					x			
	Terraformers (Westin, 2004)	X		x	x				x	*No graphics*		x
	PowerUp (Trewin *et al*., 2008)		x	x					x	x		

Source: produced by the author

The GUI is a vastly utilized feature in this type of applications, allowing the user to interact with graphical elements using direct manipulation. No video game with a sound-only interface was identified. However, 14% of the applications studied do allow the users to choose to navigate exclusively through sound, by using a graphic interface for configuration only. The reason all the applications studied have a graphic interface, despite the visual impairment of the main audience, is to increase the interaction options for users with visual loss. The interface's graphics can be either 2D or 3D combined with icons, images, and text.

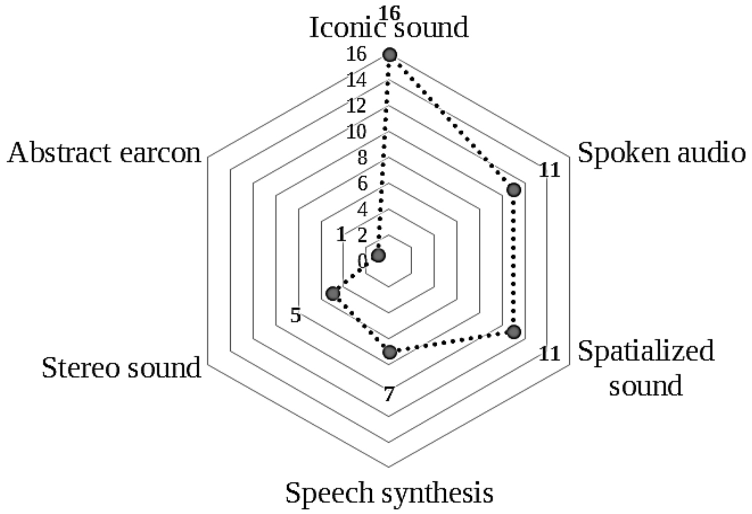
The association of the aforementioned elements helps to fill some gaps on the interaction. For instance, children with visual loss have difficulties recognizing certain 2D icons and not always associate them with the designed actions, so the use of 3D icons helps to increase the fidelity of the representation (SÁNCHEZ & SÁENZ, 2006). Besides, when the game disposes of a graphical interface, a facilitator can support the interaction with the video game, observing the learner's navigation and the cognitive aspects (SÁNCHEZ, CAMPOS & ESPINOZA, 2014).

Although the graphics are substantial features to the interfaces of the studied multimodal video games, the essential interface feature is the Audio. All the analyzed applications use at least one aural interface element, although most of the cases combine two or more aural elements. The prevailing combination is between iconic and spatialized sound, in 3D environments. Figure 33 illustrates the use of each audio feature in the considered applications.

Iconic sounds are specific sounds associated with each available object and action in the environment. Every time the user executes a certain action or interacts with a particular object, the corresponding representative sound is heard – for example, distinct steps sounds for different varieties of floors. It is the most common audio feature, occurring in 16 applications (76%). Spatialized or 3D sounds are stereo sounds that are digitally processed to appear to come from particular locations in the three-dimensional space, aiming to simulate the acoustic experienced by a listener within a specific environment.

A 3D sound navigable environment serves as an aural representation of the space and surrounding entities, helping the players who are blind to assemble a mental image of an environment. It was the second most used audio feature, present in 11 (52%) applications. Spoken audio refers to the use of sentences pre-recorded in a human voice, usually describing the game status or relevant information about the actions and objects. The spoken audio occurs in 11 applications (52%) while the speech synthesis, which is the artificial creation of the human voice, appears in seven (33%). Five applications combine these two approaches.

Figure 33 – Distribution of the audio features found in the 21 studied applications.



Source: produced by the author.

Stereo sound consists in the mixing of two channels of sound recorded in two separate sources, with the distinction of left and right channels. Stereo sound is present in five applications (23%) and it provides information regarding the nature and location of objects, using intuitive associations (e.g., the sound of flowing water representing a fountain). Abstract earcons appear in only one application, using music/tones to represent different objects. It refers to the use of sounds unrelated to the elements they represent. The use of abstract earcons requires the user to learn with what they are associated. However, it is possible to represent a much wider range of concepts than by using iconic sounds (DULYAN & EDMONDS, 2010).

4.3.3 Cognitive Dimension

The studied multimodal video games and virtual environments meticulously combine the *interaction* and *interface* dimensions' features, not only for entertainment but also for learning and stimulating cognitive processes (SÁNCHEZ, SAENZ & GARRIDO, 2010; DULYAN & EDMONDS, 2010; ESPINOZA, SÁNCHEZ & CAMPOS, 2014). The *cognitive* dimension deals with which cognitive skills an application aims to improve. Some of the applications help the development of more than one skill. Besides, some skills are secondarily stimulated while playing.

Table 17 summarizes which are the main skills the studied applications aim to improve. Six types of skills that compose the *cognitive* dimension were identified: mental models, mental maps, spatial structures, orientation and mobility (O&M), problem solving and social collaboration.

Some of the multimodal games for players who are blind did not specify how they improve cognitive skills. Most of the applications work O&M skills (44%). It is a set of techniques, which helps visually impaired children and adults to develop and master the concepts and competencies necessary to be able to move safely and efficiently within their world. While navigating the video game environment, people who are blind can perceive the audio and haptic elements and use them as references for orientation and mobility (SÁNCHEZ, 2012).

The improvement of mental modeling involves the user adopting and restructuring a mental model of spatial dimensions, based on audio and haptic cues after interacting with a video game (SÁNCHEZ, 2012). The adequate orchestration between audio and haptics also helps the user who is blind to build up a model of a fantasy world and of how a game works (MCCRINDLE & SYMONS, 2000; WESTIN, 2004). Specific mental models are stimulated by 27% of the studied applications.

Mental maps are mental representations of the space being navigated and its defining features, e.g., overall structure, spatial components, landmarks, dimensions, and relative positions (LAHAV & MIODUSER, 2008). Having a mental map of space is fundamental to the efficient development of orientation and mobility techniques processes (SÁNCHEZ, SAENZ & GARRIDO, 2010).

From the applications that improve cognitive skills, 27% help developing mental maps. Cognitive spatial structures stimulated by 16% of the applications studied, relates to spatial and temporal reference frames, implying the connection between visual and haptic space (FRESKA, 1997). The spatial properties include location, size, distance, direction, separation and connection, shape, pattern, and movement. Humans acquire spatial knowledge and beliefs directly via sensorimotor systems that operate as they move about the world (SMELSER & BALTES, 2001). Hence, while navigating in multimodal environments, players who are blind acquire spatial knowledge indirectly with the help of maps and images, 3D audio and graphics models, and the language.

Problem solving can be understood as the act of consciously applying rules and procedures to bridge the gap between the initial problem state and a solution state (GLATZEDER, 2010). Working this skill while playing multimodal video games involves navigating and interacting while solving tasks, challenges, and issues (SÁNCHEZ & SÁENZ, 2006; GUERRERO & LINCON, 2012). Besides, it includes other competencies such as learn and interpret points on a two-dimensional plane (DULYAN & EDMONDS, 2010), and searching, mobilization, localization and designing strategies (SÁNCHEZ & SÁENZ, 2006).

Table 17 – Types of evaluation performed on the considered games

GAME / ENVIRONMENT	EVALUATION	
	USABILITY	COGNITVE IMPACT
e-adventure (Torrente et al. 2009)	*no*	*no*
AINIDIU (Guerrero & Lincon, 2012)	*yes*	*no*
e-Adventure / Case Study: "My First Day at Work" (Torrente et al. 2014)	*no*	*no*
MOVA3D (Sánchez, Sáenz & Garrido, 2010)	*yes*	*no*
AudioGene (Sánchez & Aguayo, 2008)	*yes*	*yes*
Audio Haptic Maze (AHM) (Sánchez, 2012)	*yes*	*yes*
Audio Space Invaders (Mccrindle & Symons, 2000)	*no*	*no*
AudioDoom (Lumbreras & Sánchez, 1999)	*yes*	*yes*
Multi-Sensory Virtual Environment (Lahav & Mioduser, 2008a)	*no*	*yes*
AUXie (Dulyan & Edmonds, 2010)	*yes*	*no*
Tower Defense Game (Espinoza, Sánchez & Campos, 2014)	*yes*	*yes*
Audiopolis (Sánchez & Mascaró, 2011)	*yes*	*yes*
Audio-based Environment Simulator(AbES) (Sánchez et al., 2010)	*yes*	*yes*
The Natomy's Journey Game (Sánchez & Saénz, 2009)	*yes*	*no*
AudioNature (Sánchez & Flores, 2008)	*yes*	*no*
AudioChile (Sánchez & Sáenz, 2006)	*yes*	*no*
Multi-sensory virtual environment (Lahav & Mioduser, 2008b)	*no*	*yes*
AudioMetro (Sánchez & Sáenz, 2010)	*yes*	*yes*
AudioVida (Sánchez & Sáenz, 2006)	*yes*	*no*
Terraformers (Westin, 2004)	*yes*	*no*
PowerUp (Trewin et al., 2008)	*yes*	*no*

Source: produced by the author.

Skills concerning to social collaboration refers to help multiple people interact and share information to achieve a common goal. These skills can be improved while multimodal gaming when users who are blind and sighted users solve collaborative tasks (SÁNCHEZ & AGUAYO, 2008). It creates an inclusive learning context where users work together collaboratively and achieve commonly shared objectives.

4.3.4 Evaluation Dimension

The last dimension defined to classify the analyzed games is *evaluation*, which concentrates on two main aspects: usability and cognitive impact verification. Further details on the founds about methods and instruments for usability and cognitive impact evaluation were previously discussed in Chapter 2, as they composed the theoretical background of this work.

It is important to point out that both evaluations are necessary to assure the quality of multimodal video games for cognitive enhancement purposes. According to the ISO/IEC 9126 (2001) quality, relates to "[...] all the features of a product or service that exert their abilities to meet the stated or involved needs". It makes clear that usability is an important aspect of the game's quality. However, without a proper cognitive impact evaluation, one cannot assure that a particular application can develop or enhance any cognitive skills for people with visual disabilities.

Usability evaluation is the most frequent type of end quality (users and expert user's acceptance) assessment in this context, performed more often than cognitive impact evaluation. Among the applications analyzed that aim to enhance cognition, only 50% performed a cognitive impact evaluation (TABLE 18) while 64% carried out at least one type of usability evaluation. However, in this context both evaluations are essential.

Considering the types of evaluations performed on the set of the video games and environments analyzed, there is no evidence of a particular model, methodology or any guidance to support the cognitive impact and usability evaluation of this type of multimodal games. However, the most used instruments and activities for the usability and cognitive impact evaluation were identified, which are further discussed.

Table 18 – Classification of the games according to the *cognitive* dimension

GAME / ENVIRONMENT	MAIN COGNITIVE SKILL						
	MENTAL MODEL	MENTAL MAP	SPATIAL STRUCTURES	O&M	PROBLEM SOLVING	COLLABORATION	NON SPECIFIED
e-adventure (Torrente *et al*. 2009)							x
AINIDIU (Guerrero & Lincon, 2012)							x
e-Adventure / Case Study: "My First Day at Work" (Torrente *et al*. 2014)					x		
MOVA3D (Sánchez, Sáenz & Garrido, 2010)		x		x			
AudioGene (Sánchez & Aguayo, 2008)					x	x	
Audio Haptic Maze (AHM) (Sánchez, 2012)	x			x			
Audio Space Invaders (Mccrindle & Symons, 2000)	x						
AudioDoom (Lumbreras & Sánchez, 1999)			x				
Multi-Sensory Virtual Environment (Lahav & Mioduser, 2008a)		x		x			
AUXie (Dulyan & Edmonds, 2010)	x						
Tower Defense Game (Espinoza, Sánchez & Campos, 2014)		x			x		
Audiopolis (Sánchez & Mascaró, 2011)			x	x	x		
Audio-based Environment Simulator(AbES) (Sánchez *et al*., 2010)			x	x	x		
The Natomy's Journey Game (Sánchez & Saénz, 2009)		x					
AudioNature (Sánchez & Flores, 2008)					x		
AudioChile (Sánchez & Sáenz, 2006)				x	x		
Multi-sensory virtual environment (Lahav & Mioduser, 2008b)		x		x			
AudioMetro (Sánchez & Sáenz, 2010)				x			
AudioVida (Sánchez & Sáenz, 2006)		x	x				
Terraformers (Westin, 2004)		x					
PowerUp (Trewin *et al*., 2008)		x					

Source: produced by the author.

For the usability evaluation, three types of commonly applied instruments were identified: specialized questionnaires, common questionnaires, and likert-based surveys. The typical activities executed in the usability evaluation of the multimodal games and environments analyzed are observation, interview, and heuristics evaluation. For the cognitive impact evaluation, the instruments most commonly used are logs, checklists, questionnaires and modeling kits. The typical activities identified relates to the research structure of the quasi-experimental design of non-equivalent groups, including pretest, training tasks, cognitive tasks, and posttest, performed in this order.

4.4 Final Considerations

Multimodal interfaces through video gaming can help to improve cognitive skills and thus to make possible that the playful aspects of the game and their associated technologies positively influence the motivation of end-users. While developing these applications, one must carefully consider several factors: the context of use, the desired skills to be developed and the severity of the audience's visual impairment, among others. Aiming to identify trends in interface characterization, the interaction style, as well as instruments and activities for evaluation of usability and cognitive impact of these games, this chapter described the results obtained in the first step of this research methodology: Literature Review.

The SLR conducted revealed that there are some gaps related to when and how to employ the interface and interaction elements to fulfill the application's cognitive requirements. Significant issues remain neglected in the evaluation of multimodal video games for blind learner's cognition enhancement. This research step aimed to help reducing the problems aforementioned by presenting necessary insights for the practical understanding of the issues involved in their design and evaluation of such applications.

The 4-dimension classification proposed describes the features for design and evaluation of multimodal games for cognition of people who are blind, considering four dimensions: *interaction, interface, cognition,* and *evaluation*. Besides that, it was provided a comprehensive overview of the works to date on multimodal video games for the cognition of people who are blind.

The set of video games and the dimensions identified in this research step served as basis for the Preliminary UEM Comparison step. On the other hand, the list of authors from the analyzed papers, as well as the main evaluation practices they used, were later used as input for the Expert Opinion Survey step of this work research methodology.

5. DEVELOPMENT AND EVALUATION OF PRATICAL AIDS TO SUPPORT USABILITY IN VIDEO GAMES FOR LEARNERS WHO ARE BLIND

This chapter presents the development and evaluation of three practical aids (SLUP, CLUE, and PLUMB) aiming to support usability in different ways, resultant of three of the research steps followed in the present work: Preliminary UEM Comparison (Step 2), Development of Usability Evaluation Instrument (Step 3) and Expert Opinion Survey (Step 4). Hence, this chapter partially addresses RQ2 (*What are the main evaluation principles to evaluate multimodal video games based on audio and haptics for learners who are blind?*), RQ3 (*Given a set of the most used UEMs when field-testing games for learners who are blind, what types of usability issues can each of them disclose?*), and RQ4 (*During field tests involving multimodal games for learners who are blind, how can UEMs be combined to evaluate interaction modalities?*).

Section 5.1 describes the methodology of the preliminary comparison of usability evaluation methods, presents the Standard List of Usability Problems (SLUP) and the comparison UEM results. Section 5.2 describes the methodology applied for the development of the CheckList for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE), as well as its application in a real scenario. Finally, Section 5.3 presents the methodology and results of the expert opinion survey, and its results which include challenges on evaluation of multimodal games for learners who are blind and the PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind (PLUMB).

5.1 Preliminary Comparison of Usability Evaluation Methods

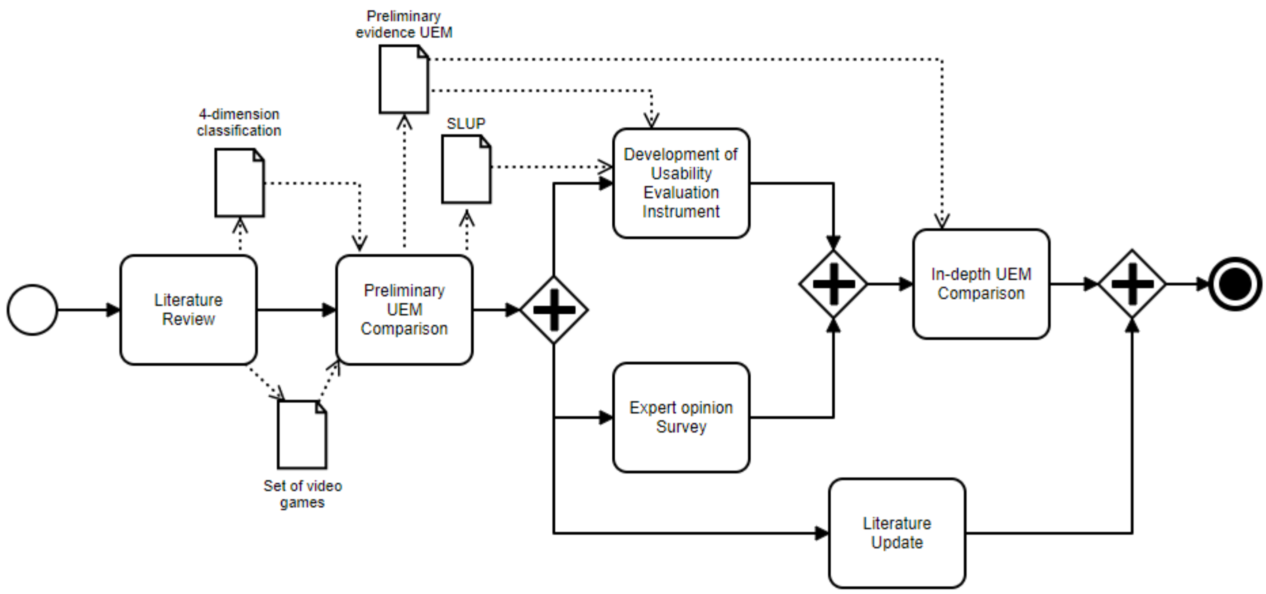
The second step of the research methodology followed in this work (FIGURE 34) was an initial effort towards proposing a solution to help assuring that children who are blind would be able to interact pleasantly and correctly with a multimodal video game while playing and learning.

As discussed in Chapter 1, a pleasant and adequate interaction is decurrent from correcting the issues identified during a proper usability evaluation. In their turn, evaluators have to consider that the applicability of general UEMs to the various domains is debatable and that they are mainly designed to be applied with users without disabilities. To investigate this topic further, in this step, an initial comparison between the most used UEMs was conducted using a subset of the video games identified during the Literature Review.

As results, first, typical problems affecting the interaction of learners who are blind with audio and haptic-based multimodal video games were approached and discussed, resulting in the proposal of SLUP. It consists in a categorized list of problems to help designers avoid recurrent usability issues in the design of multimodal games for learners who are blind. Then, it was found primary evidence concerning what types of usability issues the different UEMs under analysis can identify.

Later, SLUP was used as basis for the step of Development of Usability Evaluation Instrument, and the preliminary evidence on issues disclosed by each UEM was thoroughly examined during the last step, the In-depth UEM Comparison.

Figure 34 – Incomes and outcomes of the second step of the research methodology: Preliminary UEM Comparison



Source: produced by the author.

5.1.1 Methodology

The methodology of Hartson *et al.* (2001) for comparing usability evaluation methods propose to identify a "standard" set of usability problems that occur in a target system serves as the basis for methods comparison. Starting from this principle, a Standard List of Usability Problems (SLUP) was established as a first step towards comparing the suitability of different UEMs to evaluate multimodal video games designed for developing cognitive skills in learners who are blind.

However, instead of choosing one target application, a set of usability evaluation reports from five target multimodal video games were chosen and analyzed, namely AbES, Audiopolis, AHM, AudioSims, and AudioGeometry. The criteria for selection of the games were: (i) the possibility to obtain the original usability evaluation reports; (ii) the availability to install the games locally; (iii) the games should include distinct combinations of interaction devices, feedback and interface; (iv) the games should stimulate the development of cognitive abilities (e.g. O&M, mental maps, logical reasoning and spatial structures).

Due to the different combinations of interaction devices and feedbacks (TABLE 19), which are common in this type of applications, the analysis of the usability reports revealed various issues that occur while learners who are blind play multimodal games. In the five reports analyzed, 22 unique (non-duplicated) usability problems reported by users were identified and 35 unique problems were pointed out by evaluators[9].

Table 19 – Dimensions considered in the analysis of usability problems

Game	**Interaction**		**Interface**		**Cognition**
	Mode	***Feedback***	***Graphics***	***Audio***	
AbES	Keyboard	Sonorous, visual	2D	Speech synthesis, iconic sounds, spatialized audio	Problem solving Spatial structure O&M
Audio Sims	Joystick	Sonorous, visual, haptic	3D	Spoken audio, iconic sounds, spatialized audio	Mental mapping O&M Auditory and haptic senso-perception
Audio Geometry	Touch screen (Tablet)	Sonorous, Visual, Tactile	2D, 3D	Spoken audio, Iconic sounds	Mental mapping Spatial structure Logical reasoning
Audiopolis	Keyboard	Sonorous, Visual, Force feedback	3D	Iconic sounds, Spatialized audio	Spatial structure O&M Problem solving
Audio-Haptic Maze	Keyboard, Joystick	Sonorous, Visual, Force feedback	3D	Iconic sounds, Spatialized audio	Mental Mapping O&M Problem solving

Source: produced by the author.

In order to validate SLUP, seven independent experts in usability evaluation and two teachers specialized in learners who are blind answered to a 58-item questionnaire in which they could rate usability problems on a 7-point Likert scale of agreement and explain

[9] A usability problem is any negative phenomenon in interaction, such as user's incapability to reach a goal, inefficient interaction, or user dissatisfaction provoked by a mix of user interface design aspects and context of use factors (MANAKHOV & IVANOV, 2016), as previously discussed in Chapter 2.

their point of view (TABLE 20). All the respondents were familiar with conducting usability evaluations of multimodal games with learners who are blind.

Table 20. Experts' profiles

ID	Degree of Schooling	Experience	Expertise Area
E1	Computer Science PhD	5-10 usability evaluations	Audio games development and usability
E2	Computer Science PhD	> 10 usability evaluations	Games for cognition of children who are blind
E3	Master's degree in Computer Science	5-10 usability evaluations	Audio games usability
E4	Master's degree in Computer Science	> 10 usability evaluations	Applications for people who are blind
E5	Undergraduate degree in Computer Science	> 10 usability evaluations	Multimodal games design and usability
E6	Undergraduate degree in Computer Science	> 10 usability evaluations	Multimodal games design and usability
E7	Undergraduate degree in Computer Science	> 10 usability evaluations	Multimodal games design and usability
E8	Bachelor's degree in Education	5-10 usability evaluations	Cognition of children who are blind
E9	Bachelor's degree in Education	> 10 usability evaluations	Cognition of children who are blind

Source: produced by the author.

The analysis of the questionnaires showed that the experts disagreed of four items, Q15 (mean=3,57), Q16 (mean=3,86), Q54 (mean=3,25) and Q55 (mean=3,88). After considering the comments of those who disagreed and who were undecided, the sentences describing these four issues were rephrased according to the experts' suggestions. None of them was excluded because they were not rejected by all the specialists, neither any issue obtained mean below 3, which would have indicated an overall strongly disagreement. Instead, the experts that criticized them also gave recommendations to improve the issue description.

There were 13 issues that presented mean around 4, indicating a predominant neutrality of the specialists (Q3, Q4, Q6, Q10, Q13, Q18, Q22, Q39, Q40, Q49, Q52, Q59, and Q60). In these cases, more attention was given to the opinion of the experts with previous experience in identifying each specific type of usability issue. For example, Q52, Q59, and Q60 can only be identified when evaluating games that offer interaction with a haptic force feedback device, e.g., Novint Falcon or SensAble Phantom, and those experts, whose experience comprised evaluating games using these devices, agreed with the statements.

Every other issue description and category on the Standard List of Usability Problems was adjusted to be in consonance with the experts' evaluation and suggestions.

Finally, a senior usability expert who also had answered the initial questionnaire reviewed the updated version to guarantee that the SLUP matched the reality of the usability evaluation of multimodal video games aiming to improve the cognition of children who are blind.

The second step towards validating the problem list was the conduction of usability evaluation sessions with six children with different ophthalmic diagnosis (all legally blind, i.e. people with central visual acuity of 20/200 or less in the better eye with the use of a correcting lens), from 8 to 14 years old, attending between 2nd and 7th grades in schools for learners who are blind (TABLE 21).

Table 21. Children's profiles

ID	Age	Grade	Ophthalmic diagnosis
E1	8	2nd	Congenital bilateral aniridia
E2	8	2nd	Composite astigmatism, refractive amblyopia
E3	10	4th	Retinoblastoma, bilateral leukocoria
E4	12	5th	Bilateral optic nerve hypoplasia
E5	13	6th	Retinitis pigmentosa
E6	14	7th	Bilateral aphakia, retinal detachment, phthisis bulbi

Source: produced by the author.

Four researchers conducted the evaluation sessions in the real school environments, in which the children played with two of the analyzed games: AbES and AudioSims. The interaction data was gathered using the observation method adapted for children who are blind (RAISAMO *et al*., 2006), together with a Think Aloud Protocol (CHANDRASHEKAR *et al*., 2006), followed by a semi-structured interview, and the administration of the Software Usability for Blind Children Questionnaire (SUBC) (SÁNCHEZ, 2003).

This test configuration was chosen because these were identified as the most commonly used UEMs and evaluation instruments in the context of usability evaluation of multimodal video games for learners who are blind, as discussed in Chapter 4. The evaluators also used an initial version of SLUP adapted as a checklist to observe the children interactions, developed according to the problem list previously validated by the experts.

During the evaluation with users, all the problems initially described in SLUP were identified at least once, except those related to haptic force feedback, as the video games tested did not support this interaction mode. After the user observations, with the endorsement of two senior usability experts, four issues were added to the updated version of SLUP (Q11, Q12, Q33, and Q38), resulting in a final list describing 61 usability issues, which is available on http://bit.ly/SLUP-full.

5.1.2 SLUP Proposal and Evaluation

SLUP consists in a structured list containing usability issues related to the multimodal gaming interaction, users' gameplay behavior, and users' characteristics. In addition to overall usability issues related to learnability, efficiency, satisfaction, and difficulties in handling the different modalities, SLUP details usability problems related to audio, customization, interaction mode, and feedback. These problems are grouped in subcategories as shown in Figure 35.

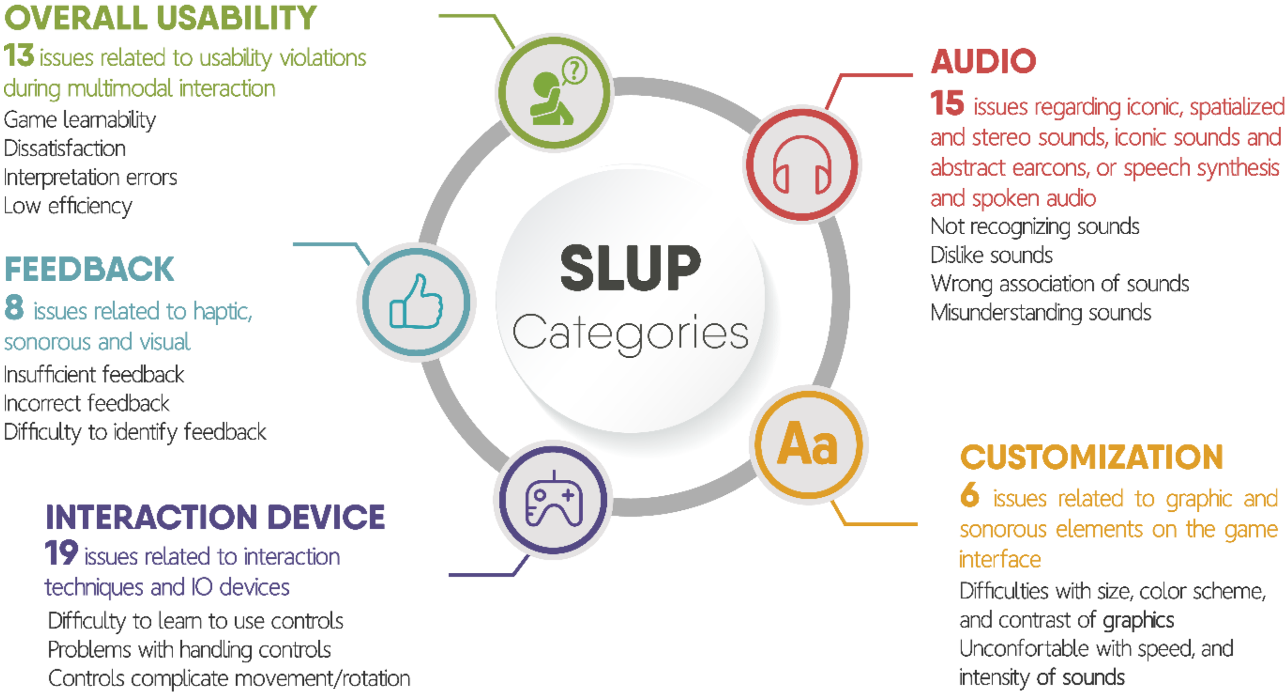
Being familiar with the types of issues that affect the interaction of learners who are blind with the main features of multimodal games can help researchers avoid these problems, as well as discover them more efficiently during usability evaluations.

The final version of SLUP specifies:

- 15 audio issues that can affect iconic, spatialized and stereo sounds, iconic sounds and abstract earcons, or speech synthesis and spoken audio;
- Six customization issues that can be caused by the size, color scheme, or contrast of graphic elements, or even by the speed and intensity of sounds and voices;
- 13 issues related to the overall usability of the game, addressing learnability, satisfaction, errors, and efficiency;
- Eight feedback issues that can occur either in haptic (kinesthetic or tactile), aural or visual responses to the user interaction; and
- 19 issues that can be related to the game interaction techniques and devices, and that affect the user interaction with the game inputs and outputs.

The establishment of SLUP for multimodal games for children who are blind serve multiple purposes, such as comparing which problems different UEMs can disclose, helping designers to avoid predictable issues in project time, and supporting the evaluation of these applications. The most significant problems in SLUP are discussed in the following.

Figure 35 – Summary of the types of issues detailed in the SLUP categories



Source: produced by the author.

5.1.2.1 Problems related to overall usability

Twelve problems related to overall learnability and satisfaction, errors, and efficiency were identified. For example, users can report perceiving the game as difficult to learn how to play (Q14); and perceiving help or extra information offered by the video game as useless (Q15, Q16). The overall satisfaction with the game is affected when users feel that the game does not challenge them enough (Q18) or does not allow them to be in control as much as they expected (Q19). Users can also demonstrate dissatisfaction with the game controls (Q20) or feel disinterested for having difficulty to play without helping mediation (Q17).

Although mediation is acceptable in the context of usability evaluation with learners who are blind (RAISAMO *et al*., 2006; TURNBULL, 1995), it cannot cross the line where learners are unable to perform most activities by themselves and keep making errors when the mediator stops explaining the game interaction and goals. On the other hand, observers can detect when users have difficulties to either move in the virtual environment (Q35) or recognize different scenarios in the game (Q37). Both issues are often related to troubles with the controls (Q20), understanding game goals (Q38), or with the quality of the game information (Q13, Q14).

5.1.2.2 Problems related to audio

Audio is essential to video games for learners who are blind because they learn to rely on their audition to compensate for their lack of sight (INMAN, LOGE & CRAM, 2000). A number of 15 usability problems related to different types of audio were identified. The users can perceive when iconic sounds and abstract earcons are difficult to identify (Q1); when they do not convey information properly (Q2); and when they are poorly or wrongly associated with actions or objects (Q3, Q7, Q8).

They can perceive recorded voices or speech synthesis as unpleasant or unfamiliar (Q5, Q6). They can also demonstrate difficulties in relating a sound to an action, or with their previous knowledge. Alternatively, the experimenters can recognize, by observing the user interaction, whether the spoken or TTS-based information for user orientation or current location in the game is unclear (Q25 to Q28). Likewise, they can detect when the learners have a low acceptance of a sound (Q31); and have difficulties to recognize (Q29) or associate a sound to what it represents in the real world (Q30).

Frequently, the comments and questions of users lead the experts to identify multiple different usability issues. For example, the difficulty to understand the information conveyed by a sound (Q2) (reported by learners in simple comments such as “What does this sound mean?” during the observation with thinking aloud) can make the experts discover associated problems. In this case, Q1 can be related to any issue from Q25 to Q30.

In this sort of situations, it is up to the experimenter to find an association among usability issues. For instance, learners could have difficulties in the identification of a sound because they cannot understand the accent or do not know the words used in the spoken audio (Q25, Q26), or even because the TTS audio is too fast or too slow (Q27, Q28).

Some problems can also be indirectly identified, as they are a cause of another issue. For example, it is uncommon that learners notice they do not have the knowledge required to determine the meaning of a specific sound (Q4). However, suppose that a student is playing a game and listens to beep sounds coming from a heart rate monitor. It is possible that the student does not understand the meaning of the sound in the game because it does not match their prior knowledge. In these cases, to provide the correct adjustments it is necessary to identify clearly both problems: Q2 and its cause, Q4.

Furthermore, it is important to highlight the need to be attentive to accidental sounds that cause dissatisfaction, especially in learners with total blindness, because they are more sensitive to sounds than those who rely on some visual cues (MUCHNIK *et al*., 1991;

OHUCHI *et al*., 2006). Two of the children who played AudioSims commented: “I don’t like this sound” and “This sound is ugly” (Q5) and they both were talking about the sound of the joystick while vibrating in contact with the table surface.

5.1.2.3 Problems related to customization

Video games for people with visual disabilities should support at least the customization of size, color scheme, and contrast graphic elements (TORRENTE *et al*., 2014; TURNBULL, 1995). Issues involving these aspects apply primarily to users with low vision. These users can still learn by using their visual modality despite the need for magnification, enhancement of contrast, and change of font type and size (TURNBULL, 1995).

Initially, three issues were listed in the SLUP that commonly emerge in multimodal video games for learners who are blind failing customization. The initial list included difficulties in understanding the information conveyed by images (Q9); difficulties in understanding the information conveyed by colors (Q10); and problems with the sizes of figures, diagrams, or other elements (Q32). All these problems were related to graphics.

However, during the evaluations with learners, new issues related to audio customization were identified. Two participants with low vision and who were familiar with console games complained that, although they could understand it, the spoken audio was too slow in AudioSims; “As if the lady is sleepy”, in the words of one of them. However, this was not a problem for the learners with total blindness who were also not experienced with console games. Another learner who is legally blind and also has hearing loss could not hear well the audio feedback in AbES and constantly asked: “What did it just say?”. The games did not present volume control nor the option to adjust voice levels and TTS speed. Thus, these issues related to difficulties with the speed of spoken audio or TTS (Q11), and with the intensity of sounds and voices (Q12, Q33), were added to SLUP.

5.1.2.4 Problems related to interaction mode and feedback

Learners with visual disabilities often use the tactile and kinesthetic input to learn about their surroundings and receiving information via contact and use of objects (COX & DYKES, 2001). A number of 19 problems related to interaction mode and eight related to feedback were identified. Regarding the interaction, the users may perceive the controls as difficult to learn (Q21) and having trouble to move through the virtual environment due to poor understanding of the use of controls (Q24).

In parallel, the experimenters noticed when the controls complicated the user's movement or rotation throughout the virtual environment (Q45, Q46), and when handling the haptic devices was difficult (Q23, Q47). In fact, most of the input issues could be more easily reported by experimenters because they addressed very specific aspects of the game interaction. For instance, in cases where haptic devices are the game input, the experimenters could identify if the users had difficulties in recognizing a specific 2D or 3D figure or associating it with what it represents in the real world (Q48-Q51).

Experimenters could also observe if the interaction techniques used were inappropriate to provide the user with the best degree of differentiation and perception of haptic elements (Q60, Q61). These issues are some of the probable causes for the textures and forms being difficult to perceive, discriminate, or recognize with the haptic device (Q54-Q57). The feedback issues were connected to audio and interaction problems. Experimenters could perceive whether the vibrating or audible feedback was insufficient or incorrectly applied to the execution of an action (Q41-Q44), or even inappropriate to the usage context (Q22).

The users could report difficulties in identifying the actual intent of a specific feedback (Q21), and in a parallel way, the experimenters could perceive if the users understood the feedback incorrectly or were unable to notice it (Q40). This situation happened a few times with AbES when the learners were sure that the sound of the character hitting a table was a glass breaking, and when they ignored the "monster" approaching them because they could not identify the meaning of the correspondent sound.

5.1.3 Results of Preliminary UEM Comparison

As discussed before in the results of the Literature Review, in the context of usability evaluation of multimodal video games for learners who are blind, the most used evaluation methods are observation, interview, and heuristics, while the most common evaluation instruments are specialized and straightforward questionnaires and Likert-based surveys.

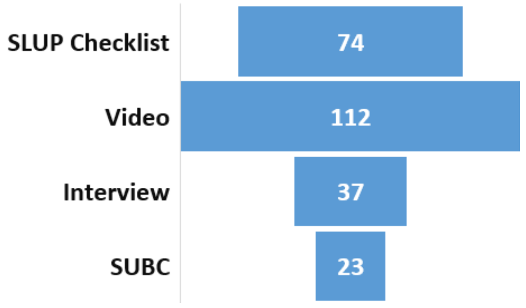
The data gathered from the usability evaluation sessions with six children (TABLE 21) playing with AbES and AudioSims were analyzed. The analysis included the observation with think-aloud protocol (during which the observers took notes and filled a checklist based on the SLUP), the videotaped observation, the videotaped interview and the answers to the SUBC questionnaire, answered online by children themselves in a fun and accessible version. The initial evidence is that the analysis of the videotaped observation can reveal the greater amount of usability issues listed in SLUP (FIGURE 36) in all the dimensions analyzed (FIGURE 37).

However, a less time and effort-consuming analysis of the observation checklist based on SLUP revealed a considerable amount of relevant usability issues as well comparing to video. This result leads us to the refinement of the checklist, which became the Checklist for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE), detailed in Section 5.2.

The preliminary evidence on the types of usability issues disclosed by each UEM in field tests showed that the SUBC questionnaire could not reveal any feedback and interaction problems, but it was more useful than the interview in identifying customization and overall usability issues (FIGURE 37). On the other hand, the feedback, customization, and audio issues found in the interview indicate that combining this method with the use of the SUBC would be beneficial for a rapid evaluation.

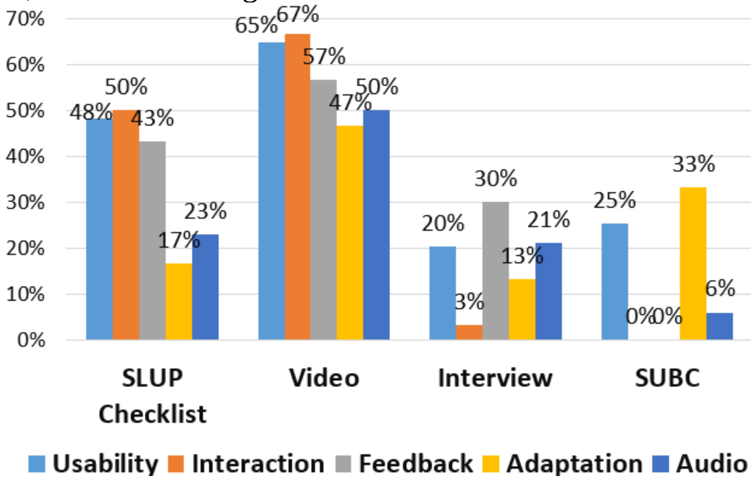
This combination, however, seems to be insufficient to uncover interaction issues, which interviews barely revealed, and it was absent in SUBC answers. The analysis of the results gathered from the SLUP-based checklist showed that this instrument was effective in finding interaction, feedback, and overall usability issues, but much less efficient than video in revealing audio issues. Compared to interview and the SUBC, the SLUP-based checklist was better in finding all dimensions of problems during user observation, except for customization issues.

Figure 36 – Total usability issues found per UEM in the six user evaluations, with two video games



Source: produced by the author.

Figure 37 – Comparison of usability issues dimensions disclosed per UEM in the six user evaluations, with two video games



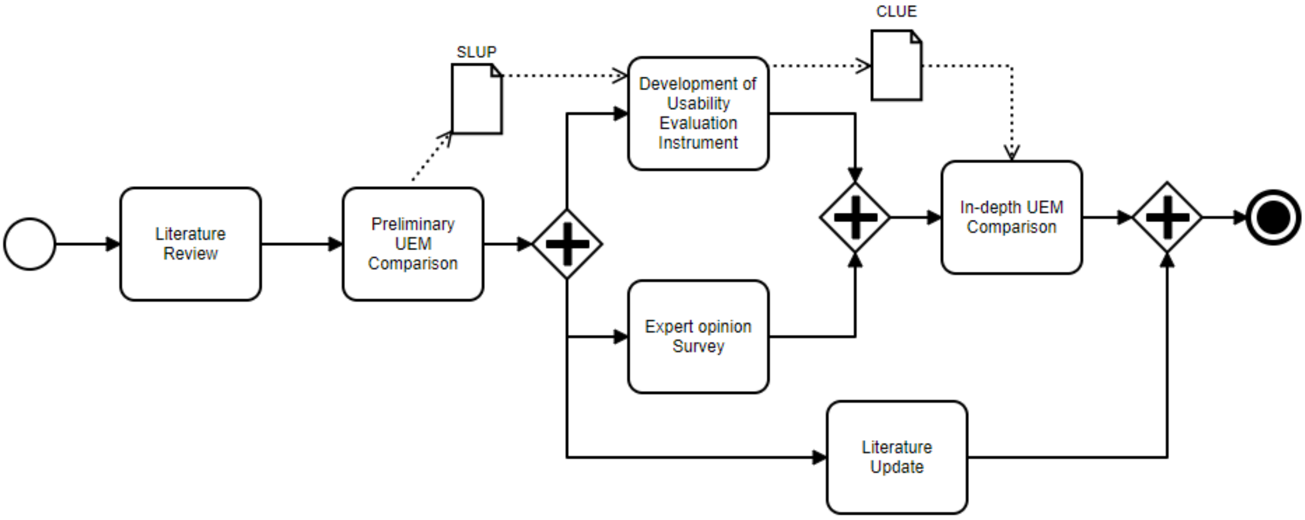
Source: produced by the author.

5.2 Development of a Usability Evaluation Instrument

The third step of our research methodology was decurrent from the evidence that a checklist based on SLUP would be helpful to assist researchers and practitioners in field studies of usability evaluation, addressing multiple aspects of gameplay and multimodality, including audio, graphics, and haptics (FIGURE 38). The present section explains how the Checklist for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE) was proposed and validated.

CLUE was designed to guide researchers and practitioners conducting field research on usability evaluation employing video, audio or participatory user observation with young people who are blind. For this, CLUE contains 40 checkpoints defined to support the identification of the most relevant interface and interaction issues when young people who are blind are playing multimodal video games for cognitive purposes.

Figure 38 – Incomes and outcomes of the third step of the research methodology: Development of a Usability Evaluation Instrument



Source: produced by the author.

The aim of this instrument is not to come up with a new proposal for the usability evaluation of serious video games or multimodal interfaces *per se*. There is already a diversity of sound proposals for evaluating serious games with non-disabled users (OLSEN, PROCCI & BOWERS, 2011; MAYER *et al*., 2013; YÁÑEZ-GÓMEZ, CASCADO-CABALLERO & SEVILLANO, 2017), as well as for evaluating general-purpose multimodal interfaces (COUTAZ *et al*., 1995; DUMAS, SOLÓRZANO & SIGNER, 2013). Instead, the main contribution brought by CLUE is focusing the evaluation on the analysis of multimodal interface elements and game interaction, disclosing issues that affect the cognitive purposes of the video games for children and youngsters who are blind.

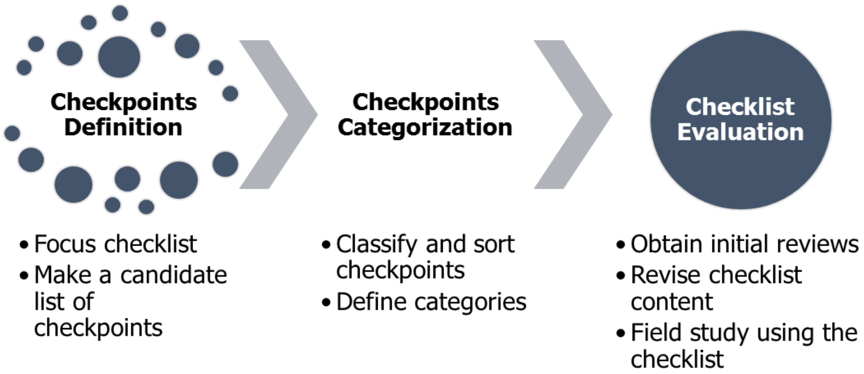
CLUE is an observational tool to be used by evaluators during usability field tests. It was designed to clarify the basic aspects that should be observed when evaluating multimodal video games for cognitive development and enhancement of children who are blind. Thus, CLUE aids the evaluator not to forget important criteria and enhances the objectivity and reproducibility of evaluation.

CLUE checkpoints instruct the experimenter to verify overall difficulties the children may experience while playing video games for cognitive development and enhancement. CLUE can be used not only by practitioners and researchers but also by specialized institutions and schools for learners who are blind, helping teachers and instructors to identify whether a game can be helpful to the children rather than create a barrier to their learning and cognition.

5.2.1 Methodology

The exploratory research toward proposing CLUE was based on Stufflebeam's (2000) guidelines for developing evaluation checklists. The applied methodology consisted of three main steps, as summarized in Figure 39.

Figure 39 – Steps followed for the development of CLUE



Source: produced by the author.

The intended uses for CLUE were established during the Checkpoints Definition. The first use is to help an evaluator to disclose usability issues in video games based on audio and haptics while watching a child who is blind playing. The video game purpose has to include, but not necessarily be limited to, the development and enhancement of cognitive skills in children with total or partial blindness. The second use is to serve as an auxiliary resource to the analysis of recorded gaming sessions in the same context. To delimit our understanding of what is a usability problem, Manakhov and Ivanov's (2016) concept was considered, which is the same concept used to develop SLUP.

Then, to assemble a candidate list of checkpoints, the relevant literature on the theme was analyzed, as discussed in Chapters 2 and 3 of this thesis. Bernsen's (2010) definition of modality was considered, as a way of representing information in a certain medium, by using a specific physical carrier, which appeals to a certain human sensor system.

SLUP was the basis for the candidate checkpoints list, in addition to the four dimensions related to Interaction, Interface, Cognition, and Evaluation in multimodal games, and to Bernsen's (2010) modalities taxonomy. The modalities usually present in multimodal video games for people who are blind are characterized as shown in Table 22, grouped into the interface and interaction dimensions previously presented in Chapter 4.

Table 22 – Interface and interaction features considering the characteristics of modalities

MEDIUM	MODALITY CHARACTERIZATION		
GRAPHICS	**Interface** Bidimensional images, maps or graphs; Tridimensional images, maps or graphs; Written text.	**Feedback** Contextual visual cues (using graphic interface features).	**Customization** Size; Contrast; Color Scheme.
ACOUSTICS	**Interface** Spoken audio; Speech synthesis; Iconic sounds; Spatialized sounds; Stereo sounds; Abstract earcons.	**Feedback** Contextual audio cues (using audio interface features).	**Customization** Speed; Intensity.
HAPTICS	**Interface** Tactile; Kinesthetic.	**Feedback** Force; Vibration; Pressure; Motion.	**Customization** Intensity; Frequency.

Source: produced by the author.

After this, the Checkpoints Categorization step consisted in the listing, describing and defining of the checkpoints, before sorting them into categories based on the correspondence presented in Table 22. The first categories were audio, customization, interaction mode, and feedback. Then, a review version of the checklist was designed, consisting in 42 checkpoints associated with three options, “Yes,” “No” and “Not Applicable (N/A)”. Each item in CLUE addresses one or multiple issues in SLUP to simplify the experimenter’s analysis while observing the user.

Finally, the Checklist Evaluation occurred in two main phases. First, five specialists (TABLE 23) analyzed the checkpoints and gave feedback via email and non-structured interviews, discussing the pertinence and adequacy of the checkpoints to the intended use. They also gave further details on the comprehensiveness of the checkpoints and provided suggestions and corrections. All the respondents were familiar with conducting usability evaluations of multimodal video games with learners who are blind. After this, the reviewed version of CLUE was updated based on the feedback received. Some checkpoints were rewritten or replaced according to the consolidation of the reviewers’ answers. Two checkpoints were excluded, as all experts agreed they could not be observed.

Table 23. Profiles of CLUE reviewers

DEGREE OF SCHOOLING	EXPERIENCE	EXPERTISE AREA
Master's degree in Computer Science	5-10 usability evaluations	Audio games usability
Ph.D. Candidate in Computer Science	> 10 usability evaluations	Technology and applications for people who are blind
Bachelor's degree in Education	5-10 usability evaluations	Cognition of children who are blind
Bachelor's degree in Education	> 10 usability evaluations	Cognition of children who are blind
Undergraduate degree in Computer Science	> 10 usability evaluations	Multimodal games design and usability

Source: produced by the author.

The second step towards validating CLUE occurred during the Preliminary UEM Comparison, described in Section 4.3, involving the conduction of preliminary usability evaluation sessions aiming to obtain reviews of CLUE from intended users and experts while engaging them to field-test the checklist. As detailed before, six children with different ophthalmic diagnosis (all legally blind), from 8 to 14 years old, attending between 2nd and 7th grades in schools for learners who are blind participated in the evaluation sessions.

The version of CLUE used in these evaluations contained 40 checkpoints organized as Overall Usability (10 items), Interaction Mode (8 items), Feedback (6 items), Graphics/Customization (3 items), and Audio (13 items). During the user observation, the evaluators filled the CLUE to help them observe the children's interactions, checking "Yes" or "No" for each checkpoint, indicating whether the event described in the checkpoint had occurred during the game session. After finishing each user observation, the evaluators would also answer "Yes," "No" or "N/A" to the question "Is it possible to verify the situation described in this item during a user observation?". In addition, they provided comments to the adjustment of some checkpoints. The results showed that all the evaluators agreed that a trained usability experimenter could disclose all the checkpoints using CLUE in a field research.

In a non-structured interview after the user observation sections, the evaluators described which specific usability issue led them to check each CLUE item marked as "Yes." For example, the checklist item number 7 instructed the experimenter to check if the child had difficulties to "accomplish the game tasks". If an evaluator checked this item as "Yes" during a user observation, it may have been caused by the SLUP issue Q19 ("The user feels that the game does not allow him to be in control as much as he expected"). It could also have been caused by Q38 (“The user has difficulties in understanding the game goals”), or even a combination of both. This procedure allowed us to verify if each CLUE checkpoint was being correctly interpreted and used during the data interpretation.

Finally, after finishing the Checkpoint Evaluation, CLUE was updated once again resulting in simplified checkpoints descriptions. After the user testing, the checkpoints were also reorganized into new categories to facilitate the observation and modular use of the checklist. The current version of CLUE contains 40 checkpoints grouped in 4 categories: Gameplay (14 items), Acoustics (11 items), Haptics (12 items) and Graphics (3 items). *Gameplay* contains items related to game overall usability and playability. *Acoustics* aggregates items related to the comprehensibility and adequacy of multiple types of sounds present in the user interface. *Haptics* contains checkpoints regarding the use of haptic interaction techniques and devices that affect the user interaction with the game inputs and outputs. *Graphics* contains items related to visual aspects of the user interface. Each category also contains checkpoints related to the user’s feeling and satisfaction towards the specific game and modality aspects, and to the types of feedback provided by each modality.

The modular use of CLUE was an improvement designed to allow the independent use of the checkpoint groups, according to the context. For example, video games for children who are blind can be either based on audio-only or audio-haptic stimulus. In the first case, an experimenter could use the checkpoints related to Gameplay and Acoustics, while in the second the Haptics category would also be necessary. Whenever a child with low vision is participating in the tests, evaluators should also check the Graphics category. The current version of CLUE also contains a column where the experimenter can check the problem severity and indicate in which task the problem occurred. The full version of CLUE is available in Appendix B.

5.2.2 Testing CLUE in a real scenario

The use of an initial version of CLUE during the Preliminary UEM Comparison (referred to as SLUP-based checklist) allowed comparing the analysis of the data collected with the proposed checklist and the data coming from the analysis of video, interview, and SUBC questionnaire. Applying the checklist during this phase generated feedback to improve the checklist after its use in a real scenario, which is the reason why the current version of CLUE was only finished after the Preliminary UEM Comparison, in a separate research step.

However, even the use of a preliminary version of CLUE showed that the proposed instrument is effective in finding most of the interface and interaction problems that affect the game interaction of learners who are blind.

By using CLUE exclusively, evaluators identified 66% of usability issues disclosed later by video analysis and surpassed the problems revealed by using questionnaire and interviews. The evidence coming from this initial testing is that the analysis of the recorded observation can disclose the greater amount of usability issues listed in SLUP in all the dimensions analyzed, especially those related to audio.

From the total amount of 181 non-unique usability issues identified in all user sessions with AbES and AudioSims, 112 were identified in video analysis, from which 74 were also disclosed by CLUE. The analysis of recorded user interactions confirmed all the problems identified by using CLUE. The strength of CLUE was in finding interaction, feedback, and overall usability issues. Compared to semi-structured interview and the specialized SUBC questionnaire, CLUE presented a better result in the search for all dimensions of problems, except for customization. The identification of customization issues was more effective by receiving direct user feedback using SUBC.

In each category, the UEMs revealed usability issues at different levels. The problems related to audio features can be summarized as difficulties to recognize sounds, wrong association of sounds, misunderstanding information conveyed by a sound and somehow disliking a sound. Video analysis identified twice the number of problems related to misunderstanding and not recognizing sounds than CLUE. Interview and CLUE found the same quantity of issues regarding sounds that the user disliked, but CLUE was better than interview to help identifying the other types of audio issues. SUBC could reveal only a few indications of difficulty to recognize sounds.

The overall usability issues address problems of multimodal interaction, learnability, efficiency, and satisfaction. In this dimension, CLUE revealed a number of usability problems much superior to those obtained with interview and SUBC, in all subcategories, except satisfaction. CLUE was particularly good at identifying multimodal interaction and learnability problems, being comparable to the results obtained with video analysis. However, regarding efficiency, CLUE could identify only 25% of the problems disclosed by video, while results from interview and SUBC were unexpressive. Regarding user satisfaction, SUBC identified as many issues as video, followed by CLUE and interview respectively.

Regarding the interaction mode, which comprised problems that are related to the use of the game controls, relevant results were revealed only by using CLUE and video. CLUE found 67% of the problems identified in video analysis related to difficulties to learn and use the controls; and 59% of the problems associated with movement and rotation inside the game environment. The feedback problems can be related to difficulties in identifying a feedback and incorrect or insufficient feedback. CLUE found the same number of problems regarding feedback identification and use of incorrect feedback as video analysis. Interview identified the same quantity of problems reporting insufficient feedback as CLUE.

Overall, the results indicate that using CLUE as an observational checklist during user field studies result in a less time and effort-consuming analysis when compared to video, yet revealing a substantial number of relevant usability issues. We highlight that further tests are still needed to establish CLUE as a sound evaluation checklist.

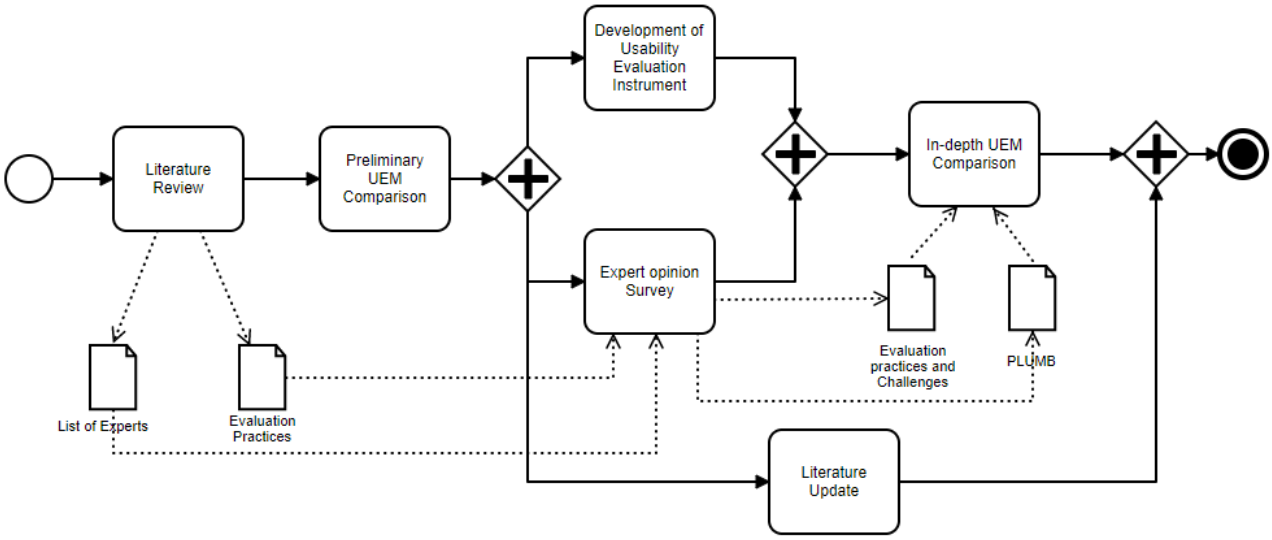
All the UEMs applied in our tests have advantages and disadvantages. For example, while the combination of SUBC and interview is easier to apply and satisfactory at revealing customization and feedback issues, CLUE helps raising a greater number of usability issues related to overall usability, audio, feedback, and interaction. Furthermore, CLUE analysis is faster and more straightforward than analyzing interview data. On the other hand, applying CLUE in usability testing demands at least two experienced evaluators to identify the issues, without jeopardizing the observation.

Further evaluations involving CLUE were executed during the In-Depth UEM Comparison phase of this work methodology (described in Chapter 6). However, the initial results discussed in this Chapter are relevant because they demonstrate that CLUE is a solid alternative to administering interview and questionnaire methods, which are broadly applied in this field, as discussed before. CLUE can additionally help to make the analysis of recorded user interactions an easier process, guiding the identification of interaction patterns and recurrent usability issues, even by evaluators with little experience.

5.3 Expert Opinion Survey

The fourth step of this work methodology aimed to deepen the understanding related to the evaluation in this field, for which purpose international researchers in the area were surveyed, using an Expert Opinion Survey (ARMSTRONG, 2001). The survey was emailed to the researchers previously identified in the Literature Review, regarding the set of evaluation practices they reported. The main results of this research step were a set of principles for choosing UEMs and information about evaluation practices and challenges in the field (FIGURE 40). Both results were used as inputs to the In-depth UEM Comparison step. The Expert Opinion Survey addressed research question 2: *What are the main evaluation principles to evaluate multimodal video games based on audio and haptics for learners who are blind?*

Figure 40 – Incomes and outcomes of the fourth step of the research methodology: Expert Opinion Survey



Source: produced by the author.

5.3.1 Methodology

Expert Opinion Surveys can be used to serve a variety of purposes and they result in predictions of how others will behave in a particular situation, according to persons with knowledge of the situation (ARMSTRONG, 2001). This technique can be used to assist in problem identification and in clarifying the issues relevant to a particular topic, by consulting individual experts (POULSON, ASHBY & RICHARDSON, 1996). Although it can be seen as a relatively informal technique, as individual expert opinion is not infallible; if a number of different experts provide the same feedback it is likely that real issues exist (POULSON, ASHBY & RICHARDSON, 1996).

As part of a continuing effort to improve usability evaluation of multimodal video games for cognitive enhancement of children who are blind, the expert opinion survey was conducted. It aimed to update the published literature review results, as well as to deepen and to enrich the developing understandings of challenges and principles in this topic.

The survey consisted of 15 questions and was emailed to 16 international researchers that reported usability evaluation in 21 games and virtual environments for cognitive enhancement of people who are blind, which had been previously identified in the literature review step. Personalized emails were sent to all the identified authors. These emails included the title of the paper in which each researcher described a usability evaluation, a brief description of the ongoing study with a hyperlink to the survey, and an estimate of the time needed to fill out the questionnaire. This approach was chosen because using personalized email in soliciting participation appears to be the most effective method to increase participation in surveys (HOLLAND, SMITH, HASSELBACK & PAYNE, 2010)

A vast majority (87,5%) did not respond to the initial emails. For two months, biweekly reminders were sent, until the response rate stopped improving. Researchers that had already responded the survey were contacted and kindly asked to remind their coauthors to answer our survey. About fifty-six percent of these researchers never answered, despite reminders and/or personalized emails to their coauthors. Hence, a response rate of 43,75% (N = 7) was obtained, corresponding to seven authors responsible for nine of the previously analyzed papers.

Despite the small number of respondents, the strength of this exploratory approach resides in the fact that the respondent experts have a diverse background and work in different countries and research groups, which helps to avoid specific trends in their opinions. Among the respondents, there are researchers from North and South America, Europe and Asia, who answered the questionnaire independently.

The research literature also attests the fairness of the response rate obtained in this work. For instance, Rowe and Wright (2001) discuss principles for the use of expert opinions and state that the most relevant forecasts rely on unaided expert opinions. The authors indicate, based on previous research findings, that when conducting expert opinion surveys researchers should obtain independent answers from between 5 to 20 experts. In addition to that, according to Lazar, Feng & Hochheiser (2017), if the research goal is to gather requirements from domain experts, in-depth discussions with two or three motivated individuals can provide a wealth of data, which corroborates the adequacy of the approach this research purposes.

5.3.2 Overview of Survey Results

The participant's profiles are summarized in Table 24, based on the characterization of their research experience and practice on evaluating multimodal applications for people who are blind. The experts are from five different countries and work in different research groups, except for A3 and A6, who belong to the same University. Most of the experts are University professors and researchers (A2, A3, A4, A6, and A7).

A1 works with virtual environments, usability and accessibility at IBM Research and A5 investigates educational video games at the Organización Nacional de Ciegos Españoles (ONCE), a Spanish national nonprofit social corporation of public law. Some of the researchers had more than one paper identified in our previous literature review, such as A2 (3 papers) and A5, A6 and A7, with two papers each. In the survey, they answered specific questions regarding the types of usability instruments and methods administered in the evaluations described in each of these papers.

Regarding their research experience in the field, 43% have been researching applications designed for people who are blind for about four to six years (A4, A5, and A6), and 29% have been researching in this area for seven to nine years (A2 and A7). While one expert has been researching this field for up to ten years (A1), another one occasionally collaborates with researchers involving evaluation with people who are blind (A3). It is interesting to point out that neither the most experienced nor the occasional researcher are familiar with any particular models for the design and evaluation of multimodal applications, as well as most of the experts (57%).

The experts that reported being familiar with models for the design or usability evaluation of multimodal interaction mentioned the CARE properties (NIGAY & COUTAZ, 1993) the CASE model (COUTAZ, NIGAY, SALBER & BLANDFORD, 1995), and the AMITUDE model (BERNSEN & DYBKJÆR, 2009). However, none of them based their evaluation instruments in any of these models. Instead, all the researchers use mostly ad-hoc instruments during the usability evaluation of multimodal applications for people who are blind. In this work, they are classified as ad-hoc any instruments generated by the authors, according to the specific goals of an ongoing evaluation, but not formally validated and often not reusable.

Table 24. Profiles of respondent researchers and their behavior towards multimodal usability evaluation

ID	Country	No. of papers on Literature Review	Research experience in the field	Familiarity with multimodal models	Types of usability instruments administered	Types of usability methods carried out
A1	USA	1	Up to 10 years.	Unfamiliar with any particular models.	Validated instruments, Ad-hoc instruments.	Both quantitative and qualitative methods.
A2	Chile	3	7-9 years.	Unfamiliar with any particular models.	Ad-hoc instruments.	Both quantitative and qualitative methods.
A3	Spain	1	Occasional.	Unfamiliar with any particular models.	Ad-hoc instruments.	Both quantitative and qualitative methods.
A4	Ecuador	1	4-6 years.	Unfamiliar with any particular models.	Ad-hoc instruments.	Both quantitative and qualitative methods.
A5	Spain	2	4-6 years.	CARE properties, CASE model.	Ad-hoc instruments.	Both quantitative and qualitative methods.
A6	Spain	2	4-6 years.	AMITUDE model, CASE model.	Ad-hoc instruments.	Both quantitative and qualitative methods.
A7	Israel	2	7-9 years.	CASE model.	Validated instruments, Ad-hoc instruments.	Quantitative methods only.

Source: produced by the author.

Although A7 is familiar with CASE model and uses validated instruments reportedly, his evaluations usually do not employ any instrument based on that model. Instead, his research group developed and validated a number of quantitative specific instruments to measure usability in the specific context of their research. This information implies that their familiarity with formal models describing multimodal interaction models does not affect the conduction of usability evaluations.

All the researchers agreed that the use of both quantitative and qualitative methods is necessary to assess the interaction of people who are blind with multimodal interfaces. Although also agreeing with the use of quantitative and qualitative methods, A7 focus in the use of quantitative evaluation methods and instruments, as his research usually measures the cognitive impact of multimodal games on the intellect of people who are blind.

5.3.3 Challenges Identified on Usability Evaluation of Games for Learners who are Blind

When answering the survey, the experts provided a detailed discussion of the topics approached, revealing challenges and needs in the field of usability evaluation of multimodal video games for cognitive development of children who are blind. Some insights emerged from the experts' answers on their recent research work and evaluation practices, as well as challenges related to usability evaluation of multimodal video games for learners who are blind. These results are further discussed in the remainder of this section.

5.3.1.1. Challenge 1: the need for guidance on the conduction of usability evaluation.

Overall, experts indicated that it is common to perform informal usability evaluation in this field, which usually consists in applying ad-hoc questionnaires or interviews after a gameplay session. According to them, it happens due to time or team issues, as well as for the need to perform multiple types of tests (e.g. performance and cognitive impact). In practice, little time is left for planning and conducting a usability evaluation because most of the project schedule accommodates the development and other types of tests.

In addition to that, usually, the team is unfamiliar with usability evaluation instruments or methods that offer useful specific support to this context. Even experienced researchers who are familiar with models for design and evaluation of multimodal applications (e.g. CARE, CASE, and AMITUDE) claim that the use of these models for multimodal usability evaluation is complicated and too laborious, mainly when performed by practitioners. They argue that, in this scenario, it seems more beneficial to create their own evaluation instruments that are easier to administer and context-specific.

Indeed, some usability aspects – efficiency and effectiveness, for instance – can be evaluated independently of the domain (FRØKJÆR, HERTZUM, & HORNBÆK, 2000). However, all the researchers agreed that a drawback of doing this is the lack of guarantee of meeting the user's needs, principally considering the game cognitive requirements. Ratifying this concept, researcher A3 highlighted that visual disabilities are very particular, and each user is a world, so it is hard to apply very general solutions for usability evaluation in this context.

The applicability of general UEMs to diverse areas is questionable when evaluating specific characteristics, because they may not be adequate for the new contexts of use, generating gaps in the evaluation (ZAHARIAS & POYLYMENAKOU, 2009). In fact, all the expert researchers agreed that, according to their experience the multimodal inputs, the specificities of users' visual disabilities and the type of cognitive skills to be supported are specific characteristics that profoundly affect the usability evaluation of an application designed for learners who are blind.

Hence, these characteristics have to be considered in any usability evaluation in this context. Researcher A6 further remarked that, while it is true that all of these aspects can have an impact on the usability evaluation, the most significant challenge in measuring usability is that the solutions that grant accessibility for some levels of visual impairment actually hinder their usability for other levels.

The discussion raised by the researchers pointed out that there is a need for practical guidance on usability evaluation in this field. It is necessary to ensure that multimodal game interaction and interface elements suit the game cognitive purposes and the learners' characteristics, leading them to interact pleasantly and correctly while playing and learning. All the experts affirmed that they would welcome evaluation principles to assist researchers in choosing the methods that better fit their usability requirements to assess diverse aspects of multimodal interfaces in this context.

5.3.1.2 Challenge 2: to assess the multimodal interaction while considering the cognitive dimension.

The usability evaluations described in the experts' papers showed that the crucial features to be evaluated during the interaction of learners who are blind with multimodal gaming interfaces are audio, customization capability, interaction mode, and feedback (including audio and haptic stimulus). However, the experts highlighted that these aspects could not be evaluated apart from the game target cognitive aspects.

Despite that, they reportedly conduct usability evaluation more frequently than cognitive impact evaluation because the last one requires specialized people and procedures. All the experts agreed that it is not possible to assure that any multimodal application or game is capable of developing or enhance any cognitive skills in learners with visual disabilities if an adequate cognitive impact evaluation is not conducted.

Having performed cognitive impact evaluation in this context several times, experts A2 and A7 suggested that the key for the success of this type of evaluation is the understanding of what data to collect from users, in order to compare, analyze and measure the skills and the development of the subjects. They recommend the use of tests based on experimental and control groups or two-sample test analysis based on a pretest-posttest of the same group. Besides, researchers were unanimous in their opinion that it is crucial to investigate how multimodal game elements can be meaningfully used to develop cognition in learners who are blind.

5.3.1.3 Challenge 3: to go beyond both usability and cognitive impact evaluation.

Although researchers spoke in one voice regarding the need for sound usability evaluation of multimodal games for learners who are blind, they also demonstrated concern about evaluating other aspects. According to the researcher A7, when a usability evaluation is applied to the users' context, the mental model and the cultural environment are also critical because the interface was created specifically for them. In other words, all the interaction is part of the design for people who are blind, including all their culture. Besides, A7 suggested that an equally important challenge could be these users' experience with the multimodal interface because the experience is more than usability.

For the experts, usability is clearly an important aspect for the game quality, but there are other aspects to consider related to pleasure-based human factors, such as the satisfaction of learners who are blind, the multisensory aesthetic experience and their emotional response. In addition, they indicated that the behavior of learners who are blind towards multimodal games should also be evaluated considering gameplay experience, social interaction, fun, and playability.

There is an opportunity for the academic community to take an active role in creating diverse types of evaluation instruments, as well as evaluating the effectiveness of the existing ones, in the context of multimodal video games for blind learner's cognition enhancement.

5.3.4 PLUMB Proposal

Seeking to meet the identified challenges regarding usability evaluation, a set of PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind (PLUMB) were proposed. It is based on the analysis of the Expert Opinion Survey; on usability evaluation reported in the literature; and on the Standard List of Usability Problems (SLUP) in multimodal video games for learners who are blind.

PLUMB is a practical aid to help researchers and practitioners to properly plan and conduct usability evaluation of multimodal video games based on audio and haptics, designed for enhancing and improving cognition in children who are blind. It can be used by specialized Institutes and Schools for learners who are blind, helping teachers and instructors to evaluate multimodal video games, identifying whether a game is helping children instead of creating a barrier to their learning and cognition.

Furthermore, PLUMB can provide support to research groups and practitioners interested in performing usability evaluations capable of disclosing the most relevant issues related to the interface and interaction with multimodal games designed for cognitive purposes of children who are blind.

When asked about their opinion regarding the establishment of principles to assist researchers and practitioners in choosing the methods that better fit their usability requirements, to assess diverse aspects of multimodal interfaces in this context, all the authors agreed that it would be a useful aid to theirs and others' research. A6 commented that this outcome would fill significant gaps in their original research, while A7 stated that it would be useful to have a simple guideline on how to make a usability testing with people who are blind.

Inspired by the experts' comments on this topic and based on reviews of previous related studies and observations of current trends, PLUMB was created as a list of five principles for evaluating the usability of multimodal video games for learners who are blind.

The usability issues detailed in SLUP include problems reported by users and issues pointed out by researchers. Considering that, and in addition to the discussion and results presented in this section regarding the experience of researchers in this field, we propose that the usability evaluation of multimodal video games for developing cognition in people who are blind should observe the following principles:

1. **Be connected to the design process, in a formative way**. The identification of usability issues in this context should follow a "find-and-fix" approach, to ensure an interaction free of possibilities to distract the learner who is blind from the game cognitive purposes. Hence, the usability evaluation should be planned focused on identifying usability problems before the game is completed. A formative evaluation during the game design process can maximize the chances of effecting change and implementing the usability recommendations.

2. **Combine quantitative and qualitative methods to provide a holistic view of the data**. This approach can help develop rich insights into phenomena of interest while evaluating multimodal games for learners who are blind that cannot be fully understood using only a quantitative or a qualitative method. This principle aims to guarantee that usability evaluation uses multiple ways to

understand the interaction and possible issues between the user who is blind and the multimodal gaming interface. Hence, data collection should involve any techniques available to researchers that allow at least two types of data (e.g., numerical and text), two types of data analysis (e.g., statistical and textual) and two types of conclusions (e.g., objective and subjective).

3. **Combine empirical and analytical methods to comprehend both the users and researchers' point of view**. This principle aims to improve the accuracy of the identification of usability issues sources in the gaming interface and interaction. The use of both empirical (test-based) and analytical (inspection-based) usability evaluation methods provides direct information about how people who are blind use the multimodal game and their exact issues with its interface, while also having usability specialists judging whether each interactive element follows the necessary usability principles.

4. **Include both users who are blind and with visual impairments, preferably in the real context of use**. This principle aims to guarantee that the usability evaluation considers the different issues that arise from the diversity of perception and behavior between learners who still rely on visual residues and those who rely on hearing and touch only. Besides, the multimodal video game has to adequate the presentation of abstract information, feedback, and game stimulus to the real conditions where learners who are blind interact with the game: in schools or at home, assisted by a tutor.

5. **Guarantee a combination of methods capable of analyzing:**

    a. the user's perception of each interaction modality to execute specific tasks in the game;

    b. the user's understanding of the relationship between the modalities offered and the game tasks;

    c. the user's comprehension of the game goals and context, including the cultural and social context of the game narrative;

d. the user's ability to perform the expected tasks in the game correctly, in a way that the planned cognitive skills can be exercised;

e. whether the user can distinguish the diverse sonorous, visual and haptic feedbacks, associating them with the correct actions and objects in the game;

f. whether the user can combine modalities to achieve a goal in the game successfully;

g. whether the combination of modalities offered by the gaming interface and devices is adequate for executing the game tasks;

h. whether the modalities are appropriate to convey the information related to the game tasks;

i. whether the game devices offer the desirable support for the game modalities;

j. whether the modalities offered can ease the execution of a task;

k. whether the user can recognize visual, aural and haptic feedback in a game task;

l. whether the user can associate visual, aural and haptic feedback to a game task;

m. whether the user has a positive acceptance to the visual, aural and haptic feedback associated with the game tasks, objects, and instructions.

The criteria for setting a usability evaluation environment and for choosing UEMs in this context should be used as a guide to help practitioners and researchers to employ the most appropriate UEMs to evaluate the required aspects of these games in a particular context. However, we highlight that PLUMB is not a closed list. It can be expanded and improved, particularly as more knowledge is produced on the suitability of usability evaluation methods in this field.

5.4 Final Considerations

Identifying usability problems in serious multimodal video games designed with cognitive proposes for children who are blind matters because these issues will make them focus on the problems, distracting them from learning cognitive skills when interacting with the video game. However, the planning and conduction of usability field tests involving these users is not an easy task. For this reason, these tests are often conducted using inappropriate instruments, UEMs and procedures to their contexts, or even left aside.

Intending to offer clarity and structure to the conduction of usability field studies involving video games for cognitive development of young learners who are blind, three of the research steps followed in this research were presented in this chapter: Preliminary UEM Comparison, Development of Usability Evaluation Instrument and Expert Opinion Survey.

First, typical problems affecting the interaction of learners who are blind with audio and haptic-based multimodal video games were approached and discussed, introducing Standard List of Usability Problems (SLUP) to help designers avoid recurrent usability issues in the design of these games. Then, primary evidence concerning what types of usability issues different UEMs identify was presented, showing that SLUP can be useful to create focused usability evaluation instruments, such as the Checklist for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE). This checklist was designed to guide researchers and practitioners conducting field usability tests employing video, audio or participatory user observation.

Finally, to deepen the founds related to evaluation in this field, international researchers were surveyed, using an Expert Opinion Survey that produced data on challenges related to usability evaluation of multimodal video games for learners who are blind. To meet these challenges, a set of PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind (PLUMB) was proposed, based on the analysis of the Expert Opinion Survey and on SLUP.

SLUP, CLUE and PLUMB are practical aids proposed as part of a larger effort to scaffold knowledge in researchers and practitioners in this field. They represent a firm understanding that usable and pleasant multimodal games affect the lives of children who are blind by helping them in developing skills that will allow them to be more independent in their everyday lives and better integrated and included into society.

6. DESCRIPTIVE MODEL OF USABILITY EVALUATION INVOLVING LEARNERS WHO ARE BLIND

The present chapter proposes a descriptive model that reunites and summarizes the results obtained from the In-depth UEMs comparison (Step 6). It also presents the research hypothesis testing, which showed evidence about the difference of UEMs effectiveness regarding the different dimensions of multimodal interaction. This chapter addresses *RQ3 (Given a set of the most used UEMs when field-testing games for learners who are blind, what types of usability issues can each of them disclose?)* and *RQ4 (During field tests involving multimodal games for learners who are blind, how can UEMs be combined to evaluate interaction modalities?)*

Section 6.1 describes the followed methodology, detailing the subjects' profiles, the evaluated video games, the UEMs under comparison, and the procedures for evaluation and data analysis. Section 6.2 presents the statistical analysis of data obtained from UEM comparison, according to a set of criteria. Section 6.3 discusses the threats to validity of the experiment results. Section 6.4 introduces a descriptive model that reunites and summarizes all the knowledge produced on this research. Section 6.5 discusses some final considerations.

6.1 Methodology

The 6th step of the research methodology applied in this work (FIGURE 41) intended to test the research hypothesis and to deepen the evidence previously obtained from the Preliminary UEM Comparison. To achieve that, a comparative single-factor within-subject experiment design was used to assess the significance of UEMs effectiveness at three treatments.

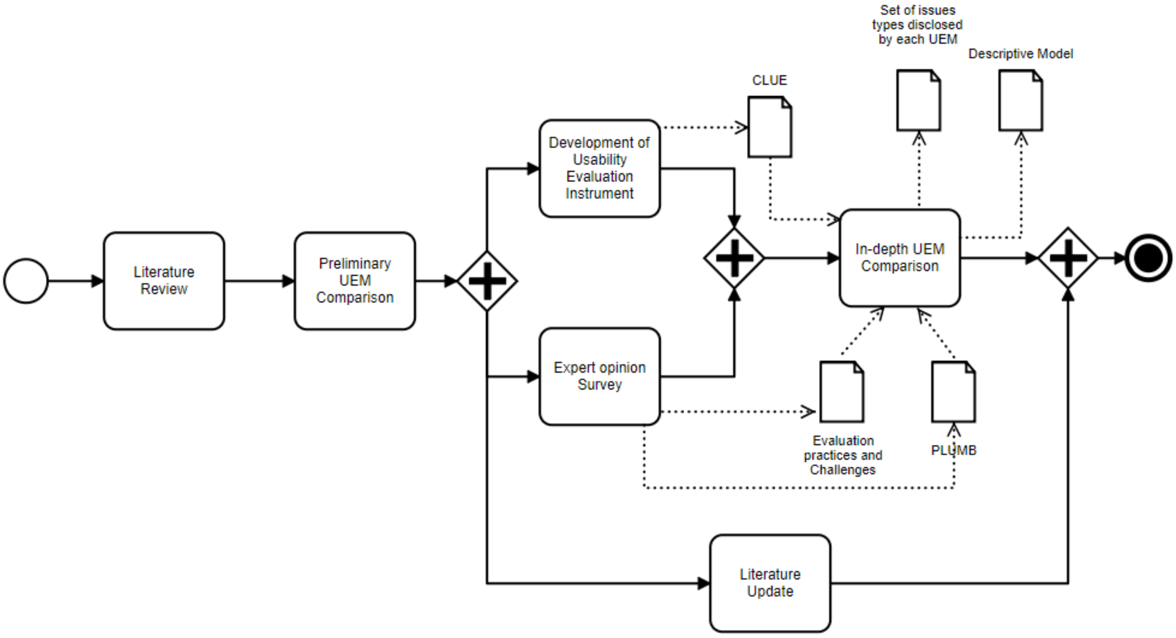
First, to collect data twenty independent onsite user evaluations were performed by two experimenters, using observation together with a Think-Aloud Protocol, semi-structured interview and CLUE. Half the users took part in the evaluations playing a role-playing desktop game, while the other half played a puzzle game for tablet. The goal of using two different games was to repeat the experiment and analyze whether the UEMs showed similar behavior in detecting usability issues.

After that, following the UEM comparison design approach discussed by Harston, Andre and Williges (2003), the list of usability issues produced by each UEM was compared. To do that, researchers defined an ultimate criterion for establishing the "goodness" of a particular method. After this, researchers select one of many possible actual criteria to approximate the ultimate criterion for UEM comparison. Such actual criteria are measures that serve as indicators or predictors of the ultimate criterion. In the present work, these criteria are thoroughness, validity and effectiveness.

Then, the experimenters applied a method representing the actual criterion to identify a “standard” set of usability problems existing in the target system interaction design. In the present research, the “standard” set of usability problems existing in each evaluated game was stablished by the video analysis of recorded test sessions, based on an adaptation of Erickson’s (2006) part-to-whole deductive approach, with data transcription of portions of the events recorded according to a coding scheme (DERRY et al., 2010).

After that, the experimenter applied the UEMs under comparison to the target design and calculated UEM performance metrics using the resulting usability problem lists about the “standard” usability problem list. Finally, the UEMs effectiveness were statistically compared to determine whether they were significantly different.

Figure 41 – Incomes and outcomes of the fourth step of the research methodology: In-Depth UEM Comparison



Source: produced by the author.

As a result, the UEM comparison revealed the difference among UEMs effectiveness and the types of usability issues disclosed by each UEM. Built on such results and on the evaluation practices and principles previously identified (see Chapter 5), a descriptive model of usability evaluation of multimodal video games for children who are blind was organized. It serves as basis for thinking about usability tests planning and conducting in the context of children who are blind playing multimodal video games, for cognitive development. Each of the phases followed in the process summarized above are detailed in the next subsections.

6.1.1 Usability Evaluation Methods Under Comparison

This study performed a comparison of UEMs applied during field studies and onsite user usability testing, since people who are blind should be included in the evaluation of this type of application, preferably in their real context of use. Although expert evaluations on multimodal video games for children who are blind is valuable, this research has demonstrated that proper guidance on usability testing is a primary concern in this field, as previously discussed in the Expert Opinion Survey (See Chapter 5).

Consequently, this research focus relies on comparing UEMs while collecting empirical data during the observation of representative end users, using the product to perform realistic tasks (RUBIN & CHISNELL, 2008). This approach employs an iterative cycle of tests intended to expose usability deficiencies and gradually shape the final product, which is compatible with the process followed for the development of games and environments for learners who are blind (DARIN, SÁNCHEZ, ANDRADE, 2015).

All the UEMs analyzed in this work can be used in empirical user studies, i.e., in which usability is assessed by testing the interface with real users (NIELSEN, 1995). They are also adequate for exploring usability issues in the field, which allows the collection of in-depth data about the product itself because the context is familiar to the user (KANTNER, SOVA & ROSENBAUM, 2003).

The goal of a UEM is to produce descriptions of usability problems observed or detected in the interaction design for the purpose of analysis and redesign (HARSTON, ANDRE & WILLIGES, 2003). Considering that, the UEMs under comparison in this comparative study are observational notes (also known as field notes), CLUE observational checklist – both obtained independently during direct real-time observations with Think Aloud Protocol (TAP) - and an after test contextual semi-structured interview.

TAP is a verbal protocol method used to gather usability data during system evaluation by asking the users to vocalize their thoughts, feelings and opinions while interacting with the system (ERICSSON & SIMON, 1984). TAP is a widely used method in usability testing to gain insight into the participant’s thought process and consists in one of the six major characteristics of a valid usability test (DUMAS, 2003). In TAP, before the task, the facilitator instructed the participant on how to think aloud, gave a brief example and a chance to practice the protocol. During the task, the facilitator observed and recorded the session, and would remind the participants to keep reporting on their thoughts. The focus was on users' interactions with the game being tested, encouraging reporting on thoughts, expectations, feelings, and anything else the participants had on their minds.

Field notes contain observations and researchers' personal reflections and impressions on user test, with the purpose of capturing firsthand behaviors and interactions that might not be noticed otherwise (WEST & LEHMAN, 2006; STOJANOV, 2012). Each test session produced one or more sets of annotated test materials reflecting administrator and observer notes (KANTNER, 1994). These notes started during the actual observation, when the observer wrote what was necessary to fill in the details later. Then, as soon after the observation as possible, the notes were augmented with as many details as the observer could remember (SEAMAN, 1999). Besides, data was also used as numerical evidence by extracting quantitative data from the collected text (MAXWELL, 2010). In this work, experimenters used a predefined template of observation sheet to write their field notes down, using the fields strengths, weaknesses, errors, doubts and general observations.

Semi-structured contextual interviews capture the individual richness of user behavior in a specific work context, especially when associated to qualitative observation and analysis of social settings (BAECKER, 2014). The contextual interview was used to answer questions about issues that are broader than individual tasks (KANTNER, SOVA & ROSENBAUM, 2003). It consisted in asking probing questions to uncover specific details needed to complete or clarify the observation details, asking for feedback from the participants about their experience using the interface. This type of interview should be conducted in the users' natural environment whenever possible, as occurred in the present research (WOOD, 1997; KANTNER, SOVA & ROSENBAUM, 2003).

In this work, the interview had 16 questions and was developed according to the techniques proposed by Wood (1997) for semi-structured interviewing in user-centered design. As so, it included the following types of questions: object identification (Grand Tour and Case-Focused), object relationship (Dyadic Contrast and Category Label), and TAP-generated (Concurrent, Aided Recall and Cross-examination).

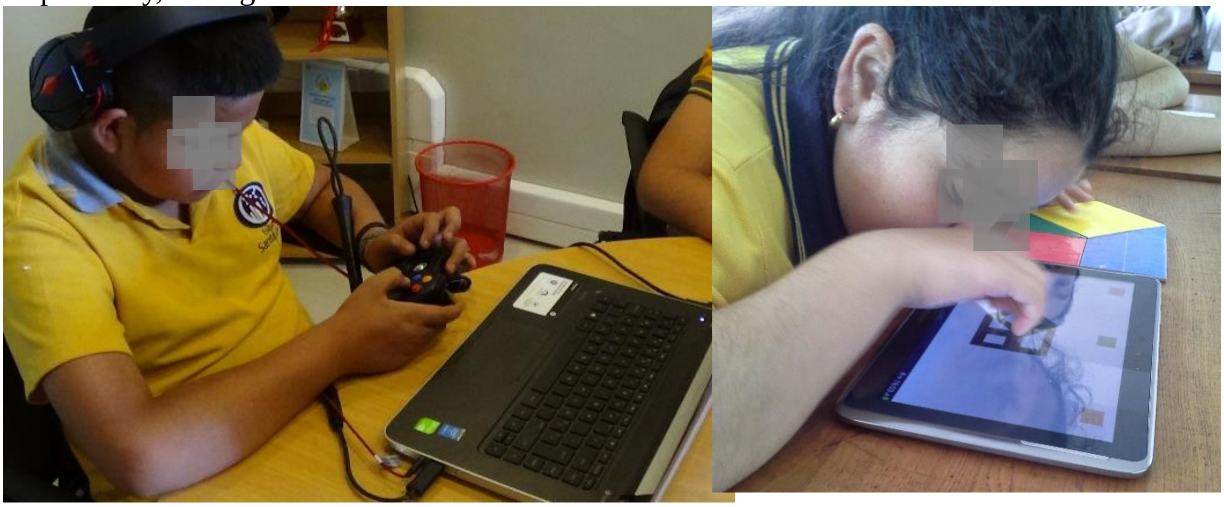
6.1.2. Target Multimodal Video Games

The comparison of UEMs requires that the different methods under comparison be applied to the target design, to calculate each UEM performance metrics using the resulting usability problem lists produced by each UEM (HARSTON, ANDRE & WILLIGES, 2003). In this study, the target designs were two multimodal video games designed for the cognitive development of children who are blind: AudioSims and AudioGeometry (FIGURE 42). These games were chosen among the five games previously analyzed during the Preliminary UEM Comparison (See Chapter 5), mainly because they were developed using technologies ans plataforms available nowadays, while the others required old Operating Systems installation. Furthermore, AudioSims and AudioGeometry were available to install locally and included distinct combinations of interaction devices, feedback and interface, which are important for this work.

AudioSims is a role-playing game for PC in which players access a virtual environment with the support of sounds and 3D images. Using their auditory and haptic perception and O&M knowledge, players are supposed to solve navigational problems while interacting using a joystick with haptic feedback. They aim to enhance players cognitive skills of mental mapping, Orientation & Mobility and auditory and haptic senso-perception. AudioGeometry is a puzzle role-playing game for tablet that provides a multi-touch interaction with a 3D graphic interface (for activities on the Island) and 2D graphic interface (for solving math problems), together with sonorous, visual and tactile feedback

AudioSims cognitive tasks are designed to improve mental mapping, orientation and mobility, and auditory and haptic senso-perception. AudioGeometry, on the other hand, is projected to improve skills related to mental mapping, spatial structures, and logical and geometrical thinking. The variety of video games allowed the examination of problem lists addressing different types of game modalities and their associated feedback. More details about both games are available in Section 3.1.2.

Figure 42 – Children who are blind interacting with AudioSims and AudioGeometry, respectively, during field tests.



Source: Photograph taken by evaluators, in Santiago (Chile)

6.1.3 Sampling Plan

In this phase of the present study, each of the two selected video games was evaluated with 10 users who are legally blind, in their real context of use (special schools), totalizing in 20 test sessions to be compared. It is important to highlight that this work examines and records the quality of interaction rather than quantifiable human performance, and focuses on formative usability evaluation, as well as on the use of UEM and usability instruments instead of the participants' performance per se. Therefore, the lists of problems generated after the test sessions by each UEM applied in the 20 sessions was compared for each video game.

6.1.3.1 Sample size estimation

The reasoning behind the use of 10 users for each video game evaluation had roots in two main reasons: (i) the predictions offered in the literature about formative usability tests sample sizes (LEWIS, 2014); and (ii) the difficulty to involve participants with disabilities in onsite and lab-based usability tests (LAZAR, FENG & HOCHHEISER, 2017).

The present work considered the analysis of challenges related to usability evaluation discussed by Lewis (2014) regarding the validity of the sample size predictions for formative usability testing. It included the best known "magic number" 5 (NIELSEN, 2000; NIELSEN & LANDAUER, 1993), and other common predictions of 8 participants (PERFETTI & LANDESMAN, 2001; SPOOL & SCHROEDER, 2001) and 10±2 participants

(HWANG & SALVENDY, 2010). Hence this research followed Lewis' (2014) recommendation that, rather than relying on magic numbers of any kind, when planning samples sizes for a one-shot or iterative formative usability testing, the use of formulas or tables based on the cumulative binomial probability formula is more reasonable.

To achieve that, the cumulative binomial probability formula, which is an aid in sample size estimation for problem-discovery studies (LEWIS, 1984), was used in this work:

$$P\ \textit{(at least one occurrence)} = 1 - (1 - p)^n$$

Nielsen (1994), Virzi (1990,1992), and Wright and Monk (1991) have shown that this equation can predict the proportion or fraction of the total existing problems (P) that one would expect to find, given the average detection rate (p) of each iteration/session with a user and the number of iterations/users (n). The detection rate is the fraction of existing problems found in one iteration (e.g., with one user in lab testing). This equation can also be used to judge how many participants (n) are required in an evaluation study to identify a specific percentage of problems (P) in the interface (VIRZI, 1992).

In the present research this formula was initially used to estimate how many participants would be necessary in the usability tests. For that matter, the literature-based estimation found by Lewis (1994) and Virzi (1992) was used. It predicts that the average rates of problem detection (p) in usability formative user tests range from .16 to .42 for any one individual. This estimation has been verified and proved in several experimentations (LEWIS & JAMES, 2001; ANDRE, HARTSON & WILLIGES, 2003; TURNER, LEWIS & NIELSEN, 2006; BASTIEN, 2010).

Using the cumulative binomial probability formula to estimate the number of users (n) for p=0.16 and for p=0.42, to identify 85% (P=0.85) of the existent UI problems, it was obtained that it would be needed to test on average n=10.88 users; and n=3.48 users to discover the same percentage of problems p=0.42. Thus, for this research it was estimated that 10 participants would be adequate to discover most of the problems in each of the two evaluated games.

To verify the adequacy of the 10-users sample, after the tests were finished, a matrix of users and problem occurrences was used to calculate the actual problem occurrence rate (p) for each game. For AudioSims, given the distribution of 107 total problems identified amongst 10 users, the normalized problem occurrence rate was p=0.39, for P=0.95. Hence, the cumulative binomial probability formula was used once again to calculate the number of users for p=0.39, showing that it would have been enough to test on average n=6.06 users to discover 95% percent of the existent UI problems in AudioSims. For AudioGeometry, given the distribution of 88 total problems identified amongst 10 users, the normalized problem occurrence is p=0.36, for P=0.95. It means that it would have been sufficient to test on average n=6.71 users to discover 95% percent of the existent UI problems in AudioGeometry.

Thereby, the chosen sample size was considered satisfying, corroborating with Macefield`s (2009) findings that for comparative studies group sizes of between eight and 25 participants typically provide valid results, with 10 to 12 being a good baseline.

As previously stated, the choice of a sample size of 10 users per game was also impacted by the difficulty to involve participants with disabilities in usability tests. According to Lazar, Feng and Hochheiser (2017), one of the greatest challenges of researching with users with disabilities is having access to the participants themselves and finding appropriate users with the specific impairment that is the focus of the study. The authors argue that, in researches focusing on users with disabilities, it is generally acceptable to have 5-10 users with a specific disability taking part in a study.

6.1.3.2 Population characteristics

The 20 users were selected among students in two special schools in Santiago (Chile), because of the access to users fulfilling the following criteria: (i) to be a child or adolescent between seven and 18 years old; (ii) to be a student from 1st grade to 8th grade[10]; (iii) to have a proven ophthalmological diagnosis regarding legal blindness; and (iv) to dispose of 1h to take part in an evaluation session. Given these criteria, the participants were randomly selected by the school principal, among the children who were free from their regular activities, by the time that the evaluators initiated the tests.

Each participant answered a brief initial questionnaire before the testing session to identify their previous experiences with technology and with digital video games, but these factors were not parameters for selecting or excluding participants. Consequently, the technique to choose participants in this work was classified as selective or purposeful sampling (COYNE, 1997), since it was shaped by the availability of children at schools, and time and users' restrictions.

[10] In Chilean Education System, the Primary/Basic Education encompasses from 1st to 8th grades, according to information available at the Chilean Ministry of Education (http://escolar.mineduc.cl/basica)

Female (40%) and male (60%) learners who are totally blind (30%) and with visual loss (70%), ranging from 9 to 13 years old, attending from 3rd to 7th grade participated in tests with AudioSims. Female (50%) and male (50%) learners who are totally blind (20%) and with visual loss (80%), ranging from 10 to 13 years old, attending from 4th to 8th grade participated in tests with AudioGeometry. Table 25 summarizes the characteristics of participants, while Table 26 and Table 27 detail their profiles for each game.

Table 25 - Summary of gender and age characteristics for users who participated in test sessions with AudioSims and AudioGeometry

	NUMBER OF USERS			AGE		
	Female	Male	Total	Mean	Range	SD
AudioSims	4	6	10	10.8	9-13	0.84
AudioGeometry	5	5	10	10.9	10-13	0.9

Source: Produced by the author

Table 26 - Profiles of users who participated in test sessions with AudioSims

USER	AGE	GENDER	GRADE	VISUAL ACUITY	DIAGNOSIS
C1	11	M	5th	Visual loss	Moderate nystagmus and severe acute visual loss
C2	10	F	4th	Visual loss	Horizontal nystagmus and myopia
C3	10	F	4th	Blind	Bilateral congenital aniridia
C4	9	M	5th	Blind	Bilateral optic nerve atrophy due to retinopathy of prematurity
C5	11	M	4th	Visual loss	Retinal detachment
C6	13	M	6th	Visual loss	Bilateral astigmatism, anisometropia, nystagmus and amblyopia (Right eye)
C7	12	M	7th	Visual loss	Cone-rod dystrophy, high myopia and astigmatism
C8	11	F	3rd	Blind	Leber congenital amaurosis
C9	10	F	5th	Visual loss	Congenital cataract and high myopia
C10	11	M	4th	Visual loss	Leber congenital amaurosis

Source: Produced by the author

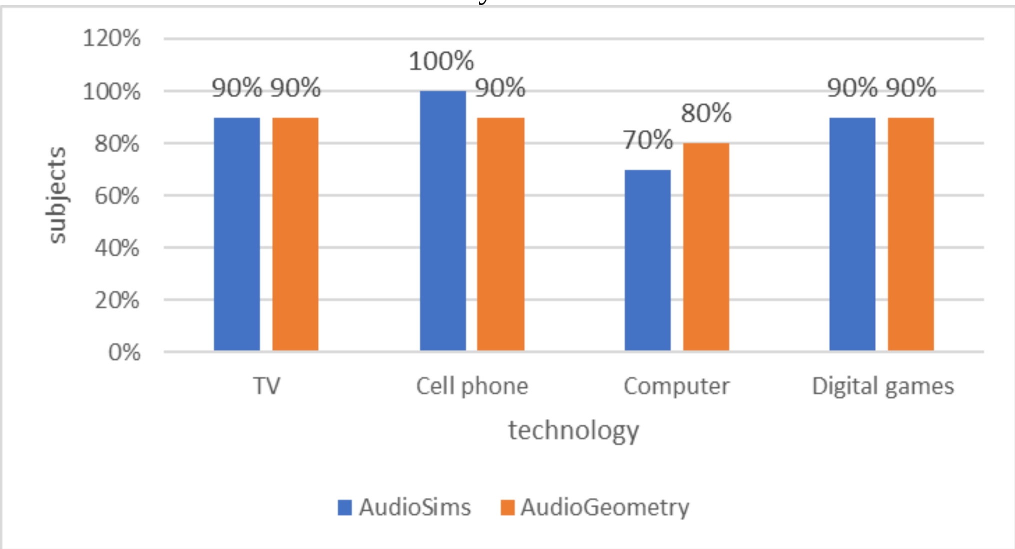
Table 27 – Profiles of users who participated in test sessions with AudioGeometry

USER	AGE	GENDER	GRADE	VISUAL ACUITY	DIAGNOSIS
C11	11	M	4th	Visual loss	Retinal detachment
C12	12	M	6th	Visual loss	Bilateral myopic astigmatism, anysometropy, amblyopia (right eye) and nystagmus
C13	10	M	5th	Visual loss	Toxoplasmosis with macular compromise in both eyes and bilateral nystagmus
C14	11	F	5th	Visual loss	Bilateral congenital cataract
C15	10	F	4th	Blind	Bilateral congenital aniridia
C16	10	F	5th	Visual loss	Congenital cataract
C17	13	F	8th	Visual loss	Anophthalmia (right eye) and peters' anomaly (left eye)
C18	10	F	4th	Visual loss	Horizontal nystagmus and myopia
C19	12	M	6th	Visual loss	Retinopathy of prematurity
C20	10	M	5th	Blind	Bilateral optic nerve atrophy due to retinopathy of prematurity

Source: Produced by the author

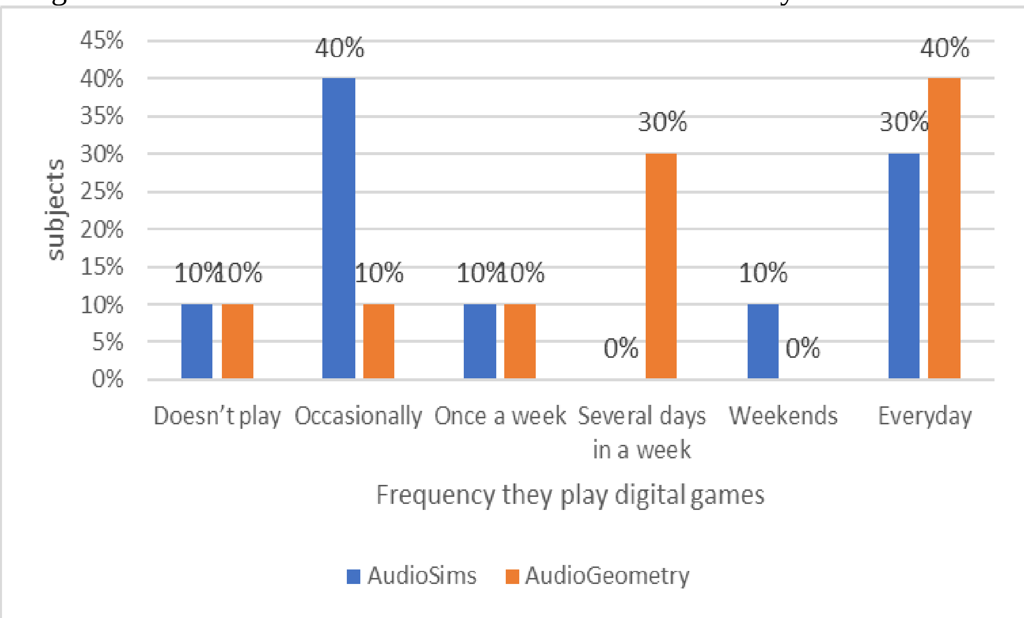
All the participants had previous experience with at least one type of interactive technology including television, cell phone and/or smart phone, computer and digital games (platform and/or mobile), as summarized in Figure 43. Besides, 90% of the users who participated in the tests are familiar with video games, playing in variate frequency in their everyday lives (FIGURE 44).

Figure 43- Experience with technology reported by users participating in the test sessions with AudioSims and AudioGeometry



Source: Produced by the author

Figure 44 - Frequency of playing any types of digital games reported by users participating in the test sessions with AudioSims and AudioGeometry



Source: Produced by the author

6.1.4 Data Collection

Each usability test session was conducted by two independent experimenters (head and auxiliary/observer) from the Center for Computing and Communication for the Construction of Knowledge, who worked together in every session (TABLE 28). Both evaluators had experience in dealing with children who are blind during usability evaluations. They both followed the instructions from a research protocol detailing each procedure that must be followed during evaluation. The information collected from user testing was properly kept anonymous and private and was used exclusively for the analysis of the game in question in the scope of this investigation.

Table 28 - Profiles of experimenters who conducted the test sessions with AudioSims and AudioGeometry

Degree	Experience	Expertise
Bachelor degree in Education	> 10 usability field evaluations	Cognition of children who are blind
Undergraduate degree in Computer Science and Engineering	> 10 usability field evaluations	Multimodal games design and usability

Source: Produced by the author

Before beginning the test session, the evaluator requested from the school a room with no distractions, and set the evaluation environment, including a camera with a tripod so that each child's play session could be recorded. The camera was placed in a way that it framed the game screen, the child's hands and a partial view of the child's face. The camera was placed close to the child to capture properly the audio of the game, the users' TAP comments, and the experimenter's interventions, questions and comments.

Before a child entered the room, the camera, all game controls and devices, and all evaluation instruments were already available and organized. When a child entered the room, the experimenter explained what the investigation was about, as well as the game that would be played and its controls.

Once the session started, the experimenter avoided any interruptions and should avoid giving explanations about what was happening in the game, or about what the children should do in the next activity, as an important part of the evaluation is to verify whether the game communicates its tasks and its controls properly and if the children understand them. However, if the children asked what to do, or expressed that they could not recover on their own from a situation, the experimenter would intervene and assist them until the situation was back to normal.

In each game session, students first answered to an initial questionnaire to collect demographics data and information related to users' experience with games and digital technology. They then received instructions about TAP, and about the game controls. After that, they played the first two stages of the game. While the children played, the experimenters observed their interaction with the game and filled CLUE and annotations sheet. After the gaming session, the users answered the semi-structured contextual interview.

The activities users executed during test sessions addressed the first two phases of each video game, which were the training phase and Level 1 for AudioSims (4 tasks), and levels 1 and 2 for AudioGeometry (4 tasks and their correspondent puzzles). In AudioGeometry, since the puzzles are slightly different for different grade levels, this option was preselected by the head experimenter before the test, according to the user profile. The task audio descriptions provided by AudioSims is presented in Table 29, while the ones given by AudioGeometry are shown in Table 30.

Table 29 - Description of the tasks that users playing AudioSims performed

TASKS	TASK AUDIO DESCRIPTION[11] IN THE GAME
Initial Instructions	You are at your home. While executing your activities, you have to satisfy four basic needs. First, hunger: you satisfy it by eating. You should go to the refectory for a snack or to the kitchen to prepare some food. Second, hygiene: satisfy it by washing your hands are taking a bath. You should go to the bathroom and use the sink or the shower. Third, sleep: satisfy it by resting or sleeping at your room. Lastly, bladder: satisfy it by using the toilet. Your bladder, stomach, energy and smell will let you know when you have to go to the bathroom, to feed, to sleep, or to bath. You have to find in the house the correspondent place to satisfy your needs. Hello, nice to meet you. I am Mario Castillo, the president of the Sports Federation. Congratulations, you made it to the University. I came to welcome you, we are all very happy to have you here. I am going to walk you personally to your residence here at the sports campus C5Sims. I have to say that the coaches have been talking very well about you. I have great expectations about you. I take this chance to inform you that the federation assigned a home to live for all the scholars, which is completely furnished. You have at your disposal living room, dining room, bathroom, kitchen, activity room and of course, your room. We arrived! Accommodate and install your belongings. I hope you like it. Oh, it is so late! I am leaving. I almost forgot: here are your keys. I will see you when the competitions begin.
Task 1	You are in front of your home. Locate the door and get inside the home. In front of you, you will find a hall that communicates with all the dependencies of your home. You will leave your bags in the room that is at Southwest. The route is this: walk down the hall towards south; at the end, you will find the door to the training room. Turn to West and the next door to your left is your room. Once inside, check the room and put your clothes in the closet.
Task 2	[A bell rings once] The bell rang! Go to the door to see who it is. The route is this: leave your room; then, a quarter of a turn to the east; walk to the end of the hall; turn north; and continue going straight ahead down the hall until you get to the door.
Task 3	Good morning, these are the C5SIMS magazines. They appear once a month with campus information and sports news. This month issue is dedicated to soccer. I will come by and deliver them monthly. Thanks and bye. You can leave the magazines in the living room. For your recognition, go rest for a while. The route is this: half turn, go down the corridor to the south, the first door on the right.
Task 4	The bathroom is at southwest. The route is this: exit to the corridor, turn south, continue until the end of the corridor, turn west, and in the left, the next door after your room corresponds to the bathroom. Then, you can go back to the living room and watch television.

Source: Produced by the author

[11] The original audio of both games is in Spanish, which is also the mother language of the evaluators and participants. The descriptions presented in this work are translations that closely follow the form and organization of the original Spanish audio transcription.

Table 30 - Description of the tasks that users playing AudioGeometry performed

TASKS	TASK AUDIO DESCRIPTION IN THE GAME
Initial Instructions	Welcome to the geometric island. This game is a representation of a virtual world where you are the main character. You are a survivor from a shipwrecking and you have just arrived to an unknown island with mysterious geometric puzzles. Your mission is to collect the necessary material to build a boat and leave the island. To do that, you have to solve each challenge located in special places in the island. You will find various dangers and risky situations, but more importantly: you will have to use all your knowledge from the geometry classes and your senses to be able to go back home!
Task 1	Hello, welcome to the island! We do not see much different faces around here. If you want to go back home you should help the inhabitants of the island. Go to the farmer.
Puzzle 1	You find two walls with small sides. How are they represented with geometry? The horizontal line is the ground. [The game screen changes for the 2D puzzle interface] the angle of inclination of the cliff that you must climb is obtuse. Which one should you choose? A) The wall of the left. B) The wall on the right.
Task 2	Nice to see you! It has been a long time since the last time I saw a person. As a reward for your visit, I will give you an emerald. Go visit the shaman who is in the temple, towards south from here.
Puzzle 2	You climb the cliff very carefully using hands and feet firmly. You realize that the wall has a map with a mark that looks like a coordinate. [Game interface changes for 2D puzzle interface]. This point represents a special place on the island that you must reach. The following grid map shows the coordinate. What is it exactly? Locate it: A) It is the point 4,3 B) It is the point 2,0
Task 3	Welcome to the Geometric Island. I see that you are new in this mysterious place and in equal to all you have been swallowed. I will try to see how good you are with geometric exercises. [A bell rings]
Puzzle 3	[Game interface changes for 2D puzzle interface] which figures make up the following scheme: A) Square, rectangle, pentagon. B) Square, rectangle, triangle.
Task 4	I see that you are quite skilled. Take these trunks that will help you make a boat. Come back in a minute, I have something else for you.
Puzzle 4	Hello again. I need your help this time. Complete the next challenge I have prepared for you [Game interface changes for puzzle interface] Explore the following figures and identify which of them have perpendicular and parallel sides. A) The figure of the left. B) The figure on the right. C) The two figures. D) None of the figures.

Source: Produced by the author

6.1.5 Qualitative Analysis for the Identification of Usability Problems

After carrying out the usability tests, the process of data analysis followed the approach discussed by Rubin and Chisnell (2008), which consists mainly in compiling and summarizing data before analyzing it. All the data analysis was done separately for each UEM and then grouped by video game, to identify the lists of usability problems produced by the UEMs under comparison. To compile and organize data, first the raw data was systematized. Raw data was obtained from the experimenters' field notes, CLUE, recorded test sessions, and contextual interview. In the remainder of this section, the procedures for data analysis followed for each UEM, as well as for the identification of usability problems are presented.

6.1.5.1 Description of Data Analysis

The raw data in handwritten experimenters' field notes were organized into readable narrative descriptions with major themes, categories, and illustrative case examples. They were extracted inductively using qualitative content analysis, according to the approach described by Patton (2005). Then, they were sorted into qualitative and quantitative data onto a spreadsheet, to help recognizing patterns.

CLUE data was verified for the presence or absence of each problem addressed by CLUE. The problems identified were codified and tabulated, as well as their frequency, severity, and in which task they occurred. The additional comments made by observers in CLUE items were analyzed in the same way as field notes.

The answers from the contextual interview were transcribed, and critical comments were identified by using open and axial coding approaches for the categorization of transcripts and identification of goals connections among the findings they revealed (BURNARD, 1991).

Finally, for the analysis of the videotaped user sessions, first, preliminary logfiles for each of the evaluation sessions were completed by looking through all videos. Then, portions of events of each video recorded were transcribed and categorized (DERRY et al., 2010), according to a same coding scheme. The video analysis tool BORIS (FRIARD & GAMBA, 2016) was used to register the coding and notes during the video analysis.

The coding scheme used to code and categorize qualitative data obtained during the video analysis, as well as the qualitative data produced by the others UEMs, was an adaptation of the coding scheme proposed by Barendregt and Bekker (2006), which lists 15 breakdown indication types for children's computer games (TABLE 31). They take into account that fun, in addition to usability, is an important factor in games. Also, they understand that children behave differently from adults. Each of these aspects impacts in the user interaction.

To address the specificities of the interaction of children who are blind, in this work the original Barendregt and Bekker`s (2006) categories description were matched with SLUP items, using an affinity diagram to organize the items into subgroups based on the similarities between them (COHEN, 1995). The final coding scheme used in each qualitative analyses of this work contains 17 breakdown indication types, as shown in Table 32.

Table 31 - Original categories of breakdown indication types

Short Description	Definition
Breakdown Indication Types Based on Observed Actions With the Game	
wrong action	An action does not belong in the correct sequence of actions. An action is omitted from the sequence. An action within a sequence is replaced by another action. Actions within the sequence are performed in reversed order.
execution/motor skill problem	The user has physical problems interacting correctly and in a timely manner with the system.
passive	The user stops playing and does not move the mouse for more than 5 sec when an action is expected.
impatience	The user shows impatience by clicking repeatedly on objects that respond slowly, or the user expresses impatience verbally.
subgame stopped	The user stops the subgame before reaching the goal.
Breakdown Indication Types Based on Verbal Utterances or Nonverbal Behavior	
wrong goal	The user formulates a goal that cannot be achieved in the game.
wrong explanation	The user gives an explanation of something that has happened in the game, but this explanation is not correct.
doubt, surprise, frustration	The user indicates: Not being sure whether an action was executed properly. Not understanding an action's effect. The effect of an action was unsatisfactory or frustrating. Having physical problems in executing an action. That executing the action is difficult or uncomfortable.
puzzled	The user indicates: Not knowing how to proceed. Not being able to locate a specific function.
recognition	Recognition of error or misunderstanding: The user indicates recognizing a preceding error or misunderstanding.
perception problem	The user indicates not being able to hear or see something clearly.
bored	The user verbally indicates being bored. The user nonverbally indicates being bored by sighing or yawning.
random actions	The user performs random actions, indicated verbally or nonverbally.
help	The user cannot proceed without help and either asks for it or the researcher has to intervene in order to prevent serious problems.
dislike	The user verbally indicates disliking something.

Source: Barendregt & Bekker`s (2006)

Table 32 - Categories of breakdown indication types after being enriched with SLUP items. These categories were used in this work for codification during qualitative analysis of videos, interview and field notes

SHORT DESCRIPTION	DEFINITION
BREAKDOWN INDICATION TYPES BASED ON OBSERVED ACTIONS WITH THE GAME	
WRONG ACTION	An action does not belong in the correct sequence of actions. An action is omitted from the sequence. An action within a sequence is replaced by another action. Actions within the sequence are performed in reversed order
EXECUTION OR MOTOR SKILL	The user has problem/physical difficulty to: interact correctly and in a timely manner with the game; handle the haptic device; move in the virtual environment; rotate in the virtual environment.
PASSIVE	The user stops playing and does not move the character for more than five seconds when an action is expected
IMPATIENCE	The user shows impatience by repeating an action that responds slowly. The user expresses impatience verbally.
SUBGAMES STOPPED	The user stops the game, puzzle, task or quest before reaching the goal.
BREAKDOWN INDICATION TYPES BASED ON VERBAL UTTERANCES OR NONVERBAL BEHAVIOR	
POOR FEEDBACK	The available vibrating feedback for a specific object or action is incorrectly applied. The available audio feedback for a specific object or action is incorrectly applied. The available vibrating feedback for a specific object or action is insufficient. The available audio feedback for a specific object or action is insufficient. The user has difficulty to identify the purpose of a specific audio feedback.
WRONG GOAL	The user formulates a goal that cannot be achieved in the game. The user has difficulty to understand the game goal.
WRONG EXPLANATION	The user gives an explanation of something that has happened in the game, but this explanation is not correct. The user associates wrongly game sounds with game objects or action. The user does not realize that a sound is related to an action.
DOUBT, SURPRISE OR FRUSTRATION	The user indicates: not being sure if he/she has done right; not understanding the effect of an action; finding the effect of an action frustrating; having physical problems in executing an action; that executing the action is difficult or uncomfortable; that accomplishing game goals is too difficult or frustrating.
PUZZLED	The user indicates: not knowing how to proceed; not being able to understand the orientation/location information received from the game; having difficulties to follow the game instructions received; not being able to locate a specific function; being confused about how to use the game controls.
RECOGNITION OF ERRORS	The user indicates recognizing a preceding error or misunderstanding.
RANDOM ACTIONS	The user performs random actions, indicated verbally or nonverbally.
MOTIVATING STORY	The user has difficulty to recognize and differentiate the game scenarios. The user has difficulty to recognize and differentiate the game characters. The user has difficulty to understand the distinct roles existing in the game.
PERCEPTION PROBLEM	The user indicates not being able to: hear the game sounds clearly; discriminate the form of game elements; discriminate the textures of game elements; perceive textures; recognize a haptic figure; associate a sound to his/her prior knowledge; recognize a sound; identify a sound; make correspondence between a haptic figure and a real-world object. The user indicates not being able to perceive clearly: the information conveyed by colors; the information conveyed by images; the information conveyed by sound.
HELP	The user cannot proceed without help and neither asks for it, or the researcher has to intervene in order to prevent serious problems.
DISLIKE	The user verbally indicates disliking some of the game elements. The user verbally indicates being: annoyed by any of the game controls; annoyed by the frequency of haptic feedback; annoyed by sounds or voices; uncomfortable with the speed of spoken audio or TTS.
BORED	The user verbally indicates being bored. The user nonverbally indicates being bored (sighing or yawning).

Source: Produced by the author

6.1.5.2 Usability Problems Identification

During the analysis and codification of all the obtained data, they were examined thoroughly for the identification of errors, difficulties of interaction and usability problems, including tasks that users failed. Then, a source of error analysis was conducted to identify the cause for each problem. As the usability problems were identified, they were described in detail and ranked in relation to their severity. Experimenters identified usability problems in each user session, for each game and constructed a problem set for each UEM per game, comprising the lists of problems of all participants. That set formed the basis for the participants' problem matching, for each game.

To assure quality in usability problem description and reporting, Lavery, Cockton and Atkinson's (1997) model to structure the representation of usability problems was used, seeking to allow a sound comparison and matching of problems. According to Lavery and colleagues' model, the descriptions of usability problems have four components, which were used to document the identified usability problems: a cause (e.g., a design fault), a breakdown (e.g., the user misinterprets feedback), a behavioral outcome (e.g., the user's task failed), and a design change (e.g., modification of a feature).

In addition to these aspects, other information complemented the descriptions to avoid inconsistency of terms and values of usability defect data and a classification of problems based on insufficient attributes, as indicated by Yusop, Grundy and Vasa (2017). Table 33 describes the 12 fields selected to document each usability problem identified by each of the UEMs.

The four components of Lavery, Cockton and Atkinson's (1997) model were also used for matching usability problems, as suggested by Hornbæk and Frøkjær (2007), by using the four components as the basis for determining the extent to which problem descriptions were in agreement. Two evaluators matched the problems in degrees depending on the number of components on which they matched: for every group of problems this degree went from 0 (no overlap in any component) to 4 (overlap with respect to the problems' cause, breakdown, outcome, and design changes). The other aspects in the problem description were used to clarify any doubts and provide context to the analysis. Later, they were also useful for the comparison of UEMs problems lists.

Table 33 – Fields used to describe and report the usability problems found in user tests with both video games

PROBLEM DESCRIPTION FIELD	FIELD DESCRIPTION	RESULTS FORMAT
ID	Unique identifier for usability problem per user	P[user code][problem number] Ex. Problem IDs for user C01: PC0101, PC0102, PC0103... PC0113 ...
PROBLEM TRANSCRIPTION	Transcription of the video/audio file where the problem was identified	*Text in the following format*: [context description] C[user code]: what the user said Evaluator: what the evaluator answered [any actions that happened in between]
SEVERITY	Severity rating for assessing the impact of a problem, following Rubin (1994) and Dumas and Redish (1999).	Assigned from 1-4 according to whether the problem: 1: prevents task completion 2: causes a significant delay or frustration 3: has a relatively minor effect on task performance 4: is a suggestion
CONTEXT	The context describes when the problem occurs, suggesting possible frequency and, in some circumstances, the solution	Textual description
COGNITIVE TASK	Cognitive task points which of the game tasks the user was performing when the problem occurred	*One of the following:* Initial instructions Task 1 Task 2 Task 3 Task 4 Throughout the whole game
WHAT IS THE CAUSE	The cause describes what is wrong and needs to be fixed	Textual description
TYPE OF CAUSE	Type of cause that may lead to a breakdown in the user's interaction	*One of the following:* 1 game design fault 2 audio interface design fault 3 haptic interface design fault 4 graphic interface design fault 5 knowledge required 6 input device fault
CATEGORY OF BREAKDOWN SUFFERED	Category of breakdown suffered, according to the coding scheme used	*One of the following:* 1 wrong action 2 execution or motor skill 3 passive 4 impatience 5 task stopped 6 poor feedback 7 wrong goal 8 wrong explanation 9 doubt, surprise, frustration 10 puzzled 11 recognition of errors 12 random actions 13 motivating story 14 perception problem 15 help 16 dislike 17 bored
DESCRIPTION OF BREAKDOWN SUFFERED	Definition of the breakdown suffered	One of the items described in the right column of Table 32
BEHAVIORAL OUTCOME	It addresses the unfolding of the interaction following a breakdown. For example, after the user forms an incorrect goal, does not select the correct action, or misinterprets the system response, the user may stop and so their task fails, or they may try some other actions.	Textual description
PERFORMANCE OUTCOME	Whereas a behavioral outcome fits into a narrative, this form of outcome is a statement and is related to usability criteria. Common statements can include: time to perform a task increased, the user's task failed and the user recovered from the breakdown	*One of the following:* 1 the user suffered task failure and required assistance 2 the user took longer than necessary to achieve the task 3 the user did not suffer task failure and was able to continue without assistance 4 the user suffered an increase in anxiety 5 the user recovered from the breakdown 6 the user suffered task failure, but did not notice it
SOLUTION	Suggestion of solution for the cause	Textual description

Source: Produced by the author

For the purposes of this work, the main outcome from analyzing the data resultant from the usability tests are the usability problem lists produced by each UEM under comparison. According to the approach discussed by Harston, Andre and Williges (2003), in practice, each UEM produces a list of usability problems, and the comparison of UEMs consists in comparing and manipulating their usability problem lists. Consequently, the comparison of UEMs in terms of problem sets allows to identify, for example, whether a given UEM finds a certain known problem in a target design, or what usability problems the outputs of UEM_1 and UEM_2 have in common, or even what is the result of merging the outputs of UEM_1 and UEM_2.

The reasoning behind the use of a list of problems in UEM comparison, according to Hartson and colleagues (2003), is that if an evaluator could hypothetically have a complete list of all the real usability problems that exist in a given target interaction design, that evaluator could ascertain the realness of each candidate usability problem found by a UEM. The authors discuss that, in order to establish this list, a "standard" UEM can be used to generate a touchstone set of usability problems deemed to be "the real usability problems" existing in the target interaction design under study. In this work, the problem list generated by the videotaped Think Aloud user tests sessions was used as the standard usability problem list.

A usability problem found by a UEM should be considered real if it is a predictor of a problem that users encounter in real work-context usage, having an impact on usability, either user performance, productivity, satisfaction, or all three (HARSTON, ANDRE & WILLIGES, 2003). Hence, in this work were considered real problems those that fulfilled simultaneously the following conditions:

1. The field *type of cause* had to be described with one of the following values: "1 game design fault", "2 audio interface design fault", "3 haptic interface design fault", "4 graphic interface design fault", or "6 input device fault";

2. The field *severity* had to be described with one of the following values: "1 prevents task completion", "2 causes a significant delay or frustration", or "3 has a relatively minor effect on task performance";

3. The field *performance outcome* had to be described with one of the following values: "1 User suffered task failure and required assistance", "2 the user took longer than necessary to achieve the task", "4 the user

suffered an increase in anxiety" or "6 the user suffered task failure but did not notice it".

6.1.6 UEM Comparison Criteria

According to Hartson, Andre and Williges (2003), to compare the effectiveness of UEMs, usability researchers must establish a definition for effectiveness and an evaluation or comparison criterion, or criteria. The criteria are stated in terms of one or more performance-related (UEM performance, not user performance) measures, which work as effectiveness indicators, and are computed from raw empirical usability data (e.g., usability problem lists) yielded by each UEM.

As so, this research adopted the following criteria for the comparison of UEMs in the context of field evaluation of multimodal video games for cognitive development of learners who are blind:

i. **Ultimate criterion**: How well does the most used UEM in this context help evaluators discover real usability problems?

ii. **Actual criteria**: Three measures for examining a UEM were adopted, as a way of quantifying the question of how well a UEM meets the actual criteria, in agreement with Bastien and Scapin (1995), Sears (1997) and Hartson, Andre and Williges (2003):

a. ***Thoroughness***: This measure is relevant because evaluators want results to be complete; they want UEMs to find as many of the existing usability problems as possible. It is a measure indicating the proportion of real problems found using a UEM to the real problems existing in the target interaction design, being calculated as follows:

$$Thoroughness = \frac{\text{number of real problems found}}{\text{number of real problems that exist}}$$

b. ***Validity***: The importance of this measure resides in the fact that evaluators want results to be "correct;" they want UEMs to find only problems that are real. Validity is a measure of how well a method does what it is intended to do. It indicates the proportion of problems found by a UEM that are real usability problems, and it is calculated according to the follow equation:

$$Validity = \frac{\text{number of real problems found}}{\text{number of issues identified as problems}}$$

c. ***Effectiveness***: This measure captures the simultaneous effect of UEM thoroughness and validity in a "figure of merit", defined to be the product of thoroughness and validity, as follows:

$$\text{Effectiveness} = \text{Thoroughness} \times \text{Validity}$$

6.1.7 Hypothesis Testing

Aiming to compare the UEMs based on the aforementioned criteria, the null hypothesis of the experiment conducted in this work is:

During onsite usability evaluation involving learners who are blind playing multimodal video games for cognitive development, there is no significant difference among the Usability Evaluation Methods employed for disclosing specific types of usability issues directly associated with the interaction modalities.

The alternate hypothesis is:

During onsite usability evaluation involving learners who are blind playing multimodal video games for cognitive development, Usability Evaluation Methods effectiveness differ significantly for disclosing specific types of usability issues directly associated with the interaction modalities.

Seeking to identify if there was enough evidence to reject the null hypothesis, an analysis was run using Friedman test (FRIEDMAN, 1937, 1940) to determine if there was a significant difference among the means of effectiveness for each UEM under comparison. After this, a Mann-Whitney U test (MANN & WHITNEY, 1941; FAY & PROSCHAN, 2010) was run as post-hoc test in order to decide pairs of UEMs were significantly different from each other (HETTMANSPERGER & MCKEAN, 1998). All statistical tests were run with the software Minitab version 18.1.

Friedman test analyzes three or more measures made on the same sample from a single factor, for experiments following a repeated measures design - measurements on same sample either over time or under different conditions (SHELDON, FILLYAW & THOMPSON, 1996). In the Friedman test, the sample data do not need to be normally distributed and exactly one observation for each combination of treatment and participant is required. Besides, the measurement (i.e., response variable) must be continuous or ordinal. In this work, there was a sample of 10 subjects (C1-C10 for AudioSims, and C11-C20 for AudioGeometry) each measured at three treatments (field notes, CLUE and semi-structured interview) with effectiveness as the continuous response variable, totalizing in 30 observations for each game.

It is important to highlight that several studies have been applying Friedman test to identify significant effects of diverse usability metrics, due to the nonparametric nature of the data obtained from user testing sessions (SIM, MACFARLANE & READ, 2006; SIEGENTHALER, WURTZ, & GRONER, 2010; HVANNBERG & LAW, 2017; AGNISARMAN, 2017). This test was selected to the present experiment because the use of nonparametric test methods for comparing paired or unpaired means and for validating the one-way analysis of variance test results is indicated for non-normal data in small sample size studies (DWIVEDI, MALLAWAARACHCHI & ALVARADO, 2017).

6.2 Results of UEM Effectiveness Comparison

Several relevant insights on usability problems resulted from the present analysis, disclosed by the UEMs under comparison, as well as on the conduction of usability evaluation in the context of games for learners who are blind. They were incorporated in the Descriptive Model proposed in section 6.3.

The analysis of the videotaped Think-Aloud usability tests generated a baseline problem sets, to be used as a standard-of-comparison set of real usability problems known to affect users in each of the games. Through asymptotic user testing with 10 participants (C1-C10), 25 different real problems were documented in the gaming interface of AudioSims, and 18 distinct real problems in AudioGeometry (C11-C20). The two baseline sets of real problems from the usability tests formed the key component of the criteria for comparing UEMs. In the remainder of this section, these results are detailed for each game.

6.2.1 AudioSims Baseline Problems Set

The 25 unique usability problems identified after the matching (out of 107) of the AudioSims usability problems identified on video analysis are summarized in Table 34. It lists the problems identification code (AS1–AS25), frequency of occurrence (out of 10 users), brief description, cognitive task and category of breakdown. The list is also sorted by frequency of occurrence, from highest to lowest.

Based on the 25 unique problems, the mean number of usability real problem instances recorded for each user was 11.2 (SD = ±6.24). Two users who are totally blind encountered respectively 23 and 25 usability problems, whereas one user encountered as few as two usability problems. The mean detection rate of real problems in the video analysis of usability tests was 0.448 (mean problem identification of 11.2 divided by 25 real problems).

Among the real problems identified, 48% prevented task completion (Severity 1) and 52% caused a significant delay or frustration (Severity 2). Most of the problems occurred in general gaming interactions, instead of in a specific task, hence being recurrent during the whole gaming experience (56%). The most problematic tasks were Task 1 (16%) and Task 3 (12%). The most recurrent breakdown categories were: wrong action (20%), doubt, surprise, frustration (20%) and puzzled (20%), followed by poor feedback (12%). The other types of breakdowns identified were: execution or motor skill, motivating story, perception problem, help, dislike, bored and random actions, each representing 4% of the real problems.

The 25 baseline usability problems showed that 10 problems (40%) were caused by game design, nine problems (36%) were caused by audio interface, two problems (8%) were due to haptic interface and four problems (16%) were due to difficulties with the input device. No usability problems regarding graphic interface were identified. Table 35 shows how many of these problems (frequency) were disclosed by the alternative UEMs.

The 25 real usability problems identified as the baseline problem set formed the basis for calculating thoroughness, validity, and effectiveness metrics of the alternative UEMs. All these metrics scores were calculated using equations presented in section 6.1.6, based on the 25 real user problems isolated in the video analysis of AudioSims user tests. Results of the individual calculations for thoroughness, validity, and effectiveness for each UEM are shown in Table 36, and a side-by-side comparison is illustrated in Figure 45.

Table 34 – Reduced report of AudioSims baseline problem set

ID	FREQ	ABREVIATED PROBLEM DESCRIPTION	COGNITIVE TASK	BREAKDOWN CATEGORY
AS19	10	The game gives no feedback when a task is finished. Players are unsure if they accomplished the task, and about what to do next.	Whole game	9 DOUBT, SURPRISE, FRUSTRATION
AS9	8	After receiving instructions, players do not remember what they are supposed to do because the instructions are confusing and intercalated with game narration.	Task 1	1 WRONG ACTION
AS20	8	Instructions to execute two activities are given to players. However, if the players accomplish only the last one, the game gives no feedback warning that one activity is missing. Instead, it gives instructions to Task 4, even though task 3 is not fully completed.	Task 3	1 WRONG ACTION
AS21	6	After the game gives instructions for a task, players do not understand that the instructions are finished. They stay quiet until the evaluator instructs them to press any button, or to start to walk.	Task 1	1 WRONG ACTION
AS1	5	The feedback is the same for hitting a wall or any other object (vibration only, using the same frequency) so players do not know how to differentiate what is happening.	Whole game	6 POOR FEEDBACK
AS3	5	The vibrating feedback is not sufficient for players to notice that they are repeatedly hitting a wall rather than walking forward.	Whole game	6 POOR FEEDBACK
AS8	5	There is no clear pattern on how to interact with game elements (some objects require pressing a button, other objects trigger an interaction by the character proximity)	Whole game	1 WRONG ACTION
AS11	5	The game lacks an audio feedback indicating where the player is entering (or leaving) at each time. Players make errors and cannot tell if succeeded in going inside or outside a specific room.	Whole game	13 MOTIVATING STORY
AS14	5	The game provides no mechanisms to help players to recover whenever they get lost in the game environment.	Whole game	1 WRONG ACTION
AS15	5	The audio instructions are unclear and complex. Players cannot proceed without help.	Task 4	15 HELP
AS10	4	The audio location instructions are not sufficient to make players with more severe visual loss (or without any visual residues) to perceive their surroundings and follow a specific cardinal direction. Players get lost and needs systematic mediation to continue playing.	Whole game	10 PUZZLED
AS12	4	The proximity to an interactive object is not represented in any modality but graphics. Players miss interactive objects because they do not know objects are in front of them	Whole game	6 POOR FEEDBACK
AS13	4	The audio instructions are too long and contain multiple instructions. Players do not remember the instructions just received.	Tasks 2 and 3	12 RANDOM ACTIONS
AS18	4	Players verbally express dissatisfaction with the overall gameplay experience, after making a series of errors and being helped by the evaluator	Whole game	17 BORED
AS23	4	The game provides no interactive input alternative to joystick. Players complain about interacting with the joystick and cannot execute basic game operations by themselves.	Task 1	10 PUZZLED
AS24	4	The game controls are difficult to memorize. Players ask repeatedly about which button they should press whenever they need to interact.	Whole game	10 PUZZLED
AS16	3	Players verbally express impatience, surprise or frustration with the difficulty to correctly guide the character to a specific room in the game environment, according to instructions received	Task 1	9 DOUBT, SURPRISE, FRUSTRATION
AS17	3	Players verbally express dissatisfaction with the use of the game joystick	Whole game	16 DISLIKE
AS22	3	The game information about location of rooms and cardinal directions are not clear enough for players with more severe visual loss (or without any visual residues). Players cannot understand or execute the tasks by themselves; they need a systematic mediation.	Whole game	10 PUZZLED
AS25	3	After executing each of the actions required by game tasks, the audio feedback is not enough for players to be sure about the effect of their last action. Players constantly ask: did it work?	Whole game	9 DOUBT, SURPRISE, FRUSTRATION
AS4	2	Some of the joystick buttons have no associated function in the game. Players with more severe visual loss (or without any visual residues) press these joystick buttons and get frustrated when nothing happens.	Whole game	9 DOUBT, SURPRISE, FRUSTRATION
AS5	2	The game narration is too fast, and there is no option to adjust it. Players cannot understand the information conveyed by narration.	Task 3	14 PERCEPTION PROBLEM
AS6	2	The initial instructions to select the character gender include multiple information at a time. After instructions are finished, players do not know how to proceed to select an option.	Initial instructions	10 PUZZLED
AS7	2	The game joystick impose difficulty for players to turn the character right or left.	task 4	2 EXECUTION OR MOTOR SKILL
AS2	1	The feedback for selecting the character gender is not enough for players with more severe visual loss (or without any visual residues) to notice when their choice was made.	Initial instructions	9 DOUBT, SURPRISE, FRUSTRATION

Source: Produced by the author

Table 35 – Frequency of problems identified in AudioSims by each UEM

		FREQUENCY			
TYPE OF CAUSE	**PROBLEM ID**	**VIDEO**	**NOTES**	**CLUE**	**INTER**
1 game design fault	AS08	5	3	4	0
	AS09	8	4	6	1
	AS12	4	1	4	1
	AS14	5	1	4	1
	AS16	3	1	3	3
	AS18	4	0	2	1
	AS19	10	0	7	2
	AS20	8	0	2	0
	AS22	3	1	3	2
	AS24	4	1	3	4
2 audio interface design fault	AS02	1	0	0	0
	AS05	2	0	3	2
	AS06	2	0	2	0
	AS10	4	2	4	0
	AS11	5	2	4	2
	AS13	4	1	4	2
	AS15	5	2	5	1
	AS21	6	0	3	0
	AS25	3	0	3	0
3 haptic interface design fault	AS01	5	0	2	1
	AS03	5	0	2	0
6 input device fault	AS04	2	0	1	2
	AS07	2	1	2	1
	AS17	3	1	1	2
	AS23	4	1	4	3

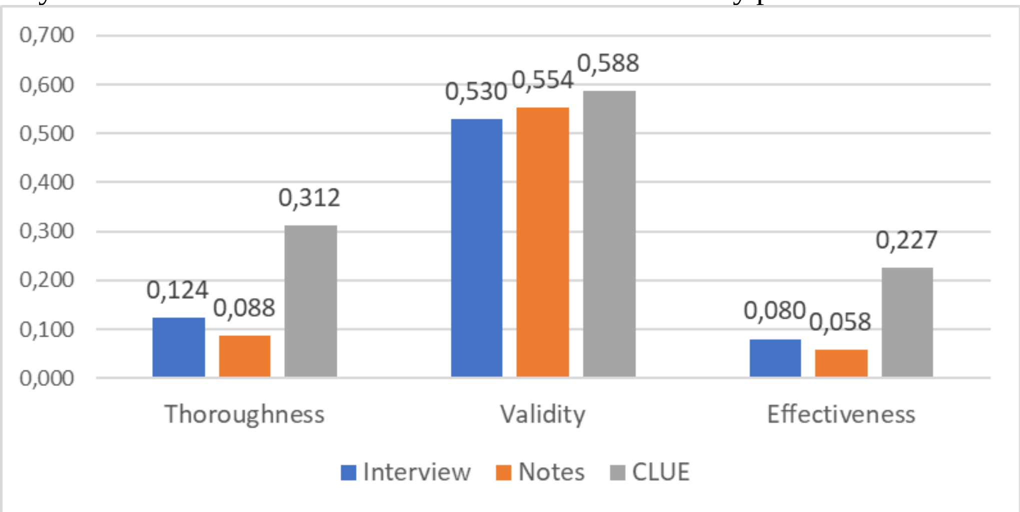
Source: Produced by the author

Table 36 – Individual calculations of UEM metrics with AudioSims

Individual measures by UEM (n=10)	**Interview**		**Field Notes**		**CLUE**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Thoroughness	0,124	0,089	0,088	0,067	0,312	0,250
Validity	0,530	0,242	0,554	0,328	0,588	0,225
Effectiveness	0,080	0,074	0,058	0,041	0,227	0,232

Source: Produced by the author

Figure 45 - Mean value of thoroughness, validity, and effectiveness for AudioSims, using video analysis of user test data as the standard set of real usability problem



Source: Produced by the author

6.2.2 AudioGeometry Baseline Problems Set

The 18 unique usability problems identified after the matching (out of 88) of the AudioGeometry usability problems identified on video analysis are summarized in Table 39. It lists the problems identification code (AG1–AG18), frequency of occurrence (out of 10 users), brief description, cognitive task and category of breakdown. The list is also sorted by frequency of occurrence, from highest to lowest.

Based on these 18 unique problems, the mean number of usability problem instances recorded for each user was 6.7 (SD = ±3.24). Two users who are totally blind encountered respectively 17 and 10 usability problems, whereas one user encountered as few as two usability problems. The mean detection rate of real problems identified in the video analysis of usability tests was 0.372 (mean problem identification of 6.7 divided by 18 real problems).

Among the real problems identified, 67% prevented task completion (Severity 1), 28% caused a significant delay or frustration (Severity 2) and 6% had a relatively minor effect on task performance (Severity 3). Similar to AudioSims, in AudioGeometry evaluation most of the problems occurred in general gaming interactions, instead of in a specific task, hence being recurrent during the whole gaming experience (61%). The most problematic tasks were Task 1 (22%), followed by Task 2 (11%) and initial instructions (11%). The most recurrent breakdown categories were: puzzled (16%) and poor feedback (12%). In addition to those, the breakdown types doubt, surprise, frustration, task stopped and perception problem each represented 8% of the real problems; while each of the categories wrong action, execution or motor skill, help, impatience and wrong goal constituted 4% of the real problems.

The 18 baseline usability problems showed that seven problems (39%) were caused by game design, six problems (33%) were caused by audio interface, two problems (11%) were due to graphic interface and three problems (17%) were due to difficulties with the input device. No usability problems regarding haptic interface were identified. Table 37 shows how many of these problems were disclosed by the alternative UEMs.

The 18 real usability problems identified as the baseline problem set formed the basis for calculating thoroughness, validity, and effectiveness metrics of the alternative UEMs. All these metrics scores were calculated using equations presented in section 6.1.6, based on the 18 real user problems isolated in the video analysis of AudioGeometry user tests. Results of the individual calculations for thoroughness, validity, and effectiveness for each UEM are shown in Table 38, and a side-by-side comparison is illustrated in Figure 46.

Table 37 – Frequency of problems identified in AudioGeometry by each UEM

		FREQUENCY			
TYPE OF CAUSE	**PROBLEM ID**	**VIDEO**	**NOTES**	**CLUE**	**INTER**
1 game design fault	AG01	2	2	2	0
	AG02	2	0	2	1
	AG04	4	0	3	0
	AG05	4	1	3	2
	AG09	9	0	7	5
	AG12	2	0	2	1
	AG18	3	1	2	2
2 audio interface design fault	AG06	4	1	3	2
	AG07	6	2	6	2
	AG08	4	0	3	2
	AG14	10	2	8	3
	AG15	7	0	7	0
	AG17	4	0	3	2
4 graphic interface design fault	AG03	4	0	4	0
	AG16	10	0	7	3
6 input device fault	AG10	2	0	2	0
	AG11	3	0	3	1
	AG13	2	1	2	0

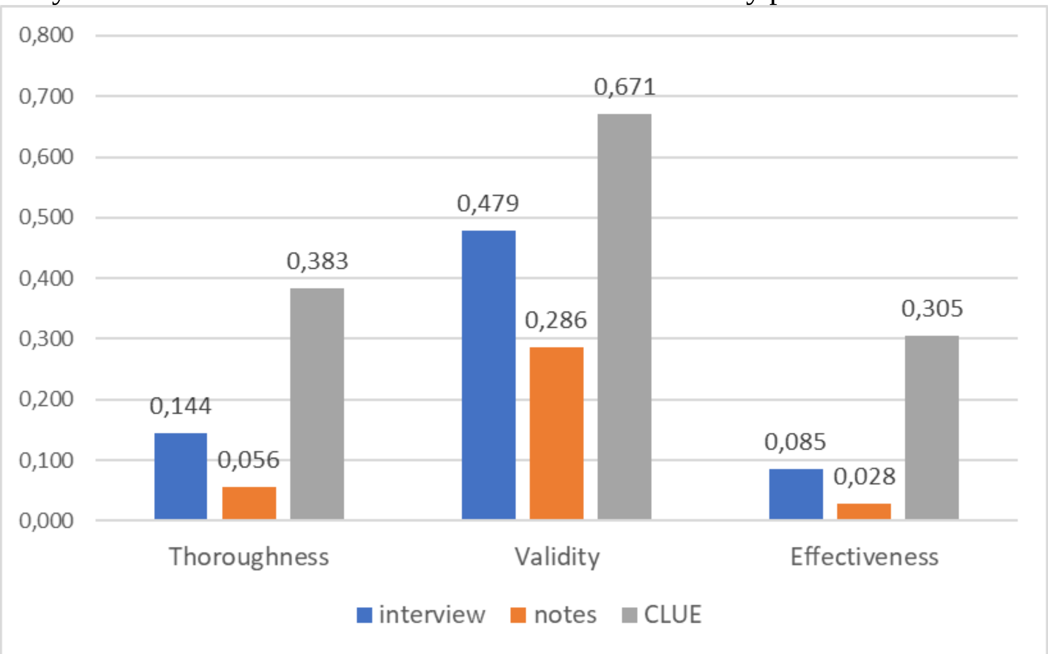
Source: Produced by the author

Table 38 – Individual calculations of UEM metrics with AudioGeometry

Individual measures by UEM (n=10)	Interview		Field Notes		CLUE	
	Mean	SD	Mean	SD	Mean	SD
Thoroughness	0.144	0.129	0.056	0.069	0.383	0.339
Validity	0.479	0.285	0.286	0.342	0.671	0.411
Effectiveness	0.085	0.103	0.028	0.032	0.305	0.283

Source: Produced by the author

Figure 46 - Mean value of thoroughness, validity, and effectiveness for AudioGeometry, using video analysis of user test data as the standard set of real usability problem



Source: Produced by the author

Table 39 – Reduced report of AudioGeometry baseline problem set

ID	FREQ	ABREVIATED PROBLEM DESCRIPTION	COGNITIVE TASK	BREAKDOWN CATEGORY
AG11	10	The on-screen game gestures do not offer sufficient control for players to move deliberately the character throughout the game environment. Players get confused because they lose control of the character and keep making errors.	Throughout the whole game	10 PUZZLED
AG15	10	The feedback of the environment limits (a type of invisible wall) does not inform players that they cannot go on and that they have to ask for directions again. Players do not understand the feedback meaning and keep trying to walk forward.	Throughout all the game, while walking	6 POOR FEEDBACK
AG5	9	The game instructs players to find the farmer, but gives no information about his location neither directions for the players to follow. Player feels puzzled and do not know what they are supposed to do next.	Task 1	10 PUZZLED
AG12	7	The game provides no mechanism to help players to recover when they get lost in the environment (or when they are no longer trying to accomplish the received task). When it happens, players have to be guided step-by-step by the evaluator.	Throughout the whole game	15 HELP
AG9	6	The game gives no information/instructions about what players have to do in order to receive the Task 1. Players stay quiet waiting for something to happen.	Task 1	5 TASK STOPPED
AG10	4	Walking the character in a specific direction is difficult because a minor slide movement on the screen changes the character direction, and often players do not notice.	Throughout the whole game	2 EXECUTION OR MOTOR SKILL
AG13	4	The game provides no alternative or complementary modality of interaction to access essential game information. Players with more severe visual loss (or without any visual residues) sometimes are unable to locate the orientation information in the game.	Throughout the whole game	10 PUZZLED
AG14	4	The game does not give immediate feedback about cardinal direction when the character turns. Players are confused due to the lack of information (especially when he turns unintentionally) or annoyed for having to press a button each time they turn in order to get feedback.	Throughout the whole game	6 POOR FEEDBACK
AG3	4	The puzzle proposed has a long audio contextualization, while nothing changes in the game interface. When the puzzle interface suddenly appears, in the middle of the audio explanation, players with visual loss are immediately attracted to press the red buttons in the screen corners, deviating their attention from the audio description necessary to solve the puzzle.	Task 2	1 WRONG ACTION
AG4	4	In the puzzle interface, there is no clear mapping between the geometric figure and the buttons in the screen corners. Players tap the own geometric figure instead of tapping its corresponding button.	Throughout the whole game	10 PUZZLED
AG8	4	There is a delay between when players tap the compass or location buttons and when the corresponding audio feedback is played. Players get impatient and tap the button several times in a row.	Initial instructions	4 IMPATIENCE
AG17	3	In direction instructions, the pronunciation of the following word pairs seems too similar for some players, causing misunderstanding: "Southeast"-"Southwest" and "Northeast"-"Northwest"	Throughout the whole game	14 PERCEPTION PROBLEM
AG7	3	The audio description is too complex. After carefully listening to the audio description, players verbally express that they did not understand what they are supposed to do.	Task 2	7 WRONG GOAL
AG1	2	In the puzzle interface, the game does not provide enough information to allow players with more severe visual loss (or totally blind) to locate the four different possible answer buttons by themselves.	Throughout the whole game	9 DOUBT, SURPRISE, FRUSTRATION
AG16	2	The contrast and text size of the corner buttons is not sufficient for players with visual loss to perceive the graphic information.	Throughout the whole game	14 PERCEPTION PROBLEM
AG18	2	The game tasks impose too much difficulty for players who are totally blimd. They are not able to accomplish the game tasks and can only play following a systematic mediation. The game offers these players too little encouragement and they give up playing.	Task 1	5 TASK STOPPED
AG2	2	In the puzzle interface, the game does not provide sufficient information to allow players with more severe visual loss (or totally blind) to understand where in the screen the geometric figures are positioned, neither how they can explore nor identify the geometric figures through vibration.	Task 1	9 DOUBT, SURPRISE, FRUSTRATION
AG6	2	The aural feedback indicating if players are making turns or walking forward is not clearly distinguishable for players with more severe visual loss (or totally blind). While trying to walk forward, players keep making turns in the same spot instead, without realizing what is going on.	Initial instructions	6 POOR FEEDBACK

Source: Produced by the author

6.2.3 Results of Statistical Tests

Friedman tests followed by Mann-Whitney post-hoc tests were run to determine whether effectiveness was significantly different for field notes, interview and CLUE in each of the two games evaluations, as explained in section 6.1.7. The variables AS-Effectiveness and AG-effectiveness represent, respectively: AudioSims variable response, based on the observations of 30 effectiveness values for sample C1-C10 each measured with the three UEMs under comparison; and AudioGeometry variable response, based on the 30 observations of effectiveness values for sample C11-C20 each measured with the three UEMs under comparison. Shapiro-Wilk W test (SHAPIRO & WILK, 1965) showed that neither AS-Effectiveness ($W=0.7391$, $p<0.001$) nor AG-effectiveness ($W=0.7387$, $p<0.001$) followed a normal distribution. They both followed a positively skewed distribution, as summarized in Table 40.

First, to meet Friedman test assumption that a sample must be randomly collected to represent accurately the entire population from which it comes, a Wald–Wolfowitz runs test was executed (BRADLEY, 1968). This test can be used to decide if a data set comes from a random process, to eliminate selection bias (NIST/SEMATECH, 2003). Wald-Wolfowitz Runs test showed that the AudioSims data ($N=30$) was randomly distributed (number of runs=11, $p=0.247$), as well as AudioGeometry data ($N=30$, number of runs=15, $p=0.277$)

After this, the outliers were identified for AS-Effectiveness and AG-Effectiveness, by categorizing the variables by block (AS-Subjects and AG-Subjects) and treatment (AS-Methods and AG-Methods). Outliers were not removed or transformed because Friedman test accommodates outliers. As it is a rank-based test, an outlier is simply recognized as a case that is ranked one above (or below) the next less extreme case. However, it is important to explain the identified outliers.

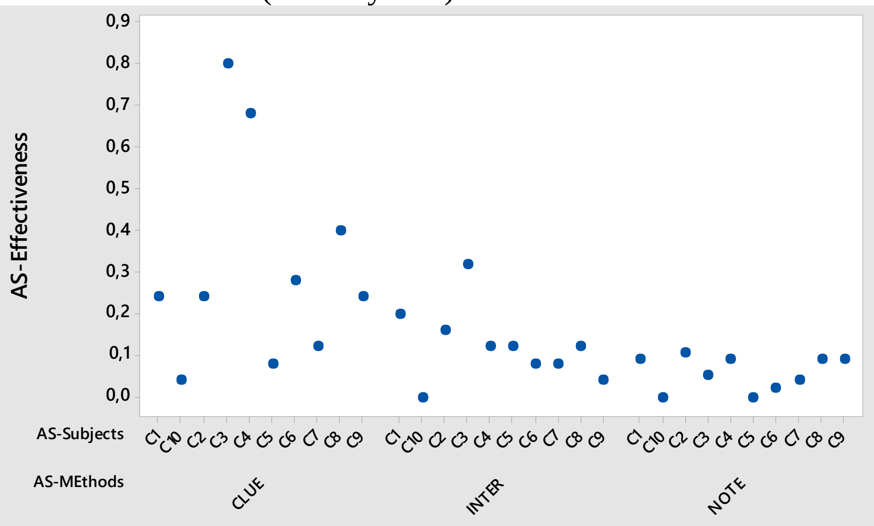
In AudioSims dataset, two outliers were identified: C3 (AS-Effectiveness = 0.680) and C4 (AS-Effectiveness = 0.800), as shown in Figure 47. In AudioGeometry dataset, three outliers were identified: C11 (AG-Effectiveness = 0.778), C15 (AG-Effectiveness = 0.778) and C20 (AG-Effectiveness = 0.889), as represented in Figure 48. All the outliers occurred with the use of CLUE with those subjects that encountered the greatest numbers of usability problems because, in these cases, CLUE presented a much superior effectiveness than the other UEMs. It is noteworthy that 80% of these cases (C3, C4, C15 and C20) occurred with subjects without any visual residues, in both games.

Table 40 – Descriptive statistics of AS-Effectiveness and AG-Effectiveness

VARIABLE	N	MEAN	SD	MIN	Q1	MEDIAN	Q3	MAX	SKEW	KURT
AS-Effectiveness	30	0.164	0.185	0.000	0.050	0.099	0.240	0.800	2.233	5.324
AG-Effectiveness	30	0.194	0.249	0.000	0.042	0.111	0.222	0.889	1.721	2.087

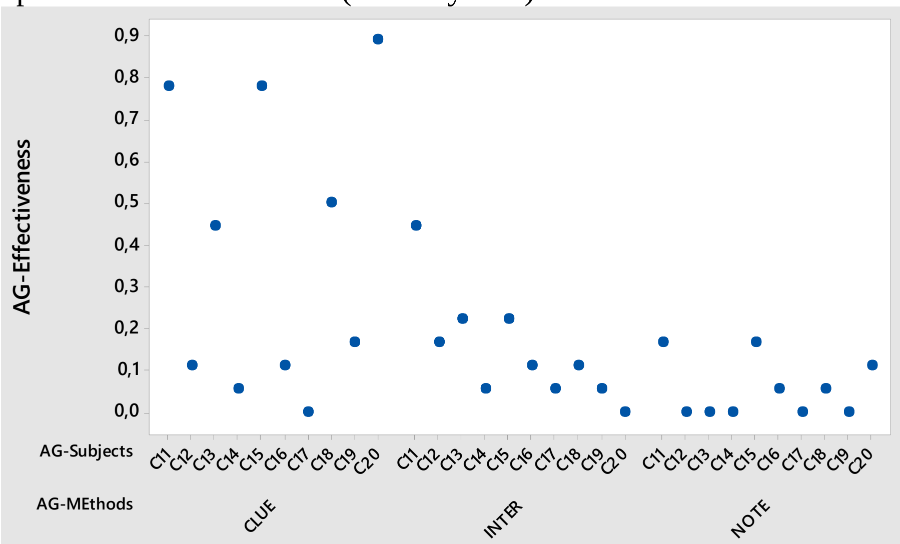
Source: Produced by the author

Figure 47 – Individual value plot of the effectiveness calculated for AudioSims, where each circle represents one observation (UEM by user)



Source: Produced by the author

Figure 48 – Individual value plot of the effectiveness calculated for AudioGeometry, where each circle represents one observation (UEM by user)



Source: Produced by the author

From the dataset produced by AudioSims user tests, a Friedman test revealed a significant difference between the UEMs effectiveness (χ^2 = 15.35, DF= 2, p<0.001). The median responses for field notes (0.0838) and interview (0.1183) are close to the overall median (0.1494), but the median response for CLUE (0.2461) is substantially higher. These results indicated that CLUE might be more effective than the other types of UEMs. Post hoc Mann-Whitney tests revealed that effectiveness was greater for CLUE than both field notes (W= 143.5, p= 0.002) and interview (W= 131, p = 0. 026). Effectiveness was also greater for interview than field notes (W= 129.5, p = 0.034).

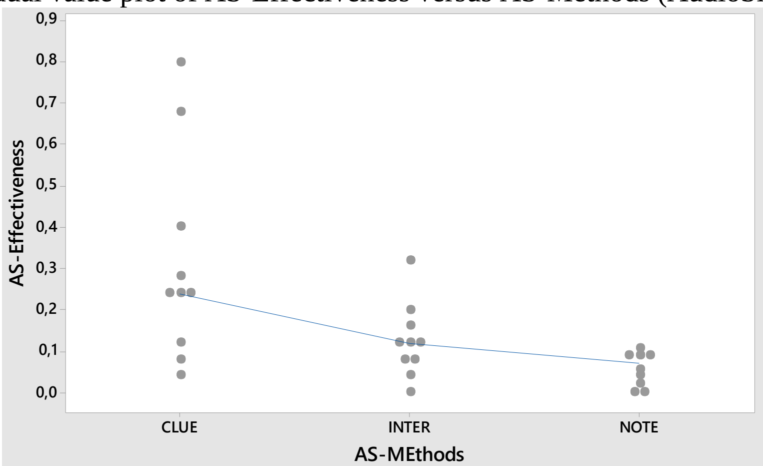
From the user sessions with AudioGeometry, Friedman test revealed a significant difference between the UEMs effectiveness (χ^2 = 11.85, DF= 2, p= 0.003). The median responses for interview (0.125) is close to the overall median (0.1620), while the median response for CLUE (0.3194) is substantially higher and for field notes (0.0416) is considerably lower. Once again, these results indicated that CLUE might be more effective than the other types of UEMs. Post hoc Mann-Whitney tests revealed that effectiveness was greater for CLUE than field notes (W= 137.5, p = 0.008), but the difference between CLUE and interview was not significant (W=124, p=0.081). Effectiveness was also significantly greater for interview than field notes (W= 129.5, p = 0.035).

Since effectiveness is a ratio between thoroughness and validity, further tests were conducted to identify which of these variables influenced the significant difference among UEMs effectiveness, found by Friedman tests. The results showed that no significant difference was found among UEMs validity in AudioSims (χ^2 = 0.84, DF= 2, p=0.656) neither in AudioGeometry (χ^2 = 4.15, DF= 2, p=0.125). This demonstrates that none of the UEMs under comparison was prone to find more real problems than the other ones. However, Friedman test pointed a significant difference among UEMs thoroughness both in AudioSims dataset (χ^2 = 14, DF= 2, p=0.001) and in AudioGeometry dataset (χ^2 = 12.81, DF= 2, p=0.002). This means that the UEMs that demonstrated being significantly more effective than the others were capable to find a greater number of the existing usability problems previously identified in the baseline problems sets.

These results supported the acceptance of the research hypothesis, showing that the effectiveness of the UEMs compared differ significantly from each other. The results also showed that the problems disclosed by each UEM have different focuses and are associated with specific interaction modalities and game characteristics. For example, although field notes were the less effective of the UEMs in both games, their strength was in identifying problems related to the player behavior towards game tasks. They also helped to find some of the problems related to player satisfaction and comprehension of the use of game device and of the game tasks. CLUE and interview stood out in finding game design and audio interface issues. While CLUE disclosed most of the problems related to input devices in both games, interview was as good as CLUE in this aspect when the user could more clearly identify the input device (AudioSims) than when the game used a more natural interaction (AudioGeometry).

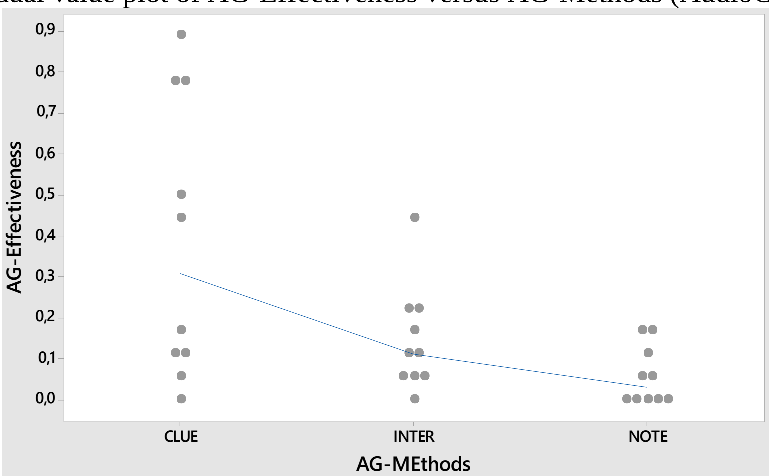
To help comparing the spread of the effectiveness for each UEM, an individual value plot displays the individual values in each sample for AudioSims (FIGURE 49) and AudioGeometry (FIGURE 50). The blue line in both graphs represents the median of the observations. In both cases, CLUE presents the most spread data, while field notes values tend to be more centered.

Figure 49 – Individual value plot of AS-Effectiveness versus AS-Methods (AudioSims)



Source: Produced by the author

Figure 50 – Individual value plot of AG-Effectiveness versus AG-Methods (AudioGeometry)



Source: Produced by the author

6.3 Threats to Validity

The general framework proposed by Wohlin et al. (2012) was used to analyze the validity of the experiment run to compare UEMs. This framework groups validity issues into four major classes: conclusion, internal, construct, and external threats. The identified threats and the strategies used to mitigate them in this research are explained in the following.

Conclusion Validity is concerned with the relationship between the treatment and the outcome, i.e., it ensures that a statistical relationship exists, including, for example, threats to reliability of the measures used, low statistical power, the violation of the assumptions of statistical tests and random heterogeneity of subjects. To mitigate reliability threat, objective measures (independent from a human judgment) well stablished in the literature were used to calculate UEM validity, thoroughness and effectiveness. However, it was not possible to measure UEM reliability between evaluators, due to the lack of experienced evaluators available to participate in the experiment, the same two evaluators conducted all user test sessions together. To diminish the possibility of bias in the identification of problems, these evaluators did not take part in the other phases of UEM comparison, which followed a well-structured procedure to identify, match and report usability problems.

Aiming to mitigate the threats of low statistical power and violation of the assumptions of statistical tests, first, the Shapiro-Wilk test was applied to assess if the data followed a normal distribution and the Wald–Wolfowitz runs test was applied to identify whether the datasets were random. Then, since the data was random and did not follow a normal distribution, it was applied the non-parametric statistical Friedman test, and the Mann-Whitney was used as post-hoc test. Finally, to mitigate the threat of random heterogeneity of subjects, the participants were randomly selected among a broad profile of learners in two different institutions.

Construct Validity focuses on the relation between the theory behind the experiment and the observations, i.e., that treatment reflects the construct of the cause well and that the outcome reflects the construct of the effect well. Its main threats concern experiment design, such as mono-method and mono-operation biases. To mitigate this type of threats, the experiment used a desktop and a mobile game using different modalities, three types of UEMs, three types of measures and different groups of subjects. Besides, it followed a detailed test protocol, and it was previously assessed in a pilot study.

However, a possible threat is the under representation of the construct, since the games evaluated did not present a balanced quantity of usability issues for the different types of usability problems identified. This threat was identified only after data analysis was finished, since it could not be predicted unless the usability problems had been injected in the games design. A larger sample of video games could have helped to mitigate this threat, because it would be more feasible that the other types of problems could have been identified. However, it would have not been possible to execute the experiment and analyze data in an acceptable time with more games and more subjects.

Internal Validity focuses on making sure that the treatment causes the outcome and comprise group threats including history, maturation, instrumentation, selection and mortality; and social threats which are diffusion/imitation treatments, compensatory equalization, compensatory rivalry and resentful demoralization. Since different subjects played each game for the first time (C1-C10 for AudioSims, and C11-C20 for AudioGeometry) each measured at three treatments (field notes, CLUE and semi-structured interview) that collected data independently from each other, history and maturation threats were mitigated. The previous experience of evaluators with the UEMs under comparison also helped to mitigate these threats.

There were no dropouts of the experiments, avoiding mortality threat, and selection threat was mitigated by not inviting volunteers and selecting a random sample within a predefined profile. To help mitigating instrumentation threat, field notes data collection forms and CLUE were submitted to previous validation and several pilot tests were run. Besides, interview and think-aloud sessions were recorded in video and audio to avoid losing data. Regarding the social threats, as participants of test sessions with one game were not aware of the other game, and were all submitted to the same UEMs, a possible wish to be in the other group was avoided. It mitigated the threats of compensatory equalization of treatments, compensatory rivalry and resentful demoralization.

External validity threats include any conditions that limit the ability to generalize the results to a broader context, outside the scope of the research. In this regard, the main threat identified was the use of two games developed by the same research group, and the subjects from similar communities (special schools in Santiago, Chile). Evaluating more games originated in different groups and with more distinct goals, involving learners who are blind with distinct culture and background could yield a more reliable data set. Nevertheless, it would demand an effort incompatible with the time and team available for the present research.

6.4 Descriptive Model Proposal

To synthesize the knowledge produced in this research, a descriptive model was produced, aiming to provide practical guidance on the specificities of usability evaluation involving learners who are blind playing videogames for cognitive improvement. It was modeled mainly according to the results of UEM effectiveness comparison presented before in the present chapter. Overall, it reunites the results obtained in Steps 4 to 6 of the methodology followed in this work.

Hence, it can be used as a basis for planning usability user tests in this context, assisting in the choice of a combination of UEMs that suits the game modalities, the evaluation criteria, and the available time and team. In addition, the descriptive model proposed in this work offers advice on the user test conduction and on problems reporting, considering the game cognitive tasks. In the remainder of this section, the definition chosen as basis to develop the descriptive model, as well as the descriptive model itself are presented and discussed.

6.4.1. Chosen Definition of Descriptive Model

It is important to clarify that, in software engineering, descriptive models usually are related to software development and project dynamics, and state how a software or project behaves under specific circumstances, being they desirable or not, responding to an entire range of stimuli (SCHNEIDER, 2004). Therefore, descriptive models are created after the original, and applied aiming to make some specific information about the original easily and quickly accessible, or to document the development process and software behavior, or even to run simulations based on a given formalism (SCHNEIDER, 2004; LUDEWIG, 2003). According to this definition, descriptive models have the main goal of helping developers and project managers understand qualitative-quantitative aspects of software project behavior, in order to avoid future misconceptions during development (LUDEWIG, 2003).

Nevertheless, as a legacy of the Social Sciences, descriptive models are understood differently in Human-Computer Interaction. They are a qualitative rather than mathematical way of organizing a problem space into a divided domain, providing a verbal analytic description of a phenomenon, usually based on data gained through empirical observation (MACKENZIE, 2012; CARROL, 2003). In this context, descriptive models are tools for studying and thinking about the user interaction and for empowering researchers and practitioners to reflect about the problem space in a different way, before making choices.

Hence, descriptive models are supposed to provide a framework or context for thinking about or describing a problem or situation. They are often comprised by little more than a verbal or graphic articulation of categories or identifiable features (CARROL, 2003). As simple as it can be, a descriptive model that emerges from an HCI research helps to focus on certain parts of the problem space, to consider how one part differs from - or relates to - another one, and to weigh strengths, weaknesses, advantages, or disadvantages of certain parts over others (MACKENZIE, 2012).

6.4.2 Descriptive Model of Usability Evaluation involving Learners who are Blind

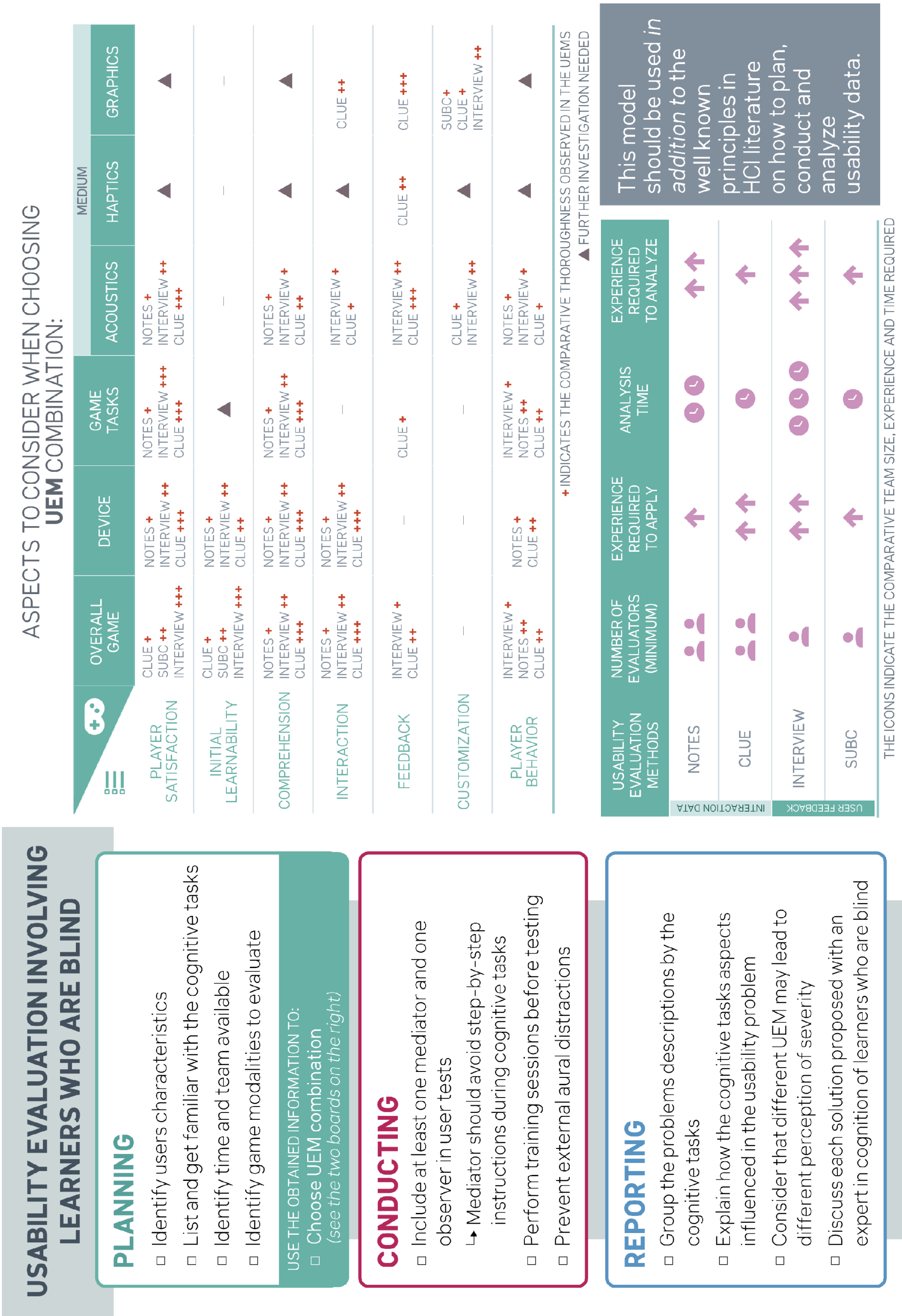
Following the HCI approach, this research produced a descriptive model of current work practice that can be used to guide further usability evaluations of games designed to improve cognition of learners who are blind. The model is represented by a verbal and graphic articulation of usability evaluation activities, usability problems categories and identifiable game characteristics.

In the present work, the model was not yet submitted to further validation, since it consists in a summary of the direct outcomes obtained throughout the previous steps of the methodology followed in this research. The main findings of this research which were used as basis to organize the descriptive model are the dimensions for characterization of multimodal videogames, SLUP, CLUE, PLUMB, and the evidence obtained on which UEMs are more effective to disclose usability issues during field tests.

Figure 51 presents the descriptive model designed as a qualitative way of organizing the knowledge produced in this work, in order to propose responses to the research problem addressed in this work:

> *How to conduct usability onsite evaluation of multimodal video games based on audio and haptics, designed for enhancing and improving cognition in learners who are blind, employing UEMs adequate to the users' individualities and to the evaluation goals?*

Figure 51 – Descriptive Model of Usability Evaluation involving Learners who are Blind



Source: Produced by the author

The boxes in the left side of the model were organized according to the main activities involved in usability tests: planning, conducting and reporting (ROGERS, SHARP & PREECE, 2011), while the right side shows comparative boards systematized to give information about the use of UEMs and their characteristics. The guidance provided for each of the activities, was based on PLUMB (see chapter 5) and on the conduction and analysis of qualitative data, during In-Depth UEM Comparison.

It is important to highlight that this descriptive model is intended to help evaluators and practitioners planning to execute usability evaluations involving people who are blind to consider the specific aspects of usability tests of games for the cognitive improvement of these users. However, it is not a substitute for the HCI well-known best practices and guidelines on how to plan, conduct, and analyze usability user tests data for each of the compared UEMs. Instead, the intention of the Descriptive Model of Usability Evaluation involving Learners who are Blind is to build upon the body of knowledge in HCI research, based on the results of this work.

In the remainder of this section, the model elements and their content are explained and discussed.

6.4.2.1 Planning box and comparative boards

An adequate UEM combination is more likely when the *planning* activity includes reasoning about the target users' specific characteristics (e.g., totally blind or with visual loss) and how many evaluators are available to collect and analyze the data, considering their experience with usability tests and with the users' condition. Because the cognitive tasks are considered the core of usability evaluation in this scenario, before choosing UEMs, it is fundamental that evaluators select and get familiar with each game cognitive task that is to be played by learners during the tests. All the game modalities associated to the cognitive tasks selected are to be evaluated in user tests.

Once the aforementioned aspects have been defined, in addition to those traditionally considered in usability evaluation planning (e.g.: evaluation goals, specific questions to be addressed, ethical issues), evaluators can make an informed choice about which UEMs to use. To assist evaluators in this effort, the model shows a comparative overview of the UEMs use to disclose different types of usability problems. It compares the UEMs on the basis of their relative thoroughness regarding a set of types of usability problems (player satisfaction, initial learnability, comprehension, interaction, feedback, customization and player behavior) in relation to the game characterization (overall game, game tasks, device and graphic, acoustic and haptic modalities).

These categories were defined based on the dimensions of multimodal games characterization (see chapter 4), on SLUP categories of problems (see Chapter 5) and on the categories of breakdown indication types used in the analysis of qualitative data, during In-Depth UEM Comparison (TABLE 32). The UEMs and the information in the board were based on the results of the Preliminary UEM Comparison (see Chapter 4) and of the In-Depth UEM Comparison discussed in the present chapter.

In the comparative board showing aspects to be considered when choosing UEM combination, in some cases, instead of the comparison among UEMs a triangle is shown. It happens, for example, for the initial learnability of game tasks and the player behavior towards haptics and graphics. This symbol means that these cases should be further investigated because the games analyzed did not produce enough data on these specific types of problems. In other cases, the board shows a dash instead of the UEMs. In those cases, no relationship was found between the game aspect and the type of usability problem. For example, the device feedback is actually represented by either graphic or haptic feedback. The same occurs for customization of overall game, device and game tasks, since these aspects usually do not allow any customization on themselves. Instead, games usually allow customization of haptic, acoustic and graphic game elements.

Interview and SUBC disclosed usability issues based on direct user feedback, while field notes and CLUE relied on observable user interaction. A combination of both categories of UEMs can cover a broader range of game aspects and types of usability problems. While user interaction data is a key source of insight in the search for usability problems, users' design feedback could be biased due to several factors. For example, in diverse cases during the Preliminary UEM Comparison and In-Depth UEM Comparison, players declared that the games were "very easy to learn and understand", when they actually made several errors and were not able to complete the cognitive tasks. They probably affirmed this because they did not notice most of their errors and had fun playing, even though they could not achieve the cognitive goal proposed in that task. Despite that, these types of methods are valuable to obtain users' perceptions and experience with the game, as well as to deepen issues revealed during user observation.

Interview stood out in identifying player satisfaction and initial learnability of the overall game. This UEM was also very helpful in identifying initial learnability and comprehension of device and the overall game, in addition to feedback about customization of acoustics and graphics. SUBC strength was in identifying player overall satisfaction and initial game learnability. It also disclosed issues related to graphic customization.

Field notes gave initial evidence of satisfaction, learnability, comprehension and interaction problems. In general, the primary reasons for task failure that emerged in the field notes corresponded to those identified in the video analysis (baseline method). However, many secondary issues that were identified by the video analysis were not reliably reported in the written comments. Field notes were especially useful to identify issues related to behavioral observations such as how users explored the UI, erroneous behaviors that did not lead to task failure, and bugs in the game, probably not caught during product testing.

CLUE was helpful to find several different combinations of game aspects and types of problems. It stood out in identifying problems related to graphic and acoustic feedback, device interaction, overall and game tasks comprehension, and player satisfaction with game device and sounds. Besides, it was also helpful to identify issues involving acoustic comprehension, graphic interaction and player behavior towards game tasks.

As expected, video analysis of the think-aloud sessions surpassed the other UEMs in identifying all types of interaction problems. However, its analysis is very time-consuming in practice and requires high expertise. Hence, the results found in this work agree with Holzinger's (2005) advice that video analysis would me more worthful to perform formal impact analysis of usability problems, considering that the time needed to analyze a videotape is approximately 10 times that of a user test.

Finally, the auxiliary board on the bottom of the model helps evaluators to think further about the team and time issues while choosing UEMs. Therefore, they can decide whether, for example, they should use CLUE or interview to evaluate player satisfaction with game tasks, according to how experienced are the evaluators who will run the analysis. Undoubtedly, the decisions that evaluators have to make are much more complex than this and involve considering multiple aspects at the same time. For that reason, the model organized the information in a way that evaluators can carefully analyze what usability aspects are to be evaluated in each of the game characteristics, while simultaneously identifying the effectiveness of UEMs and if they are a real possibility, given the time and team resources.

6.4.2.2 Conducting box

Each of the UEMs compared have specific well-defined guidelines on their use and analysis, as discussed in Section 6.1.1. In addition to that, evaluators should also consider observing the advice present in the *conducting* box in the descriptive model. They were compiled from the experience of evaluators conducting user tests during Preliminary UEM Comparison and In-Depth UEM Comparison. They encourage evaluators to have an adequate conduct and to follow simple procedures that can help to obtain more trustworthy results.

One of the main precautions that should be taken while conducting a usability test with learners who are blind is to always include at least two evaluators: one mediator and one observer. If the same evaluator who gives instructions and mediations also tries to fill CLUE or to make detailed field notes, he/she is more prone to neglect some usability issues.

Besides leading the user test, the mediator role includes guiding children who are blind to use devices, especially if they are not familiar with the technology used. They are also responsible for linguistic guidance and helping learners to experience any unfamiliar multimodal interaction. The mediator should also offer guidance and help whenever the learner needs it, besides trying to elicit children's ideas and comments during the gameplay. However, it is essential that the mediator avoid, at all costs, instructing the interaction step-by-step during the execution of cognitive tasks.

For example, suppose that, during a task to enhance location and orientation skills the game instructs the player: "*Walk down the hall towards South; at the end, you will find a door to the training room. Turn right and enter in the next room*". If the mediator gave systematic mediation, such as "*Press left. Now press left again. Ok, now you are in the hall. Press up. Keep going on, you are walking. Now press right…*", the usability test would produce false results, because it would not reflect the real user interaction and experience.

Training sessions, on the other hand, are essential. Before the collection of data from usability test sessions begins, a mediator should demonstrate to the learner all the basic game controls, and necessary information, such as well as navigation and location information. Any other aspects that evaluators judge relevant should be included in the training session, taking care to keep the session practical and brief. After this, the learner can feel more confident to play and explore the game environment, producing meaningful results. However, the training sessions should not count as data collection for usability tests, because it could also lead to false results.

Finally, another important care that evaluators need to observe while conducting usability tests with learners who are blind is to prevent any aural distracters that could have the attention of learners who are blind drawn away. It includes evaluators' phone notification and ringing sounds (vibration too!), chatting between evaluators and so on.

6.4.2.3 Reporting box

As approached in Section 6.1.5, the analysis and description of usability problems should follow specific procedures and use templates detailed according to the evaluation requirements. In addition to that, evaluators should also pay attention to the recommendations present in the *reporting* box in the descriptive model. They were compiled from the experience of evaluators analyzing data during Preliminary UEM Comparison and In-Depth UEM Comparison. They encourage evaluators to execute some steps that help to identify how the usability problems affect the game cognitive tasks, during data analysis.

During the data analysis, when identifying usability problems in multimodal games for learners who are blind, evaluators should group the problems description by cognitive task. Knowing what usability issues are affecting the learners' interaction with a given game cognitive task – and their severities - can help to prioritize usability problems to solve, based on their impact on the cognitive task.

To support the clarification of the impact of usability problems on each cognitive task, when describing a usability problem, one should consider explaining briefly how it influences the task attributes. For example, consider the problem AS15: "*The audio instructions are unclear and complex. The player cannot proceed without help*". It affected the cognitive enhancement goal designed by Task 4 (TABLE 29), as the players were not able to overcome to problem and follow the instructions received.

When evaluating severity, evaluators should also observe that different UEM could lead to different perception of severity due to the difference in UEMs effectiveness and in the type of data gathered. Different UEM may report very different frequencies, impact and persistence for the same usability problem, which will affect in the severity rating attribution. For example, during an interview, players can report that a specific issue was easy to overcome (low impact). However, the interaction data may show that they were not able to recover from that problem (high impact). Methods with very different thoroughness also influence the severity perception. For instance, field notes could have registered that an issue involving acoustic comprehension occurred in two out of ten user tests (low persistence), while CLUE could have indicated the same issue for eight out of ten tests (high persistence).

Hence, evaluators should not rely on a unique source of usability data to report tests results. It is necessary to compare data from different UEMs to understand how problems affect the interaction of learners who are blind, aiming to suggest adequate design changes. Furthermore, each design solution proposed should be discussed with an expert in cognition of learners who are blind, familiar with the game cognitive tasks. The goal is to find balance between solving the usability problems and maintain the cognitive goal designed for that task.

6.5 Final Considerations

The present chapter aims to help filling in the gap on what game aspects to evaluate and how to proceed with the usability evaluation of multimodal video games for learners who are blind. This gap is frequently demonstrated by the fact that, frequently, studies evaluating usability of multimodal games and virtual environments involving people who are blind follow broadly different procedures, even when they have very similar goals and setups.

Hence, this chapter detailed and discussed the results of a UEM comparison, seeking to contribute to the answer on how to conduct usability onsite evaluation of multimodal video games based on audio and haptics, designed for enhancing and improving cognition in learners who are blind, while employing UEMs adequate to the users' individualities and to the evaluation goals. As the final step on the present research methodology, this chapter showed the calculus of UEM performance metrics for each of the UEMs under comparison: field notes, CLUE and semi-structured interview. Then, a series of statistical tests verified this work research hypothesis demonstrating that, during onsite usability evaluation involving learners who are blind playing multimodal video games for cognitive development, each Usability Evaluation Method employed is effective for disclosing specific types of usability issues directly associated with the interaction modalities.

As a result, a descriptive model of usability evaluation of multimodal video games for learners who are blind was proposed to provide a framework for thinking about usability planning and test conducting in this context. The model reunites and summarizes all the knowledge produced and previously validated in this research. It describes structured and practical guidance on usability evaluation of multimodal video games for cognitive development of children who are blind, aiming to support the effective use and combination of UEMs in this context.

All the UEM compared in user tests showed advantages and disadvantages. When planning usability tests, the evaluators have the responsibility to decide which are the more suitable UEMs and tools to apply, given the available resources and the evaluation goals. The results presented in this work - summarized in the descriptive model - can support and guide evaluators through decisions by offering them a tool for thinking about an effective combination of UEMs, in the context of learners who are blind playing multimodal games for cognitive development.

In addition to the initial classification scheme of the interface and interaction features existing in multimodal video games, and to SLUP, CLUE and PLUMB, the descriptive model presented in this chapter compose the scaffolding to guide the administration of UEMs while considering the learners' characteristics and the game interaction modalities, in this context.

7. CONCLUSIONS

This thesis investigated the use of Usability Evaluation Methods during usability field studies involving the use of video games for cognitive development of learners who are blind. The main goal of this research was to provide a scaffolding to guide researchers and practitioners to employ the most appropriate combination of UEMs to assess such games, given the characteristics of the target users, the game cognitive tasks, and the interaction modalities. As results, this work proposed a set of practical aids to support usability evaluation that can be used in different contexts of society, such as special Institutes and Schools, research groups and practitioners.

The present chapter concludes the thesis, synthesizing the contributions obtained in this research, following the organization described next. Section 7.1 presents an overview of the approach followed to address the research problem. Section 7.2 summarizes the main results of this thesis. Section 7.3 discusses the hypothesis investigated. Section 7.4 discusses the limitations of this work. Finally, Section 7.5 motivates the development of future work.

7.1 Overview

Multimodal video games can incorporate a series of sound learning principles endorsed by research in cognitive sciences (GEE, 2003), encouraging the fostering of diverse kinds of specific cognitive skills in people with disabilities (SÁNCHEZ & OLIVARES, 2011; DURKIN et al., 2013; CHENG et al., 2015). This later helps learners to virtually transfer this knowledge to a real environment and, ultimately, to everyday life (CONNORS et al., 2014; PINCINALI et. al, 2014; LAHAV et al., 2018). Several video games have been developed for improving and enhancing cognitive skills in people who are blind or helping them in the execution of everyday activities, as first introduced in Chapter 1 and further detailed in Chapter 3. In these cases, the development and enhancement of the target cognitive skills is related to how well the game represents abstract information by associating the interaction modalities with interface elements and feedback (LAHAV & MIODUSER, 2008; SÁNCHEZ & SÁENZ, 2010).

Consequently, the game modalities must afford a precise interpretation of the information conveyed, as well as to support a comfortable and pleasant interaction. If multimodal video games fail to combine the controls and feedback to represent abstract information in adequate modalities, learners who are blind can misinterpret the game elements and goals (SÁNCHEZ, SAÉNZ & GARRIDO, 2010; BELLOTTI, BERTA & DE GLORIA, 2010; BERNSEN & DYBKJÆR, 2009), possibly facing interaction problems with the game interface that will distract them from learning (ARDITO et al., 2006).

This matter is especially delicate when the evaluation involves children with visual disabilities, because they require specific attention during the conduction of evaluation (RAISAMO et al., 2006), as explained in Chapter 2. Evaluators have to further consider that users who interact for learning generally behave differently from general users, as they do not possess domain expertise, are heterogeneous (including their learning styles), and may not be intrinsically motivated (QUINTANA et al., 2013).

Consequently, as also discussed in Chapter 2, usability is fundamental in this scenario, especially considering that video games usually require constant interaction, and focusing on usability issues rather than on learning would be frustrating and undesirable. Administering an accurate usability evaluation is hence a necessary step towards assisting learners who are blind in the construction of cognitive skills while playing video games.

As presented in Chapter 3, many studies have been reporting usability evaluation involving users who are blind. However, since the approaches are not focused on multimodal games for learners who are blind, they can miss usability issues that affect the game interaction and the fostering of target cognitive skills in these users. Hence, planning and conducting usability user tests to identify relevant issues on multimodal video games for learners who are blind is not a trivial task and lacks guidance, as demonstrated by the results of the Systematic Literature Review (Chapter 4) and of the Expert Opinion Survey (Chapter 5). For example, the reasoning behind the choice of a UEM combination to evaluate a game in this context should consider that traditional UEMs differ when used with different application types, contexts and types of users (BOWMAN, GABBARD & HIX, 2002; HARTSON, ANDRE & WILLIGES 2003; DUH, TAN & CHEN 2006; EDWARDS & BENEDYK, 2008; MIAO et al., 2016).

To help overcome the lack of reasoning about usability evaluation involving games for learners who are blind, the goal of this work was to provide scaffolding to guide researchers and practitioners in the administration of UEMs while considering the learners' characteristics and the game interaction modalities. This thesis achieved this goal by offering clarity and structure in planning and conducting usability evaluation, while giving the researcher freedom to construct new insights.

The usability scaffolding for evaluating multimodal video games for learners who are blind is a product of all the accumulated knowledge acquired in this work. It provides contextual discussions in addition to structured, practical guidance by means of:

(i) A classification scheme of the features existing in multimodal video games for cognitive development of children who are blind (Chapter 4);

(ii) A set of usability evaluation principles called PLUMB (Chapter 5);

(iii) Two usability supporting instruments, the list of problems SLUP and the observational checklist CLUE (Chapter 5); and

(iv) A descriptive model of usability evaluation involving learners who are blind (Chapter 6).

7.2 Main Results

Ultimately, this work created a usability scaffolding that assembles the knowledge produced and acquired in this work (See Figure 5). It can be relevant in different spheres and contexts of society to guide researchers and practitioners to employ the most appropriate combination of Usability Evaluation Methods (UEMs) to assess such games, given the characteristics of the target users, the game cognitive tasks, and the interaction modalities.

When putting together the discussions raised and this research main outcomes, the present work provides a usability evaluation scaffolding comprising mainly the results summarized as follows:

- **4-dimension features classification.** This scheme was assembled from the systematic literature review results and describes the interface and interaction characteristics of multimodal video games for the cognition of people who are blind, as well as the usual types of evaluation conducted, and the types of cognitive skills addressed by those games.
- **PrincipLes for Evaluating Usability of Multimodal Video Games for Learners who are Blind (PLUMB).** PLUMB describes a set of five principles that should be met in the evaluation of multimodal video games for learners who are blind. It is a practical aid to help researchers and practitioners to properly plan usability evaluation of those games. PLUMB can be used by specialized Institutes and Schools for learners who are blind, helping teachers and instructors to identify whether a game is helping children instead of creating a barrier to their learning and cognition.
- **Standard List of Usability Problems (SLUP)**. SLUP is a categorized list of problems devised to help designers avoid recurrent usability issues in the early design stages of multimodal games for learners who are blind. Besides, SLUP

can be useful as basis for the creation of focused usability evaluation instruments.

- **CheckList for Usability Evaluation of Multimodal Games for Children who are Blind (CLUE)**. CLUE is an observational tool to be used by evaluators during usability field tests. It was designed to clarify the basic aspects that should be observed when evaluating multimodal video games for cognitive development and enhancement of children who are blind. Thus, CLUE aids the evaluator not to forget important criteria and enhances the objectivity and reproducibility of evaluation.
- **Descriptive model of usability evaluation of multimodal video games for children who are blind**. The model was organized as basis for thinking about usability test planning, conducting and reporting, in the context of children who are blind playing multimodal video games for cognitive development. It aims to assist researchers and practitioners in the choice of a combination of UEMs that suits the game modalities, the evaluation criteria, and the available time and team.

Furthermore, five papers were published in conferences, as a direct result of the research performed in this work. Table 41 presents the references of these papers. The first paper (DARIN, ANDRADE & SÁNCHEZ, 2018) presents the creation and validation of CLUE, depicted in Section 5.2. The next paper (DARIN, ANDRADE, MERABET & SÁNCHEZ, 2017) concerns the description of the preliminary comparison of UEM and the creation of SLUP, described in Section 5.1. The paper (DARIN, SÁNCHEZ & ANDRADE, 2015) presented the 4-dimensions classification (see Section 4.3). The paper (DARIN, 2015) introduced the initial proposal of this thesis work. The systematic literature review and the its decurrent discussion presented in Section 4.2 were described in the papers (SÁNCHEZ et al., 2015) and (SÁNCHEZ, DARIN & ANDRADE, 2015).

During the development of this research, other six papers in the areas of HCI interaction and gaming for people who are blind were published, not directly related to the contribution here presented, but somehow contributing to the acquired knowledge and research skills (TABLE 42).

Table 41 – Publications as a direct consequence of this thesis research

CITATION	QUALIS
DARIN, T., ANDRADE, R., SÁNCHEZ, J. *CLUE: A Usability Evaluation Checklist for Multimodal Video Games Field Studies with Children Who Are Blind* In: Collaboration Systems and Technologies - Human-Computer Interaction: Informing Design Utilizing Behavioral, Neurophysiological, and Design Science Methods, 2018. Proceedings of the 51th Annual Hawaii International Conference on Computer Science. IEEE, 2018. p. 245-254. DOI: 10.24251/HICSS.2018.034	A1
DARIN, T G. R. ; ANDRADE, R M. C.; MERABET, L B. ; SÁNCHEZ, J. *Investigating the Mode in Multimodal Video Games*. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI EA '17). ACM, New York, NY, USA, 2487-2495. DOI: https://doi.org/10.1145/3027063.305317	A1
DARIN, T. G. R. ; SÁNCHEZ, J.. ; ANDRADE, R. M. C. . *Dimensions to Analyze the Design of Multimodal Videogames for the Cognition of People Who Are Blind*. In: XIV Simpósio Brasileiro sobre Fatores Humanos em Sistemas Computacionais (IHC 2015), 2015, Salvador. p. 193-202.	B2
DARIN, T. G. R.. *Towards a Methodology to Evaluate Multimodal Games for Cognition in People who are Blind*. In: 15th IFIP TC.13 International Conference on Human-Computer Interaction - INTERACT, 2015, Bamberg. Adjunct Proceedings of the 15th IFIP TC.13 International Conference on Human-Computer Interaction - INTERACT 2015, v.468, p.61-65, University of Bamberg Press.	(Doctoral Consortium)
SANCHEZ, J. ; DARIN, T. G. R. ; ANDRADE, R. M. C. ; CARVALHO, W. V; GENSEL, J. . *Multimodal Interfaces for Improving the Intellect of the Blind*. In: TISE - XX Conferência Internacional sobre Informática na Educação, 2015, Santiago. Nuevas Ideas en Informática Educativa, 2015. v. 11. p. 404-413.	B4
SANCHEZ, J. ; DARIN, T. G. R. ; ANDRADE, R. M. . *Multimodal Videogames for the Cognition of People Who Are Blind: Trends and Issues*. In: International Conference on Human-Computer Interaction (HCII), 2015, Los Angeles. International Conference on Human-Computer Interaction (HCII), 2015. p. 535-546.	B2

Source: produced by the author

Table 42 – Secondary publications during the development of this thesis

CITATION	QUALIS
ARAÚJO, MARIA C. C. ; Façanha, Agebson R. ; DARIN, TICIANNE G. R. ; Sánchez, Jaime ; ANDRADE, ROSSANA M. C. ; VIANA, WINDSON . Mobile Audio Games Accessibility Evaluation for Users Who Are Blind. Lecture Notes in Computer Science. .ed.: Springer International Publishing, 2017, v. , p. 242-259.	B2
ALMEIDA, R. L. A.; Darin, T. G. R. ; VIANA, W. ; ANDRADE, R. M. C. . Um Mapeamento Sistemático sobre Avaliação de Modelos Mentais e Conceituais de Interfaces Digitais. In: XXI Congreso Internacional de Informática Educativa, 2016, Santiago. Nuevas Ideas en Informática Educativa, 2016. v. 12	B4
ARAÚJO, MARIA C. C. ; SILVA, ANTÔNIO R. S. ; DARIN, TICIANNE G. R. ; DE CASTRO, EVERARDO L. ; ANDRADE, ROSSANA M. C. ; DE LIMA, ERNESTO T. ; Sánchez, Jaime ; DE C. FILHO, JOSÉ AIRES ; VIANA, WINDSON . Design and usability of a braille-based mobile audiogame environment. In: the 31st Annual ACM Symposium, 2016, Pisa. Proceedings of the 31st Annual ACM Symposium on Applied Computing - SAC '16, 2016. p. 232.	A1
DARIN, TICIANNE; ANDRADE, ROSSANA ; MACEDO, JOSÉ ; ARAÚJO, DAVID ; MESQUITA, LANA ; SÁNCHEZ, JAIME . Usability and UX Evaluation of a Mobile Social Application to Increase Students-Faculty Interactions. Communications in Computer and Information Science. .ed.: Springer International Publishing, 2016, v. , p. 21-29.	B2
Darin, T., Barbosa, J., Rodrigues, B., & Andrade, R. M. (2016). Greatroom: Uma aplicaçao android baseada em proximidade para a criaçao de salas virtuais inteligentes. In Workshop de Ferramentas e Aplicações (WFA). Simpósio Brasileiro de Sistemas Multimídia e Web.	B2
CARVALHO, W. V. ; SANCHEZ, J. ; ANDRADE, R. M. C. ; ARAUJO, M. C. C. ; Darin, T. G. R. ; FACANHA, A. R. . Um Estudo das Recomendações de Acessibilidade para Audiogames Móveis. In: Simpósio Brasileiro de Jogos e Entretenimento Digital, 2015, Teresina. Anais do XIV Simpósio Brasileiro de Jogos e Entretenimento Digital, 2015	B2

Source: produced by the author

7.3 Recapitulating the Research Hypothesis

In Chapter 1, the research hypothesis that guided this thesis work is first presented. This research hypothesis was analyzed (see section 6.2.3) based on the evidence shown by the evaluations described in Chapter 6, in addition to the results presented in Chapter 4 and Chapter 5. This analysis is summarized in the following.

Null Hypothesis: *During onsite usability evaluation involving learners who are blind playing multi-modal video games for cognitive development, there is no significant difference among the Usability Evaluation Methods employed for disclosing specific types of usability issues directly associated with the interaction modalities.*

Research Hypothesis (Alternate hypothesis): *During onsite usability evaluation involving learners who are blind playing multimodal video games for cognitive development, Usability Evaluation Methods effectiveness differ significantly for disclosing specific types of usability issues directly associated with the interaction modalities.*

The research hypothesis was accepted. Friedman test rejected the null hypothesis for the tests run with both games, as detailed in Chapter 6. Hence, it was possible to gather evidence that the compared UEMs (semi-structured interview, field notes, CLUE and video) presented a significant difference in effectiveness. It was explained by the significantly different thoroughness among the compared UEMs. Furthermore, the results showed that the problems disclosed by each UEM have different focuses and are associated with specific interaction modalities and game characteristics.

7.4 Limitations

Although the scaffolding produced in this research achieved its main purposes and can contribute to the planning and guidance of usability evaluation of multimodal games for learners who are blind, it has some limitations. First, the scaffolding components address only empirical UEMs. Even though the administration of empirical methods is essential in this context, the comparison of analytical methods would also be useful.

Second, the scaffolding elements do not concern the evaluation of cognitive impact of multimodal video games for learners who are blind. Third, the results presented in this thesis only address usability, they do not cover other types of interaction measures, such as accessibility and user experience. Besides, the results do not address the evaluation of measures of engagement and interaction, such as flow and user control.

7.5 Future Work

Motivated by the scarcity of work in the literature addressing guidance in conducting evaluation of multimodal video games and virtual environments for cognitive development of learners who are blind, this study leaves the following future work:

- To conduct comparison of analytical UEM in this context, including the use of specific heuristics and cognitive walkthroughs;
- To propose a set of heuristics for usability inspection and/or principles for expert walkthrough based on specific usability guidelines in this context;
- To investigate and compare the evaluation methods for cognitive impact evaluation in this field;
- To propose guidance for evaluating the cognitive impact of multimodal video games and virtual environments for people who are blind;
- To propose guidance for evaluating the user experience and the cognitive flow of the game experience in multimodal video games and virtual environments for people who are blind;
- To investigate the relationship between the interaction modalities of such video games and the cognitive skills meant to be enhanced or improved while playing;
- To expand and generalize SLUP and CLUE to comprise different interaction modalities less common in video games, but more used in other types of application for people who are blind, such as voice commands and head mounted devices;
- To propose a reporting template of usability problems identified using CLUE;
- To perform similar studies comparing UEMs for onsite tests including a larger sample of users and videogames;
- To submit the descriptive model proposed to the validation of experts and practitioners;
- To implement long-term full field studies applying the usability instruments proposed in this work, including the statistical analysis of inter-evaluators reliability.

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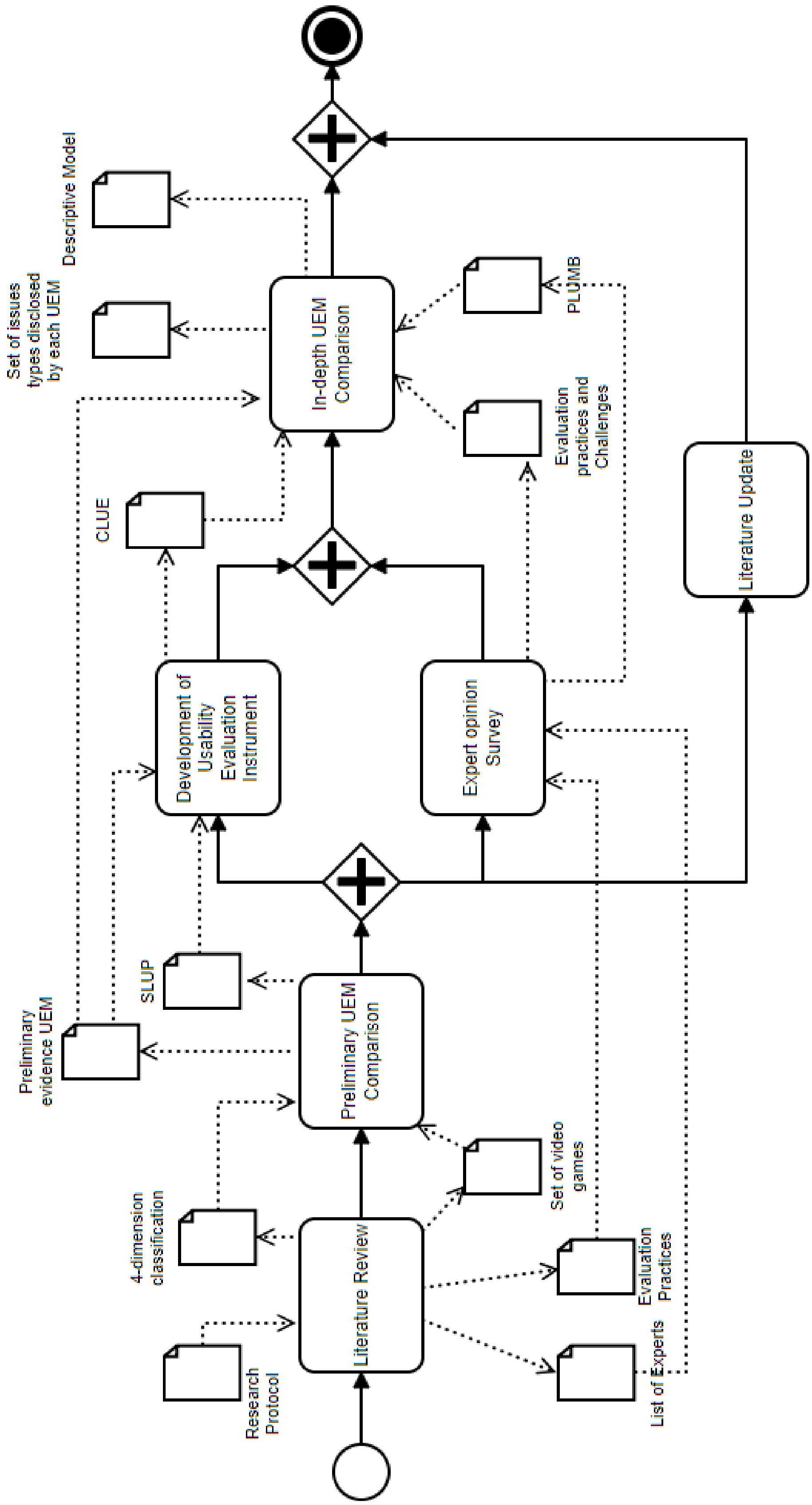
APPENDIX A - DETAILED VERSION OF FIGURE 6 DEPICTING THE INPUTS AND OUTPUTS OF EACH RESEARCH STEP



APPENDIX B – FULL VERSION OF CLUE

Observer identification:

Game under evaluation:

User identification: Age:

GAMEPLAY

1. Check if the player has ***difficulties*** to:	Did it happen?		In which task?	Severity			
1.1 Learn how to play	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.2 Learn how to use the controls	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.3 Handle the controls	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.4 Understand the game goals	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.5 Play without mediation	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.6 Play according to the information provided by the game	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.7 Accomplish the game tasks	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.8 Move through the virtual game environment	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.9 Rotate in the virtual game environment	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.10 Recognize different scenarios in the game	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.11 Distinguish the different characters in the game	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.12 Distinguish the distinct roles in the game	❒ YES	❒ NO		❒1	❒2	❒3	❒4
Check if the player demonstrates to *feel*:							
1.13 Bored, or uninterested while playing	❒ YES	❒ NO		❒1	❒2	❒3	❒4
1.14 Annoyed by any of the game controls	❒ YES	❒ NO		❒1	❒2	❒3	❒4

ACOUSTICS

2. Check if the player has ***difficulties*** to:	Did it happen?		In which task?	Severity			
2.1 Hear the game sounds	❒YES	❒NO		❒1	❒2	❒3	❒4
2.2 Identify a specific sound	❒YES	❒NO		❒1	❒2	❒3	❒4
2.3 Recognize a specific sound	❒YES	❒NO		❒1	❒2	❒3	❒4
2.4 Understand the information conveyed by a sound	❒YES	❒NO		❒1	❒2	❒3	❒4
2.5 Realize that a specific sound is related to a specific action in the game	❒YES	❒NO		❒1	❒2	❒3	❒4
2.6 Associate the game sounds with his prior knowledge	❒YES	❒NO		❒1	❒2	❒3	❒4
2.7 Associate the game sounds with the right objects or actions in the game	❒YES	❒NO		❒1	❒2	❒3	❒4
2.8 Understand information about orientation and location in the game environment	❒YES	❒NO		❒1	❒2	❒3	❒4
2.9 Identify the purpose a specific audio feedback				❒1	❒2	❒3	❒4
Check if the *audible feedback*:							
2.10 Are sufficient to the execution of the game activities	❒YES	❒NO		❒1	❒2	❒3	❒4
2.11 Are correctly applied to the game objects and execution of game activities	❒YES	❒NO		❒1	❒2	❒3	❒4
Check if the player demonstrates to *feel*:							
2.10 Uncomfortable with the speed of spoken audio or TTS	❒YES	❒NO		❒1	❒2	❒3	❒4
2.11 Annoyed by specific sounds or voices	❒YES	❒NO		❒1	❒2	❒3	❒4

HAPTICS

3. Check if the player has ***difficulties*** to:	Did it happen?		In which task?	Severity			
3.1 Recognize a haptic figure using force feedback	❒YES	❒NO		❒1	❒2	❒3	❒4
3.2 Associate a haptic figure with its meaning in the real world	❒YES	❒NO		❒1	❒2	❒3	❒4
3.3 Accept a haptic figure	❒YES	❒NO		❒1	❒2	❒3	❒4
3.4 Perceive different textures of game elements	❒YES	❒NO		❒1	❒2	❒3	❒4
3.5 Discriminate the textures of game elements	❒YES	❒NO		❒1	❒2	❒3	❒4
3.6 Discriminate the forms of game elements	❒YES	❒NO		❒1	❒2	❒3	❒4
3.7 Handle the haptic device	❒YES	❒NO		❒1	❒2	❒3	❒4
3.8 Recognize the force feedback	❒YES	❒NO		❒1	❒2	❒3	❒4
Check if the *vibrating feedback*:							
3.9 Are sufficient to the execution of the game activities	❒YES	❒NO		❒1	❒2	❒3	❒4
3.10 Are correctly applied to the game objects and execution of game activities	❒YES	❒NO		❒1	❒2	❒3	❒4
Check if the player demonstrates to *feel*:							
3.11 Uncomfortable with the intensity of vibration or force feedback	❒YES	❒NO		❒1	❒2	❒3	❒4
3.12 Annoyed by the frequency of haptic feedback	❒YES	❒NO		❒1	❒2	❒3	❒4

GRAPHICS

ONLY FOR CHILDREN WITH VISUAL RESIDUES:

4. Check if the player has ***difficulties*** to:	Did it happen?		In which task?	Severity			
4.1 Understand the information conveyed by images	❒YES	❒NO		❒1	❒2	❒3	❒4
4.2 Understand the information conveyed by colors	❒YES	❒NO		❒1	❒2	❒3	❒4
4.3 See fonts, figures, diagrams or other graphic elements	❒YES	❒NO		❒1	❒2	❒3	❒4