



Exploring Multisensory Extended Reality Approaches for Autistic Children : Improve Well-Being and Assess Auditory Perception

Valentin Bauer

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Exploring Multisensory Extended Reality Approaches for Autistic Children: Improve Well-Being and Assess Auditory Perception

*Explorer des Approches Multisensorielles en Réalité
Étendue pour des Enfants Autistes : Améliorer le
Bien-Etre et Évaluer la Perception Sonore*

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conférences.

Thèse soutenue à Paris-Saclay, le 25 janvier 2023, par

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Title: Exploring Multisensory Extended Reality Approaches for Autistic Children: Improve Well-Being and Assess Auditory Perception

Keywords: Autism; Extended Reality; Multisensory; Audio; User-centered design; Head-mounted display

Abstract: This thesis focuses on the design and use of Extended Reality (XR) environments for supporting autistic children regarding sensory perception.

It is common today to refer to Extended Reality (XR) as all technologies ranging from Augmented Reality (AR) to Virtual Reality (VR). While autism XR research is promising to extend practitioners' interventions, it mainly addresses the socio-emotional abilities of autistic children with mild learning disabilities. Yet, common interventions address the entire spectrum by targeting a range of abilities, including sensory perception. Based on these observations, I conducted 34 interviews with autism stakeholders to compare their practical needs with the literature XR uses and designs. Findings confirmed the presence of a research gap, provided a set of XR guidelines, and called for further exploration of XR sensory and mediation approaches. Furthermore, to better consider autistic children with severe learning disabilities and more complex needs, AR seemed more suited than VR, as allowing children to keep contact with the real environment and their usual practitioner. To examine this objective, two research endeavors were conducted within clinical settings in collaboration with practitioners.

In the first part of this thesis, I investigated the possibility of using sensory and mediation XR approaches to support reassurance and to reinforce the child-practitioner relationship. To that end, an AR application called Magic Bubbles was created to complement usual sensory interventions, such as Snoezelen and Sensory Integration Therapy, which are sometimes limited in terms of flexibility or access. A user-centered design process was conducted for a day hospital setting with two psychologists and one psychiatrist, and validated by

a clinical team of eleven practitioners. After acceptability and usability testing with ten children with neurodevelopmental conditions, a long-term field study with seven autistic children confirmed its potential for reassurance and social interaction. Moreover, using a grounded theory approach, I built a categorization of children's experiences, which could inform future autism XR research. To be able to use Magic Bubbles with a larger number of autistic children, the application then had to be further individualized based on an ecological assessment of sensory stimuli inducing negative or positive experiences among these children.

In the second part of this thesis, I thus focused on using AR to assess the Atypical Auditory Functioning (AAF) of autistic children, in collaboration with a psychomotor therapist. Indeed, although AAF largely impacts the everyday life of these children, current sensory profiles and auditory exams prevent practitioners from testing various auditory stimuli in ecological settings. This makes it hard to differentiate between emotional and physical reactions towards sounds, and thus to develop appropriate sensory strategies. To address this issue, I started by developing a sound taxonomy being representative of autistic AAF through a systematic literature review. The items of the taxonomy were then validated, ranked, and enhanced, through an online questionnaire answered by 68 stakeholders. At last, an AR application and experimental protocol were designed to perform such assessments. Following a participative process involving autistic individuals and practitioners, first assessments of the AAF of autistic children are planned at the therapist's office in the Ile de France area.

The thesis concludes by drawing research perspectives based on the main research findings.

Titre : Explorer des Approches Multisensorielles en Réalité Etendue pour des Enfants Autistes: Améliorer le Bien-Etre et Évaluer la Perception Sonore

Mots clés : Autisme; Réalité Etendue; Multisensoriel; Audio; Conception centrée utilisateur; Visio-casque

Résumé : Cette thèse se concentre sur la conception et l'utilisation d'environnements de Réalité Etendue comme soutien à la perception sensorielle d'enfants autistes.

Il est courant aujourd'hui de désigner par Réalité Etendue (RE) l'ensemble des technologies allant de la Réalité Augmentée (RA) à la Réalité Virtuelle (RV). Bien que la recherche sur l'autisme en RE soit prometteuse pour étendre les interventions des praticiens, la majorité des recherches actuelles se concentrent sur les compétences socio-émotionnelles d'enfants autistes avec de légers troubles de l'apprentissage. Pourtant, les interventions courantes ciblent le spectre entier au travers de nombreux aspects, dont la perception sensorielle. Partant de ce constat, j'ai mené 34 entretiens avec des personnes de la communauté de l'autisme pour comparer leurs besoins éventuels avec les études existantes en RE. Les résultats ont confirmé que certaines approches demeurent sous-explorées, permis de dresser un ensemble de recommandations de conception d'environnements de RE, et encouragé à plus explorer les approches sensorielles et de médiation. Pour considérer les enfants autistes avec de sévères troubles de l'apprentissage et des besoins plus complexes, la RA semble également plus adaptée que la RV, car elle permet de garder un contact avec l'environnement réel. A partir de ces résultats, deux initiatives de recherche ont été lancées au sein d'environnements cliniques en collaboration avec des praticiens.

Dans la première partie de cette thèse, j'ai étudié la possibilité d'utiliser des approches sensorielles en RE pour sécuriser des enfants autistes et renforcer leur lien avec le praticien. L'application de RA Magic Bubbles a ainsi été créée pour compléter les interventions sensorielles courantes, telles que Snoezelen et la thérapie par l'intégration sensorielle, qui sont parfois limitées en termes de flexibilité ou d'accès. Un processus de conception centrée utilisateur a été mené pour

un hôpital de jour avec deux psychologues et une médecin psychiatre, puis validé avec onze praticiens. Après des tests d'acceptabilité et d'usabilité auprès de dix enfants avec des conditions neurodéveloppementales, une étude de terrain de plusieurs mois avec sept enfants autistes a confirmé son potentiel de réassurance et d'interaction sociale. De plus, en utilisant la théorie ancrée, j'ai construit une catégorisation de leurs expériences qui pourrait renseigner de futures recherches en RE sur l'autisme. Afin de pouvoir utiliser Magic Bubbles avec un plus grand nombre d'enfants autistes, une plus grande individualisation de l'application, basée sur une évaluation écologique des stimuli sensoriels perçus comme négatifs ou positifs par ces enfants, était nécessaire.

Dans la seconde partie de cette thèse, je me suis donc concentré sur l'utilisation de la RA pour évaluer le Fonctionnement Auditif Atypique (FAA) d'enfants autistes, en collaboration avec un psychomotricien. En effet, bien que le FAA impacte fortement la vie quotidienne de ces enfants, les profils sensoriels et tests auditifs actuels ne permettent pas de tester des stimuli variés dans des contextes écologiques. Ceci empêche de différencier leurs réactions émotionnelles de leurs réactions physiques par rapport aux sons et donc de développer des stratégies sensorielles appropriées. J'ai commencé par développer une taxonomie sonore représentative du FAA autistique au travers d'une revue systématique de la littérature. Je l'ai ensuite validée, hiérarchisée, et améliorée avec un questionnaire en ligne répondu par 68 personnes de la communauté de l'autisme. Une application en RA et un protocole expérimental ont enfin été conçus pour réaliser de telles évaluations. A l'issue d'une démarche participative avec des personnes autistes et des praticiens, les premières évaluations du FAA d'enfants autistes sont prévues dans un cabinet de psychomotricité de la région parisienne.

Cette thèse conclut en dressant des perspectives de recherches issues des résultats principaux.

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Table of contents

1	Introduction	1
1.1	Rationale	1
1.2	Research approach	2
1.3	Thesis structure	3
1.3.1	XR supports for autism: literature versus field practices	4
1.3.2	<i>Magic Bubbles</i> : a Multisensory AR mediation environment	4
1.3.3	Towards more ecological auditory assessments with AR	5
1.4	Thesis Contributions	5
1.5	Audiovisual examples	8
I	Extended Reality Technologies for Supporting Autism Interventions: Theory Versus Field Practices	9
	Abstract	10
2	State of the art	11
2.1	What is autism?	11
2.1.1	Main traits	11
2.1.2	Daily challenges	12
2.1.3	Sensory features	12
2.1.4	Cognitive theories	14
2.1.5	Views and associated discourses	14
2.2	"Traditional" interventions without digital tools	16
2.2.1	Overview of existing interventions	16
2.2.2	Sensory interventions	16
2.3	Digital supports for autistic individuals	18
2.3.1	The four HCI Waves	19
2.3.2	Fields of use of digital supports for autism	20
2.3.3	Stakeholders' views	22
2.3.4	Designing Tools for Autistic Individuals	23
2.4	Extended Reality technologies for autistic children	24
2.4.1	What is Extended Reality?	24
2.4.2	Using XR to support autistic individuals	26
2.5	Conclusion	30
3	Comparison of existing XR uses with stakeholders' needs	31
3.1	Introduction	31
3.2	Method	31
3.2.1	Method for the Semi-Directed Interviews	32

3.2.2	Method for the Literature Survey	36
3.3	Results	37
3.3.1	Analysis of Common Autism Interventions	37
3.3.2	Comparison Between Stakeholders' Needs and Literature XR Uses	39
3.3.3	Comparison Between Stakeholders' XR Design Insights and Literature Guidelines	41
3.4	Discussion	51
3.4.1	Summary of Results	51
3.4.2	Suggestions of Use Cases for Future Autism XR Research	51
3.4.3	Suggestions of XR Autism Design Guidelines	53
3.4.4	Limits	54
3.5	Conclusion	55

II *Magic Bubbles: a Multisensory Augmented Reality Mediation Environment* 57

Abstract	58
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4 Designing an Extended Reality Application to Expand Sensory Interventions for Autistic Children with Severe Learning Disabilities: Participation of Practitioners 59

4.1	Introduction	59
4.2	Design process with practitioners	60
4.2.1	Methodology	60
4.2.2	Initial use case	60
4.2.3	Use case adaptation for a day hospital context	62
4.2.4	Apparatus & Development	63
4.3	Evaluation with a clinical team	65
4.3.1	Participants	65
4.3.2	Method	65
4.3.3	User experience: Subjective results	66
4.3.4	Design ideas from practitioners	67
4.4	Discussion & Recommendations	68
4.4.1	How XR design can expand sensory strategies?	68
4.4.2	How can XR design suit practitioners?	70
4.4.3	Evaluation of the user experience of children	71
4.4.4	Limits	72
4.5	Conclusion	72

5 Evaluating the Acceptability and Usability of a Head-Mounted Augmented Reality Approach for Autistic Children with Severe Learning Disabilities 73

5.1	Introduction	73
5.2	Method	73
5.2.1	Participants	73
5.2.2	Development of the semi-structured questionnaire	74

5.2.3	Procedure	74
5.2.4	Data collection	76
5.2.5	Data analysis	77
5.3	Findings	78
5.3.1	Acceptability	78
5.3.2	Usability	79
5.3.3	Agency	79
5.3.4	Engagement	80
5.3.5	Social Interaction	80
5.3.6	Evolution of the child's state	80
5.3.7	Real versus Virtual	81
5.3.8	Exploration of the body and space	81
5.3.9	New Hypotheses	82
5.4	Discussion	83
5.4.1	Accepting and Using <i>Magic Bubbles</i>	83
5.4.2	Communicating with practitioners	84
5.4.3	Getting secure	84
5.4.4	Limitations and Future Perspectives	85
5.5	Conclusion	86

6	Head-Mounted Augmented Reality to Support Reassurance and Sharing for Autistic Children with Severe Learning Disabilities	87
6.1	Introduction	87
6.2	Method	87
6.2.1	Demographics	88
6.2.2	Procedure	88
6.2.3	Adaptations to the procedure	90
6.2.4	Data collection	91
6.2.5	Data analysis	91
6.3	Results	91
6.3.1	Conducting the analysis	92
6.3.2	The emerging categories	94
6.3.3	The category called Encountering the AR setting	94
6.3.4	The category called Experience sharing over time	101
6.3.5	The category called Ways of getting secure	103
6.4	Discussion	105
6.4.1	Children's AR experiences with Magic Bubbles	106
6.4.2	Limits of the study	107
6.4.3	Perspectives	107
6.5	Conclusion	108

III Using Augmented Reality to Assess the Autistic Atypical Auditory Functioning 110

Abstract	111
7 Building a sound taxonomy being representative of autistic auditory perception	112
7.1 Introduction	112
7.2 The everyday listening of autistic people	113
7.3 Method	114
7.3.1 Search strategy	114
7.3.2 Inclusion and exclusion criteria	114
7.3.3 Screening process	115
7.3.4 Rationale for building the taxonomy	115
7.4 Findings	116
7.4.1 Study selection	116
7.4.2 Study characteristics	116
7.4.3 Taxonomy coming from the literature	118
7.5 Discussion	119
7.5.1 Limits	119
7.5.2 Perspectives	122
7.6 Conclusion	122
8 Validation of the Sound Taxonomy with Autism Stakeholders	125
8.1 Introduction	125
8.2 Method	125
8.2.1 Development of the online questionnaire	125
8.2.2 Recruitment process	127
8.2.3 Participants	127
8.2.4 Data collection and analysis	128
8.3 Findings	129
8.3.1 Validation of the classification	129
8.3.2 Ranking the sound taxonomy	130
8.3.3 Improving the classification	134
8.3.4 Other insights	139
8.4 Discussion	140
8.4.1 Differences with the literature	141
8.4.2 Limits	142
8.4.3 Future perspectives	142
8.5 Conclusion	143
9 ASD_AudioEval: An AR Application to Assess the Auditory Perception of Autistic Children with Severe Learning Disabilities	145
9.1 Introduction	145
9.2 Creation of the soundbank <i>ASD_SoundBank</i>	146

9.3	Design of <i>ASD_AudioEval</i>	147
9.3.1	Environment	147
9.3.2	Interactions	148
9.3.3	Activities	148
9.3.4	Data logs	151
9.3.5	Apparatus & Development	151
9.4	First version of an experimental protocol	152
9.4.1	Intended participants	152
9.4.2	Protocol	152
9.4.3	Data collection and analysis	154
9.5	Discussion	155
9.5.1	Limits	156
9.5.2	Next design iterations with autism stakeholders	156
9.5.3	Future perspectives	157
9.6	Conclusion	158
10	Conclusion and Perspectives	159
10.1	Summary of the contributions	159
10.2	Discussion and Perspectives	161
10.2.1	Directions for future research	161
10.2.2	Towards new methodologies targeting the entire spectrum	164
A	Material Related to the Interviews with Autism Stakeholders	167
B	Material Related to the Validation of the Sound Taxonomy	173
C	Subset of Sounds Selected for the AR Application <i>ASD_AudioEval</i>	203
D	First Steps Towards XR Music Therapy for Autistic Children	205
D.1	Introduction	205
D.2	Music therapy and XR	206
D.2.1	Music therapy practices with digital tools	206
D.2.2	XR music instruments	206
D.3	First XR Music Therapy Use Case	207
D.3.1	User-centered design: VR balafon	207
D.3.2	Preliminary experimentation	209
D.3.3	Findings	213
D.3.4	Discussion and Conclusion	215
D.4	Second XR Music Therapy Use Case	217
D.4.1	Initial use case	217
D.4.2	Adaptation for a day hospital setting	218
D.4.3	Ongoing experiment	219
D.5	Conclusion and Perspectives	219

Synthèse en français

Cette thèse se concentre sur la conception et l'utilisation d'environnements de Réalité Etendue comme soutien à la perception sensorielle d'enfants autistes.

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Dans la seconde partie de cette thèse, je me suis donc concentré sur l'utilisation de la RA pour évaluer le Fonctionnement Auditif Atypique (FAA) d'enfants autistes, en collaboration avec un psychomotricien. En effet, bien que le FAA impacte fortement la vie quotidienne de ces enfants, les profils sensoriels et tests auditifs actuels ne permettent pas de tester des stimuli variés dans des contextes écologiques. Ceci empêche de différencier leurs réactions émotionnelles de leurs réactions physiques par rapport aux sons et donc de développer des stratégies sensorielles appropriées. J'ai commencé par développer une taxonomie sonore représentative du FAA autistique au travers d'une revue systématique de la littérature. Je l'ai ensuite validée, hiérarchisée, et améliorée avec un questionnaire en ligne répondu par 68 personnes de la communauté de l'autisme. Une application en RA et un protocole expérimental ont enfin été conçus pour réaliser de telles évaluations. A l'issue d'une démarche participative avec des personnes autistes et des praticiens, les premières évaluations du FAA d'enfants autistes sont prévues dans un cabinet de psychomotricité de la région parisienne.

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List of figures

3.1	Method used to conduct and analyze the semi-directed interviews.	32
4.1	Design of <i>Magic Bubbles</i> Game – Content: 1 Bubble; 2 Bubble Column; 3 Panel; 4 Water Pond; 5 Music Bubble; 6 Image Panel; 7 Drawing panel (added after user testing); 8 Recording Bubble (added after user testing) – Therapist UI (E,F): 1 Add/Remove elements; 2 Trigger stimuli; 3 Add/Remove Feedback; 4 Information; 5 Show/Hide the UI.	62
4.2	AR video see-through technical setup	64
4.3	Pre-tests conducted with practitioners at the day hospital. Left: setting - Right - a practitioner testing <i>Magic Bubbles</i> AR application.	65
5.1	Questionnaire's answers regarding the acceptability, usability, agency, engagement, and social interaction, for the ten children with neurodevelopmental conditions and ID who tested <i>Magic Bubbles</i> . For enhanced readability, Q16, Q23, and Q24 were displayed using a 1-5 scale, rather than the 1-7 scale that was used in the questionnaire. Bars represent the median, rectangles represent the interquartile range (IQR) (50% of the sample's values), and circles represent outliers. For each question, 1 and 5 respectively represent the minimum and maximum observable impact.	78
5.2	Questionnaires' answers about children's state. Bars represent the median, rectangles represent the interquartile range (IQR) (50% of the sample's values), and circles represent outliers.	81
5.3	Drawing that ID16 made, representing herself next to the practitioner.	82
5.4	Photographs of critical incidents for four children. (A.) ID6 hitting a pond with his foot, (B.) ID7 unloading on the music panel while keeping in control. (C.) ID8 trying to write his name on the drawing panel. (D.) ID5 stepping over the border of the column. (E.) ID14 giving the equipment to the practitioner after proposing him to test the HMD.	82

6.1	Evolution of children's drawings over time. The abscissa axis refers to the session number and the ordinate axis for children's identifiers. Some boxes are left empty as children did not draw every week (only drawing if they wanted to). We can notice the following features: ID1 drew himself with the headset at s1, and on another boy's shirt at s3; ID3 drew the setting multiple times and gradually added elements to it, reflecting his exploration; ID4 added a red dot at s5 when being unhappy against CL; ID10 represented his relatives when undergoing a challenging time at s2, s3, s4, and maybe VB at s1 (after meeting him for the first time); ID13 may have represented himself at s2 and s6; ID2 just added himself a beard to look like OD on OD's drawing, reflecting a strong dyadic relationship; ID12 never drew.	93
6.2	Photographs of critical incidents that illustrate the concepts and subconcepts coming from the grounded theory analysis and are presented in the results' subsections: (A) ID2 managing to wear the headset alone at s5, (B) ID3 auto-stimulating by jumping at s5, (C) ID13 comparing his virtual drawing to the real practitioner's drawing at s5, (D) ID4 trying to reach practitioner's hand which was hidden by a virtual water pond at s2.	93
6.3	Overview of the four emerging categories of the grounded theory: categories related to the child's experience are displayed by using rectangles filled with orange stripes, and environmental conditions influencing the experience with a rectangle filled with green. Their sizes represent the percentage of phrasings that they gather with respect to the total number of phrasings in the grounded theory (/t). Arrows indicate the main influences that categories have over others. The rectangle on the right connected with dash lines to the category about environmental conditions gives an inside-view of this category by displaying its concepts. Concepts are represented with circles. Their sizes correspond to the percentage of phrasings that they gather with respect to the number of phrasings in the category.	95
6.4	Overview of the concepts (rectangles) and subconcepts (circles) in the category called Encountering the AR setting that emerges from the grounded theory analysis of children's experiences. The lines show an "inside-view" of the concepts by displaying their respective subconcepts. The arrows between concepts display their respective influences. The size of the circles represents the respective importance of subconcepts with respect to the number of phrasings in the category.	96

6.5	Quantitative answers from the questionnaire being related to the emerging category called Encountering the AR setting, about A Acceptability, B Usability, C Agency, and D Engagement.	96
6.6	Overview of the category called Sharing experience over time emerging from the grounded theory analysis of children's experiences. The six concepts corresponding to stages of sharing over time are represented over the abscissa axis. The three sharing profiles that appeared are represented over the ordinate axis, corresponding to different ways of sharing over time. Arrows mark the evolution from one stage to another, and the first stage and last stage that children experienced according to their sharing profiles.	101
6.7	Quantitative rating from the questionnaires corresponding to the emerging categories called sharing experience over time and ways of getting secure. (A) Evolution of communication over time; B Pre vs. Post Child's state.	102
6.8	Overview of the category called ways of getting secure emerging from the grounded theory analysis of children's experiences. Its two concepts called getting secure and getting insecure are respectively represented on subfigures A and B. Subconcepts are displayed with yellow circles. Their sizes illustrate their number of phrasings with respect to the total number of phrasings in these two concepts. The two subfigures are organized following four time windows: during sessions (left part), after sessions (right part), during discovery (top part), or after discovery (low part).	104
7.1	Flow diagram of the review selection process.	117
8.1	Participants' rankings related to the relative impacts of negative sound contexts over autistic AAF. (A) Categories of negative sound contexts. (B) Concepts of negative sound contexts. The order of presentation of the participant groups within each impact level (e.g., low, moderate) has no relevance over the ranking. Concepts and categories are sorted according to the number of strong and very strong ratings.	131
8.2	Concepts and categories for which a significant relationship was observed between participants groups and the rankings. (A) Concepts of negative sound contexts. (B) Categories of sound parameters. .	132
8.3	Participants' ranking related to the relative impacts of the positive sound contexts over autistic AAF. The order of presentation of the participant groups within each impact level (e.g., moderate) has no relevance over the ranking. Concepts and categories are sorted according to the number of "strong" and "very strong" ratings. . .	133

8.4	Participants' rankings of the impact of the different categories of sound parameters. The order of presentation of the participant groups within each impact level (e.g., low, moderate) has no relevance over the ranking.	134
8.5	New classification of positive and negative sound contexts being representative of autistic AAF. Black rectangles with solid lines represent categories. Rectangles with dashed lines in red and green respectively delimit all the negative and positive concepts pertaining to a specific category. Circles represent concepts, their size being adjusted according to their number of phrasings. Number of phrasings are indicated with Xp (where X is a number). New concept or categories that emerged are written in blue. Concepts that derive from pre-existing ones are written in purple. Concepts left unchanged are written in black. The star displayed next to the category called <i>cries</i> signals that this category was the most reported negative sub-context in G2-Q3, even if it hardly appeared in participant's comments.	137
8.6	New classification of sound parameters being representative of autistic AAF. Red and green rectangles respectively represent categories and sub-categories of sound parameters. Circles represent concepts, their size being adjusted according to their number of phrasings. Number of phrasings are indicated with Xp (where X is a number). New concept or categories that emerged are written in blue. Concepts that derive from pre-existing ones are written in purple. Concepts left unchanged are written in black.	140
9.1	Diagram of the environment and interactions in <i>ASDAudioEval</i> . (A) AR view seen by the child when manipulating the tablet (example of the cursor activity). (B) Therapist's interface on a computer to monitor and control the activities' unfolding (example of the cursor activity)	148
9.2	Diagram of the activities in <i>ASDAudioEval</i> . (A) Free-play activity: this activity intends to get the child used to the AR setting. (B) Cursor activity: this activity seeks to assess sound pleasantness and thus to rank the child's preferences and difficulties in terms of semantic contexts, intrinsic parameters, and extrinsic parameters. (C) Executive activity: this activity seeks to assess the influence of semantic contexts, intrinsic parameters, and extrinsic parameters over the child's attention.	149
D.1	Design of the Virtual Balafon. (A.) Real Balafon, (B.) Virtual Balafon.	208

D.2	Part of the music therapy VR questionnaire to be answered by the autistic child with support from the therapist.	210
D.3	Ben playing with the real and virtual balafon at session 2. (A.) Music play with the virtual balafon (VR view)). (B.) Music play with the VR balafon (real view). (C.) Music play with the real balafon.	211
D.4	Questionnaire's ratings. (A.) Evolution of the child's state between the beginning and the end of sessions. (B.) Difference in terms of enjoyment between playing with the virtual and real balafon. QX stands for Question X (where X is a number).	213
D.5	Children's interactive experience with the virtual and real balafon. QX stands for Question X (where X is a number).	214
D.6	Children's relationship with the therapist with the virtual and real balafon. QX stands for Question X (where X is a number). "Neg. behaviours" stands for negative behaviours. "Q22 - Social interact." was a question asking if children interacted more in virtual than in real life.	215
D.7	Design of the VR Train. For the elements that were added or adjusted during the design process we respectively write (<i>added</i>) and (<i>changed</i>). (A.) Child's VR view of the VR train crossing bridges while manipulating the lever – Content: 1 lever; 2 +/- volume buttons; 3 pitch knob; 4 whistle; 5 train; 6 bridge; 7: flag on top of bridges (<i>added</i>). (B.) Avatar of the therapist greeting the child. – Content: 8: avatar of the therapist (<i>changed</i>); 9: colour button (<i>added</i>). (C.) Child and therapist playing together in the room (ongoing testing).	218

List of tables

3.1	Profiles of the participants	33
3.2	Semi-directed questionnaire addressed to the participants. Demog: Demographics.	35
3.3	Fields of interests of the participants regarding XR use cases for autism interventions	42
3.4	Comparison of XR guidelines coming from the literature with sug- gestions from the participants.	44
4.1	Practitioners' needs about using XR at the day hospital.	62
4.2	Design insights from the practitioners	68
4.3	Ways of assessing the quality of children's experiences being pro- posed by the practitioners	69
4.4	Main XR design insights for autistic children with SLN	69
5.1	Profiles of the children who participated to the study. M/F stands for Male/Female. IQ stands for Intellectual Quotient.	74
5.2	Semi-directed questionnaire answered by the psychologists about children's states and experiences. In the column called "Answers", "1-5" and "1-7" represent the types of Likert-type scales that psy- chologists had to answer, with respect to the different questions. We used 1-5 or 1-7 scales depending on the literature references that the questions drew from. "cmt" means that practitioners can add optional comments. The column called "Ref" corresponds to the literature references.	75
6.1	Profiles of autistic children. Condition is defined according to the ICD-10 classification. CARS assesses the significance of autism symptoms: 15-29.5 (non-autistic), 30-36.5 ("mild-moderate" autism), 37-60 ("severe" autism). KABC assess the cognitive condition, with the Mental Processing index (MPI) (Luria model), or the Non- Verbal Index (NVI): below 69 (very inferior to mean), 70-84 (in- ferior to mean), 85-115 (mean). "Ses" represents the number of sessions that each child had. smt. Differences in terms of the num- ber of sessions are due to adaptations to the procedure that were made (see section 6.2.3). "smt." means sometimes.	89
6.2	Design choices and expected children's AR experiences. "im.": images.	90

7.1	Summary of selected contributions (n = 36). Context: Semantic sound context, Params: Sound parameters, P: the study mentions positive sound contexts, N: the study mentions negative sound contexts, A: the study evokes sound contexts or parameters but precise examples are absent.	118
7.2	Presentation of the sound taxonomy for autistic AAF with respect to negative sound contexts, positive sound contexts, and sound parameters. PT stands for the types of sounds suggested by the psychomotor therapist. Mc: Music.	120
8.1	Semi-directed questionnaire answered by autism stakeholders about autistic atypical auditory functioning. cmt: comment.	126
8.2	Demographics. mod: moderate.	128
9.1	Questionnaire ASDAudioEvalQInter. Under: Under-sensitivity. Over: over-sensitivity, Ref.: References, Cat.: Category, Seeking: Sensory Seeking, I: item.	151
9.2	Questionnaire ASDAudioEvalQEnd. Under: Under-sensitivity. it.: items.	151
A.1	Autism interventions without the use of digital tools mentioned by the participants	167
A.2	Autism interventions already using digital tools mentioned by the participants. AAC: Alternative and Augmented Communication; Act.: Activity; AT: Assistive Technologies; C: Desktop Computer; Cat.: Category; Cons: Video Game Console; Diag.: Diagnosis; Edu: Education; Ki: Kinect; Lang: Language; Med: Mediation; Narr: Narrative; Perc: Perception; NS: Non-specified; P: Tablet and/or Phone; PS: Projected Screen; R: Robot; Sens: Sensoriality; TI: Tangible Interface; Unders: Understanding.	171
C.1	Set of sounds being used in the experiment. Cat.: Category; Sub-cat.: Subcategory.	203
D.1	Questionnaire addressed to the therapist (as well children for the last section) about children's experiences with the real and VR balafons. In the column called "References" the letter "i" next to literature references refers to the items of the questionnaires being reported in these references that inspired our questions. "pres" stands for "presence".	211

Terminology

In this thesis, I try to adopt a terminology being respectful of the autism community. To do so, potentially offending terms are avoided, such as “disorder” or “deficit”. I also intend to respect terminological preferences from autistic individuals [30, 151]. In particular, first-person language (e.g., “autistic individual”) is preferred over person-first language (e.g., “individual with autism”). Moreover, rather than referring to autism “severity” levels as defined by the Diagnostic and Statistical Manual of Mental Disorders (fifth edition) [5], which can sometimes be perceived as offending, I will use the phrasings “autistic people with Severe Learning disabilities and complex Needs” (SLN), and “autistic people with Mild Learning disabilities and low support Needs” (MLN). These categories mainly refer to the level of interaction and communication difficulties that autistic individuals face in their everyday life, to difficulties to cope with change, and to their required level of support to complete everyday actions. For instance, on the one hand, individuals with MLN may have difficulties interacting in a shop, or with academic tasks. On the other hand, individuals with SLN may be limited verbally or non-verbal, easily stressed when coming to new spaces, or may struggle to participate in unstructured activities [30]. These terms are used for the sake of clarity and conciseness throughout this dissertation, but do not account for autism strengths (one autistic person with SLN may have a really good visual memory), nor for a potential Intellectual Disability (ID). Therefore, when referring to ID, it will be precised in the dissertation next to SLN or MLN.

In addition to that, the words headsets and Head-Mounted Display (HMD) are often used interchangeably in this dissertation, as well as the terms practitioner and caregiver.

The following abbreviations are adopted in this thesis:

AAC	Augmentative and Alternative Communication
ADHD	Attention Deficit / Hyperactivity Disorder
AR	Augmented Reality
ASC	Autism Spectrum Condition
ASD	Autism Spectrum Disorder
AT	Assistive Technology
ICD-10	The International Statistical Classification of Diseases and Related Health Problems, 10th revision (medical classification list by the World Health Organization)
DSM-5	Diagnostic and Statistical Manual of Mental Disorders, fifth edition
HCI	Human Computer Interaction
HMD	Head-Mounted Display
ICT	Information and Communication Technology

ID	Intellectual Disability
MLN	Mild Learning disabilities and low support Needs
MR	Mixed Reality
MT	Music Therapy
NDC	Neurodevelopmental Conditions
PECS	Picture Exchange Communication System
SLN	Severe Learning disabilities and complex Needs
VE	Virtual Environment
VR	Virtual Reality
XR	Extended Reality

1 - Introduction

1.1 Rationale

Autism is a neurodevelopmental condition which concerns around one percent of people worldwide [177]. It is mainly characterized by interaction and communication difficulties, focused interests, and atypical sensory perception [5]. These features, added to various levels of adaptive (e.g., with executive skills) and cognitive abilities, sometimes with Intellectual Disability (ID), can largely impact autistic people's lives, for instance leading to loss of autonomy, stress, or social isolation. To help them cope with these daily challenges, researchers and practitioners often use technology-based interventions with various interfaces (e.g., tablet, robot) [119, 172, 271]. Such tools can bring positive outcomes since they are flexible, predictable, safe, and often appealing for autistic individuals, despite some limits in terms of multisensory capabilities. Recent reviews suggest that Extended Reality (XR)¹, including Augmented Reality (AR) and Virtual Reality (VR), could overcome these limits due to its immersive multisensory and interactive capabilities, and thus benefit to children over the entire spectrum [126, 149].

However, most existing XR studies address the training of socio-emotional abilities or teaching of specific skills [149]. This focus induces two research gaps. First, it leaves sensory interventions under-explored, although sensory issues concern between 69% and 95% of autistic individuals [16, 312]. In particular, decreased sound tolerance affects around half of autistic people [332]. It is often reported in first-hand accounts as a source of pain or fear [47], as expressed by the autistic scientist Temple Grandin [111, p. 107]: *"My hearing is like having a hearing aid with the volume control stuck on 'super loud.' It is like an open microphone that picks up everything. I have two choices: turn the mike on and get deluged with sound, or shut it off. [...] Hearing tests indicated that my hearing was normal."* Second, this focus excludes many individuals who cannot directly work on such abilities, due to having Severe Learning disabilities and complex Needs (SLN), or ID [31]. Indeed, autism being a spectrum, some people have difficulties initiating social interaction and performing academic tasks, whereas others are non-verbal or very limited verbally, and display significant difficulties to participate in everyday activities [30]. Recent estimates of minimally verbal children and ID among the autistic population are high, being respectively around 25% to 35% [260], and 50% to 55% [263]. This observation is concerning as it entails that the current XR findings may not be applicable for a large part of the spectrum. Moreover, the focus of

¹Within the Milgram and Kishino [198]'s Virtuality continuum, Mixed Reality (MR) covers systems from Augmented Reality (AR) to Augmented Virtuality (AV). Related to the same continuum, we use Extended Reality (XR) terminology to target not only MR, but also Virtual Reality (VR).

existing XR studies may not match all autism stakeholders' needs (autistic people, relatives, practitioners), as already pointed out for autism research in general [234] or focusing on digital tools [230, 294].

In this thesis, we are interested in using XR to complement the sensory interventions being commonly used by practitioners for children over the entire autism spectrum. We take advantage of multisensory XR capabilities, and more specifically auditory capabilities, to explore two main research avenues: (i) enhance autistic children's well-being and self-expression through free-play creative multisensory spaces, and (ii) better assess the lived auditory experiences of autistic children. These two research endeavours are complementary. Indeed, (i) implies securing children and reinforcing the child-practitioner relationship, in turn making them readier to experience the auditory assessments described in (ii), which is particularly important for autistic children with SLN. Moreover, (ii) focuses on developing holistic auditory assessments that could then help to further adapt the multisensory XR spaces described in (i), as well as real spaces.

Regarding the first research avenue, the objective is to overcome the limits of current interventions such as Sensory Integration Therapy [11] or Snoezelen [168] in terms of flexibility, portability, or cost, while using technology to "open doors to communication" [230, p. 13]. This goal encompasses many research problems, for instance related to the design of meaningful situated experiences for children being minimally verbal and with ID, and the evaluation of their holistic XR experiences. Doing so, we try to go beyond a mere focus on autism considered as a "disability", by better considering children's strengths and lived experiences [148].

About the second research avenue, our goal is to use XR to devise more ecological auditory assessments, while making autistic children with SLN more in control of these assessments. Our hypothesis is that this approach could overcome the limits of current auditory assessments, which are not yet capable of capturing their everyday listening experiences. This objective comprises many research problems. In particular, the everyday listening of autistic people has been largely unexplored so far [331], whereas it has been largely studied for non-autistic people in the field of *acoustic ecology* [122]. Furthermore, similar to our first research avenue, it involves methodological challenges related to the design of experiments and to the assessment of the quality of children's experiences.

1.2 Research approach

This thesis investigated the possibility of leveraging the XR multisensory capabilities to complement sensory interventions for children over the entire spectrum in accordance to stakeholders' needs.

Therefore, our first objective was to get a deep understanding of existing autism interventions with or without digital tools, and of potential stakeholders' needs in terms of XR tools to complement them. To do so, we conducted a *practical* state

of the art through interviews with autism stakeholders and compared it with a *theoretical* state of the art of the interdisciplinary literature on the topic. Findings suggested to explore several XR use cases related to sensory and mediation issues, and to use AR rather than VR for autistic children with SLN. These XR use cases entailed two research problems: ensure that the designed use cases could be integrated in clinical settings and usable with autistic children with SLN, and devise relevant methodologies to assess the experience of such children.

To tackle the first research problem, we decided to conduct user-centered design processes with clinical practitioners as well as field testing. To do so, we initiated and then relied on two clinical collaborations:

1. With the day hospital André Bouloche, and more specifically with two clinical psychologists (Olivier Duris, Charlotte Labossière) and one psychiatrist (Marie-Noëlle Clément),
2. With a psychomotor therapist being specialized in sensory integration therapy (Aurélien D'Ignazio).

These clinical collaborations allowed us to design, validate, adapt, and test our initial XR use cases with autistic children with SLN. We also precised our research interests to match practitioners' concerns and practices. This process led to pursue our two initial research objectives (i) and (ii), while trying to extend existing interventions with XR.

To capture and analyze the holistic and situated experiences of autistic children with SLN in clinical settings, and assess the outcomes of studies, mixed methods of inquiry were used (qualitative and quantitative). Indeed, working with such children generates many methodological constraints, for instance due to the impossibility for children to answer self-report questionnaires being commonly used in Human-Computer Interaction (HCI) and XR. Our methods of evaluation were largely informed by qualitative approaches and particularly the grounded theory approach [48, 109], as being adapted to clinical psychology. Due to children's minimally verbal state, they mainly relied on practitioners' interpretations through various data sources (e.g., interviews), but also included some first hand-accounts (e.g., children's drawings), to minimize the bias associated with each source, consider various viewpoints, conduct in-depth analysis, and raise new insights.

1.3 Thesis structure

This dissertation is organized in three parts. The first part (chapters 2 and 3) provides XR guidelines for working with autistic users, informed by stakeholders' potential needs and lived experiences. These guidelines drive the two other parts of this thesis. The second part (chapters 4, 5, and 6) describes the design, development, and testing of a multisensory mediation AR environment with self-expressive capabilities intended for autistic children with SLN. The third part (chapters 7, 8,

and 9) explores the use of AR to overcome the limits of current auditory assessments for autistic children with SLN. Details for each part are given in the following subsections.

1.3.1 XR supports for autism: literature versus field practices

Chapter 2 describes background relevant to the creation and testing of XR environments intended for autistic individuals. After describing autistic people's lived experiences, interventions without and with digital tools are presented with respect to their underlying concepts and theories. Existing autism XR research is finally reviewed in terms of uses, designs, and challenges.

Chapter 3 reports on interviews that were conducted with autism stakeholders, mainly including practitioners, to check if they agreed with the current focus of autism XR research, and to derive XR uses cases and design guidelines being representative of their potential needs.

The most part of the studies reported in these two chapters was published in:

- [A] Bauer, V., Bouchara, T., Bourdot, P. Extended Reality Guidelines for Supporting Autism Interventions Based on Stakeholders' Needs. (2022). *Journal of Autism and Developmental Disorders*. 34 pages.

1.3.2 Magic Bubbles: a Multisensory AR mediation environment

Chapter 4 presents the design and development of the Head-Mounted Display (HMD)-based AR multisensory environment called *Magic Bubbles*, which aims at securing autistic children with SLN and reinforcing the child-practitioner relationship. This design process was published in:

- [B] Bauer, V., Bouchara, Bourdot, P. (2021, October). Designing an Augmented Reality Application to Expand Clinic-Based Sensory Strategies for Autistic Children Requiring Substantial Support: Participation of Practitioners. In *Proceedings of the 2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, Bari, Italy. pp. 254-259.

Chapter 5 describes a study conducted prior to the long-term testing, which enabled to validate the acceptability and usability of *Magic Bubbles* for autistic children with SLN, or a related neurodevelopmental condition. This study was published in:

- [C] Bauer, V., Bouchara, T., Duris, O., Labossière, C., Clément, MN., Bourdot, P. (2022, September). Evaluating the Acceptability and Usability of a Head-Mounted Augmented Reality Approach for Autistic Children with High Support Needs. In *Proceedings of the 19th EuroXR International Conference (EuroXR 2022)*, Stuttgart, Germany. pp. 53-72. [Scientific Paper Honorary Mention Award]

Chapter 6 introduces a long-term field study relying on *Magic Bubbles*, conducted with autistic children with SLN. This study investigated aspects related to reassurance, sharing, and the quality of their AR experience. It has been submitted as a journal paper in:

[D] Bauer, V., Bouchara, T., Duris, O., Labossiere, C., Clement, M.-N., Bourdot, P. (2022). Head Mounted Augmented Reality to Support Reassurance and Social Interaction for Autistic Children with Severe Learning Disabilities. *Frontiers in Virtual Reality* [submitted]

1.3.3 Towards more ecological auditory assessments with AR

Chapter 7 reports on a taxonomy being representative of autistic Atypical Auditory Functioning (AAF) that was derived from a systematic literature review.

Chapter 8 presents a study that was conducted with autism stakeholders to check if the taxonomy previously created matched the lived auditory experiences of autistic children. The goal was to validate and improve the taxonomy, and to rank its different items in terms of their relative significance over the perceived sound discomfort and preferences of autistic children.

Chapter 9 describes the design of the AR application called *ASD_AudioEval* and of an experimental protocol, which aim at providing more comprehensive auditory assessments for autistic children with SLN. As soon as the development will be finished, a participative process involving autistic individuals will be conducted to validate and refine our designs, before to conduct testing with autistic children.

Two paper submissions about the findings of these three chapters are planned. The first paper submission concerns the creation of the sound taxonomy, thus summarizing the outcomes reported in chapter 7 and 8. The second paper submission focuses on the design, development, and testing of *ASD_AudioEval*, thus including some of the insights described in chapter 9.

Chapter 10 is dedicated to the conclusion. After summarizing the contributions of thesis, with respect to its three parts, directions for future research are drawn.

1.4 Thesis Contributions

The thesis offers the following theoretical, technological, and empirical contributions.

Theoretical contributions

In this thesis, the following categorizations and guidelines were built, which could inform the design, development, and methodologies of future XR studies focusing on autism:

- A categorization of existing autism interventions without or with digital tools,

in terms of uses, practices, and challenges, was derived from an analysis of interviews with autism stakeholders.

- XR technological and design guidelines were constructed from an analysis of interviews with autism stakeholders. Findings encouraged to explore more the use of sensory and mediation approaches. Moreover, AR seems more suited than VR to work with autistic children with SLN, as it allows them to keep contact with the real world and with their usual practitioner.
- A categorization of autistic children's holistic experiences with AR was constructed, taking into account various contextual aspects, such as the time and place of the experiment.
- A taxonomy of sounds being representative of the autistic atypical auditory functioning was built based on a systematic literature review, and then validated and enhanced through an online questionnaire answered by autism stakeholders.

Innovative resources

To address the research questions in my thesis, several tools have been created:

- *AR Magic Bubbles* offers children and practitioners with a soothing multisensory environment including free-play activities with self-expressive capabilities, informed by common sensory interventions, such as Snoezelen.
- *ASD_SoundBank* is an audio dataset which intends to support practitioners when conducting auditory assessments with autistic children. It gathers different sound contexts and parameters being representative of the autistic atypical auditory functioning.
- Still under-development, *ASD_AudioEval* is an AR application, which seeks to allow practitioners to conduct more ecological auditory assessments with autistic children, while giving them more control.

As most methods used in the XR autism field were ill-suited to work with autistic children with SLN, we also devised new methods to conduct our experiments. In particular, several questionnaires were built to collect practitioners' insights, in addition to gathering children's views through various ways (e.g., drawings).

Empirical findings

Through various XR experiments with autistic children, observations were made which could inform the design of future XR studies focusing on autism:

- Children with neurodevelopmental conditions and intellectual disability who tested the AR environment *Magic Bubbles* had a positive acceptability, usability, and engagement. They often required practitioners' verbal and physical support to be able to wear and use the headset.

- During our long-term field testing with *Magic Bubbles*, autistic children with SLN displayed a similar evolution in terms of sharing, from an inner experience when accepting the headset, towards a shared experience with practitioners over time. The pace of this evolution relates to how they encountered the AR setting, in line with their respective profiles.
- During our long-term field testing with *Magic Bubbles*, half of the children directly felt secure, while the other half gradually got more secure after grasping the novelty of the setting.
- Findings from our long-term field study with *Magic Bubbles* suggested new insights related to children's self-perception, exploration, and understanding of what is real and virtual.

Beyond the scope of the thesis, the work conducted allowed us to participate to the creation of two VR applications intended to complement existing music therapy approaches for autistic children, and to conduct preliminary testing with three autistic children. This work is reported in appendix D, and was carried out in collaboration with the *Multisensory Experience Lab* (ME-Lab) at Aalborg University Copenhagen (more specifically with Ali Adjorlu), with a music therapist at Paris-Saclay Departmental Music Conservatoire (Delphine Girard), and with the practitioners whom I collaborated with regarding the design and testing of Magic Bubbles at the day hospital André Bouloche. Moreover, the work in this thesis allowed us to question the new expressive possibilities afforded by XR related to music production. Such reflections were shared in scientific communications with or without proceedings:

- Pedersen, B. L., Adjorlu, A., Bauer, V. (2022, June). Exploring the Possibilities of Music Therapy in Virtual Reality: Social Skills Training for Adolescents with Autism Spectrum Disorder. In *Proceeding of the Sound and Music Computing 2022 conference (SMC-22)*, Saint-Etienne, France. 8 pages.
- Bauer, V., Bouchara, T. (2021, April). First Steps Towards Augmented Reality Interactive Electronic Music Production. In *Proceedings of 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (SIVE 2021)*, online. pp. 90-93.
- Bauer, V. (2021, June). *Musiques électroniques et technologies immersives Visuelles* [Oral presentation]. CIEREC : Mondes Spatialisés : Composition et Spatialisation sonore et musicale dans les environnements en Réalité Virtuelle, Augmentée et Mixte, Online.

1.5 Audiovisual examples

Throughout this dissertation we propose several audiovisual and audio examples. The goal is to illustrate the interactive multisensory XR applications that were created, and the sounds being addressed and/or used, which are often difficult to explain only with visuals (e.g., diagrams). Examples for the second part are available at this link: <https://valentinbauer.com/research/doctorat/>. Resources for the third part are available at this private link²: https://drive.google.com/drive/folders/1ru06knkhfIxrdLA8Z03G9_4JF-oNn4l9?usp=share_link.

²Resources for the third part will be made publicly available under the same link as for the second part as soon as the related studies are published.

Part I

Extended Reality Technologies for Supporting Autism Interventions: Theory Versus Field Practices

Abstract

The first part of this thesis aims at providing a whole picture of existing autism XR research while identifying research gaps. To do so, a theoretical state of the art is first conducted, which focuses on autistic people's lived experiences, interventions without and with digital tools, and existing XR uses and designs (see chapter 2). In particular, findings suggest discrepancies between the current focus of autism XR research, around the rehabilitation of socio-emotional abilities or teaching of specific skills, and autism stakeholders' potential needs and views. To validate this observation, and to derive XR uses cases and design guidelines being representative of their potential needs, a practical state of the art is then carried out through interviews with stakeholders, mainly including practitioners (see chapter 3). Findings confirm the presence of discrepancies, encourage to pursue autism XR research focusing on sensory and mediation issues, and offer a set of XR design guidelines intended for autistic users. These findings then drive the two next parts of this thesis.

2 - State of the art

This chapter first gives an overview of autistic people's lived experiences, with respect to the autism condition, cognitive theories, and associated views. Non-digital existing interventions are then introduced, including details about their underlying theories and clinical concepts. After that, existing digital supports for autism are described, with respect to their uses, designs, and to the underlying HCI waves and concepts that drive them. At last, existing Extended Reality (XR) uses and designs for autistic individuals are presented, along with their associated limits. Parts of this chapter can be found in [A], [B], [C], and [D].

2.1 What is autism?

2.1.1 Main traits

Autism is a neurodevelopmental condition with a worldwide prevalence of around one percent [177] and a 3:1 male-to-female ratio [174]. It is characterized by social communication and interaction difficulties, restricted interests, and repetitive behaviours [5]. Moreover, atypical sensory perception concerns up to 90% of people over the different sensory channels [255]. Autistic people¹ can display various levels of cognitive - sometimes with Intellectual Disability (ID) - and adaptive - regarding executive skills - levels of abilities. The latter for instance includes difficulties to deal with change. Autistic people can also struggle to identify and name their own emotions as well as others'. At last, co-occurring conditions are common, such as Attention Deficit / Hyperactivity Disorder (ADHD) [188].

The "Diagnostic and Statistical Manual of Mental Disorders" (DSM-5) [5] defines autism as a spectrum, to highlight the diversity of autistic profiles. It defines three main "severity" levels: level one ("requiring support"), two ("requiring substantial support"), and three ("requiring very substantial support") [5]². These levels respectively correspond to difficulties initiating social interaction, limited social interaction and frequent repetitive behaviours, and very limited verbal and non-verbal communication. While ID remains more frequent for levels two and three, these three levels cover a wide range of cognitive and adaptive abilities [327]. They are often referred to as mild, moderate, and severe levels by other scales (e.g., the Childhood Autism Rating Scale [277]). Since these terms are sometimes perceived as offending by autistic people [30], as described in the terminology section, I will use instead in this dissertation the phrasings autistic people with

¹This dissertation uses identity first-language (e.g., "autistic individual"), in line with autism stakeholders' preferences [30, 151]

²The recent "International Statistical Classification of Diseases and Related Health Problems 11th Revision" [223] now also refers to autism in terms of a spectrum (code 6A02).

"Severe Learning disabilities and complex Needs" (SLN) or with "Mild Learning disabilities and low support Needs" (MLN).

To diagnose the level of autism, practitioners use autism-rating scales that consist of structured observations of the child (e.g., Autism Diagnostic Observation Schedule version 2 [175]), complemented by interviews with families (e.g., ADI-R [176]). Complementary evaluations also exist to target adaptive behaviours (e.g., Vineland Adaptive behaviour Scale [290]) and ID (e.g., Wechsler Adult Intelligence Scale [325]). Moreover, the autism diagnosis is dynamic and changes over time with respect to the developmental level of the individual. Therefore, with respect to the variety of autistic profiles, conducting assessments with autistic individuals requires to use holistic evaluations so that to understand the individual as a whole (e.g., individual's history).

While 50% of autistic people have associated ID, 94% of research that was published in 2016 overlooked them [263]. This gap may stem from three main causes [263, 291, 304]: individuals with SLN are hard-to-reach, they can display challenging behaviours, and their limited verbal abilities or associated ID can generate methodological difficulties (e.g., about data collection and analysis).

2.1.2 Daily challenges

Autistic features can impact everyday activities in various ways depending on the autism level. For instance, autistic children with SLN can struggle to cross a street, or feel unwell in crowded places, leading to loss of autonomy, whereas those with MLN can have academic difficulties. Difficulties also concern families, including stress and anxiety, sometimes leading to isolation or depression [28, 181].

Psycho-social challenges often affect individuals. In particular, anxiety is common, with both anxieties affecting the general population (e.g., fear of animals) and autism-related fears (e.g., sensory-related) [171]. Social anxiety is most reported and displays multiple causes [19, 211]. For instance, at school, children can actively look for friends, and want to 'fit in'. Though, their misunderstandings of social cues can lead to being teased (e.g., name-calling) or bullied (e.g., physical violence) [135]. Their narrow interests can also make their peers less willing to interact, and repetitive behaviours can be stigmatizing, and lead to social exclusion. Challenges often remain after the school period, for instance during the transition to adulthood [310], or when looking for jobs [134]. Such life events can gradually make individuals construct a negative perception of themselves [69, 135], and induce isolation or depression thought patterns [105, 272]. However, some positive relationships with peers can outweigh these challenges through support and understanding (e.g., friends at school) [135].

2.1.3 Sensory features

2.1.3.1 Common sensory features

Sensory Processing Disorders (SPD) have long been overlooked, being only included as a core autism feature in 2013 by the DSM-5 [5]. Even if most reported

during childhood [20], SPD are lifelong, and mainly concern sound, touch, and movement [45]. As such, they largely contribute to the child's atypical development [255], due to impeding the correct integration of incoming stimuli, in turn preventing children from adapting their behaviours accordingly.

Many first-hand accounts refer to SPD as a source of distress and isolation hindering their daily life and autonomy [169, 254]. They can also be highly stressing for families, due to the variety of potentially overstimulating environments and the uncertainty about how children would react [13].

Three types of SPD exist [200]: *sensory modulation disorders*, *discrimination disorders*, and *motor disorders*. Sensory modulation disorders are caused by a non-appropriate regulation of incoming sensory stimuli by the neural system. They include over-responsivity to stimuli, leading to negative responses such as avoidance or distress [115]. In particular, atypical responses to sounds are common, with children covering their ears, or speaking out loud to cover sounds, such behaviours being sometimes referred to as "stereotypies" [225, 297]. Under-responsivity is also common, with difficulties to identify stimuli (e.g., cold temperatures). Individuals thus require high-intensity stimuli to get involved in tasks. Such needs can induce sensory seeking behaviours to increase the level of arousal while performing a self-regulatory function (e.g., humming). These behaviours are also referred to as self-stimulatory practices ("stimming") or stereotypies. The second type of SPD consists of sensory discrimination difficulties, for instance when two sounds are heard simultaneously. The third type refers to sensorimotor disorders, including postural disorders and dyspraxia (e.g., people not being aware of their physical presence in space).

2.1.3.2 Auditory perception

Autistic people often display an Atypical Auditory Functioning (AAF), involving a Decreased Sound Tolerance (DST) towards everyday sounds (e.g., toilet flushing) and atypical sound preferences (e.g., pink noise) [132, 225, 297, 331]. Williams et al. [332]'s recent meta-analysis estimates that DST affects 38 to 45% of autistic people during their entire life, leading to social isolation or stress.

Three theories try to explain the causes of autistic AAF [225, 297, 331]: *physiologic*, *psychoemotional-behavioural*, and *enhanced perceptual functioning*. The physiological perspective refers to *hyperacusis*, i.e., an over-sensitivity to physical sounds parameters (i.e., sound intensity) irrelevant of the context [138, 297, 331]. Conversely, as difficulties are often context-dependent, the psychoemotional-behavioural perspective accounts for difficulties processing affective auditory cues [180, 297], with both *phonophobia* and/or *misophonia* [297, 331]. Phonophobia consists in a *fear* of sounds (e.g., dogs barking) [138, 331]. *Misophonia* characterises strong emotional reaction to sounds in specific contexts and/or with a specific meaning to the individual (e.g., chewing) [138]. While under-studied so far, it could play a major role [331]. At last, enhanced perceptual functioning states that autistic individuals tend to outperform non-autistic individuals regarding the

perception of low-level auditory information (e.g., pitch differences), but struggle to integrate complex auditory scenes (e.g., sound in noise) [208, 269].

Previous studies and first-hand accounts have suggested that hyperacusis, phonophobia, misophonia, and enhanced perceptual functioning may all be part of autistic AAF [47, 274, 331]. Though, to our knowledge, no sound taxonomy accounting for autistic AAF exists so far. While Scheerer et al. [274] conducted an online questionnaire answered by 88 autism stakeholders on this issue, findings only include some key sound contexts and parameters, and overlook sounds being often experienced positively. This research gap may stem from terminological issues, as the term “hyperacusis” holds various meanings depending on studies [297, 331]³.

2.1.4 Cognitive theories

Since Kanner [147] coined the term “autism” in 1943, many cognitive theories have been proposed. In particular, two major theories have emerged, which mainly focus on autism difficulties: *Theory of Mind* (ToM) deficit, and *Executive dysfunction* [235]. The former refers to difficulties to put oneself in someone else’s shoes, i.e., understanding what other people may think. The latter accounts for planning difficulties and difficulties to cope with change.

Given that these theories tended to overlook autistic strengths, such as good visual memory [235], Frith [92, 93] proposed the “*weak*” *central coherence theory* (WCC). WCC posits that autistic people have an acute perception of the details of a situation, but can struggle to grasp the global picture. For instance, they can perform better than non-autistic individuals regarding auditory detection tasks, but can get overwhelmed in complex sound environments including many sound events. This theory is close to another vision developed by Gepner and Tardif, which states that the world can be perceived as going too fast by autistic people, due to not having enough time to integrate everything [103].

2.1.5 Views and associated discourses

Similar to other disabilities, autism is subject to many entangled discourses, depending on who speaks and in which context. Three main views exist: the *medical model of disability*, the *social model of disability* [221], and the *neurodiversity movement*. As they largely influence the design of digital supports for autism, being connected to some HCI concepts that are detailed in section 2.3.4, this subsection successively presents them. Doing so will then allow us to better situate where our thesis belongs within the autism field and between these narratives.

2.1.5.1 Medical Model of Disability

The *medical model* refers to autism in terms of diagnosis, as described by the DSM-5 or CIM-11. It thus considers autism as a disability needing to be “fixed” with respect to a *social norm*, for instance related to social interaction or repet-

³We here refer to the definition of hyperacusis proposed by Williams et al. [331] that is described above.

itive behaviours. While the model comes with negative terms such as “disorder”, “impairment”, “deficit”, “restricted”, or “abnormalities”, it provides diagnosis categories which enable to tailor the level of support for autistic individuals [135]. For instance, the theories above mentioned of ToM deficit, executive dysfunction, and WCC employ negative terms, but led to significant progress in autism research. The *medical model* is mainly related to HCI studies focusing on rehabilitation, that fall into the first and second HCI waves being presented in the next subsection.

2.1.5.2 Social Model of Disability

The *social model of disability* contradicts the medical view by claiming that individual’s impairments largely come from society, due for instance to a lack of adaptations or stigma [221]. Moreover, it stands against the medical model which ascribes an “autistic label” [112], potentially entailing stigma from neurotypical individuals⁴, with negative consequences over how autistic people view themselves [116, 135]. Indeed, as [135, p. 31] reports, it can lead autistic children to consider themselves as “a freak”, or to dislike how other people see them: “That’s how some look at it is that I’m retarded and I really don’t like that, it really bugs me”.

Experiences of stigma and of lack of understanding can also be stressing for families, for instance when being judged as “bad” parents, or leading to feel responsible for their child’s autism [181]. Moreover, parents can be highly concerned about their children’s futures during the diagnosis process [78]. However, better explaining what autism actually is could help to decrease negative stigma [28], and shift how parents and practitioners approach diagnosis and care services, in turn leading to improved life quality for the child and families [28, p. 160].

2.1.5.3 Neurodiversity Movement

Neurodiversity bridges the gap between the medical and social views, by acknowledging both social and inner challenges. Yet, it also celebrates autism strengths and variations with respect to non-autistic individuals [148]. This community was built by autistic people on the internet in reaction to autism associations and care professionals who took decisions for them without them [148], being considered as not capable of participating. The movement advocates for the use of identity-first (e.g., “autistic person”) over person-first (e.g., person with autism) language [151, 286], and rejects medicalized language, described as *ableist* [30].

Neurodiversity focuses on holistic aspects of experience such as *quality of life* and *well-being* rather than *cure* [12]. Doing so, it condemns research overlooking autistic people’s daily experiences, e.g., medical practices encouraging eye contacts without considering their use as a potential coping mechanism, nor offering alternatives [46]. This evolution from *cure* towards alternative ways of *being* has similarities with the fourth HCI wave, that will be described in section 2.3.1.

⁴Neurotypical individuals refers to individuals with a typical neurological development or level of functioning.

2.2 “Traditional” interventions without digital tools

Many interventions without digital tools exist to address the diverse needs of autistic individuals [270]. This section attempts to provide an overview of these interventions, with a particular focus on sensory issues, as they concern most individuals. It is a prerequisite to then introduce the use of digital tools and XR in autism research in the next sections.

2.2.1 Overview of existing interventions

While early, structured, and individualized approaches are advised to address autism challenges, multiple interventions exist [270]. Behavioural interventions, such as Applied-behaviour Analysis (ABA), focus on children’s behaviour, including its antecedents and consequences, with many strategies, e.g., reinforcements [179]. They can be combined with alternative communication methods, e.g., the Picture Exchange Communication System (PECS) [85], or Makaton [203]. Developmental interventions are grounded in developmental psychology and encourage active exploration and child-practitioner interactions [238]. Naturalistic Developmental behavioural Interventions (NDBI) are derived from these previous interventions to teach developmental skills within naturalistic settings [278], e.g., the Early Start Denver Model (ESDM) [257]. Other interventions mainly focus on structuring the environment, e.g., Treatment and Education of Autistic and related Communication-handicapped CHildren (TEACCH) [196]. Psychodynamic interventions then focus on the social interactions and how thoughts affect behaviour [197]. Sensory interventions also exist with various approaches intending to rehabilitate sensory issues, or to better cope with sensory-induced daily difficulties, being described in the next subsection. At last, integrative interventions take advantage of elements from different interventions to best cater for the child’s needs [159].

Yet, interventions are sometimes hard to pursue in healthcare or educational settings. While practitioners often struggle to work with autistic children with SLN or ID [162], autism research hardly considers such children [263]. Challenges can arise from the lack of flexibility of the tools or environments, that can hinder the child’s engagement over time, as well as from a lack of resources, time constraints, or hard-to-get training [162]. Such challenges can also make it hard for teachers or families to accommodate for the child’s specific needs. Families and individuals also often face difficulties accessing social and care services, inducing stress, and possibly making individuals think that “they don’t fit anywhere” [116, 181]. At last, families sometimes cannot afford the cost of interventions [258], or can be discouraged due to not seeing immediate progress.

2.2.2 Sensory interventions

Four main sensory interventions exist to support autistic individuals, being detailed below [45]: Sensory Integration Therapy (SIT) [11], Sensory-Based Interventions (SBI), environmental adaptations, and mediation interventions. They involve

different levels of children's participation, are conducted in different settings, and target various objectives (e.g., self-regulation, rehabilitation). We use this classification for the sake of clarity based on our understanding of the literature, even if studies still differ in terms of classifications and terminologies [45, 270].

2.2.2.1 Sensory Integration Therapy

SIT aims to promote children's adaptive responses with respect to sensory experiences, by enhancing the integration of multisensory interactive processes. Playful child-directed sensory activities are used (e.g., trampoline) within clinical settings, which target multiple sensory channels (often tactile, proprioceptive, vestibular) and address daily sensory issues. They aim for a "just-right" challenge: putting the child slightly out of their comfort zone and prompting responses based on their highest existing developmental skills. SIT can be used for individuals across the entire spectrum [11, 276], being considered evidence-based practice for children aged between four and twelve [276]. Yet, as clinical sensory resources may not be flexible enough, children may get bored over time, thus hindering their engagement.

2.2.2.2 Sensory-based interventions

SBI are single-sensory strategies that are used in everyday environments (e.g., school, home) to target self-regulation, and thus prevent over-arousal [45]. This adult-directed approach relies on multiple resources to target various sensory channels (e.g., brushing, massage). For instance, noise-cancelling headphones can be advised in the case of auditory over-sensitivity, to limit incoming sounds, with good outcomes in terms of self-regulation [237]. Yet, SBI are not yet considered as evidence-based practice, as the variety of practices and contexts being covered entail methodological challenges for studies studying them [45].

2.2.2.3 Environmental adaptations

When possible, therapists can suggest to adapt the environment to accommodate for children's specific needs and support self-regulation (e.g., home) [236]. For instance, occupational therapists can propose to remove noisy equipment from classrooms to enhance children's attention, or to add carpets to remove echoes.

2.2.2.4 Mediation interventions

For autistic children with SLN, directly working on specific tasks (e.g., joint attention) can be challenging. Thus, prior to that, secure and appealing activities may be used to strengthen the child-practitioner relationship⁵. To that end, *mediation* activities are often used to create a *holding* space [334], i.e., a supportive and secure environment for generating and supporting exchanges, with regards to the physical space, the activity, and people being present. Within that space, open-ended sensory activities with self-expressive capabilities can be used (e.g., drawing),

⁵This process is sometimes referred to as building the *therapeutic alliance*, depending on clinical fields.

being either child or adult directed. Two multisensory activities are common, being described below: *Snoezelen* [168, 219] and *Music Therapy* (MT) [104, 190]. Even if we mainly describe these two approaches, as they inspired some research endeavours in this thesis, other approaches also have promising effects, such as animal-assisted interventions [270], with for instance equine therapy [295].

Snoezelen aims to support emotional and behavioural regulation, and to strengthen the dyadic relationship through a multisensory safe space [168]. Many stimuli are used, which cover most sensory channels, e.g., bubbles columns, water beds, or visual projectors. Activities are directed by the child or the adult depending on the child, the practitioner, and the intended therapeutic outcomes. Despite being promising, especially for autistic children with SLN [219], it is not yet considered as evidence-based practice. Reasons may include the non-reproducibility of studies, as activities are tailored to the child's profile. Yet, resources can sometimes be too expensive for practitioners and clinical settings to afford.

Considered as evidence-based practice, MT can be used in clinical settings or at home, with individuals or groups across the entire autism spectrum [190]. MT helps to address socio-emotional reciprocity, verbal and non-verbal communication, attention, initiative-taking, self-esteem, as well as motor skills [104, 190]. Children interact with the therapist through music rather than directly, which can be easier. Multiple activities exist (e.g., singing songs), being directed by the child or the adult depending on approaches (i.e., active or receptive MT) [104, 190]. The child-practitioner relationship plays a key role in the success of MT interventions [190, 209], with active and improvisation techniques being the most promising. Yet, four main limits exist: MT may induce social anxiety for autistic children [19], resources may have limited flexibility and multisensory capabilities, resources may not be accessible for families, and MT still lacks of recognition in Europe [247].

2.3 Digital supports for autistic individuals

Sandgreen et al. [271] and Grynszpan et al. [119]'s meta analyses suggest that digital tools⁶ are promising to overcome the limits of common interventions. This is particularly due to their flexibility, accessible cost, predictability, safety, possibility to rehearse actions, in addition to being controllable and often appealing for autistic individuals [119, 172, 271]. Moreover, they can grant access to existing approaches that would otherwise not be accessible for families [162]. However, while they enable to target individuals across the entire spectrum [126], most studies concern autistic children with MLN [119] and without ID [119, 263]. This dearth of research mainly stems from three causes [263, 291, 304]: this population is hard-to-reach, they can display challenging behaviours, and limited verbal abilities or ID can generate methodological issues (e.g., about data analysis).

⁶By "digital tools", we refer to all low-immersive technologies, thus excluding high-immersive technologies such as XR, which will be described in the next subsection.

Over the last then years, more and more digital supports have been created by research and industry [271, 338]. Applications have mainly addressed socio-emotional abilities (e.g., emotion recognition), with various interfaces, such as computers, touchscreen interfaces (smartphone, tablet), or robots [119, 155, 271, 294]. Yet, despite their potential, methodological discrepancies between studies still prevent from considering digital supports as evidence-based practice.

This section draws a state of the art of low-immersive digital supports for autism. After presenting the evolution of the consideration of the user in HCI through the four HCI waves, we introduce current uses, stakeholders' views, and design guidelines. This section is a prerequisite to then detail how high-immersive interfaces such as XR can complement these digital supports in the next section.

2.3.1 The four HCI Waves

The four HCI waves correspond to various design research agendas which appeared over time and now co-exist. They went from assessing user experiences in terms of performance, to more subjective accounts. While all waves are detailed below, our work in this thesis mainly falls within the third and fourth waves.

The first HCI wave is driven by an engineering perspective. Digital solutions are created to optimize existing processes (e.g., documentation), with testing focusing on performance metrics (e.g., task completion time). The second wave explores technology with respect to user actions and their underlying cognitive processes [128]. Users' acceptability and usability are more valued, as well as how they communicate with computers. New measures appear to assess these features, for instance targeting the ease of learning. These two first HCI waves are sometimes criticized for reducing people's experiences to facts, without considering their subjective experiences. Parallels can be drawn with criticisms made about the medical and social models, which reduced disability either to inner or external causes.

To tackle this issue, the third wave, also called *situated perspectives*, focuses on *user experience*, in terms of meaning or emotions with respect to the users' culture or embodiment [128]. Two approaches informed our work: *positive technology* [251] and *probes* [99]. *Positive technology* fosters well-being, by seeking to improve users' quality of experience, adaptive behaviours, and positive functioning. To do so, it focuses on affective quality, engagement, and connectedness between users. *Probes* are open-ended playful digital resources encouraging exploration. They aim to get insights about the users' quality of experience [99], by valuing *uncertainty* and *subjective interpretations*, to overcome "researchers' tendency to apply their own conceptual frameworks to the phenomena they observe" [99, p. 2]. Parallels could be drawn with developmental and sensory approaches above mentioned, since they both rely on play to gradually work on abilities.

A fourth wave called "Entanglement HCI" has recently appeared. It tries to understand user interactions through a network of relationships between humans and non-humans (in particular digital technologies) [89]. This wave advocates for increasing users' *agency*, i.e., their perceived ability to act.

2.3.2 Fields of use of digital supports for autism

Digital supports can be classified into four main categories: rehabilitation and education, assistive technologies, well-being, and information about autism. While simplified, these categories are presented below to give a global picture of the field, drawing upon existing classifications [119, 271, 294].

2.3.2.1 Rehabilitation and education

Most studies which explore the use of digital tools for autistic users address the rehabilitation of socio-emotional abilities or the teaching of specific skills, through various interfaces (e.g., touchscreen devices, computers) [294]. This observation is confirmed by two recent meta-analyses about digital supports for autism [119, 271], and a recent review about video games for autistic users [139]. Moreover, evaluations mainly rely on extrinsic measures (e.g., performance, usability), in relation to the first and second HCI waves. Four main purposes are explored, being driven by the medical model of disability, and described in the four next paragraphs: socio-emotional abilities, education, therapy, and behaviour analysis.

Socio-emotional abilities are largely addressed, such as verbal and non-verbal communication, social interaction (joint attention, collaboration), or Theory of Mind (ToM) (emotion recognition, empathy, imitation) [294]. For instance, Kandalaft et al. [146] developed a social cognition training program for autistic people running on a computer, which includes various scenarios such as meeting new people, dealing with a conflict, or doing a job interview⁷. Ten sessions with eight autistic adults had positive outcomes in terms of ToM and emotion recognition. Golan et al. [110] created the animated series called *The Transporters*, running on interactive DVDs, where faces with emotions are displayed at the front of trains. Testing with twenty autistic children with MLN were positive in terms of emotion recognition. Trémaud et al. [314] experimented the use of *AMIKEO*® applications on a tablet to train various skills (communication, socialization). After a one-year experiment with eleven autistic children with ID, in comparison to eleven autistic controls, a positive evolution was observed for children using the tablet.

Education is largely addressed, by teaching children about everyday contexts, for instance through storytelling or social stories, or by learning strategies to stay focused [294]. In particular, short stories with text and visuals are common in traditional interventions, to teach how to behave in specific social contexts (e.g., hairdresser) [113]. Though, they have limits in terms of flexibility and individualization that digital tools seem promising to overcome [42, 125]. Video modeling is also widely used, consisting of looking at a video of somebody doing a target behaviour, and imitating it, with positive outcomes, e.g., for teeth brushing [65].

Some applications are specifically developed for clinical settings, to extend

⁷This study self-identified as VR, as using a 3D virtual world generated by the *Second Life*™ software [166]. However, we classified it as a traditional digital tool as it runs on a low-immersive interface (desktop computer).

existing therapies (e.g., ABA), or propose new ones (e.g., robot-assisted therapy) [294]. For instance, the LearnEnjoy[©] applications were created based on ABA principles [220]. A two-year experiment with forty autistic individuals enhanced their ability to cope with change. Bartoli et al. [17] also focused on sensorimotor issues, through three motion-based touchless games intended for autistic children with SLN. A three-month testing with ten autistic children was promising in terms of learning, attention, and motor and visual abilities.

Autism research also focuses on behaviour analysis, often using little to non-intrusive technologies [294]. Biosensors are promising to measure physiological aspects related to anxiety (e.g., heart rate) [306, 317]. Doing so, they can provide autism stakeholders with more information about the emotions of individuals who struggle to name or express them. For instance, Van Laarhoven et al. [317] could identify some anxiety-provoking contexts for five autistic adults with or without ID (e.g., the bus ride) by using a wearable device monitoring breathing. Although such technologies may not suit individuals who display tactile over-sensitivities, they represent promising research avenues [284]. Non-intrusive technologies can help to understand autistic perception. For instance, Grynszpan et al. [118] examined what autistic people tend to visually focus on, by displaying animated scenes including virtual characters on a computer screen, and recording their eye movements. Testing with thirteen autistic teenagers with MLN and fourteen non-autistic teenagers suggested less eye movement modulation for autistic participants.

2.3.2.2 Assistive Technologies

As defined by the World Health Organization (WHO), Assistive Technologies (AT) concern all technologies that could be added to people's daily life, to improve well-being, independence, and functioning [329], being driven by the social model of disability. Yet, they only represent 11.5% of all digital supports for autism [294]. Common uses include digital versions of paper-based alternative communication methods relying on visual pictograms (e.g., adding audio output), with promising outcomes over social communication [313].

Yet, most AT for autism are in fact driven by a medicalized view [250, 294], contrary to AT created for physical disabilities which target agency and quality of life [250]. For instance, most studies identified by Syriopoulou-Delli and Stefani [301]'s review about AT for autism adopt a rehabilitation perspective. Therefore, "most technologies imply that neurotypically oriented communication is a desired norm instead of trying to aim for a more mutual understanding" [294, p. 16]. To pursue this latter intent, Ringland et al. [250] suggest developing more holistic AT, targeting everyday environments and focusing on life quality (e.g., self-management), with similarities to what the third and fourth HCI Waves advocate for.

2.3.2.3 Well-being and Play

Some studies focus on play, exploration, and the quality of experience, with objectives being also stated by the neurodiversity movement, and the third and

fourth HCI Waves. Two main approaches exist: multisensory settings and co-design of technologies.

Several digitally-augmented multisensory settings with full-body interactive capabilities have been created in collaboration with clinical teams, with positive outcomes in terms of relational and well-being issues for autistic children [37, 57, 95, 100, 204, 227, 248]. In these environments, most physical items are augmented to trigger sensory stimuli based on users' body actions. Children can see and act with people around, including practitioners. While *Mediate* [227], *Land of Fogs* [57, 204], the *Responsive Dome Environment* [37] used child-directed free-play activities, *Magika* [100], *Magic Room* [95] and *Sensory Paint* mainly relied on adult-oriented task-oriented activities. About the contexts of use, *Mediate* was conducted in a large space, *Magic Room*, *Magika*, and *Sensory Paint*, used a projected screen, a ball and a Kinect camera, *Land of Fogs* used a large floor projection and a butterfly net to interact with, and the *Responsive Dome Environment* consisted of a small dome with a tangible interface. Yet, such settings display some limits, due to being bulky or too expensive for clinical settings.

Another approach consists in co-creating technologies with autistic children, to capture their holistic experiences based on their actions and feedback, rather than on researchers' interpretations, being informed by the third and fourth HCI Waves. Spiel et al. [291] carried out such a process with four autistic children over a year, through the *OutsideTheBox* project. A qualitative analysis led to uncover a detailed account of children's experiences, and to suggest new ways of assessing experiences with them. Yet, such projects being time-consuming for researchers, they remain limited to a low number of children.

2.3.2.4 Information about Autism

While little explored so far, some applications or videos have been developed to overcome negative assumptions about autism. For instance, Bratitsis [33] managed to elicit empathy among ten neurotypical children towards autistic peers regarding five aspects (e.g., hand flapping) by using digital storytelling. The National Autistic Society also made a video under the provocative title "Can you make it to the end?", where the viewer is put in the shoes of an autistic child in a supermarket [289]. Though, to our knowledge, the outcomes of this project were not reported.

2.3.3 Stakeholders' views

Findings from an international survey answered by 388 parents of autistic children about their use of digital tools at home suggested that they are often appealing for children over the entire spectrum [172]. They are often used for recreational activities, for instance with video games on various interfaces (e.g., touchscreen devices, computer). As suggested by other interviews with 58 autistic adults, video games can indeed bring positive outcomes such as entertainment/thrill, stress relief, and social connection [192]. Though, risks of addiction or isolation exist in case of overuse [192]. As illustrated by the emergence of the neurodiversity movement

on the internet, digital tools are largely used by autistic people to bond with each other, through social media [323], or gaming communities [192], such as *Minecraft* [249]. Parents seem positive about such use, but tend to prefer uses related to education, and are sometimes concerned about the risks above-mentioned [172].

Many practitioners already use digital tools to complement their interventions [271], or to support the children's daily needs and autonomy [187, 250]. Though, others remain reluctant to using them, due to risks above-mentioned [127].

2.3.4 Designing Tools for Autistic Individuals

Previous guidelines have been proposed for autistic users, which intend to inform the design of new tools and to assess the level of evidence of existing tools [307, 338]. Regarding the former, Tang et al. [307] suggested design guidelines for serious games addressing emotion recognition, informed by interviews with autistic children and practitioners. Children often suggested the use motivational factors (e.g., hidden messages), and practitioners often mentioned elements to promote the generalization of the skills learned (e.g., using real-life scenarios). About the latter, Zervogianni et al. [338] gathered an international group of autism stakeholders and researchers to agree on a set of design guidelines⁸. They suggested three categories to assess the relevance of applications: reliability, engagement, and effectiveness.

As autistic individuals have a specific way of perceiving the world, the design of digital supports should be grounded on user-centered and participative design approaches [84, 230]. The goal is to conduct research endeavours matching their interests, by giving a voice to all stakeholders during the design process. For instance, findings from a two-year seminar involving 240 stakeholders indicated that design process should pay more attention to how autistic people experience the world, and encouraged to pursue studies in real-life settings [230].

Despite the potential benefits of digital supports for autism that were reported in this section, several limits emerged, related to their main focus on socio-emotional issues, and to their lack of immersive multisensory capabilities. Indeed, focusing on such issues can induce social anxiety [294]. Moreover, the lack of multisensory immersive capabilities makes it difficult to extend sensory interventions, and to prevent potential over-arousal caused by real-life environmental stimuli. This observation is surprising, considering the common use of sensory interventions for children over the entire spectrum, and the fact that 90% of autistic people have sensory issues [255]. Moreover, it raises several research questions. First, which digital supports autism stakeholders use on a daily basis ? Are the objectives of technology-based interventions close to non-digital interventions? Moreover, would stakeholders benefit from using more multisensory immersive capabilities? If yes, for what purposes? These questions will be investigated through interviews with stakeholders being reported in the next chapter.

⁸This project was publicly released at <https://beta-project.org/en/about/>.

2.4 Extended Reality technologies for autistic children

This section presents the current state of Extended Reality (XR) technologies with respect to the autism field. It only considers high-immersive devices, thus excluding tools using 3D visualizations on low-immersive devices, some of them being presented in the previous section.

2.4.1 What is Extended Reality?

In 1968, Sutherland [300] created the first Head-Mounted Display (HMD), a see-through device enabling to display virtual 3D objects as “transparent ‘wire frame’ line drawings” onto the real environment [300, p. 2]. This system aligned with his concept of the “ultimate display”: “A room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. [...] A bullet displayed in such a room would be fatal.” [299, p. 2]. While the system was heavy, uncomfortable, and had a limited 40-degree field of view, it still made users say that they perceived *realistic* images (e.g., image of a cube). Twenty years later, Jaron Lanier, another XR pioneer, imagined using VR to go beyond what is possible in real life: “You might very well be a mountain range or a galaxy or a pebble on the floor. Or a piano... I’ve considered being a piano” [130, p.3]. These two visions have co-existed since the beginning with mutual influences: recreating reality or exploring alternate realities.

Extended Reality (XR) technologies, ranging from Augmented to Virtual Reality (AR and VR), have rapidly evolved over the last decade. This evolution partly stems from the advent of a new generation of HMDs, with better portability, resolution, immersive capabilities, a wider field of view, and a lower cost [232]. XR multisensory (audio, visuals, haptics) and interactive capabilities can provide users with compelling immersive experiences. Thus, XR technologies have gradually reached many fields, such as psychiatry, psychology, education, or gaming.

This section reviews the current state of autism XR research. To do so, key constructs about XR and spatial audio are first introduced. Then, XR uses in clinical psychology and more specifically autism are successively presented. We conclude by describing existing XR design guidelines for autistic users.

2.4.1.1 Definitions and constructs

With these two visions in mind, how to define VR? To answer this question, Milgram and Kishino [198]’s suggested the *virtuality continuum*. At one end, VR consists in immersive and interactive experiences being entirely synthetic, which isolate users from real life. Such experiences can be delivered with HMDs or immersive room-centric displays, such as Cave Automatic Virtual Environment (CAVE) [58]. At the other end we find the real environment, being seen directly or through video displays (e.g., camera). AR is right next to it, affording to add virtual elements (e.g., audio, visuals) onto reality. AR can be experienced with immersive headsets (e.g., Hololens[©], Google Glass[©]) or low-immersive devices (e.g., tablets).

At last, Mixed Reality (MR) covers systems with a mixed proportion of real and virtual elements. It spans from AR to Augmented Virtuality (AV), where real life elements are included into a virtual environment. Related to the same continuum, the XR terminology is used to target not only MR, but also VR.

Two main constructs relate to users' XR experiences: immersion and presence. Immersion relates to the system technical capabilities to provide some or all of the following aspects: a high-quality rendering over multiple sensory channels with a wide field of view, interactive compelling capabilities, an isolation from real life, and individualization capabilities to match the user' profiles [288]. For users to perceive a sense of presence, also defined as a "sense of being there" [129], these technical capabilities must be complemented by cognitive aspects. This involves offering natural interactions being meaningful to the users (i.e., with good affordances) [106], as well as engaging and involving users in activities. Presence is thus related to conscious and subconscious processes of being and interacting in the virtual world, and can in turn also influence users' satisfaction.

2.4.1.2 Spatial audio in Extended Reality

In addition to visual and haptic, spatial audio largely contributes to users' immersion in XR environments [18]. Indeed, while visuals are limited to what users see (e.g., up to 180°), sounds can be heard at 360°, e.g., behind the head. For HMD-based XR experiences, spatial audio is often delivered over headphones, also known as binaural audio. Binaural audio affords to position sounds in space, based on interaural time and level differences as well as spectral cues [25]. These three features are grouped under Head-Related Transfer Functions (HRTF) which are highly individual [259]. In recent years, binaural audio has been more and more used and studied to create compelling immersive experiences in various fields [259], e.g., interactive storytelling [212], museums [339], or mobile games [205].

2.4.1.3 Potential for Clinical Psychology

XR is successful to extend current psychiatry and psychology clinical approaches, as it enables to transform the inner (e.g., bodily self-consciousness) and external (e.g., fear of specific animals) experiences of individuals by engaging and immersing them into compelling virtual spaces [252]. Its multisensory embodied capabilities are particularly promising to work on cognitive aspects. Indeed, in line with *embodied cognition*, cognitive process are closely related to users' body interactions [333]. These capabilities could also make clinical practices more ecological, by presenting stimuli in ways being closer to real and authentic conditions [231].

Various XR studies in clinical psychology and psychiatry have suggested positive outcomes regarding the assessment, rehabilitation, support, or understanding of a range of conditions [201, 232], such as eating disorders [189], schizophrenia [66], or post-traumatic stress disorder [253]. VR is often used to conduct exposure therapies, by gradually adding target stimuli in controlled VR environments (e.g., spiders, cigarettes), to increase the tolerance levels of individuals. Yet, other uses

exist, such as for children with neurodevelopmental conditions such as autism regarding communicational abilities [232]. Current advances in autism XR research will be presented in the next section.

Several studies have suggested the potential of using binaural audio in clinical psychology [185, 303, 318]. For instance, Taffou et al. [302] showed that fearful reactions induced by a VR dog stimuli are higher in bimodal conditions (audio and visual) than unimodal conditions (audio or visual). Such findings makes spatial audio promising to extend current VR exposure therapies, as they often largely rely on visuals. Malinvaud et al. [185] used spatial audio in VR to decrease the user's negative perception of their tinnitus. This approach was found to be as effective as traditional cognitive behaviour therapy. Vickers et al. [318] involved individuals with bilateral cochlear implants in the design of a VR auditory training application, mainly focusing on spatial audio localization, and planned upcoming testing.

2.4.2 Using XR to support autistic individuals

The first HMD-based VR study for autistic children dates from 1996. It intended to teach traffic safety by identifying cars in different scenarios [298]. Positive findings related to acceptability and usability have inspired many research endeavours since then. Next HMD-based VR studies appeared two decades later with the advent of a new generation of HMDs [32]. Recent reviews highlight that high-immersive VR [32, 63, 149, 195] and AR [21, 154] technologies could overcome the limits of interventions with or without digital tools, due to offering safe, interactive, and precisely controlled multisensory environments.

In this thesis, we refer to high-immersive technologies when speaking about XR, VR, and AR (e.g., HMDs, CAVE, spatial audio). I make this clarification given that many studies self-identify as XR, VR, or AR without actually using immersive technologies, but rather immersive content (e.g., 3D virtual worlds). For instance, only 40% of VR studies identified in Bozgeyikli et al. [31]' review use stereoscopic displays, and most AR projects identified in recent reviews [21, 149, 154] use phones or tablets. Yet, high-immersive experiences largely differ in terms of engagement and presence. They can be more ecological and authentic, and sometimes more engaging for autistic children [124, 184, 199]. Moreover, they can maximize the efficiency of social skills therapies for such children [199].

2.4.2.1 Acceptability and usability of XR head-worn displays

Previous studies have revealed a positive acceptability and usability of VR [32, 184, 216, 217] and AR [308] head-worn displays for autistic children with or without ID. Regarding VR, Newbutt et al. [216] performed acceptability and usability testing in the facilities of a community organization, with thirty autistic adults, some with ID (17-53 years old). Various scenarios were presented on an Oculus Rift HMD (e.g., café, safari). High levels of acceptability, engagement, and presence were observed. Malihi et al. [184] carried out usability and acceptability testing with 35 autistic children without ID in a research facility (mean age: 13). They

compared users' experiences of a school bus 360° video on an Oculus Rift HMD and on a screen monitor. Better enjoyment and spatial presence were reported with the HMD, and similar levels of usefulness, efficiency, and negative effects (e.g., anxiety). Newbutt et al. [217] compared three HMDs (Google Cardboard, ClassVR, HTC Vive) in different scenarios being defined with the school staff (e.g., moon walk). Testing with 31 autistic children (age: 6-16) within their usual classroom indicated high levels of acceptability, usability, and engagement, as well as and preferences for the HTC Vive, due to higher immersive capabilities. Regarding AR, Kinsella et al. [157] tested the usability of an AR application running on Google Glass intended to give contextual social prompts during conversations. Testing with fifteen autistic children without ID (mean age: 13) suggested positive outcomes.

Yet, most XR studies target individuals with MLN without ID, in VR [32], and AR [21, 149]. Acceptability and usability issues thus remain under-explored for autistic individuals with SLN apart from two VR [96, 216] and four AR studies [7, 59, 265, 324]. About VR, twelve adults with ID participated to Newbutt et al. [216]'s study (see paragraph above) and had positive experiences. In Garzotto et al. [96]' study, five children with neurodevelopmental conditions tested a cartoonish VR story and a VR maze. Findings suggested positive acceptability (with therapists' support) and usability, but two autistic children with moderate learning disabilities initially did not want to wear the headset⁹. Regarding AR, Aruanno et al. [7] created an AR application (Hololens) to teach domestic tasks. Fourteen children with neurodevelopmental conditions and ID performed one session, with positive acceptability and usability, but six children with most severe disability "had enormous difficulties" in terms of understanding, use of gaze, and air-tap gestures. They thus had a second session during which significant practitioners' support was needed for them to then be able to use the system [7, p. 46]. Though, most children had fun. Sahin et al. [264] suggested the feasibility of using an AR application (Google Glass) delivering AR social cues in a classroom. Testing with one autistic teenager were positive in terms of usability and communication. Washington et al. [324] and Daniels et al. [59] reported on an AR project (Google Glass) intended to deliver social cues at home. Testing with fourteen autistic children suggested positive outcomes in terms of acceptability, usability, and learning of socio-effective cues.

2.4.2.2 *Feeling of presence*

Contrary to low-immersive devices, VR can induce a feeling of presence for autistic users, and generate *authentic* situations, in terms of behaviour, cognition, and perception [216, 320]. Moreover, autistic users seem to experience similar levels of presence than their neurotypical peers, as suggested by testing in a room-centric

⁹Strickland et al. [298]'s pioneering study also reported positive acceptability for such children, but difference in terms of technology make it not comparable to recent HMD-based VR studies.

VR environment with social scenarios (e.g., school playground) [320]. Autistic people also seem to be prone to adopt similar behaviours in VR and in real life. Indeed, testing with 25 autistic children without ID and 23 neurotypical peers using VR headsets suggested similar interpersonal distances with real and virtual experimenters, contrary to their neurotypical counterparts [285].

Most studies are based on the premise that XR could offer more *authentic* conditions for conducting interventions with autistic users or studying their perception. Though, as expressed by Parsons [229], aiming for authenticity requires considering many environmental factors that may affect autistic users' behaviours, including but not limited to: their profiles (e.g., sensory profile), the experimental space (e.g., clinical or research facility), the available level of support (e.g., from practitioners), the equipment (e.g., which HMD), the VR content (e.g., colors), or the VR tasks being used (e.g., social scenario). As Parsons [229, p. 153] expresses: "there is no single study, or series of studies, that has systematically unpicked and interrogated the ways in which these features may combine to influence responding and understanding.". In particular, while assessing common XR concepts such as the feeling of presence is already hard with non-autistic users, it can be even more difficult with autistic users, due to a dearth of research in this direction in line with their atypical perception. To better understand the potential of VR and AR, more research should address how various contextual elements may combine to provide users with a feeling of presence, and if differences between how presence is experienced could be observed between autistic and non-autistic individuals.

2.4.2.3 *Fields of use*

Most existing XR studies aim at training socio-emotional abilities or teaching specific skills, often with positive outcomes [31, 149, 195]. For instance, Cheng et al. [50] targeted the social understanding of social situations by creating two HMD-based VR scenarios (bus stop and classroom) in collaborations with practitioners and parents. Three autistic children went through a non-VR baseline, VR sessions, and non-VR post sessions. Findings suggested an increase of their social understanding with maintenance in real life, and that they were more relaxed in VR. Ip et al. [136] created six CAVE-based VR scenarios, one focusing on emotional control, four addressing daily social challenges (e.g., preparing for going to school), and one targeting generalization. A between-group experiment comparing the effects of VR and non-VR training was conducted over 28 sessions with 96 autistic children (mean age: 9). Positive outcomes emerged in terms of social interaction, emotion expression, and transfer of learning into real life. Adjorlu et al. [2] created a HMD-based VR supermarket to target autistic teenagers' shopping skills in collaboration with a teacher experienced with children with special needs. Nine autistic teenagers (age: 9-12) participated to a between-group experiment lasting over seven sessions, which compared the effects of VR and non-VR training. A post-session assessment in a real supermarket suggested better performances for the experimental group regarding search tasks, and a positive generalization

of skills into real life. Aruanno et al. [7] (see previous section) also created two AR scenarios in collaboration with psychologists to increase children's autonomy (laying the table and collecting garbage). Twenty children with neurodevelopmental conditions and ID performed an AR session in a clinical setting, with positive findings in terms of engagement, despite mixed findings regarding task completion.

This main XR focus on socio-emotional abilities and teaching drawing upon the medical model of disability [229] leaves other fields under-explored (e.g., sensory strategies) and excludes many autistic individuals with SLN or ID who cannot directly work on such tasks [31]. This research gap comes from similar methodological reasons than for low-immersive devices. Indeed, participants with "critical contributing factors that could affect the outcome" are often excluded Karami et al. [149, p. 21]. Such critical factors include significant repetitive behaviours, although being widespread in autistic children with SLN. It is worth noting that this under-representation outreaches the sole autism field. Indeed, [15]'s review about XR applications for individuals with communication disability and neurodevelopmental conditions has only identified two out of 53 studies targeting the feasibility of XR applications and existing challenges for individuals with ID.

Yet, according to Happé and Frith [126], VR capabilities could afford to target the entire spectrum. Moreover, the current XR focus seems disconnected from the stakeholders' needs regarding digital supports which go beyond a mere training of social abilities [230]. Furthermore, in Newbutt et al. [217]'s study, 29 autistic children said "It relaxes me and I feel calm" when being asked "What could or would you use VR HMDs for?", thus revealing needs beyond social issue. Some authors such as Johnston et al. [141] have proposed alternatives focusing on sensory issues. They created an HMD-based VR game called *SoundFields* intended to address fear responses associated with the auditory hypersensitivity of autistic children. Four weekly sessions were conducted with six autistic teenagers (age: 16-19) with MLN in their usual school. Findings suggested a gradual decrease in anxiety over time. Yet, despite this promising finding, *SoundFields* targeted anxiety management but did not focus on triggers of anxiety (e.g., pitch, intensity).

2.4.2.4 Designing XR experiments for autistic individuals

How to design immersive XR tools for autism support? When starting this thesis in 2019, one XR design review existed for such users which targeted all types of interventions [31], followed by another review specifically looking at NDBIs [63]. These reviews have proposed many guidelines related to the unfolding of activities in VR or the VR content. For instance, they advocate for offering a structured environment, making users in control, avoiding loud and unexpected sounds, or using simplified graphics and interfaces. Though, these guidelines seem to be disconnected from field practices that stakeholders encounter or use on a daily basis, as they are not informed by stakeholders' views, and thus mainly concern autistic individuals with MLN without ID. Such endeavours were started by some studies Adjorlu and Serafin [1] but mainly focused on socio-emotional abilities and

teaching. Moreover, no guidelines concern an optimal age range for using XR with autistic children, nor potential age-related methods or risks.

Currently, existing XR studies display methodological issues or discrepancies which only enable to suggest the potential of XR as a complementary tool to traditional treatments [195]. Indeed, most studies have a small number of participants, are time-limited, focus on autistic children with MLN without ID, rarely consider the overall context (e.g., influence of the experimenter) [31]. Moreover, studies are often conducted in non-ecological settings and do not measure the transfer of the skills learned into real life: “An irony exists where research in VR-HMD proposes to immerse users in computer-generated environments that represent and reflect real-world settings and activities [. . .] but often do not conduct these in real-world settings or test the generalisability of these activities to real life or the real world”, and do not measure the generalization of skills learned “Bradley and Newbutt [32, p. 12]. Assessing children’s experiences can also be highly challenging, especially for children with SLN or ID. While most studies use self-report measures of evaluation, for instance to target the feeling of presence [216, 320], they are ill-suited for many individuals who cannot answer them. This situation results in using extrinsic measures of evaluation, through practitioners’ and researchers’ interpretations. Even if challenging, new measures of evaluations should be devised to better assess the holistic and situated experiences of children.

2.5 Conclusion

The objective of this section was to draw an overall picture of existing autism XR research, while highlighting current challenges and research gaps. To do so, autism was first presented, in terms of diagnosis, experiences, and associated narratives, followed by a review of existing interventions without and with digital tools, in relation to existing trends of thoughts. At last, current XR use cases and designs for autistic users were detailed, based on a description of key XR constructs.

This state of the art suggests that while XR research is promising to extend common interventions for autism, it mainly addresses the rehabilitation of socio-emotional abilities or the teaching of specific skills, thus focusing on children with MLN without ID. Based on this observation, which is similar for low-immersive devices, several questions are raised. Does this XR focus align with stakeholders’ potential needs in terms of uses and designs? In particular, could XR be used to extend practitioners’ sensory interventions? How to assess the quality of autistic children’s XR experiences, especially the ones of children being minimally verbal or with ID? Would stakeholders prefer using VR or AR for autistic children? Would this preference vary depending on the level of learning disabilities of autistic children? To confirm these potential research gaps and investigate these questions, the next chapter reports on interviews that were conducted with autism stakeholders and analyzed in comparison to the current state of the XR literature.

3 - Comparison of existing XR uses with stakeholders' needs

3.1 Introduction

As introduced in chapter 2, discrepancies seem to exist between the current state of autism XR research and stakeholders' potential needs and views. In particular, while autism XR research mainly targets the rehabilitation of socio-emotional abilities for autistic children with MLN, common interventions address the entire spectrum and focus on other abilities, such as perceptual abilities. To confirm this observation, and derive XR use cases and guidelines being representative of stakeholders' needs and related to field practices with or without digital tools, this chapter reports on 34 interviews that were conducted with autism stakeholders, mainly including practitioners, and then analyzed. Emerging XR use cases were compared with the findings from two former systematic literature reviews, and emerging design guidelines were compared with the findings from a literature survey that we conducted. Findings suggest that collaborative XR sensory and mediation approaches could benefit children from entire spectrum. Part of this chapter were published in the *Journal of Autism and Developmental Disorders* under the same title [A].

3.2 Method

The first objective was to collect insights about common autism interventions, to then derive XR use cases and guidelines that are close to stakeholders' needs. To that respect, semi-directed interviews were designed and conducted, following methods that are described in the following subsection. The second objective was to check whether stakeholders' insights about potential XR uses as a support for interventions, that were collected during the interviews, matched the focus of the existing XR studies. As two recent systematic literature reviews focusing on XR autism interventions existed at the time of our study [21, 195], the interviews' findings were compared with the findings from these reviews. At last, we aimed at offering XR design guidelines drawing upon stakeholders' needs, as such guidelines were not provided by the two previous systematic reviews, nor by other reviews specifically focusing on XR autism design guidelines [31, 63]. Thus, an XR literature design survey was conducted to look for these guidelines. The interviews' findings were then compared with the survey's findings. The method used to conduct this survey is presented in the second subsection called "Method for the literature survey".

3.2.1 Method for the Semi-Directed Interviews

Semi-directed interviews were conducted with French autism stakeholders, mainly including practitioners. After introducing the methodology, data analyses are exposed, both being summarized in figure 3.1.

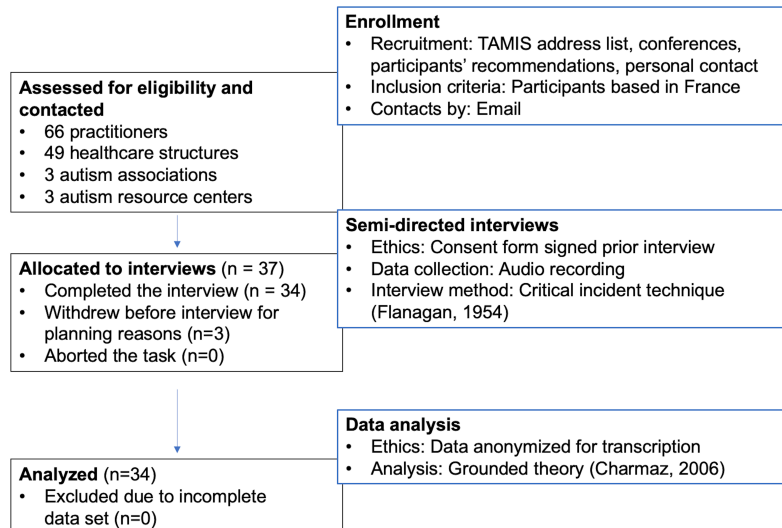


Figure 3.1: Method used to conduct and analyze the semi-directed interviews.

3.2.1.1 Participants

To get in contact with autism stakeholders, personalized emails were sent to three Autism Resource Centers, 49 healthcare structures specialized in autism and neurodevelopmental conditions, three associations representing autistic individuals and relatives, and 66 practitioners. Most contacts were found in the TAMIS¹ address list. Moreover, proceedings of recent conferences about autism, sensoriality and technology were identified, using queries with the following keywords: “ASD” OR “autism”, “digital” OR “technology”, and “sensoriality”. In Europe, sixteen conferences or workshops appeared, from 2012 to 2019, mainly in France, except for two in Spain and one in England. Every attendee’s profile was examined and contacted when their activity simultaneously focused on autism, technology, and sensoriality. Furthermore, people that we interviewed were asked for other contacts at the end of the interview. Other experts were discovered through papers, blogs, and Autism Resource Centers’ webpages. Only French participants were contacted to avoid language misunderstanding with me. Moreover, most participants were in the Ile de France area (i.e., Paris district), to facilitate further in-situ investigations, e.g., observations of clinical practice.

¹The Tamis address list details practitioners and associations specialized in autism in the Ile de France area – tamis-autisme.org.

Formal interviews were conducted with 34 stakeholders, including practitioners (n = 29), people from the autism community (n = 4), and academics (n = 1). Table 3.1 summarizes their profiles, which tend to be representative of the distribution of all autism fields. Practitioners and academics are highly experienced, often with more than ten years of practice (n = 21). Practitioners have various backgrounds, i.e., public sector (n = 10), private sector (n = 5), or both (n = 14). They mainly use NDBI (n = 9), integrative (n = 8), and sensory (n = 7) interventions. Autistic individuals and their relatives favoured NDBI (n = 4), and often mentioned the ABA method. Technology-based interventions were often reported (n = 23), and all autistic participants already used digital tools (n = 4). All participants agreed to be contacted again for further questioning or future testing.

Table 3.1: Profiles of the participants

Group Size	Practitioners (n = 29)	Autistic individuals and relatives (n = 4)	Academics (n = 1)
Sub-group features	<ul style="list-style-type: none"> - Psychologists (n = 6) - Speech therapists (n = 6) - Team supervisors (n = 5) - Psychomotor therapists (n = 5) - Music therapists (n = 2) - Psychiatrists (n = 2) - Occupational therapists (n = 2) - Specialized educator (n = 1) 	<ul style="list-style-type: none"> - Autistic individuals with MLN (n = 2): alone or with their family - Mothers of autistic children requiring high support (n = 2) 	<ul style="list-style-type: none"> - Researcher in psychopathology and neurodevelopmental conditions (n = 1)
Gender (m/f)	10/18	3/1	0/1
Years of experience or age	<ul style="list-style-type: none"> - 20 years and above (n = 16) - 10–20 years (n = 5) - 5–10 years (n = 8) - 0–5 years (n = 1) 	<ul style="list-style-type: none"> - 18–30 (n = 1 - autistic individual) - 30–50 (n = 1 - autistic individual; n = 2 - mothers of autistic children) 	<ul style="list-style-type: none"> - 20 years and above (n = 1)
Intervention	<ul style="list-style-type: none"> - NDBI (n = 9) - Integrative (n = 8) - Sensory (n = 7) - Psychodynamic (n = 4) - Did not say (n = 2) 	<ul style="list-style-type: none"> - Preference for NDBI (n = 4) 	-
Sector of activity	<ul style="list-style-type: none"> - Private and public (n = 14) - Public (n = 10) - Private (n = 5) 	-	-
Experience with digital tools	<ul style="list-style-type: none"> - Computer/Tablet/Console (n = 23) - Humanoid robot (n = 2) - VR (n = 2) (not for interventions) 	<ul style="list-style-type: none"> - Computer/Tablet (n = 4) - VR (n = 1) (not for interventions) 	None

3.2.1.2 Protocol

Interviews had two objectives: getting an overview of how autism interventions are conducted in the field, and collecting the potential needs and viewpoints of participants about technology-based interventions, and particularly with XR. Interviews were based on a semi-directed questionnaire targeting practitioners that was built in three phases, as suggested by Lallemand and Gronier [167]: phase 1 - demographics (5mn, 2 questions); phase 2 - interview body (30 mn, 9 questions); and phase 3 – ending (5 mn, 2 questions). The interview body comprised two

main parts: questions 3 to 9 (Q3 to Q9) targeted interventions without digital tools, and Q10-Q11 interventions with digital tools. About the first part, Q3 to Q7 covered the main aspects of non-digital autism interventions. These questions were derived from our knowledge at the beginning of the study, coming from a non-exhaustive review of the literature, including the French grey literature about intervention guidelines [62], as well as online communications from Autism Resource Centers. Then, Q8 addressed sensory interventions, to assess their relative importance among common practices. Q9 was added after the sixth interview, as all participants mentioned the use of mediation activities. Then, the second part investigated the current uses and potential needs regarding digital tools (Q10) and XR (Q11). All questions were rephrased depending on the participant and on the context of the interview. Table 3.1 presents the basis of the questions in column 2, with respect to the three interview phases in column 1. For each question, keywords being representative of related topics were used to ask for additional details when these topics were not spontaneously mentioned by the interviewee. The list of keywords was gradually extended and refined over time, as I gained insights about autism interventions, the final list being displayed in column 3. To elicit more insights over specific actions and practices, the critical incident technique [83] was used, i.e., participants were always encouraged to give precise examples about the elements that they mentioned, for instance by describing the last time that the element occurred. With autistic participants, non-appropriate question was removed (Q3), and two questions were added: QA1 assessed their viewpoints regarding the healthcare interventions that they experienced, and QA2 asked about their atypical sensory perception. With academic participants Q3 was removed, and technology-focused questions were more explored (Q10, Q11).

Interviews with autism experts lasted between 34' and 94' with a mean duration of 59'. They included 19 women and 11 men, and were conducted by phone ($n = 18$), visioconference ($n = 7$), or face-to-face ($n = 5$). With autistic individuals and/or their families, they lasted between 43' and 70', with a mean duration of 51', and were conducted by phone ($n = 3$) or face-to-face ($n = 1$). Two interviews were conducted with mothers of autistic children (one boy and one girl), one interview with an autistic man, and one interview with an autistic man and his family (the family being present due to his specific needs). Every participant signed a consent form prior to the interview, which precised they were free to stop whenever they wanted. All interviews were audio recorded. All data collected were anonymized for transcription and analysis, using the "itw" keyword followed by the interview number. For security reasons, no online cloud system was used to store data, and transcriptions were done manually.

3.2.1.3 Data Analysis

Data analysis mainly used a bottom-up inductive coding approach called *grounded theory* [48]. Hence, interview data were coded to extract meaningful phrasings, that were then sorted into different concepts and categories. The technique starts

Table 3.2: Semi-directed questionnaire addressed to the participants. Demog: Demographics.

	Basis of question	Additional keywords/phrasings to ask for more details
Phase 1 Demog	Q1 — Common approaches used in interventions	NDBI/psychodynamic/sensory, etc.; collaboration with others
	Q2—Practitioner's background with respect to autism interventions	Years of experience; private or public sector
Phase 2 Interview body	Q3—Typical autism intervention (<i>removed for non practitioners</i>)	Examples of easy and/or difficult session
	Q4—Evaluation methods used before/during intervention	Sensory profile; impact of sessions; generalization of skills; role of relatives
	Q5—Individualization of intervention over time	Number and planning of the sessions; impact of atypical perception
	Q6 - Common intervention practices	Typical exercises; difficulties experienced; rewards; individualization; relationship with the practitioner; structure of time and space; routines
	Q7—Use and role of playful activities during sessions	Motivation; engagement
	Q8—Multisensory rehabilitation practices	Tools; environments; type of stimuli (visual, audio, tactile); method used
	Q9—Mediation practices in interventions (<i>added after the 6th interview</i>)	Music; dance; fine art; relationship with the practitioner
	Q10—Digital tools already used by the practitioner, and possible needs or viewpoints to that respect (<i>more explored with academics</i>)	Medium (i.e., tablets, robots, XR); examples of games; collaboration with the practitioner; acceptability by children and practitioners; ideal digital tool
	Q11—Virtual or augmented reality environments that the practitioner would be interested in (<i>more explored with academics</i>)	Adaptability; evaluation; sensory integration difficulties; social aspects; covering the entire autism spectrum
	QA1—Views about common interventions (for autistic participants)	
	QA2 -Atypical autistic perception (for autistic participants)	
Phase 3 Ending	Q12—Any element that the practitioner would like to add	
	Q13—Other relevant experts to contact	

from no preconceived concepts. Instead, they are gradually built through multiple iterations between the data, concepts, and categories, which involves the use of constant comparative methods at the different analytic stages [48, p. 54]. The analysis process stops when the classification gets stable. As concepts are sometimes connected, the same phrasing can be sorted into multiple concepts. During this qualitative analysis process, my subjectivity may have influenced the findings. Thus, to limit potential biases, an objectivist approach was used: the analysis focused on the interview data for themselves, without considering how they were produced [48, p. 131]. Hence, repetitions, hesitations, and prosody were not taken into account during the transcription process.

This overall grounded theory analysis includes three main steps. First, I conducted four main grounded theory iterations at different times (i.e., offset of several weeks) to reduce potential biases. Since all interviews were conducted in French,

the concepts and categories were first created in French, and then translated and refined in English. To analyze interview data about non-digital interventions, only inductive coding was used. About data regarding digital tools and XR, inductive coding was first used, and then, from a late analytic stage, the emerging concepts were refined in connection with the autism XR literature to reveal potential gaps [48]. This comparison process started at a late analytic stage to avoid importing too many pre-conceived ideas when starting the analysis. It involved the second and third steps of our overall analysis process. During the second step, participants' needs regarding XR uses were compared with the existing XR uses that were reported by two systematic reviews [21, 195] (see results' section called "Comparison Between Stakeholders' Needs and Literature XR uses"). These reviews were selected as they were recent at the time our study, systematic, and exhaustive regarding XR existing use cases. Thus, they allowed us to derive objective percentages representing the relative significance of the different purposes of autism XR studies. Therefore, they were suitable to draw a comparison with our interviews' findings, and to reveal potential gaps. At last, during a third analytic step, since the two systematic reviews did not provide XR design guidelines accounting for stakeholders' needs, nor other reviews specifically focusing on XR autism design guidelines [31, 63], an autism XR literature survey was conducted in relation to our emerging grounded theory. The objective was to identify such guidelines that we could then compare with the interviews' findings (see results' section "Comparison Between Stakeholders' XR Design Insights and Literature guidelines"). The method that was used to conduct this literature survey is described hereafter. The three overall analytic steps were here presented sequentially for enhanced clarity, but were actually led in parallel during the late analytic stage.

3.2.2 Method for the Literature Survey

3.2.2.1 Method for the Article Selection from the Literature

Drawing from Charmaz [48, pp. 164-168]'s grounded theory method, we conducted an autism XR literature survey during the late analytic stage. The purpose was to derive literature design guidelines that we could compare with the interviews' findings. At this late analytic stage, major XR concepts about sensory and mediation issues had emerged that were not expected when conducting the interviews. Therefore, as the survey was informed by the state of the grounded theory, it focused more on XR sensory and mediation issues. Online queries were made with Google Scholar engine, to use the "cited by" option for each paper and thus reference more recent studies with similar interests. They combined the keywords: "Autism" OR "ASD", "Virtual Reality" OR "Virtual Environment" OR "Augmented Reality" OR "Mixed Reality" OR "Technology" OR "Digital Tool", "Multisensory Environment" OR "Sensoriality" OR "Mediation", and "Participative Design". Two inclusion/exclusion criteria were used: (1) autism-related stereoscopic XR studies were included (e.g., CAVE and HMDs), or computer-related studies, if presenting

relevant features for the XR medium (i.e., robot, touch-screen device, or room-centric setup); and (2) articles not offering design guidelines were excluded. Moreover, we focused more on participative design studies, as being more representative of all stakeholders' views.

3.2.2.2 Screening Process and Protocol for Analysis

I searched the literature and reviewed all the studies according to the inclusion/exclusion criteria. The title was first screened. If relevant, the abstract was then screened, and followed by a full-text reading. If relevant, the study was then included in the survey. In total, 37 articles were selected [4, 7, 17, 31, 35, 37, 44, 56, 60, 63, 73, 95, 96, 124, 152, 161, 163, 165, 178, 184, 191, 216, 218, 227, 230, 232, 256, 291, 294, 307–309, 315, 319–321, 330]. The selected articles were first screened for XR design guidelines, and then sorted along the concepts emerging from the interview analysis. If a literature design guideline matched some emerging concept from the interviews, it was assigned to it. Else, if no relevant concept could be found, a new concept was created, and the guideline was assigned to it. In that case, the already assigned phrasings from the interviews and the literature design guidelines were double checked to see if they could also fit with this new concept. This refactoring process was also applied when concepts gradually changed during the interview analysis.

3.3 Results

Stakeholders' insights about autism interventions without and with digital tools are first detailed, being summarized in tables A.1 and A.2 in appendix. Then, stakeholders' needs are compared with XR uses coming from autism research as described in two literature reviews [21, 195]. The findings are summarized in table 3.3. Finally, stakeholders' design insights are compared with XR literature design guidelines, the findings being summarized in table 3.4. For all tables, concepts and categories are reported from the most to the least reported, according to stakeholders. Throughout this chapter, the number X of participants mentioning each concept is written inside parenthesis ($n = X$), next to a literature reference if also containing it. Categories' names are italicized. Participants' quotes were translated from French to English. The term "autistic child" is often employed, as participants mainly referred to children.

3.3.1 Analysis of Common Autism Interventions

This subsection outlines how common autism interventions are conducted, first without and then with digital tools (see tables A.1 and A.2 in appendix). For enhanced readability, and due to differences between methods' names in France and other countries, methods' names are not mentioned, except when important for the overall understanding.

3.3.1.1 Common Non-digital Autism Interventions

About the intervention context, *Individualize the intervention program* and *Structure the intervention program* largely appear (respectively $n = 33$, $n = 27$). Individualization requires practitioners to be “creative”, as reported by a psychomotor therapist, depending on the intended therapeutic outcomes, i.e., starting from the child’s interests ($n = 32$) to tailor rewards ($n = 16$) and games ($n = 10$). For instance, a team supervisor says: “if a child loves the cartoon ‘Cars’ then we’ll use boxes with Cars!”. Creativity concerns long-term projects ($n = 13$), the care methods ($n = 6$), and the sessions ($n = 14$), as they depend on the child’s state (e.g., tired). Yet, individualization can be challenging ($n = 15$), especially for non-verbal autistic children with SLN. About the structure of the intervention program, at the session level, it consists in offering predictability ($n = 27$) of time ($n = 21$) and space ($n = 19$), such as routines ($n = 17$). For instance, a speech therapist always “sets the phone in the drawer to avoid unexpected ringing” and therefore not worry children. At the intervention program level, different periods of time with different activities are planned ($n = 11$) which last from days to months, depending on children. Practitioners first observe children through free-play ($n = 8$), and then start from their interests to build the dyadic relationship ($n = 7$). Yet, an environment being too structured can be detrimental ($n = 6$), as not preparing for real life ($n = 4$).

About the intervention process, most stakeholders advise to *Engage children in their intervention program* ($n = 33$), to maximize the intended outcomes. This mainly relies on using playful activities ($n = 30$), strengthening the therapeutic alliance ($n = 30$), and using behavioural strategies ($n = 26$). Reinforcing the therapeutic alliance can consist in working on the content, with individualized playful activities ($n = 27$), and on the context, for instance by adapting the practitioner’s behaviour ($n = 19$). Behavioural strategies ($n = 26$) include rewards ($n = 19$) and using gradual challenges ($n = 18$). Yet, building the therapeutic alliance can be hard ($n = 9$), especially for autistic children with SLN ($n = 9$).

Work on sensoriality in intervention ($n = 26$) largely appears, with two main concepts: Work on Sensory Processing Disorders ($n = 21$) and Provide multisensory environmental adaptations ($n = 20$). Sensory habituation is commonly used to train hypo/hyper sensitivities ($n = 15$). To that respect, multisensory spaces allow “to first remove distressing elements and then to increase them” ($n = 2$). Other practices consist in modulating the audio-visual speed ($n = 7$), or in working on multisensory binding ($n = 5$). Sensory adaptations aim to maximize attention and engagement, with various techniques. For instance, sensory loads targeting the hyposensitive channels can support behavioural and emotional regulation ($n = 13$).

At last, it is necessary to *Assess the state of the individual over time* ($n = 29$), on the long ($n = 28$) and short terms ($n = 21$). On the long term, evaluations are first conducted at the intervention start, by using standardized tests about

sensory (n = 21) and psycho-developmental features (n = 18). They include questionnaires, interviews with relatives and/or the child, and clinical observations (respectively n = 9, n = 5). Combining evaluations at regular time intervals (n = 8) also helps to infer the child's progress. On the short term, observations are used (n = 18) by looking at specific individualized features, e.g., repetitive behaviours (n = 2).

3.3.1.2 Existing Uses of Digital Tools in Interventions

Digital tools are promising to support common interventions (n = 27), as being engaging (n = 2), predictable (n = 2), individualizable (n = 2), repeatable (n = 2), responsive (n = 1), stable (n = 1), relieving from human interaction (n = 2), and allowing children to be wrong (n = 1). Tablets are most often used, followed by computers. Participant's interests fall into three main categories: *Social skills* (n = 13), *Assistive technologies* (n = 13), and *Mediation/Well-being* (n = 10). Three minor categories also appear: *Education* (n = 8), *Sensoriality* (n = 8), and *Diagnosis* (n = 2). Various games are used to adapt to the child's abilities, the intervention context, and the intended outcomes. Games with simple interfaces, little information, and clear goals are preferred (n = 5). To train social skills, social scenarios (n = 3) are common with solo (n = 4) or group (n = 2) activities. Then, assistive technologies are highly individualized. For instance, a team supervisor mentions the case of a non-verbal autistic child, who knows all Disney cartoons by heart, and uses a tablet to select and play the sentences that she wants to say from them. About mediation/well-being purposes, any appealing game can be used (n = 10). To minimize adverse effects due to over-exposition to screens (n = 5), digital tools can be presented as other activities (e.g., drawing) and within a controlled setting (i.e., with an adult and a time limit). Yet, some practitioners remain hostile to using them, as increasing the distance to the child (n = 3), or due to a phantasm to be replaced by machines (n = 1).

3.3.2 Comparison Between Stakeholders' Needs and Literature XR Uses

The findings from the comparison between the stakeholders' insights and the XR systematic reviews [21, 195] are presented following four main categories which were constructed during the analysis: *Mediation and Well-being* (n = 16), *Social, Education and Cognitive Training* (n = 14), *Sensoriality* (n = 13), and *Assistive technologies* (n = 5) (see table 3.3).

3.3.2.1 Mediation and Well-Being

Although most participants mention the *Mediation and Well-being* category (47%), it remains under-researched, only representing three percent of the studies in Mesa-Gresa et al. [195]'s review. Though, Newbutt et al. [217] previously raised this need, with 29 autistic children answering "It relaxes me and I feel calm" to the question "What could or would you use VR HMDs for?". Participants evoke

two main concepts: Make the child ready for performing challenging tasks ($n = 13$), which considers ways of getting secure before to perform them, and Support the therapeutic alliance through mediation activities ($n = 6$). Three use cases appear. First, use cases draw upon multisensory spaces such as Snoezelen ($n = 8$), to strengthen the therapeutic alliance through secure intermediate XR spaces. Second, use cases are tailored to behaviours/contexts that children use to calm down, e.g., being in a car ($n = 1$). A team director describes them as “derivatives of stereotypes”, being “less stigmatizing”. At last, creative scenarios appear, in line with common interventions ($n = 3$), e.g., music-making ($n = 2$). Yet, as some children may struggle to stop using these environments ($n = 3$), participants suggest to gradually decrease any appealing stimuli before to stop ($n = 1$).

3.3.2.2 *Social and Cognitive Training*

Whereas 41% of the stakeholders mention the *Social and Cognitive Training* category, more than 95% of the studies from the two literature reviews pertain to it [21, 195]. Real-life use cases mainly appear, with two main concepts: Train socio-emotional & Interactional abilities ($n = 14$) and Train cognitive abilities ($n = 6$). The first concept consists in gradually habituating the child to daily social situations. To that respect, task-dependent features can be modulated (e.g., number of people) for various situations ($n = 12$) (e.g., medical examinations ($n = 6$)), to promote the generalization of the skills learned into real life. Then, cognitive abilities include daily living skills ($n = 4$), at home (e.g., tooth brushing) or outside (e.g., buying things in a supermarket). Other cognitive skills are mentioned ($n = 3$), e.g., attentional abilities [77], drawing upon behavioural (e.g., ABA) ($n = 1$) or educational approaches (e.g., Boehm-3) ($n = 1$) [26]. Yet, such scenarios would only benefit individuals requiring low support, being able to understand them. An autistic participant also stresses that “No manual could ever cover all possible situations”. Indeed, a psychomotor therapist reports the case of an autistic adult who had learned the “right” way to greet people and got lost at work due to the variety of situations encountered.

3.3.2.3 *Sensoriality*

Whereas participants highly mention the *Sensoriality* category (38%), including all psychomotor and occupational therapists, it remains under-explored in the literature. Indeed, only the Magrini et al. [183]’s SEMI project focuses on training motor skills, using a kinect camera and four distinct applications. Three main concepts appear, i.e., Rehabilitate sensory disorders ($n = 10$), Assess sensory disorders ($n = 6$), and Work on action-reaction principles ($n = 4$). Two main use cases emerge from the interviews: gradually adding stimuli to reach the tolerance thresholds, and then conduct sensory habituation; or gradually removing stimuli from a multisensory scene to assess the tolerance thresholds. A psychomotor therapist says: “the challenge is to recreate contexts for assessing the tolerance thresholds while conducting a therapy”. Possible scenarios range from real-life (n

= 7) to multisensory (n = 6) spaces, depending on practitioners' preferences and children's abilities. For instance, they include a supermarket with adjustable stimuli (e.g., dimmable lights) or Snoezelen-like spaces. A psychologist stresses that working on sensory issues enables to better include non-verbal individuals with cognitive impairments. At last, an occupational therapist warns about the impossibility to recreate the richness of real-life stimuli in XR.

3.3.2.4 Assistive Technologies

Although some participants mention the minor category *Assistive technologies* (15%), it is absent from the two literature reviews considered. Two main concepts appear: Provide context-relevant information (n = 4) and Support sensory strategies (n = 1). The first one can be achieved by adding and/or removing contextual information, e.g., adding information about the emotions of people around (n = 1), or filtering a distressing noise (n = 1). The second one aims at making the child secure enough to then be able to perform challenging tasks. To that respect, a participant suggests creating a tipi-like space augmented by sounds and colors. This scenario is inspired from the real case of a child who could enter a tipi-like space in his classroom when feeling overwhelmed, to unwind and then get back to the class.

3.3.3 Comparison Between Stakeholders' XR Design Insights and Literature Guidelines

This section draws design guidelines from the comparison between the interviews' findings and the literature (see table 3.4). Its subsections follow the main categories that were derived from our grounded theory analysis.

3.3.3.1 Task Design

Individualization is advised to cater for children and practitioners, regarding both the content [31, 44, 60, 63, 230, 232, 307, 308, 330, n = 15] (e.g., stimuli, tasks), and the medium [63, n = 1]. For instance, a psychomotor therapist mentioned using video games as "modelling dough", i.e., by adjusting every possible parameter. Whereas participants mainly suggest displaying familiar XR content (n = 14) (e.g., drawings), the literature focuses on adapting the way the environment works (e.g., number of stimuli), sometimes based on physiological data [163, 165].

As in common interventions, engagement aims at maximizing the intended outcomes. According to the participants and the literature, it requires to tailor the environmental motor and cognitive complexity to the child's abilities and to the intervention context [31, 44, 63, 307, 308, 330, n = 13]. It also relies on offering predictable and simplified audiovisual content to prompt discovery [31, 44, 60], including some unexpected events [4, 37, 319, n = 3], to create a "slight strangeness", as a psychologist said. Using common NDBI principles is advised, i.e., rewards, imitation, and sense of agency. Rewards must be tailored to the performance [56, 63]. About imitation, the practitioner may imitate the child, or

Table 3.3: Fields of interests of the participants regarding XR use cases for autism interventions

Category		Concept		Objectives		Participants	Examples Literature (from MG and B reviews)
Name	Weight	Name	Weight	Name			
P	L	P	L				
Mediation & Well-being	47% n=16	MG:3% B:0%	Make the child available for challenging tasks	n=13	MG:0% B:0%	Use individualized multisensory space (n=8)	Snoezelen-inspired (n=10), tipi-like spaces (n=1) –
						Use individualized real stereotypies (n=3)	Breaking glasses (n=1), Being on a trampoline (n=1), in a car (n=1) –
						Use audio-only appealing environment (n=2)	–
		MG:0% B:0%	Support the therapeutic alliance through mediation activities	n=6	MG:0% B:0%	Do creative activities (n=3)	Painting (n=2), Making music (n=2) –
						Do any appealing activity (n=1)	Any activity for the child –
						Use Snoezelen-like space (n=1)	–
		MG:3% B:0%	Enhance Well-being through Physical Activity	n=0	MG:3% B:0%	Give motivation to do sport (n=0, MG:3%, B:0%)	<i>Astrojumper</i> VR exergame-SSS [82]
Sensoriality	38% n=13	MG:0% B:5%	Rehabilitate sensory disorders	n=10	MG:0% B:5%	Rehabilitate sensorimotor disorders (n=10, MG:0%, B:5%)	Sensory habituation to real-life scenarios (n=7): School (n=3), Supermarket (n=2), Daily situations (n=2) –
							Sensory integration in multisensory spaces (n=6): Snoezelen-like (n=6) <i>SEMI</i> Project – Four interactive games - AR – Ki [183]
		MG:0% B:0%	Assess sensory disorders)	n=6	MG:0% B:0%	Assess sensory disorders (n=4)	Real-life scenarios (n=2), e.g Supermarket (n=1) –
							Non-realistic scenarios (n=2), e.g., Snoezelen (n=2) –
							Assess progress over time (n=2) –
		MG:0% B:0%	Work on action-reaction principles	n=4	MG:0% B:0%	Get inspiration from real-life scenarios (n=3)	–

Social & cognitive training	41% MG:97% n=14 B:95%	Train socio-emotional & Relational abilities	n=14	MG:79% B:70%	Train Social & Interaction abilities (n=13, MG :55%, B:55%)	Real-life social scenarios (n=12): School (n=4), Cafeteria (n=2), transports (n=2)	Virtual dolphin to interact with as dolphin trainer – VR – R [41]; Collaborative activity involving perspective-taking – VR – C [228]; Virtual agent using artificial intelligence– VR – M and eye tracking [22]
					Anticipate fearful situations (n=7, MG: 3%, B:0%)	Medical examinations (n=6), Transports (n=2)	Real-life spaces (MG:3%): e.g., Individualized fearful scenes (e.g., dogs) – Blue Room VR Environment (RS)[191]
					Train emotions (n=1, MG:21%, B:20%)	NM	Social scenarios (home scene, school bus, school library, tuck shop, physical education class on the playground) – Half-CAVE – VR [136]; Facial expressions and emotions using an augmented storybook– AR – P [49]
		Train cognitive abilities	n=6	MG:18% B:25%	Train cognitive abilities (n=3, MG:5%, B:15%)	Adapting VB-MAPP (n=1) and Boehm concepts to XR (n=1)	Attention (n=0, MG:5%): Object Discrimination with small games, – AR – P [77]; Grasp objects – VR – gesture and eye tracking [186]
					Train daily living skills (n=4, MG:13%,B:5%)	Indoor environment: Having a shower (n=2), Brushing their teeth (n=2)	Indoor environment: Brushing teeth - marker-based AR picture prompt to trigger a video model clip of a student [54]
						Outdoor environment: NM	Outdoor environment: Real-life social scenarios (e.g., supermarket) - HMD-VR [2]
	15% MG:0% n=5 B:0%	Provide context-relevant information	n=4	MG:0% B:0%	Train abstract thinking (n=1, MG:0%, B:5%)	Implicit humor in social situations (n=1)	Pretend-Play - PP & AR - C [14]
					Add assistive virtual information (n=3)	Adding information to daily social situations (n=1), e.g., about emotions (n=1)	–
					Filter non-relevant information (n=2)	. Filtering distressing noises (n=1)	–
		Support sensory strategies	n=1	MG:0% B:0%	Offer a resourceful sensory space (n=1)	Creating an AR tipi-life space (n=1)	–

Table 3.4: Comparison of XR guidelines coming from the literature with suggestions from the participants.

Cat.	Conc.	Sub-conc.	Literature	Participants
Task design	Individualization	Content	<i>Individualize content</i> : Vary the tasks, interactions, stimuli, graphics [31, 44, 60, 63, 230, 232, 308, 330], add familiar objects into XR [307], or onto the real-environment with AR [308], use physiological data to tailor the content, e.g., gaze [163], heart rate, skin temperature [165]	<i>Individualize content</i> (n=15): Set a familiar environment with reassuring elements (n=14), adjust every sensory information (n=5), possibly switch on/off every parameter (n=2), set an open/closed space depending on the individual (n=1), individualize rewards (n=1), integrate individualized and alternative communication systems (n=1)
		Medium	<i>Individualize medium according to the child's preferences</i> [63]: Use CAVE system if HMD is not tolerated, or desktop computer or tablet if more feasible	<i>Individualize medium according to the child's preferences</i> (n=1): Use tablet/desktop computer if HMD is not accepted
	Sensoriality & perception	Structure of Time & Space	<i>Offer predictability</i> [31, 44, 60]: Avoid loud sudden sounds [31]	<i>Offer predictability</i> (n=8): Use little distractors (n=6), use visual activity timers (n=3), alert about the presence of stimuli (n=2)
			<i>Give repetition possibilities</i> [31, 44, 178]): e.g., routine in training [31, 44]	<i>Give repetition possibilities</i> (n=10)
		Interaction types	<i>Use accessible interaction types</i> [31, 37, 230], e.g., speech recognition [124], or touchless interaction [17]	<i>Use accessible interaction types</i> (n=4): ergonomic controllers (n=4), tangibles XR controllers (n=3)
			<i>Offer various ways to interact</i> [31, 227, 230]	
			<i>Use motion-based embodied interaction</i> [17, 37, 60]	<i>Use motion-based embodied interaction</i> (n=1): no teleportation (n=1)
		Meaningful experiences	<i>Draw links with the real world</i> [31, 307]	<i>Draw links with the real world</i> (n=1)
			<i>Make experiences meaningful</i> [60]: Consider autism perception, e.g., visual memory [31], and associative way of thinking [63, 319]	<i>Make experiences meaningful</i> (n=1): Use individualized communication system of the child in XR (n=1)
	Collaboration	Prompting & Reassurance	<i>The practitioner/relative can prompt the child</i> [63, 230], e.g., instructions, gestures, physical prompts	<i>The practitioner/relative can prompt the child</i> (n=2), e.g., to help (n=2)
			<i>The child can see the practitioner</i> , e.g., for reassurance [60]	<i>The child can see the practitioner</i> (n=10): for reassurance (n=2) or if context-relevant (n=2)
		Shared controls		<i>Share controls between the child and practitioner</i> (n=10)

Task design	Engagement	Fun	<i>Make it playful</i> : Use a scoring system [31, 152], challenges and hidden elements [307, 315], storytelling and short/long term goals [307, 330], non-linear gameplay [307], digital companion [307], immediate feedback, and customization of avatars	<i>Make it playful</i> (n=5): Use individual's interests (n=5) (i.e., music (n=3), circular elements (n=2)), visualize progress (e.g., scoring system, collectables) (n=3), use feedbacks/feedforwards (n=2), use rewards (n=2), play around presence/absence (n=2), play with their own shadow (n=1)
		Discovery	<i>Prompt discovery</i> : Use various non-concurrent elements [31], e.g., movement [31, 60], shapes [31], audiovisual stimuli [44], 3D animations [31], some unexpected elements [4, 37, 319] <i>Broaden the child's attention</i> [63]: Use eye-tracking to detect fixations.	<i>Prompt discovery</i> : Use unexpected elements (n=3), use various non-concurrent elements (e.g., audiovisual stimuli surrounding the child) (n=1)
		Body perception	<i>See oneself in XR</i> [31]	<i>See oneself in XR</i> (n=1): See one's shadow (n=1)
		Environmental arrangement	<i>Gradually increase/decrease</i> : motor and cognitive complexity [31, 44, 63, 307, 308, 330], i.e., number of elements (e.g., crowdedness, stimuli, dynamism) [308] or types of elements (e.g., shapes, avatar's reactions, instructions, gestural prompts) [63]	<i>Gradually increase/decrease</i> (n=13): number and types of stimuli (n=8), realism level (for social scenarios) (n=4), predictability (n=3), neutrality (n=3), control over elements (n=1), number of distractors (n=1), dynamism (n=1), prompts (n=1)
		Rewards	<i>Individualize rewards</i> [63, 307]: Use personal [155, 330] sensory-based [31, 44] or generic [56] rewards, often assess new child's rewards [63] <i>Adjust rewards</i> : Consider the child's performance and progression (e.g., antecedents and behaviours) [56, 63], as well as the child's abilities [63]	<i>Individualize rewards</i>
		Sense of Agency	<i>Make the child feel in control</i> [31, 60, 230, 294]: Use child-initiated episodes (e.g., from what they like, or by making them choose between different actions/activities/game pathways) [63, 227, 230, 307, 330], adjust the information speed [309], use various interactive possibilities (e.g., gestures, voice) [227] <i>Allow the user to author the XR space</i> [230]	<i>Make the child feel in control</i> (n=14): Use child-initiated episodes (e.g., from what they like, or by making them choose between different activities (n=6)), give them the possibility to freely move in space (n=2) <i>Allow the user to author the XR space</i> (n=3): Record/repeat sounds/videos (n=3)
		Imitation	<i>Use modelling partners who simulate situations</i> [63], e.g., peers, avatars <i>Use avatars who imitate the child</i> [63], e.g., language, play, and body movements	<i>Use modelling partners who simulate situations</i> (n=1) <i>Use avatars who imitate the child</i> (n=1)

Protocol to conduct XR sessions	Intervention context	Secure environment	<i>Give predictability:</i> Practitioners may wear the HMD and suggest the child to handle it before to wear it [96]	<i>Give predictability</i> (n=5): Clarify planning prior to start (n=3), use pictograms showing what the XR space will look like (n=1), practitioners may wear the HMD before the child (n=1)
			<i>Make the experience meaningful for the child:</i> Combine different elements and strategies [63]	<i>Make the experience meaningful for the child:</i> Use understandable vocabulary to present the experience (n=4), make sure things are understood prior to start (n=2)
			<i>The practitioner can control every XR parameter</i> (n=9): See the child' view (n=2)	
		Organization of sessions		<i>Get the child used to the system during first sessions</i> (n=3): Possibly use sensory habituation to the HMD (n=3), use free play to detect the child's preferences (n=1)
			<i>Keep the child engaged:</i> Make short sessions with breaks [31]	<i>Keep child engaged</i> (n=8): Alternate work and relaxation activities in XR (n=5), alternate work in XR and real life (n=2); keep sessions short (n=1) (e.g., 15mn)
	Mixed methods	Quantitative Evaluation	<i>Include XR experiment as part of the global intervention:</i> Make long-term studies [31, 256]	<i>Include XR experiment as part of the global intervention</i> (n=4): Have regular sessions (n=2); use XR at specific therapy moments (n=1), make long-term studies (n=1)
			Establish detailed procedures and provide training for the practitioners [63]	
			<i>Assess initial child's state</i> [184, 191]	<i>Assess initial child's state</i> (n=1): Conduct sensory profile
			<i>Assess the child' experience:</i> No consensus exists: Collect behavioural data [63], e.g., repetitive behaviours [227], interaction logs [63], eye-tracking [63, 161]; collect physiological data [165]; use custom questionnaires [7, 95, 96, 308]; use XR presence/anxiety [184, 320, 321] and autism intervention questionnaires [184, 191]	<i>Assess the child' experience and performance</i> (n=2): Collect physiological data for stress measurement (e.g., biosensors, pressure sensors) (n=2), log observational data (n=2)
		Qualitative Evaluation	<i>Assess practitioners' actions</i> [63], e.g., behavioural data, prospective adjustments	
			<i>Measure the ongoing progress</i> [63]: Collect data from multiple measures	
			<i>Conduct behavioural observations:</i> Film sessions [227] and take notes [37]	<i>Conduct behavioural observations</i> (n=2): film sessions (n=2), take notes (n=1)
			<i>Conduct interviews</i> , i.e., with caregivers/parents [227] and children (use videos, images, drawings if non-verbal, and closed questions, with screenshots, smileys if verbal) [291]	<i>Conduct interviews</i> (n=1): if children can answer (n=1)

	Design process	Participative	Participative design	Use participative design [31, 35, 63, 230, 294]: Value child's design experience [230] Explicit all questions between stakeholders before to engage in collaboration [230]	Use participative design (n=5)
			Inclusivity	Consider the entire autism spectrum: Consider autism strengths and difficulties, include individuals requiring substantial support and adults [31, 230]	Consider the entire autism spectrum (n=7): Include individuals requiring substantial support (n=5) and adults (n=2)
		Equipment	Context-Dependent	Use ergonomic and affordable equipment, i.e., light [31], portable, small [216], non-tethered, affordable [230]	Use ergonomic and affordable equipment (n=4): resistive (n=3), not cumbersome (n=2), portable (n=2), affordable (n=2), non-tethered or with long wires (n=1)
			Task-dependent	Use AR to aid in the generalization from virtual to the real world [63]	
		Ctext	Setting	Conduct experiments in ecological settings [31, 230]	Conduct experiments in ecological settings (n=1)
			Age range	Age range: Possible from 13 years old for neurotypical people [102] Use little tasks to complete, e.g., unique goal per gaming session [44]	Age range: is task-dependent (n=7) Use little tasks to complete (n=4)
	Information presentation	Little & Clear Information	Little information	Avoid stimuli when not task-relevant [31, 44, 319]: Use simplified graphics [31, 308]	Avoid stimuli when not task-relevant: Use neutral (n=7) and simplified stimuli (n=4)
				Display clear information [31]: foreground/background differentiation, clutter-free	Display clear information: Use clear foreground/background differentiation
				Minimize transitions: between game states (no sound, animations) [44]	Minimize transitions (n=1): Gradually decrease appealing stimuli before to stop
				Avoid using metaphors [31]	Avoid using metaphors (n=4)
			Adaptation to the child's pace	Make it possible to repeat or adjust information speed [309]	Make it possible to repeat or adjust information speed (n=13)
				Use minimal prosody: no emotions [73], little text/language [44]	
		Task-dependent	Socio-emotional abilities	Allow for rapid shifts between XR environments [63]	
				Use adjustable realistic naturalistic settings [63]: Support the adult-child relationship, give precise control over the virtual surroundings	Use adjustable realistic naturalistic settings (n=5): to better generalize the skills
				Train a variety of skills instead of specific skills [63]	
				Train balanced turn-taking [63]: Use various contexts, visual prompting, rewards	
			Others		Realistic and non-realistic environments won't interest the same practitioners (n=1)

Information presentation Avatars	Look	Use cartoonish non-human avatars [31, 218]	Use cartoonish non-human avatars (n=1)
		Make XR avatars customizable [31, 218]	
		Only hear a XR avatar instead of both hearing and seeing it [218]	
		Position the avatars at real-world height [31]	
	Use	Use avatars as tutors for children [31]	

conversely, with promising outcomes over the therapeutic alliance and the training [63, n = 1]. Supporting the sense of agency then consists in making the child active [31, 60, 230, 294, n = 14], possibly through authoring activities [31, 227, 230, n = 3], e.g., drawing upon the painting VR game *Tiltbrush* [336, n = 2]. All these features and other strategies [31, 152, 307, 315, 330, n = 5], such as using a scoring system [31, 152], aim at promoting the child's fun.

Considering autistic atypical perception enables to create well-suited designs for children from the entire spectrum. To that respect, structuring the time and space is advised [31, 44, 60, n = 8], e.g., using time timers and enabling to rehearse actions [31, 44, 178, n = 10]. Due to sensory issues, accessible interactions are preferred, such as touchless interaction [31, 37, 230, n = 4], as well as offering varied interaction possibilities [31, 227, 230]. To move in space, embodied interaction is preferred over teleportation techniques [31, n = 1]. Finally, drawing links with the real world is advised to make experiences meaningful, e.g., including familiar objects into XR [31, 307, n = 1], and by considering autistic perception during the design process, e.g., associative thinking [63, 319, n = 2].

Collaboration possibilities are recommended, as the child-practitioner relationship is at the core of interventions. Hence, practitioners should be able to prompt children [63, 230, n = 2], while children could see them, so that to be reassured [60, n = 10]. Moreover, controls must be shared between them (n = 10) so that to make the child active. Indeed, a psychomotor therapist suggests that the impossibility in many VR applications to be with the patient decreases practitioners' acceptability. According to two participants, the practitioner must be visible only if context-relevant regarding the XR scenario, e.g., for medical examinations.

3.3.3.2 Protocol to Conduct XR Sessions

Stakeholders insist on creating a secure context to reduce potential biases caused by participants' anxiety. Before and during sessions, it consists in offering predictability [96, n = 5], making the experience meaningful [63, n = 4], and supporting engagement [31, n = 8]. In the long run, it relies on including the XR experiment as part of the overall intervention [31, 256, n = 4], and/or on planning a free play period to get the child used to the system (n = 3).

Mixed methods (i.e., qualitative and quantitative methods) that are adapted to children's abilities may help to assess their experience. Although no consensus exists in the literature, and a comprehensive overview is beyond the scope of our study, our analysis suggests major practices. Before sessions, clinical questionnaires may be used to assess developmental and sensorimotor abilities [184, 191]. A quantitative analysis of behavioural and physiological data before and during sessions may help to infer the child's state [63, 161, 165]. Then, custom questionnaires, often self-report, may be used to assess engagement [7, 95, 96, 308], along with standardized XR questionnaires, e.g., targeting the feeling of presence [320, 321]. Evaluations must consider the practitioner's impact over the child [63]. Their comparisons at regular time intervals may raise insights about the child's

evolution. Such evaluations may be combined with qualitative evaluations, i.e., observations [37, 227, n = 2], or interviews with practitioners, relatives, and the child if possible [291, n = 1]. Yet, a psychiatrist says that assessing the intervention outcomes remains challenging, as “during the week the child does 300.000 things”

3.3.3.3 Design Process

Creating autism-friendly environments requires using participative design [31, 35, 230, 294, n = 5], to consider all stakeholders’ needs, including autistic individuals requiring substantial support [31, 230, n = 7]. According to the participants and the literature, equipment choices must depend on: the healthcare setting, e.g., being affordable [230, n = 2]; the child’s abilities, e.g., being resistive and non-tethered [31, 60, 216, n = 1]; and the XR tasks [63], e.g., using AR to prompt the generalization of skills. Whereas four participants are reluctant about using HMD, mainly due to risks of isolation (n = 2), the other participants advocate for a controlled use, namely, with a practitioner. Yet, practitioners stress that acceptability and usability may be child-dependent (n = 9). Moreover, to not induce anxiety, wearing the HMD may require to use sensory habituation beforehand (n = 3), and to conduct the experiment within the usual child’s clinical setting [31, 230, n = 1]. At last, although manufacturers recommend using XR from the age of 13 [102], participants advocate for using task-dependent age recommendations, based on the child’s abilities and the practitioner’s expertise (n = 7), e.g., 7/8 for sensory and mediation purposes (n = 2), and 10/13 otherwise (n = 5).

3.3.3.4 Information Presentation

Displaying little and clear information [31, 44, 319] and simplified audiovisual stimuli [31, 308, n = 4] is advised due to autism filtering difficulties. Adapting to the child’s pace may also support understanding, e.g., adjusting the information speed [309, n = 13].

The level of details and the realism of the graphics must be task-dependent (n = 7), e.g., realistic for social scenarios (n = 5), and abstract and creative for mediation purposes (n = 1). To that respect, a psychologist stressed that “realistic and non-realistic environments won’t interest the same practitioners” (n = 1). About social scenarios, adjustable collaborative realistic settings are advised to train various skills, and especially for turn-taking during social interactions [63].

Since little information is advised, simplified cartoonish avatars with customization possibilities are preferred to represent the others as well as the self [31, 218, n = 1]. The avatar of the child has to be positioned at real-world height [31]. Moreover, due to common perceptual filtering difficulties, only hearing others’ avatars instead of both hearing and seeing them can sometimes be preferable [218].

3.4 Discussion

3.4.1 Summary of Results

The first objective of this chapter was to check whether autism stakeholders' XR needs matched the existing XR uses. Our comparison between 34 interviews conducted with stakeholders, mainly including practitioners, and the literature, revealed that whereas around 87 percent of studies focused on training socio-emotional abilities, participants highlighted three main XR objectives: well-being and mediation, social and cognitive training, and sensoriality (see table 3.3). These objectives draw upon the main features of interventions without or with digital tools (see tables A.1 and A.2 in appendix). This gap calls for more research to explore XR sensory and mediation approaches, and to consider more autistic individuals with SLN. These goals are also strongly inclusive and bridge the gap between a mere focus on training abilities, coming from the medical model, and an only focus on changing society to improve the well-being of autistic individuals, coming from the social model (see section 2.1.5). To that respect, our findings extend Parsons et al. [230]'s research roadmap for the XR medium. Possible use cases that implement these categories, particularly with AR, are discussed in the next subsection. The second objective of this chapter was to provide XR design guidelines being representative of stakeholders' views. Whereas the guidelines from the interviews and autism XR literature presented similarities, discrepancies also emerged (see table 3.4). More specifically, stakeholders advised paying more attention to the intervention context and to using collaborative designs. XR design guidelines are outlined in the third subsection, followed by limits to our work.

3.4.2 Suggestions of Use Cases for Future Autism XR Research

To train social abilities, stakeholders advise using VR social scenarios (e.g., school playground) with a precise control over all stimuli by the practitioner. Yet, more research is needed to maximize the generalization of skills learned from VR into real-life [31]. Whereas shifting between different VR use cases could enhance the intended therapeutic outcomes [63], two participants stress that the richness of real-life situations could not be recreated. Hence, VR training should be considered as part of the overall intervention program. Moreover, it could be used within a gradual transition from VR, to AR, and finally real life, to gradually work in more ecological contexts due to AR capabilities [21], and to maximize the generalization of the skills learned in VR by gradually confronting the child to the unpredictability of real-life. For instance, a bakery scenario consisting in buying bread could first be trained in a VR safe space. Then, AR could be used in a real bakery to withdraw distressing information (e.g., lights) while adding contextual information (e.g., emotion detection). These findings extend the complementary training and prosthetic roles previously assigned by Tarantino et al. [308] to VR and AR.

To make the child feel secure, three XR sensory approaches may be used: multisensory relaxing spaces, derivatives of stereotypies, and mediation spaces.

Collaborative multisensory relaxing VR spaces largely emerged, often Snoezelen-inspired. A psychomotor therapist described them as “sensory backpacks”. However, VR presents risks of isolation, and autistic children with SLN could misunderstand that the avatars actually represent themselves and the practitioner. Despite also presenting risks of isolation [21], AR could overcome these issues by perceiving the virtual elements while still seeing and hearing the real surroundings and real people instead of avatars. Thus, the low appearance of such immersive AR approaches in surveys [21, 195] calls for more research. Possible use cases include real spaces where the proportion of real and virtual elements could be adapted to the session’s needs, e.g., withdrawing posters on walls.

Some participants advise creating XR “derivatives of stereotypes”, to replace the repetitive behaviours being used as coping strategies but engendering stigma, with an alternative XR approach. Both VR and AR may be used to investigate this unexplored strategy, with intended benefits both for children and families. VR use cases could be considered if a whole context must be recreated. For instance, one team supervisor mentioned the case of a boy who needs to be driven by his parents on Paris ring-road to get relaxed. AR could be also used for recreating specific elements, e.g., spinning objects.

At last, XR mediation activities focus on strengthening the therapeutic alliance through collaborative free-play activities, drawing upon non-digital mediation activities (see section 2.2.2.4). Yet, they remain unexplored in XR, even though technology can be considered as mediating tools encouraging social processes, as stated by activity theory [76]. Such approaches also draw links with common psychological concepts, e.g., the *potential space* (intermediary space for playful and creative experiences) [334]. They could be derived from previous digitally-augmented multisensory experiences that achieved promising outcomes about the therapeutic alliance, e.g., *Mediate* [227], *Magic Room* [95], or *Sensory Paint* [248] (see section 2.3.2.3). Moreover, as these bespoke projects were often expensive and/or lacked of flexibility, HMD-based AR settings could overcome these limits.

XR sensory playful activities aim at rehabilitating sensory issues, or at working on action/reaction relationships, often by gradually adding/removing stimuli. VR and AR may both provide solutions for creating such scenarios. The first half of the participants mention VR Snoezelen-like scenarios. The other half evokes realistic scenarios ranging from VR to AR, for instance by starting in a controllable VR space, and gradually going towards AR. A possible use case could consist in recreating a VR supermarket, and then work in the real supermarket while using AR to remove distressing elements and add contextual prompts. Such AR solutions may also be used as daily compensation strategies, being related to common strategies, e.g., noise-cancelling headphones. Hence, AR appears as highly inclusive, since it allows children to enter spaces usually considered as overwhelming. While such sensory AR scenarios remain under-explored, the current evolution of HMDs calls for more research in this area.

3.4.3 Suggestions of XR Autism Design Guidelines

XR task design draws upon many common intervention principles, being detailed in table A.1 in appendix, e.g., individualizing the environment. Contrary to the literature, stakeholders emphasize the importance of using collaborative designs, as common interventions largely rely on the therapeutic alliance. To that end, AR is promising, by allowing children to see their familiar environment, including their usual practitioner. Then, many design requirements being listed in table 3.4 draw from well-known educational theories which advise using handling activities, such as the ones from Piaget et al. [238] and Montessori and George [202]. In particular, AR seems well-suited to extend them, as it can easily be combined with tangibles.

Methodological insights expand previous XR recommendations [31], by suggesting to focus on two aspects of interventions: the context, and the evaluation of the outcomes. About the context, stakeholders advised paying more attention to providing children with a safe space to conduct experiments. On the short term it consists in offering predictability (before, during, and after sessions). To that respect, AR seems well-suited, due to the reasons above-mentioned. On the long term, XR protocols may split into two periods: first make the child feel secure, and then train specific abilities. To assess the XR intervention outcomes, mixed methods (i.e., qualitative and quantitative) can be used to adapt to the diversity of autistic profiles. Although it remains challenging due to the overall intervention program of children, regular evaluations may help to infer their evolution over time. So far, no standardized XR questionnaire exists to assess the autistic user's experience, and XR studies mainly focus on observable features. Yet, some custom questionnaires have been created. For instance, Tarantino et al. [308] suggest to focus on four main features, i.e., the impact of photorealism, the understanding of real versus virtual elements, the body movements, and the active exploration. Creating such questionnaires leads to reconsider some commonly measured aspects with non-autistic individuals, which affect autistic users differently. In particular, assessing the feeling of presence [288] can already lead to ambiguous results with non-autistic children, and is even more questionable with some autistic children with SLN who may struggle to say if they feel present in real-life [60]. Moreover, whereas photorealism may engage non-autistic users, it may distract autistic users [308]. At last, self-report questionnaires that are used in most studies [217] cannot be used for individuals with intellectual disability. New questionnaires have thus to be devised, addressing practitioners as well as the child if possible, inspired from Aruanno et al. [7]'s study. They could also be combined with physiological data to get anxiety markers, e.g., heart rate [317]. Yet, more research is needed to understand which relevant factors enable to get insights about complex perceptions (e.g., engagement), while using low intrusive technologies, such as light bracelets [285].

About the design process, participative design is recommended, as previously

suggested [230], as well as conducting field studies (e.g., in clinical settings). Equipment must be chosen accordingly, depending both on the use context and the intended task. While most stakeholders are positive about using HMDs, in line with the literature, they suggest using them in a controlled way, i.e., with a practitioner. Whereas absent from the literature to our knowledge, participants also suggest using task-dependent age recommendations, e.g., eight years old for mediation applications focusing on well-being.

About information presentation, in addition to simplifying the audiovisual content, in line with 2D games that can be appealing to autistic individuals (see table A.2 in appendix), and with Bozgeyikli et al. [31]' findings, our study suggests to adapt the graphics' realism both to the intended task and to practitioners' preferences. Indeed, depending on the type of intervention that practitioners use (e.g., NDBI, or psychodynamic), they may prefer using non-realistic creative scenarios or realistic scenarios. Giving control over the audiovisual speed and prosody is also advised, as in Tardif et al. [309]'s study. Indeed, decreasing the audiovisual speed may increase the child's understanding. At last, adding some unexpected events within a highly-structured XR space to enhance engagement connects with Remington et al. [246]'s findings, which stress that using too little or too many distractors may hinder the attention of autistic children. This recommendation is also linked with common compensation strategies that individuals with Attention-Deficit Hyperactivity Disorder use to stay focused. Hence, future autism XR research may consider neurodevelopmental conditions in general, due to its potential impacts beyond the scope of autism.

3.4.4 Limits

Findings must be considered in the light of some limitations. As interviews were mainly conducted with practitioners to build guidelines supporting their interventions, autistic individuals' views were less considered. Moreover, no single stakeholder could expertly provide insights about XR, but only suggestions based on their knowledge of common interventions with or without digital tools.

The evaluation of the included publications in terms of design features was conducted qualitatively and may contain inaccuracies. Also, no systematic literature review of XR design guidelines was made, and the articles were mainly hand-searched. Conducting such a systematic review about XR design guidelines and comparing it with our findings may yield further design insights.

The evolution of my understanding of the autism field throughout the interview process may have gradually changed my way to ask questions to the interviewees, and to adapt to their reactions. This also may have led to elicit more answers over time. Elements from my background also may have influenced the results of the grounded theory analysis. At last, since I am not a native English speaker, translating interviews from French to English may have led to discrepancies, even if efforts were made to remain close to the original wordings during the translation process.

Only interviewing French-speaking participants may have led to overlook some insights, possibly being more prominent with international stakeholders. This calls for further research to complement the present study by interviewing stakeholders from different countries and comparing their standpoints with our findings.

To complement and extend the findings that are reported in this chapter, it would be particularly useful to conduct XR participative design workshops with autism stakeholders being representative from all autism fields, in particular including autistic individuals.

3.5 Conclusion

This chapter reported on a comparison between autism stakeholders' views about XR uses and designs, and the current focus of autism XR research. Interviews were conducted with 34 stakeholders, mainly including practitioners. They were analyzed using a grounded theory approach, involving three steps. First, findings were categorized according to concepts and categories that were inductively built. Second, to check for potential gaps, and thus confirm the observations made in chapter 2, emerging XR use cases were compared with the use cases being reported by two systematic literature reviews [21, 195]. XR design guidelines were finally drawn by comparing the interviews' findings with an XR literature survey that we built in relation to our emerging grounded theory. This chapter has four main contributions that drive the design of the following studies presented in this thesis:

- A state of autism interventions without and with digital tools was constructed (see tables A.1 and A.2 in appendix). The success of interventions without digital tools relies on many parameters, such as an individualized and structured environment, engagement, the quality of the therapeutic alliance, and the holistic assessment of children's experiences. Practitioners commonly use digital tools to complement their interventions, with approaches being tailored to the individuals' abilities and not being limited to social issues.
- Discrepancies were confirmed between XR uses coming from the literature and stakeholders' views. In addition to targeting precise socio-emotional abilities, stakeholders advise focusing more on sensory and mediation issues. The second part of this thesis thus explores the use of XR multisensory and creative approaches for autistic children (see chapters 4, 5, 6, and ??), and the third part investigates the ecological potential of AR to assess the auditory lived experiences of autistic children (see chapters 7, 8, and 9).
- To better include autistic children with SLN, with or without ID, AR seems more suited than VR, due to more inclusive and ecological capabilities. Indeed, with AR, children can still perceive their real physical surroundings and their usual practitioner. Gradually transitioning from VR to AR could also facilitate the generalization of the skills learned in XR into real life.

- XR design guidelines for autistic users were drawn. In particular, they encourage using collaborative designs, considering XR tools as part of the child's overall intervention program, and conducting field studies within clinical settings.

Part II

Magic Bubbles: a Multisensory Augmented Reality Mediation Environment

Abstract

Based on the findings from our interviews with autism stakeholders that were reported in the first part of this thesis, the second part focuses on the design, development, and field testing of a mediation HMD-based AR environment intended for autistic children with SLN, in collaboration with clinical practitioners. This environment called *Magic Bubbles* seeks to secure autistic children and to reinforce the child-practitioner relationship, by providing multisensory free-play activities with self-expressive capabilities, while keeping contact with the real environment and the usual practitioner. After designing *Magic Bubbles* for a day hospital setting and validating its acceptability among a clinical team (see chapter 4), acceptability and usability testing were conducted with children with neurodevelopmental conditions and intellectual disability (see chapter 5). Positive outcomes then led to carry out a long-term field study with seven autistic children (see chapter 6). Findings confirmed *Magic Bubbles*' potential for reassurance, sharing, and provided a detailed account of the quality of children's AR experiences.

4 - Designing an Extended Reality Application to Expand Sensory Interventions for Autistic Children with Severe Learning Disabilities: Participation of Practitioners

4.1 Introduction

Most existing autism XR research targets socio-emotional abilities, thus excluding many autistic children with SLN who cannot directly work on them. To also include these children, XR sensory and mediation approaches may be used, as revealed by the findings from our interviews with autism stakeholders (see chapter 3). Our hypothesis is that such approaches could enable to secure these children and to reinforce the therapeutic alliance, in turn also making them more ready to then perform challenging tasks (e.g., communication).

To verify this hypothesis, a threefold research process was conducted. First, an HMD-based AR environment called *Magic Bubbles* was designed in collaboration with practitioners to be suitable for a day hospital setting and maximize its acceptability among a clinical team (see this chapter). Acceptability and usability testing were then conducted with autistic children with SLN and ID, or a related neurodevelopmental condition (see chapter 5). A long-term study was finally performed to validate our main hypothesis (see chapter 6). This chapter describes the first step of this threefold process. Two research questions are addressed:

- RQ1** According to practitioners, how to design XR applications intended to expand clinic-based sensory strategies that are commonly used for autistic children with SLN?
- RQ2** How to maximize practitioners' acceptability of XR applications which aim at complementing clinic-based sensory strategies for autistic children with SLN?

After introducing the design process that was conducted in collaboration with three clinical practitioners, a user study with eleven practitioners is presented. XR design guidelines are finally drawn, by contextualizing the findings with respect to usual clinical practices and to the autism XR literature.

This study was presented at the IEEE International Symposium on Mixed and Augmented Reality (ISMAR, October, 2021), under the title "Designing an Extended Reality Application to Expand Clinic-Based Sensory Strategies for Autistic Children Requiring Substantial Support: Participation of Practitioners" [B].

4.2 Design process with practitioners

After detailing the design of the initial XR use case, its adaption and development for a day hospital setting in collaboration with practitioners is presented.

4.2.1 Methodology

A first use case scenario emerged from the interviews that were conducted with 34 autism stakeholders (see chapter 3). It aimed at calming and engaging autistic individuals with SLN through a free-play multisensory interaction space, drawing from Sensory Integration Therapy, Snoezelen, and music therapy interventions (see section 2.2.2). Two main technological possibilities were imagined: VR versus AR. The latter allowed us to adjust the proportion of real and virtual elements based on practitioner's needs. To be adapted to a real-life clinical setting, this main use case was presented to two clinical psychologists and one psychiatrist. All of them are autism experts working in a day hospital, who use digital tools in their daily practices (e.g., i.e., video games, robots, tablet, projected screen). This approach thus followed presumptive design principles [91]: speeding up the design process by presenting advanced ideas to help practitioners to validate them and generate new ones. In addition to discussions, and to better understand the needs of autistic children with SLN, I also attended three solo and two group sessions conducted by the psychologists and using digital tools (i.e., video games, robots, tablet, projected screen), which included three autistic children.

4.2.2 Initial use case

4.2.2.1 Environment

Two types of appealing stimuli are displayed: generic and individualized. Generic visuals are bubble column, audio bubbles, and water ponds. Indeed, autistic children often enjoy bubbles and bubble columns, be it in Snoezelen spaces [168], or projects such as the *Magic Room* [97], and *New Horizon game* [44] where popping bubbles was used for relaxing purposes. Bubbles emerge from water ponds, then explode and reappear, since appearing/disappearing patterns can be appealing (see chapter 3). All visuals are simple geometric shapes for simplification purposes [31]. Generic audio stimuli are short musical sounds (e.g. marimba), inspired from previous studies [97], our interviews, sound designs from games for autistic children [338], and music therapy activities [190]. Individualized stimuli are used to create a safe familiar space. Hence, a pink "music" bubble can host the child's preferred music tracks, and an "image" panel can host visuals, e.g., drawing, photograph of relative. The practitioner has to add them prior to start the session.

Four sensory interaction are available: psychomotor, audio, visual, and tactile with the controllers' vibrations. Children can move in space and touch virtual objects by using the controllers and/or their body [17]. To prompt exploration, moving in space changes the environmental lighting color, inspired from *Mediate'* audio floor [227]. Children do not need to hit the controllers' buttons, but only

to hold them, due to possible fine motor skills issues. When touching virtual objects, five reactions may happen: (1) audio bubbles trigger their bubble sounds; (2) bubble column changes the color of all columns and panels, in line with the *Impression Wall* in *Mediate*; (3) panels change the sounds in the bubbles; (4) ponds trigger a water splash; and (5) the music bubble triggers the individualized music. Simple feedbacks also indicate that actions are taken into account, by using controllers' vibrations (if activated) or highlighting the surface of objects with another color.

Objects are spatially organized according to their roles to create clutter-free scenes with little information [31]. They are identified with simple shapes and colors, as displayed on figures 4.1 A, B, C, D. They include: bubble columns, audio bubbles, water ponds, music bubble, panels, and one "image" panel. The number of bubbles, panels and columns, can respectively be adjusted from zero to eight, three, and three. To give a sense of agency, a yellow dot indicates the line of sight [96]. A gradual real-virtual transition intends to prevent anxiety by making the virtual space neutral at the start/end of the experience. To prompt collaboration, children can always see the practitioner, i.e. directly or through an avatar. Practitioners can provide physical guidance and reassurance. Foam carpets delimit the interaction space to provide a structured space and enhance comfort.

4.2.2.2 Practitioner's Interface

Practitioners can monitor, control, and adjust all stimuli at the start or at run-time, or stop the experience, through a dedicated User Interface (UI) displayed on a large screen (see figure 4.1 E, F). The UI has four main areas: add/remove elements; trigger stimuli; add/remove feedback, e.g., controllers' vibrations (due to potential tactile over-sensitivity) or a visual timer (for predictability) [63]; or contextual information, e.g., time spent using the application. The UI can also be used to trigger unexpected events so that to prompt exploration [4].

4.2.2.3 Activities

Free-play or task-oriented activities were imagined. Free-play activities consist in a free exploration of the interaction space. They were advised by previous design studies, regarding Sandbox games [307]. Task-oriented activities have expected outcomes, which draw upon common interventions and other studies, e.g., "sound lotos"¹[97].

¹Sound lotos are listening games which consist in trying to identify daily noises (e.g. objects, animals, sounds of the house).

Table 4.1: Practitioners' needs about using XR at the day hospital.

Categories	Practitioners' needs (<i>Change Adopted (A); Already Planned in existing design (AP)</i>)
Environment	<i>Collaboration</i> : The child can perceive the real space and act with their practitioner (A) <i>Meaningful environment</i> : The virtual space has to be connected to the real space and other child's activities (A) <i>Therapist's role</i> : Practitioners can provide physical guidance (AP) <i>Sensoriality</i> : The child can move, feel controllers' vibrations, or interact without controllers (AP) <i>Common autism guidelines</i> : The space should be individualized, fun, predictable (AP) <i>Sense of agency</i> : The child/practitioner can control the speed and size of bubbles (A) <i>Amount of information</i> : Few movements and objects with clear roles are shown (AP)
Activities	<i>Free vs. Directed Play</i> : Practitioners prefer free-play for autistic children with SLN (A)
Practitioner's UI	<i>Interface</i> : Practitioners can monitor and adjust all environmental stimuli (AP)
Equipment	<i>Equipment</i> : Equipment has to be affordable, resistive, portable, non-tethered, and enable to remove the earphones. (A)

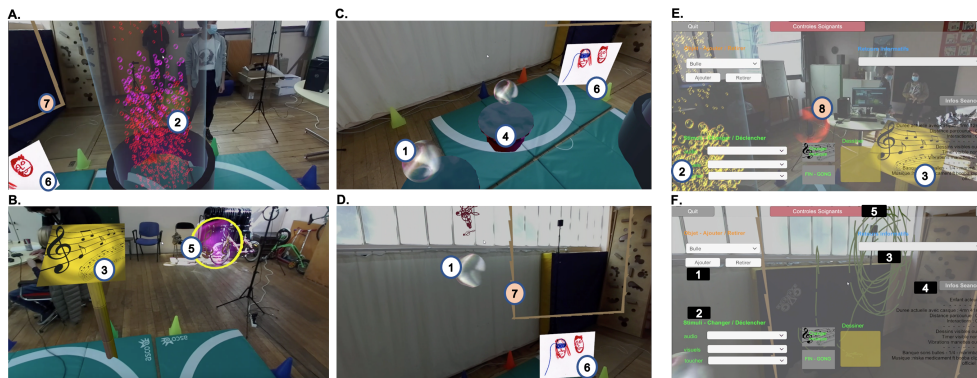


Figure 4.1: Design of *Magic Bubbles* Game – Content: 1 Bubble; 2 Bubble Column; 3 Panel; 4 Water Pond; 5 Music Bubble; 6 Image Panel; 7 Drawing panel (added after user testing); 8 Recording Bubble (added after user testing) – Therapist UI (E,F): 1 Add/Remove elements; 2 Trigger stimuli; 3 Add/Remove Feedback; 4 Information; 5 Show/Hide the UI.

4.2.3 Use case adaptation for a day hospital context

To adapt the initial use case for a day hospital settings, practitioners made design requirements leading to changes being summarized in table 4.1.

4.2.3.1 Environment

To not induce over-arousal, the speed of the bubbles in the column was decreased. Their size and speed were made controllable by stooping/standing, or using the practitioner's UI. To enhance multisensory stimulation and generate surprise, a rectangular panel was added to trigger sounds from the controllers with two short melodies created on purpose. Also, to clarify the structure of the space, activity cones² were added to delimit the interaction space.

²Activity cones are often used by psychomotor therapists during sensory activities.

4.2.3.2 Activities

Free-play AR activities were chosen for autistic children with SLN, to be meaningful, collaborative, and to keep contact with their real familiar space and their usual practitioner. Thus, the psychologists validated our assumption discussed in chapter 3 that AR was more suited than VR for such children. Moreover, they specified that it was not an issue for children to see the practitioner's monitoring screen, and that it could even be reassuring.

Two conditions were added drawing upon receptive and active techniques used in Snoezelen and music therapy: spectator or actor (see section 2.2.2). When spectator, stimuli are triggered by the practitioner and/or automatically. The child can move but not interact with virtual objects, or may ask the practitioner to trigger stimuli. When actor, the child can move and interact with all the virtual objects. Practitioners can support exploration (e.g., physically, triggering stimuli).

4.2.3.3 Practitioner's Interface

The practitioner's UI gives control over every environmental aspect at runtime, with four main interests: add/remove objects (orange), trigger stimuli (green), show/hide simple feedback (blue), and show session information (grey) (see figures 4.1E and 4.1F). To support visibility, the buttons "Contrôle soignant" and "Infos Seance" can respectively show/hide the main pane to only see the child's view, and show/hide session information.

4.2.3.4 Equipment

Equipment choices are detailed in the next subsection. They are driven by expected behaviours of autistic children with SLN, e.g. impulsivity, covering their ears. Since these children sometimes wear protection headphones, wearing a HMD was not considered to be an issue. Yet, for those displaying tactile over-sensitivities, it may require to gradually habituate them to wear it beforehand.

4.2.4 Apparatus & Development

Magic Bubbles uses an AR video see-through platform, which means that virtual objects are added to a live video stream of the real environment, through a stereoscopic camera plugged onto a HMD. To that end, the HTC Vive Pro headset was chosen with a Zed Mini camera³ to get a non-perceivable visual latency of 60ms, a correct resolution of 720p per camera, and an immersive 90° horizontal field of view. We previously tried using the front cameras of the HTC Vive Pro, but abandoned them as they achieved a lower resolution and higher latency, being possibly detrimental for autistic children. Other AR devices were excluded because they displayed a narrower horizontal field of view, e.g. 52° for the Hololens 2⁴. When it appeared that bandwidth technical limits prevented from using non-tethered AR, practitioners still preferred using tethered AR rather than non-tethered

³Zed Mini camera: <https://www.stereolabs.com/zed-mini/>.

⁴Hololens 2: <https://www.microsoft.com/fr-fr/hololens>.

VR. Indeed, perceiving the child's physical surroundings was a major requirement. Moreover, alternatives such as including the practitioner's face within VR (e.g., on a virtual television screen) was impossible for some children who could misunderstand the link between the image of the practitioner and the real practitioner.

The system total weight of 563g was not a problem for autistic children aged more than eleven, since the HTC Vive headset was accepted in Newbutt et al. [217]'s study. Two HTC Vive controllers were used. Four Vive lighthouse outside-in tracking systems covered the interaction space to avoid tracking loss due to the practitioner being close to the child. Hence, trade-offs were made regarding the portability of the system in relation to its other features. The HMD runs on a desktop computer Dell Precision 3630, with i7 CPU, 32Go of RAM, and the Nvidia Geforce RTX2080. A 27-inch screen enables to monitor the child's activities even if standing far from it. The setup is summarized on figure 4.2.

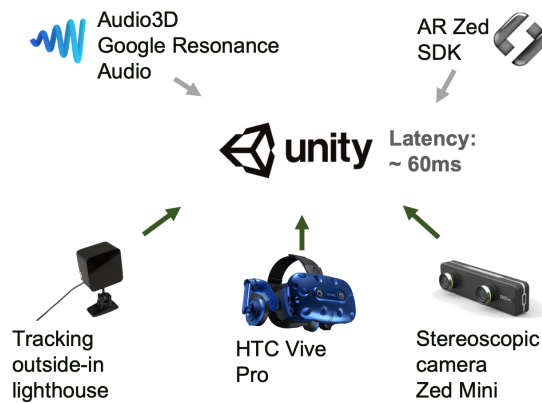


Figure 4.2: AR video see-through technical setup

A video presentation of the application is available at this link <https://valentinbauer.com/research/doctorat/>⁵. Development was done with Unity3D software, Google Resonance Audio for the 3D audio rendering, Steam VR SDK for the AR handling, and ZED SDK for the ZED Mini camera. A *game control* script handles all actions triggered by the child and practitioner. State machines are used to manage the state of elements, e.g., active/spectator condition. This script communicates with other managers: *audiovisual manager* for all audiovisual aspects; *player interaction manager* for player movements and interactions; *log manager*, to write in external files information about all the events. All virtual objects have an associated script, which sends events to the corresponding manager when interactions occur. Unity physics engine handles all collisions.

⁵This video details the interactions being available in *Magic Bubbles*.



Figure 4.3: Pre-tests conducted with practitioners at the day hospital. Left: setting - Right - a practitioner testing *Magic Bubbles* AR application.

4.3 Evaluation with a clinical team

Two pre-tests were conducted with a team of eleven practitioners at a day hospital (i.e., pre-test 1 and 2), including the two psychologists who had participated to the initial design process. This pre-study was required to: validate the consistency of the application with their interventions intended for children with SLN and ID, collect design insights to refine the application, and get their approval to then be able to work with such children. After presenting the demographics and methodology, insights about the user experience and design are reported.

4.3.1 Participants

Participants include 8 women and 3 men: educators (n=5), clinical psychologists (n=2), co-head of the day hospital (n=1), nurse (n=1), secretary (n=1), and psychology intern (n=1). Two had little XR experience with VR games. Four were 20-30 years old, three were 30-40, one was 40-50, and three were 50-60. Seven participants did the pre-test 1, and the four others did the pre-test 2.

4.3.2 Method

4.3.2.1 Protocol

Only the actor condition was tested, since this pre-study mainly targeted the suitability of the existing design and interactions used for autistic children, and possible improvements to that respect. Practitioners freely tested the application during five minutes or more, in a room of the day hospital dedicated to sensory activities (see figure 4.3). To observe their reactions when discovering the application, no detailed explanation about how it worked was given prior to start. The two psychologists who participated to the initial design observed their colleagues during the testing, to: think about new needs for autistic children; imagine how they could guide a child wearing the HMD; and precise which observable criteria could be used to assess children's state. Due to the Covid-19 pandemic, face masks were kept, equipment was cleaned between participants using disposable wipes, windows were regularly opened, and two sessions were separated by ten minutes at least.

4.3.2.2 Evaluation

During the experience, subjective insights were gathered about practitioners' experiences, through note-taking of their behaviours and comments (the three last sessions were filmed), i.e., smiles/laughs, movement quantity, or type of movements. After the experience, seven semi-directed questions addressed demographics (i.e., age, profession, previous XR experience), user experience (i.e., feeling of connection with the real space, comfort, feeling of dizziness), and preferences (i.e., object preferred). Three final open questions concerned: general feelings, possible design improvements, or additional elements that participants would like to say.

4.3.3 User experience: Subjective results

Emerging phrasings and observations were grouped into concepts representing aspects of the user experience. The number X of participants evoking each concept will be mentioned inside parenthesis using (n=X).

4.3.3.1 Participants' engagement

All participants enjoyed the experience, which was compared to Snoezelen (n=4), even if most of them had no previous XR experience (n=9), and two were anxious prior to start. All of them enjoyed hitting the bubbles. A psychologist said: "you can play squash if you send the bubbles strong enough against the cupboard". They were often surprised, smiled/laughed when realizing that they could interact with elements, and particularly enjoyed the bubbles and the ponds.

4.3.3.2 Connection to the real world

Most participants felt connected to their real surroundings (n=10), even some of them were concerned about feeling "enclosed" prior to start. This experience thus reassured them about future testing with autistic children. A psychologist also confirmed that AR had more potential than VR to be accepted by practitioners. Some behaviours evoked a possible feeling of presence (n=4): one participant made a bubble bounce on a psychologist and asked "did you see it?"; two participants hit the ponds with their feet; and one said being "in another world".

4.3.3.3 Sensorimotor behaviours

Participants adopted various sensorimotor behaviours, from being very stiff to moving a lot (stooping, jumping etc.), with the whole body being engaged. The experience can potentially be hypo or hyper stimulating, depending on how practitioners use it with respect to the child's needs (n=9).

4.3.3.4 Physical experience with the HMD device

Most participants felt comfortable (n=8), apart from three of them who: found it heavy (n=1), perceived a discomfort on the nose (n=1), or due to their face mask (n=1). A psychologist ensured that "these issues are not a problem with children as they would directly express [non-verbally] their discomfort if they had

any". One participant felt a bit dizzy at the end because its HMD was not screwed enough, thus making the image a bit blurry.

4.3.4 Design ideas from practitioners

Design recommendations are summarized in table 4.2, which could inform the design of future XR interventions for autistic children with SLN. After presenting the suitability of our design for such children, design changes are evoked, followed by insights related to the assessment of the quality of children's experiences.

4.3.4.1 Suitability of the design for autistic children with SLN

Psychologists who participated to the initial design found consistent the use of a 2D screen monitor to perceive what the child perceives. Indeed, since they also remembered the positions of virtual objects in the real space between sessions, the 2D screen was suitable to guide children. They also decided to always keep the same number of elements due to the strong ritualization of children. Hence, the basic setup including three bubbles, one bubble column, and one panel will only be used, being a good trade-off in terms of the number of elements. All participants noted that a strong attention has to be paid to the wire between the computer and HMD, to not interfere with the child's experience. Since non-tethered AR could not be used due to technical constraints, they highlighted again that they preferred tethered AR over non-tethered VR (see section 4.2.4). At last, the timer feature was deemed unnecessary at pre-test 2 as there was already a clock in the room.

4.3.4.2 New design insights

About the structure of sessions, we added the possibility to take a time at the end for the child to make a real drawing that would then be included in the image panel for the next session. According to a psychologist, it could help to temporally connect all sessions by "leaving traces that they will see again", to give a sense of agency through authoring, and to make associative projections, possibly helping to assess their experience. The image panel can be hit to navigate through all of the drawings. Then, we added a gong sound to the practitioner's UI to give predictability by allowing the practitioner to warn about the end of sessions. Since the virtual grid boundaries of the interaction space were described as a "prison" not suitable for autistic children ($n=7$), they were removed after pre-test 1.

About sensoriality, only controllers' interaction was kept after pre-test 1, as being more intuitive than body interaction. To make children more aware of their movements' velocity, three types of interaction were added to the simple "hit" for the bubbles: grabbing, throwing, or bursting them. The panel enabling to change the bubbles' sounds was removed after pre-test 1, as not offering a clear action-reaction relationship. Though, sounds can still be changed through the UI. To prevent over-stimulation, making the bubbles disappear when approaching the column was also added. Then, adding oil disks as in Snoezelen was delayed to future testing with children to check if necessary, since providing children with too

Table 4.2: Design insights from the practitioners

Concept	Participant proposals (<i>Added(A)</i> , <i>Delayed(D)</i>)
Structure	Connect all sessions with drawings (n=4)(A) Use a gong sound to end the sessions (n=3)(A) Hide the chaperone. (n=7)(A)
Sensoriality	Only interact with controllers (n=3)(A) Vary interactions with the bubbles (n=3)(A) Simplify action-reaction principles (n=3)(A) Add a visual oil disk object (n=2)(D) Prevent from entering the column (n=1)(A)
Agency	Add recording possibilities (n=3)(A) Add drawing possibilities (n=4)(A)
Equipment	Pay attention to the wire of the HMD (n=11)(A)

much information may induce over-arousal.

To give a sense of agency, one recording and one playback bubbles were added in the actor condition after pre-test 1. They allowed to play back one's voice as in some video games that autistic children tend to enjoy (n=1), e.g. *Talking Tom Cat* [224]. Since simplifying action/reaction relationships was advised at pre-test 2, we only kept one bubble for both actions. Drawing on a large panel was also added after pre-test 2. When actors, children can move controllers onto it to draw. When spectators, practitioners can draw from the UI.

4.3.4.3 Evaluation methods proposed by the practitioners

Practitioners' propositions of methods of inquiry are summarized in table 4.3. Qualitative methods are advised to assess the experience of autistic children with SLN, due to their non-verbal condition and potential ID, which prevents from using self-report questionnaires. To understand their actions, taking notes of the overall context is needed (e.g., child's state before and after sessions). Quantitative evaluations may also provide valuable insights, such as logs of AR variables (e.g. time spent with the HMD), physiological data from biosensors if tolerated by the child, and custom questionnaires filled by practitioners. Questions remain about which observable markers to consider, e.g. wearing/removing the HMD to assess the understanding of real versus virtual elements.

4.4 Discussion & Recommendations

This section discusses the two research questions (RQ1 and RQ2) based on the main findings, which are summarized in table 4.4.

4.4.1 How XR design can expand sensory strategies?

4.4.1.1 AR & therapeutic alliance

As in previous studies using digitally-augmented multisensory settings and focusing on well-being [37, 95, 100, 227, 248], practitioners aimed at reinforcing the

Table 4.3: Ways of assessing the quality of children’s experiences being proposed by the practitioners

Eval.	Engagement factors
Qualitative	<ul style="list-style-type: none"> • Consider the intervention context: child’s state, people in the room • Film sessions • Take notes of observable behaviours during the session; markers of anxiety (tiptoeing, flapping) & engagement (laugh, exploration, etc.) • Make audio recordings using a loud gain to get low-level children’s utterances for later analysis of possible words • Assess children’s experience by making them draw
Quantitative	<ul style="list-style-type: none"> • Create a questionnaire addressing the child’s experience to be filled by practitioners: (1) Understanding of real vs. virtual; (2) Exploration of space; (3) Type, quantity and velocity of movements (4) Type and number of actions • Log AR variables: movement quantity, time spent, number of objects hit • Use small biosensors if tolerated by autistic children

Table 4.4: Main XR design insights for autistic children with SLN

RQ1	<ul style="list-style-type: none"> • Use AR rather than VR to prompt collaboration • Use free-play activities • Make the general context secure • Use flexible and portable designs • Assess engagement through generic & individualized factors
RQ2	<ul style="list-style-type: none"> • Use AR rather than VR in clinical settings • Consider XR as other mediation tools • Design XR applications in clinical settings • Use XR in controlled environments to prevent any risks

therapeutic alliance through child-directed activities. An HMD-based AR system was thus chosen to maximize immersion while still perceiving the real surroundings and practitioner. Findings suggest that AR seems well-suited to support sensory strategies for autistic children with SLN, whereas VR could possibly isolate them. This validates the assumptions that we had made when analyzing our interviews (see chapter 3), complements the AR cognitive-behavioural potential [21], and the AR potential to prompt the generalization of virtual skills learned into the real-world [63]. Moreover, contrary to previous AR studies relying on Hololens[©] [7, 308], or Google Glass[©] [21], we used an AR see-through device to display a wide field of view due to the sensory and mediation focus of our application. In the future, assessing the differences in terms of children’s experiences between different sizes of augmentation windows could be worth investigating.

4.4.1.2 Free-play mediation space

Practitioners asked for using free-play multisensory activities with autistic children to give room for expressivity and symbolization processes through the gestures and choices that are made, as in *Mediate* [227], the *Responsive Dome Environment* [37], and *Sensory Paint* [248]. According to them, *Magic Bubble* may also be considered as a *potential space* [334]: an intermediate space for playful experiences situated between their inner reality and the external physical reality. Yet,

it is worth noting that other multisensory projects such as *Magika* [100] and the *Magic Room* [95] mainly relied on task-oriented games, and that the game-play preferences of autistic adults rarely include free-play sandbox games [192]. In our project, design choices drew from three causes: users are autistic children with SLN; practitioners rely on developmental practices; and free-play connects with other mediation activities at the day hospital (e.g., painting). Given the promising results of the *OutsideTheBox* project [291], where autistic children co-created smart objects through multiple design sessions, future perspectives should consider co-creating storytelling scenarios between children and practitioners within the *Magic Bubbles*' space, or within similar free-play soothing AR spaces. To our knowledge, this is the first HMD-based AR design intended for mediation purposes with autistic children with SLN.

4.4.1.3 User-centered holding environment

As our design process aimed at creating a safe multisensory space to support emotional regulation, practitioners described *Magic Bubbles* as a *holding* space (see section 2.2.2.4). To prevent possible drop-outs being observed in previous studies with video games [139], *Magic Bubbles* is also inspired from common autism interventions with or without digital tools (see chapter 3). The fact that practitioners can adapt all virtual elements to find a suitable sensory threshold and thus to maximize engagement while preventing attention loss relates to studies about attention deficit with similar goals [246]. Hence, the scope of *Magic Bubbles* may be widened for people with neurodevelopmental conditions in general.

4.4.1.4 Adaptation to real-life clinical settings

While *Magic Bubbles* supports various interaction types, as in previous multisensory projects [37, 95, 100, 227, 248], the use of HMD makes it more flexible and adaptable for clinical settings. In particular, only audiovisual interactive elements are used and no smart objects to be quickly mounted/dismounted in spaces where permanent installation would be impossible. The setting's relative portability and low price makes it usable in various ecological clinical settings, in line with stakeholders' needs [230]. With the current development of HMD technology, such features will become even more prominent over the next years. The impact of mainly using audiovisual elements on the child's experience will have to be assessed in comparison with previous projects which mainly used tactile inputs.

4.4.2 How can XR design suit practitioners?

4.4.2.1 AR versus VR for clinical settings

Practitioners had a good acceptability, usability, were engaged, and agreed on future testing with autistic children with SLN, being curious about their reactions. While initially concerned about feeling "enclosed", as non-appropriate for such children, they felt connected with their real surroundings during the experience. To our knowledge, this is the first study which suggests that AR could be more suited than

VR to extend sensory interventions with autistic children, due to being potentially more reassuring and more easily accepted by practitioners.

4.4.2.2 AR as a mediation tool

Magic Bubbles' acceptability also stems from its relationship with other sensory free-play mediation activities at the day hospital, e.g. painting. Indeed, according to Brun [38], the success of these activities relies on the sensory qualities of the medium, in relation to the child's sensory abilities, and to the therapeutic alliance. AR thus seems well suited to complement them due to its multisensory capabilities.

4.4.2.3 Conducting XR studies within clinical settings

The psychologists were keen about using AR within a clinical setting. Indeed, they remarked that most current technology-based approaches are tested in laboratories, which raises two main concerns: (1) the novelty of such setting for autistic children with SLN may be anxiety-provoking, and thus bias the experiments, and (2) such applications may not be adaptable for real-life settings. While XR reviews [21, 195] do not clearly mention which studies were conducted in clinical settings, our findings highlight that taking more into account real-life constraints is fundamental when designing autism XR studies.

4.4.2.4 Preventing XR risks

While risks linked with over-exposition to screens [127, 192] may dissuade practitioners from using digital tools with autistic children, practitioners from our study expressed that XR may be positive if used in a controlled way. Thus, they advised using it in a secure framework, i.e. with a practitioner and a time limit.

4.4.3 Evaluation of the user experience of children

4.4.3.1 Methodological insights

Several insights were related to the assessment of the quality of children's AR experiences with *Magic Bubbles*. As in previous works [216, 308], practitioners suggest that self-report questionnaires are ill-suited for such children who are not capable of answering them. Instead, they suggest using mixed methods (qualitative and quantitative) based on observations that would take into account the relationship between the child, the technology, and the entire context (e.g., time, people present). This method seems close to Latour [170]'s *Actor-Network Theory* (ANT), and to Engeström et al. [76]'s *activity theory* (AT). Indeed, ANT posits that observations must be understood through the network of relationship between these different entities, and was successfully used in the *OutsideTheBox* project [291]. AT advises to consider the breadth of the context (e.g., child's history), being previously used to analyze seminars with autism stakeholders [230]. In both cases, paying attention to the overall context requires to collect detailed insights from caregivers, relatives, and children (when possible).

For autistic children with SLN, qualitative methods of inquiry involve the use

of interviews, video recordings, observations, drawings, or alternate methods of expression tailored to the children, as suggested by Spiel et al. [291]. Audio recordings of children's mumbling could also be used for later speech analysis, but was absent from previous research. As children's idiosyncrasies may lead to different ways of responding to XR environments [229], the assessment of their experiences should be individualized, e.g., based on markers of anxiety (e.g., stereotypies) identified through interviews with practitioners and/or relatives.

Quantitative methods involve the design of custom questionnaires targeting practitioners, based on specific observations. Logging AR interaction variables may also yield valuable insights (e.g. time spent with the HMD), as well as using biosensors if tolerated by the child. Since autistic children respond differently to XR environments than their neurotypical counterparts [229], common XR measures for neurotypical people may need to be adapted. For instance, as already evoked in section 2.4.2.4, self-report questionnaires targeting the feeling of presence are not adapted for autistic children with SLN and ID who are non capable of answering them. Instead, assessing their engagement and sensory immersion through custom questionnaires filled by practitioners could offer valuable insights [308]. In particular, they could target five main categories [308]: understanding of real versus virtual elements, exploration, body movements, actions, and involvement.

4.4.4 Limits

Only practitioners' feedback were gathered due to the Covid-19 pandemic which prevented us from conducting tests with autistic children at the time of our design process. Moreover, only subjective insights were collected about the user experience and existing design. Gradually asking questions to practitioners about ideas that emerged from their colleagues could also have offered more diverse viewpoints.

4.5 Conclusion

The objective of this study, which drew upon the findings from our interviews with autism stakeholders (see chapter 3), was to build an XR multisensory environment with self-expressive capabilities to secure autistic children and reinforce the therapeutic alliance. To that end, the AR application *Magic Bubbles* was designed and developed in collaboration with practitioners, and then tested by a clinical team at a day hospital. Practitioners' experiences were assessed through observations and interviews. Findings suggest that *Magic Bubbles* may complement sensory interventions for autistic children with SLN and is well accepted among a clinical team. XR design guidelines for autistic children were also drawn, being summarized in table 4.4. Before to be able to conduct a long-term experiment with autistic children (see chapter 6), acceptability and usability testing must be conducted with autistic children with SLN, or children with a related neurodevelopmental condition. The next chapter reports on this process, being carried out in collaboration with the clinical practitioners who participated to the design process.

5 - Evaluating the Acceptability and Usability of a Head-Mounted Augmented Reality Approach for Autistic Children with Severe Learning Disabilities

5.1 Introduction

The previous chapter presented the design of a sensory and mediation AR environment called *Magic Bubbles* intended for children over the entire spectrum. This process was led in collaboration with practitioners and validated by a clinical team. For a long-term experiment to be conducted, acceptability and usability testing must first be carried out with autistic children with SLN and ID, or children with a related neurodevelopmental condition. Indeed, unknowns still remain about these issues (see section 2.4). This chapter reports on such a study, which addressed three main research questions:

- RQ1 Could autistic children accept and use *Magic Bubbles* AR environment?
- RQ2 Could autistic children get engaged with *Magic Bubbles* AR environment while still communicating with others?
- RQ3 Could autistic children get secure with *Magic Bubbles* AR environment?

To examine these questions, we conducted a study with ten children being autistic with SLN, or with a related neurodevelopmental condition, in collaboration with two clinical psychologists and one psychiatrist who had participated to the design process. After introducing the experimental design, findings are presented, and then discussed.

This study was published at the *19th EuroXR International Conference – EuroXR2022* (Stuttgart, September, 2022), under the title: “Evaluating the Acceptability and Usability of a Head-Mounted Augmented Reality Approach for Autistic Children With High Support Needs” [C].

5.2 Method

5.2.1 Participants

The two psychologists recruited ten children with neurodevelopmental conditions and associated Intellectual Disability (ID) among the patients of the day hospital André Bouloche, in agreement with the clinical team. They include six boys and four girls, from eleven to fourteen (MA:12.5, SD:0.98). Eight were minimally verbal and two were non-verbal. All children displayed significant ID, their

Table 5.1: Profiles of the children who participated to the study. M/F stands for Male/Female. IQ stands for Intellectual Quotient.

ID	M/F	Age	Condition (ICD-10)	IQ
1	M	13	Atypical autism (F841)	50<IQ<70
4	F	11	Other childhood disintegrative disorder (F843)	50<IQ<70
5	M	13	Other pervasive developmental disorders (F84.8)	50<IQ<70
6	M	13	Pervasive developmental disorder, unspecified (F849)	50<IQ<70
7	M	13	Pervasive developmental disorder, unspecified (F849)	50<IQ<70
8	M	14	Pervasive developmental disorder, unspecified (F849)	50<IQ<70
9	F	12	Mixed disorder of conduct and emotions, unspecified (F929)	50<IQ<70
14	F	12	Mixed specific developmental disorders (F83)	50<IQ<70
16	F	13	Atypical autism (F841)	50<IQ<70
17	M	11	Autistic disorder (F840)	50<IQ<70

Intellectual Quotient (IQ) ranging from 50 to 70. Four children had already experienced VR during cultural outings. None had experienced AR. The low number of children is imposed by the following inclusion criteria: children had to display a neurodevelopmental condition according to the ICD-10 [222] as well as ID, not display risks of epilepsy, and be aged above eleven, due to using HMDs in line with recent XR studies [7, 96, 184, 217]. As this low number is common in autism XR research, since this population is often hard-to-reach [149, 195], it was deemed suitable to address our research questions. Moreover, according to the psychologists, the 3:2 male to female ratio among the recruited children would not influence the findings. Children’s profiles are detailed in table 5.1.

5.2.2 Development of the semi-structured questionnaire

To assess the experience of autistic children who are not capable of answering self-report questionnaires according to the psychologists, we had to build a new questionnaire that could be completed by their respective practitioners, as in Aruanno et al. [7]’s study. A two-part semi-directed questionnaire was thus devised to be filled at the end of every child’s AR session. First, six questions addressed the child’s state, before and after the sessions. Then, nineteen questions targeted the child’s experience. At last, practitioners could add comments about the overall child’s experience. The questionnaire lasted between five to ten minutes. Each item consisted of 1-5 or 1-7 Likert-type scales (depending on the references that they drew from) and optional comments. Table 5.2 presents the questionnaire, in relation to the literature references that the items drew from.

5.2.3 Procedure

All procedures were approved by *Pol  this* Ethics Research Committee of Paris-Saclay University under reference 226.

5.2.3.1 Before the experiment

A psychiatrist explained the protocol to the child’s legal tutors and collected their informed consent. Indeed, children were unable to do it by themselves according to the clinical team. As this study did not assess the differences induced

Table 5.2: Semi-directed questionnaire answered by the psychologists about children's states and experiences. In the column called "Answers", "1-5" and "1-7" represent the types of Likert-type scales that psychologists had to answer, with respect to the different questions. We used 1-5 or 1-7 scales depending on the literature references that the questions drew from. "cmt" means that practitioners can add optional comments. The column called "Ref" corresponds to the literature references.

	Category	Questions	Ref	Answers
Child's state	State before session	Q1 - Child's anxiety	[A] [B]	1-5 + cmt
		Q2 - Child's fatigue		1-5 + cmt
	State after session	Q3 - Anxiety	[A] [B]	1-5 + cmt
		Q4 - Fatigue		1-5 + cmt
		Q5 - Reassurance		1-5 + cmt
		Q6 - Ability to start activity when leaving		1-5 + cmt
Child's experience	Acceptability	Q7 - Easiness to wear the headset	[7] [96]	1-5 + cmt
		Q8 - Disturbances when wearing/removing it		1-5 + cmt
		Q9 - Cybersickness		1-5 + cmt
	Usability	Q10 - System's complexity	[34] [335]	1-5 + cmt
		Q11 - Amount of information		1-5 + cmt
		Q12 - Need for support		1-5 + cmt
		Q13 - Confidence		1-5 + cmt
		Q14 - Easiness to use the system		1-5 + cmt
		Q15 - Ability to interact at the end		1-5 + cmt
	Agency	Q16 - Identifying stimuli	[335]	1-7 + cmt
		Q17 - Anticipating actions		1-7 + cmt
		Q18 - Actively interacting		1-7 + cmt
	Presence	Q19 - Understanding of real and virtual	[279] [7]	1-7 + cmt
		Q20 - Real-world awareness		1-7 + cmt
		Q21 - Feeling of being captivated		1-7 + cmt
		Q22 - Consistency with a real-world experience		1-7 + cmt
	Engagement	Q23 - Fun	[7]	1-7 + cmt
		Q24 - Involvement		1-7 + cmt
	Communication	Q25 - Communication with the practitioner	[95]	1-5 + cmt
	Other	Q26 - Additional insights		cmt

by the actor and spectator conditions (see section 4.2.3.2), practitioners assigned children to each condition based on their common interventions, and on their usual behaviours (mainly passive or active). Thus, ID4 and ID9 were assigned to the spectator condition, and the others to the actor condition.

5.2.3.2 During the experiment

The child tested the AR environment in a large room of the day hospital. Four investigators were always present: two psychologists, myself (for technical support), and one psychology intern. The child's educator could also come for reassurance or if interested, following common clinical practices. Sessions lasted between five minutes (minimum) and twenty minutes (maximum), depending on the child's acceptability, if they wanted to stop, or on practitioners' perception of their experience. Due to the day hospital's constraints, unexpected events could impact the session (e.g., child being late as coming from the infirmary).

Psychologists were used to the AR platform when starting the testing, as they had participated to its design process beforehand (see chapter 4). Several sessions with different children were successively conducted, spaced by a fifteen-minute break to clean the equipment and air the room according to Covid-19 security rules. Equipment was mounted (twenty minutes) and dismantled (fifteen minutes) before and after all sessions.

At the session's beginning, psychologists introduced the child to the AR system and invited them to wear the HMD. Children then experienced a free-play time, during which the practitioners could interact with them (i.e., verbally or non-verbally) while monitoring what they perceived through the screen. Children were never forced to wear the HMD, and could remove/wear it at will. Session could end up in two ways: if children expressed that they wanted to stop (e.g., verbally, or by removing the HMD), or if time ran out. In this second case, practitioners warned that the session would end in one minute (verbally, and by triggering a gong sound in AR) and proposed to do one last action. After removing the HMD (by themselves or with practitioners' support), psychologists invited children to make a real drawing with a sheet of paper and pencils. Children only drew if wanting to.

5.2.3.3 After the experiment

After the child left, psychologists completed the semi-direction questionnaire. We then took notes about the session's unfolding, by paying attention to critical incidents (e.g., unusual events). After the sessions of the six first children, to elicit more insights, semi-directed focus group interviews intended to debrief about the sessions were added. They were conducted by me with the two psychologists and the intern right after the sessions ended. They relied on three main questions, asking if the child had fun, if they seemed to feel secure, and if they were ready to start other tasks when leaving.

5.2.4 Data collection

To assess children's experiences, multiple data sources were used to mitigate the bias associated with each source. Data collected include: the semi-structured questionnaire, the semi-directed interviews, my notes, and three video recordings (two cameras from different angles and the child's view). Moreover, efforts were made to get the child's perspective: by collecting their drawings, as suggested by Spiel et al. [291]'s study about autistic children's experiences with technology, and by filling the questionnaire while asking questions to the child, as in Aruanno et al. [7]'s study. Yet, only ID16 accepted to draw and only ID7 could answer questions. Thus, data collected mainly accounted for practitioners' perspectives. In addition to that, we measured the time during which children wore the HMD. Collecting physiological data was also considered (e.g., heart rate) but abandoned, as the biosensors could hinder children's experiences according to the psychologists. All data were anonymized by assigning identifiers to the children (see table 5.1).

5.2.5 Data analysis

I started the data analysis process by transcribing the data collected. This process allowed me to familiarize with it, to ask the psychologists for clarifications, or to check their ratings when not matching their comments. To do so, psychologists looked at the videos and made corrections when appropriate. Then, two main analytic stages were conducted in parallel, by different researchers, and with different methods, to mitigate potential biases. First, I analyzed the questionnaire's answers quantitatively while considering practitioners' comments. Second, the interviews, notes, and videos were analyzed qualitatively. I analyzed the notes and interviews, and the two clinical psychologists analyzed the videos. To do so, deductive content analysis was mainly used, complemented by inductive content analysis [75]. The two main analytic stages are detailed below.

5.2.5.1 Analyzing the semi-directed questionnaire

Descriptive statistics were used to analyze the questionnaire's answers, as more advanced statistics were not meaningful with respect to the low number of participants. Figures 5.1 and 5.2 respectively display the findings related to the user experience's categories (e.g., acceptability, usability), and to the evolution of the child's state between the beginning and the end of sessions. Findings are presented with respect to practitioners' comments, through different paragraphs accounting for the different categories. Moreover, an additional paragraph accounts for critical incidents that emerged from practitioners' comments. Questions about the feeling of presence were not analyzed, as not related to the current research objectives. They will be evaluated in future works.

5.2.5.2 Analyzing the notes, interviews and videos

Deductive content analysis was mainly used to analyze the data, with respect to the questionnaire's categories. The goal was to confirm and draw comparisons with the questionnaire's findings, as well as to collect further insights about the questionnaire's categories. To complement this approach, inductive content analysis was employed, by inductively building new categories from the data.

I analyzed the interviews and notes by doing open coding, with the data analysis software called *MaxQDA*¹. To mitigate potential biases, constant comparison techniques were used to compare the initial data with the phrasings and categories that were gradually constructed. The psychologists analyzed the videos, based on their clinical expertise, as in previous studies [96]. The qualitative analysis process stopped when reaching data saturation. Findings were finally compared to look for similarities and discrepancies. They are presented together in the next section.

¹MaxQDA software: <https://www.maxqda.com/>

5.3 Findings

Findings from the two main analytic stages are presented below, based on questionnaires' answers, video observations, notes, and focus-group interviews. Questionnaire's answers about the child's experience are first presented (Q7-Q16, Q23-25) (see figure 5.1), together with the findings coming from the deductive content analysis. Answers about the child's state (Q1-Q6) are then presented (see figure 5.2), followed by three categories built using inductive coding: *Real vs. Virtual*, *Exploration of the Body and Space*, and *New Hypotheses*. Q17 and Q18 are removed as they were left unanswered for most children, being too advanced for this discovery session according to the practitioners. The times during which children wore the HMD are not presented as they happened to be unusable. Indeed, practitioners often wore the headset during sessions to support children's acceptability, and children worn and removed it multiple times, making it impossible to collect precise data. A video presentation which displays how some children interacted with *Magic Bubbles* is also available at this link: <https://valentinbauer.com/research/doctorat/>.

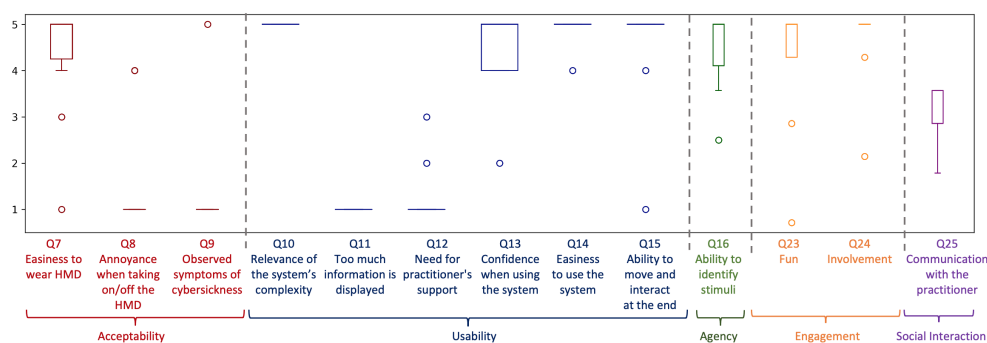


Figure 5.1: Questionnaire's answers regarding the acceptability, usability, agency, engagement, and social interaction, for the ten children with neurodevelopmental conditions and ID who tested *Magic Bubbles*. For enhanced readability, Q16, Q23, and Q24 were displayed using a 1-5 scale, rather than the 1-7 scale that was used in the questionnaire. Bars represent the median, rectangles represent the interquartile range (IQR) (50% of the sample's values), and circles represent outliers. For each question, 1 and 5 respectively represent the minimum and maximum observable impact.

5.3.1 Acceptability

Most children wore the HMD with practitioners' support: seven very easily (Q7-5/5) and ID9 easily (Q7-4/5). In particular, ID8 wore it nearly alone, and ID4 played to wear/remove it. Yet, ID6 faced some difficulties to adjust it (3/5). ID17 also wore it for a very short time (1/5), which is normal as he usually needs time to get used to new elements. Yet, some children had some apprehension: three only interacted "at arm length" and remained still, and two asked practitioners to wear

the HMD before them for reassurance. Doing so, they observed the practitioners while looking at their view through the monitor. Then, seven children had no discomfort (Q8-1/5). Yet, three were slightly disturbed, due to the HMD being too tight, heavy, due to feeling hot, or to the time needed to adjust it (Q8-4/5). Seven children had no cybersickness (Q9-1/5). No answer was given for ID6, but practitioners precised that he did not have a negative experience. Yet, ID5 said that the image was “blurred” at the start, and ID9 also expressed it during the experience and had cybersickness (Q9-5/5). Blurred images could be due to the HMD not being screwed enough, and point at the difficulty to correctly adjust the HMD for such children. At last, half of the children emphasized the institutional aspect, asking questions about the other children who participated.

5.3.2 Usability

Magic Bubbles' complexity was well-adapted for nine children (Q10-5/5), and not mentioned for ID17 as he only wore it for a very short time. The amount of information suited all children (Q11-1/5). Though, increasing complexity was advised for three children, to not induce boredom over time (ID1), particularly regarding the spectator condition: “if actor, ID4 would have stayed longer”. Most children required some support to use the system (Q12): none for seven (1/5), some verbal reassurance for ID14 (2/5), and moderate support for ID16 (3/5). Most children were confident (Q13): five entirely (5/5) and two nearly entirely (4/5). In particular, ID4 explored alone which is rare. Yet, ID9 got scared (1/5) (see details in section 5.3.6). Eight children very easily used the system (Q14-5/5), and ID16 easily used it (4/5). For instance, ID1 was “immersed and discovered everything alone”. Yet, ID14 and ID16 needed a lot of guidance. As psychologists said: “We proposed her [ID14] to stand up [...]. Then she held Olivier’s arm [one practitioner] to move around”, or “I made her [ID16] try things”. ID16 confirmed that she preferred exploring with the practitioners both verbally and through her drawing, by drawing herself next to him (see figure 5.3). At the end, most children interacted well apart from ID9 (Q15): totally for seven (5/5), or well for ID7 (4/5). Moreover, children were not bothered by some unexpected bugs, even if possibly slowing down their discovery process. The microphone bubble was hard to use, as requiring to perform two actions (touch then speak). Eight children respected the AR spatial limits, and two crossed them to observe the limits of the real space.

5.3.3 Agency

Most children who wore the HMD identified the stimuli (Q16): five with great ease (7/7), and ID1 (6/7) and ID16 (5/7) with ease. In particular, ID6 actively switched off the music when wanting to. While three children enjoyed the controllers’ vibrations, others preferred the audiovisual stimuli. Three children focused on one stimulus: the bubble column (ID1), the music bubble (ID4), and the music panel (ID7). They seemed to use it for reassurance, and/or to refocus on their body experiences after exploring. For instance, ID7 could “unload” when playing

with the panel while keeping in control (see figure 5.4B), which is unusual for him. Since ID4 little explored, practitioners were unsure about her ability to identify stimuli (3.5/7). No answer was given for ID9.

5.3.4 Engagement

Apart from the ID9 who got worried, most children had fun (Q23): seven a lot (7/7) and ID4 nearly a lot (6/7). Seven children asked for coming back the week after. This request was particularly unusual for ID6, who was slightly worried at the start. Moreover, five children described a “weird” but pleasant experience. Then, ID1 was not amused but relaxed (4/7). Surprisingly, he said that he had fun, but that he did not want to come back the week after. About involvement (Q24), apart from ID9 (3/7), most children were involved, either entirely for seven (7/7), or nearly entirely (6/7). For instance, ID7 sang, laughed, or danced, while touching the virtual panels, although he felt unwell the day before according to the practitioners. At last, ID9 was anxious due to acceptability issues.

5.3.5 Social Interaction

Most children communicated (Q25): five a lot (5/5) and three moderately (4/5). Eight children mainly had inner experiences, only communicating when needing support or answering questions. Though, this did not prevent them from sharing their experiences, which is a significant clinical finding according to the practitioners. For instance, ID1 pointed at the practitioners with the controllers, and ID8 described everything out loud. In particular, ID4, ID7, ID14, and ID17, socially interacted more than usual: ID4 struck practitioners when asking to dance together, ID7 kept eye contact, ID14 initiated shared play by giving them the HMD (see figure 5.4E), and ID17 interacted threw the monitor. At last, ID1 (3/5) and ID6 (2.5/5) mainly communicated non-verbally, maybe because not hearing well what practitioners said when wearing the HMD. At last, two children were more interested in the other rather than in technology (ID4, ID17). For instance, ID14 interacted “without disappearing in the relationship”, which is unusual for her.

5.3.6 Evolution of the child’s state

At the start, all children felt well, apart from ID17 who was tired (Q1-2/5) and ID9 (Q1-2.5/5). Six children were not anxious (Q2): five not at all (1/5) and ID17 slightly (2/5). Yet, four children were slightly worried: ID16 asked what would happen (2.5/5), ID6 asked if “it was a trap” (3/5), ID14 displayed apprehension (3.5/5), and ID9 asked if the practitioners would “scare her” (4/5). At the end, nine children were not tired (Q3-1/5) nor anxious (Q4-1/5). Thus, four children got better over the course of the session, making practitioners say that the setting was *holding* for them (ID6, ID14, ID16, ID17). Then, six children got secure (Q5-5/5) and two were as secure as before (2.5/5). Moreover, four children seemed to be more secure than usual at the day hospital: ID1 was calmer, ID4 remained calm even if several adults surrounded her, ID7 kept in control while being excited,

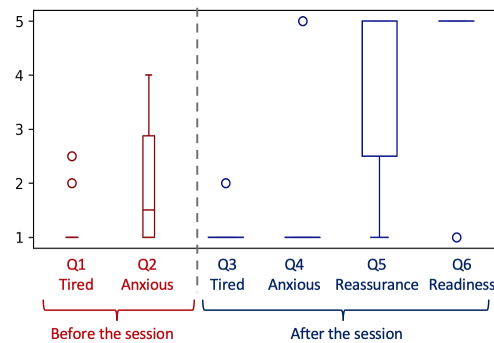


Figure 5.2: Questionnaires' answers about children's state. Bars represent the median, rectangles represent the interquartile range (IQR) (50% of the sample's values), and circles represent outliers.

and ID14 could interact more socially. In particular, practitioners said that ID7 got calmer, even though he was anxious the day before. Most children were ready to start another activity when leaving (Q6): seven entirely (5/5), and two with no answer (indicating no detrimental effect). Yet, ID9 got scared (1/5): quickly asking to stop, running out of the room, and throwing the HMD. Psychologists mitigated her attitude by evoking her condition, impulsiveness, that she was anxious when entering, that she may have got distressed due to feeling watched, and to the absence of control in the spectator condition.

5.3.7 Real versus Virtual

Five children questioned the difference between real and virtual elements. To do so, they asked if some physical elements were real, and if some virtual elements could have an impact on the adults. Moreover, eight children went through virtual elements with their limbs (head and hands) to see them disappear. Three children also experienced a possible feeling of presence (feeling of being here). Indeed, ID8 asked if the water in the column could spill on the floor, ID6 hit the ponds with his feet (see figure 5.4A), and ID5 stepped over the column's border to get inside (see figure 5.4D).

5.3.8 Exploration of the body and space

Seven children performed gentler gestures than usual. Most children focused on their body image: all looked at their hands, ID4 asked to look at herself in the mirror with the HMD, ID5 asked to be photographed, and ID16 drew herself. Five children made unusual movements: softer, more hesitant, or, conversely, dancing more for ID16. Four children adopted a different gait. For instance, three of them lied on the floor. While this may be caused by anxiety for ID4, it may account for an exploration of the space and of their body for the two others. Moreover, ID5 behaved like a robot when entering and leaving.

5.3.9 New Hypotheses

Practitioners raised four new hypotheses about using AR for children with neurodevelopmental conditions and associated ID. First, HMD could help to make longer eye contacts. This was raised after ID6 made long eye contacts. Second, AR could help to better understand the others' mental states, by perceiving the AR view of others through the monitor. Indeed, most children understood that the screen represented the practitioner's view. Third, AR could prompt body awareness. Indeed, ID14 and ID16 socially interacted without "disappearing", although unusual for them. After that, adjusting the proportion between virtual and real elements could prompt reassurance, especially regarding the body presence of others. This was raised after ID7 kept in control while being excited, although unusual for him.



Figure 5.3: Drawing that ID16 made, representing herself next to the practitioner.

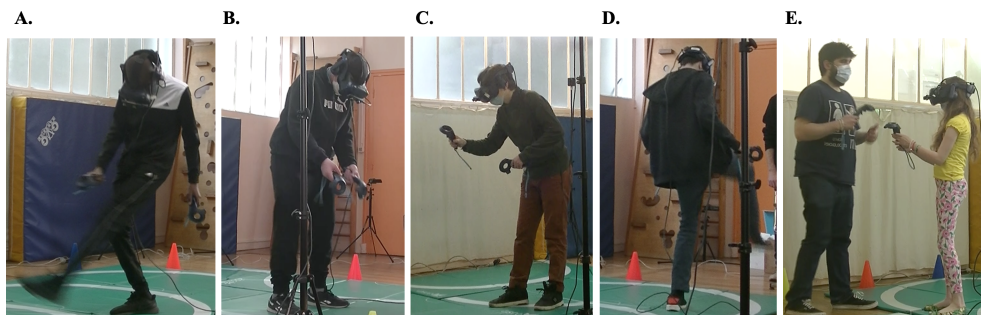


Figure 5.4: Photographs of critical incidents for four children. **(A.)** ID6 hitting a pond with his foot, **(B.)** ID7 unloading on the music panel while keeping in control. **(C.)** ID8 trying to write his name on the drawing panel. **(D.)** ID5 stepping over the border of the column. **(E.)** ID14 giving the equipment to the practitioner after proposing him to test the HMD.

5.4 Discussion

This study explored the use of the HMD-based AR application *Magic Bubbles* in a day hospital setting with ten children being autistic with SLN, or with a related neurodevelopmental condition, and displaying ID. As unknowns remained so far about how these children would react to HMD-based VR/AR displays (see again section 2.4), this study has four main contributions. Three correspond to the three research questions, about acceptability and usability (RQ1), engagement (RQ2), and reassurance (RQ3), and arose from the data analysis process. First, positive acceptability and usability were observed for most children (RQ1). Moreover, children explored two aspects in addition to the virtual interactions: the difference between real and virtual elements, and their body perception with the HMD. Second, children were engaged with an inner experience, but this did not impede communication (RQ2). Third, apart from ID9 who had cybersickness, four children got more secure, and the others remained in the same state after than before the experience (RQ3). The validation of our three research questions thus confirm the possibility of using *Magic Bubbles* during a longer period with autistic children. At last, four new hypotheses emerged in line with practitioners' concerns which are worth investigating. After presenting the findings related to the three research questions, limitations and future perspectives are drawn.

5.4.1 Accepting and Using *Magic Bubbles*

All children accepted to wear the HMD with some practitioners' support, as in previous VR [96, 216] and AR [7] studies. For instance, two children asked practitioners to wear the HMD before them for reassurance, as in Garzotto et al. [96]'s study where two out of five children did the same. Three children had some discomfort, including cybersickness for one of them. This finding echoes Newbutt et al. [216]'s findings, where four out of twenty-nine participants felt unwell and had to stop. In our study, despite their ID and limited verbal abilities, most children could express when feeling unwell, even if struggled to confirm when the HMD was correctly adjusted. Thus, future protocols should be devised to minimize potential adverse affects with HMDs for autistic children with SLN. This approach could complement Schmidt et al. [275]'s process-model that was mainly designed for individuals with MLN. At last, as the methods used for measuring acceptability through practitioners vary between previous studies [7, 96], and our study, definitions of acceptability may vary between studies. To ensure that we actually measured acceptability and not other features (e.g., engagement), new standardized XR acceptability and usability measures should be designed for children with neurodevelopmental conditions and ID that would afford to collect their views.

Most children easily used *Magic Bubbles*, apart from ID9 due to acceptability issues, and ID17 who wore the HMD for a very short time. *Magic Bubbles* was well adapted to children's sensory and cognitive abilities. For instance, despite

understanding difficulties, ID7 had fun and explored. Then, practitioners supported children during their discovery process, as in previous studies [7, 96]. Guidance was individualized, and ranged from low levels (e.g., for ID1) to moderate levels (e.g., ID16 needed physical guidance). Thus, our positive acceptability and usability findings complement the findings from the three previous HMD-based VR/AR studies including autistic individuals with SLN [7, 96, 216].

Children explored three main aspects: virtual interactions, real versus virtual elements, and self perception. First, they explored virtual interactions alone or with practitioners' support. To do so, they adopted unusual behaviours: seven used gentler gestures than usual, and three mainly focused on one stimulus. Future research should focus on better understanding these behaviours. Gentler behaviours may be linked with a shift in their self perception. Focusing on one stimulus may connect to self-regulation strategies, to prevent from getting over aroused. Parallels could thus be drawn with VR/AR use cases consisting in "derivatives of stereotypies" that our interviews with autism stakeholders suggested to investigate (see chapter 3). Second, children used various strategies to understand the difference between real and virtual elements. Future research should examine what they actually understood, and how they developed this level of understanding, with respect to their behaviours and to their profiles. Third, children were more interested in their body perception than usual. This unexpected finding may account for a shift in self perception that deserves more exploration.

5.4.2 Communicating with practitioners

Most children socially interacted while displaying inner experiences. For instance, ID1 and ID6 mainly communicated non-verbally, maybe to stay in the virtual environment (ID1, ID6), or "to benefit from the effect of immersion", as practitioners said for ID1. Three children also displayed unusual behaviours: ID4 and ID17 socially interacted more than usual, and ID14 interacted without "disappearing", even drawing herself next to a practitioner (see figure 5.3). These experiences highlight *Magic Bubbles*'s relational potential, when used with practitioners in a clinical setting. This contradicts AR risks of isolation [21] that practitioners can be afraid of for autistic children with SLN, as raised in our interviews (see chapter 3) and during the design process (see chapter 4).

5.4.3 Getting secure

All children who wore the HMD were engaged, apart from ID9 due to acceptability issues. Most of them had fun, and ID1 got relaxed. These findings confirm the positive results that were observed in previous HMD-based VR [216] and AR [7] studies. In our study, seven children asked to come back the week after. Two children also displayed unexpected behaviours accounting for their engagement: ID14 drew the shared experience and ID16 danced a lot. Moreover, ID4 felt secure enough to communicate. Furthermore, children who were engaged were still in control of their actions. In particular, ID7 could "unload" without being over-

aroused, which is unusual for him. Since four children got more secure over the course of the session, practitioners said that *Magic Bubbles* was *holding* for them [334]. Thus, *Magic Bubbles* seems promising to complement clinical interventions for autistic children with SLN.

5.4.4 Limitations and Future Perspectives

The study could not be entirely controlled as it was conducted in a clinical setting, which limits the generalization of our findings. For instance, children's behaviours may have been influenced by external noise (children shouting in the corridor). Yet, conducting the same study in a laboratory would have been impossible, as potentially disturbing and anxiety-provoking for these children, as evoked in our interviews (see chapter 3). Thus, new methods must be devised to guarantee the ecological validity of autism AR research, by conducting field studies while precisely controlling specific environmental aspects. To that end, implicit measures could be used if relevant for the study and the children (e.g., number of interactions). Physiological data could also be used (e.g., heart rate) if the clinical team and/or children's relatives deem that biosensors may be well accepted (in our study the psychologists thought that they would not be accepted). In that case, analyzing physiological data would require to compare them with psychologists' insights, to understand the parameters being representative of children's behaviours. Although this approach remains under-used in autism AR/VR research [149], it represents promising research avenues [284]. The second limitation is that the results mainly account for practitioners' perspectives. Indeed, children's limited verbal abilities and ID prevented us from directly getting their views, despite efforts being made (e.g., using drawings). Future research should thus devise new XR methodologies that would enable to get their perspectives, as also suggested by Spiel et al. [291].

Four hypotheses emerged that deserve more investigation. First, HMD could allow children with neurodevelopmental conditions and ID to make longer eye contacts, as not direct but mediated through AR. Although mainly drawing upon a medical view of autism (see section 2.1.5.1), it may be investigated if a right threshold is fixed (i.e., training basic joint attention without going too far and hurting autistic children due to their difficulties with eye contacts). Second, AR could prompt the understanding of the others' mental states, by perceiving the practitioner's AR view through the monitor. Third, AR could be used to work on body perception. Fourth, adjusting and individualizing the proportion between virtual and real elements, in particular regarding the body presence of others, could prompt reassurance. This fourth hypothesis extends the findings from our interviews, that consisted in first working in VR and then going to AR, so that to gradually fade prompts while encouraging the generalization of the virtual skills learned into real life (see chapter 3).

5.5 Conclusion

This study aimed at confirming the acceptability and usability of *Magic Bubbles*'s AR application for autistic children with SLN. Field testing were conducted with ten children being autistic with SLN, or with a related neurodevelopmental condition, and ID, in collaboration with three clinical practitioners. Findings validated its acceptability, usability, and potential for engagement, reassurance, and social interaction. Mixed methods of inquiry (qualitative and quantitative) also enabled to uncover new categories pertaining to children's experiences. In particular, these categories suggest to further investigate how children explore what is real and virtual, as well as their perceived shift in terms of self-perception with the HMD. Furthermore, four new hypotheses were raised being related to practitioners' concerns. The possibility of using *Magic Bubbles* during a longer period with autistic children at the day hospital was also confirmed. Therefore, the next chapter presents such a long-term experiment that was conducted in collaboration with the same practitioners.

6 - Head-Mounted Augmented Reality to Support Reassurance and Sharing for Autistic Children with Severe Learning Disabilities

6.1 Introduction

The previous chapter reported on acceptability and usability testing based on *Magic Bubbles* AR environment, that were conducted with autistic children with SLN, or a related neurodevelopmental condition, in collaboration with practitioners (see chapter 5). To validate *Magic Bubbles*' potential to support emotional and behavioural regulation, and to reinforce the therapeutic alliance, this chapter presents a long-term study carried out with seven autistic children with SLN. Three research questions focusing on such children are explored:

RQ1 To what extent *Magic Bubbles* can be reassuring?

RQ2 To what extent *Magic Bubbles* can prompt the dyadic relationship?

RQ3 What is the overall quality of experience with *Magic Bubbles*?

This study has three main contribution: empirical, methodological, and theoretical. First, it is one of the first long-term field AR study to our knowledge that aims at securing autistic children, prompt self-expression, and strengthen the dyadic relationship. Then, it is also one of the first AR study with such children that uses mixed methods of inquiry largely relying on the grounded theory method. A categorization of children's AR experiences is finally derived that could inform future XR research focusing on autism or neurodevelopmental conditions in general.

After presenting the related works and methodology, findings are detailed according to the concepts and categories pertaining to the grounded theory. At last, findings are discussed and perspectives are drawn. This study was recently submitted to the journal called *Frontiers of Virtual Reality* [D].

6.2 Method

The experiment was conducted with autistic children with SLN within a day hospital, in collaboration with two clinical psychologists and one psychiatrist who had worked there for a long time¹. After describing children's profiles, the procedure, data collection, and data analysis are described. The design and development of *Magic Bubbles*, and its apparatus, were previously reported in chapter 4, and therefore are not reported again in this chapter.

¹The psychologists and the psychiatrist also collaborated to the design process and acceptability testing that were previously reported in chapters 4 and 5.

6.2.1 Demographics

Seven autistic children with associated Intellectual Disability (ID) (MA: 11 ± 1.15) were recruited in agreement with the clinical team. They include six boys and one girl. This low number is imposed by the following inclusion criteria: autism diagnosis and level had to be confirmed according to the *ICD-10* classification [222] and *CARS-2* scale [277], children had to be aged between 10 and 14 (due to using a HMD), and to not display known symptoms of epilepsy.

After being recruited, children's clinical evaluations were granted to all investigators. If absent or too old according to the psychologists, new evaluations were conducted. Cognitive profiles were measured using the Kaufman Assessment Battery for Children (KABC), with the Mental Processing index (MPI) (Luria model) or Non-Verbal Index (NVI), respectively for verbal and non-verbal children [262]. Semi-structured interviews were also conducted with the psychologists to individualize the environment and assess children's experiences with respect to their usual behaviours. They focused on: individualized appealing elements, expected children's and caregivers' behaviours, usual repetitive behaviours, attitude with digital tools, ability to express anxiety, and anxiety markers. Children's names were anonymized for privacy reasons with identifiers, such as IDX (where X is a number). The identifiers do not go from 1 to 7, as they were affected during our previous acceptability and usability testing (see chapter 5).

Table 6.1 summarises children's profiles and table 6.2 their expected behaviours and the design choices that were made accordingly. All children have SLN, as the *CARS-2* scale states that five have "severe" autism and two have "moderate" autism. Six children are minimally verbal and one is non-verbal. Six have limited or moderate cognitive abilities. All need a structured environment. They are expected to be able to express their anxiety in AR, either verbally (ID1, ID3, ID10, ID13, ID3) or non-verbally (all), e.g., through echolalias. ID2 can be sensitive to sounds (e.g., covering his ears). All children but ID4 are curious about digital tools and know how to use a tablet. ID1, ID2, and ID4 have done video game workshops with the psychologists for six years, one year, or once. ID4 and ID10 have done robot workshops for one year. ID1 and ID2 have access to digital tools at home.

6.2.2 Procedure

Before the experiment, a psychiatrist explains the protocol, purposes, data collection and analysis, to the legal tutors of the child, and collects their informed consent. Children are not capable of doing it according to the psychologists. The psychologists assign half of them to the actor condition (ID1, ID3, ID10, ID13) and the other half to the spectator condition (ID2, ID4, ID12), with respect to their usual behaviour and to potential therapeutic benefits. Psychologists both know *Magic Bubbles* when starting the protocol, as they were involved in its design.

Each child participates to six weekly sessions from the time when they accept to wear the headset. If several weeks are needed, the duration is extended accordingly.

Table 6.1: Profiles of autistic children. Condition is defined according to the ICD-10 classification. CARS assesses the significance of autism symptoms: 15-29.5 (non-autistic), 30-36.5 ("mild-moderate" autism), 37-60 ("severe" autism). KABC assess the cognitive condition, with the Mental Processing index (MPI) (Luria model), or the Non-Verbal Index (NVI): below 69 (very inferior to mean), 70-84 (inferior to mean), 85-115 (mean). "Ses" represents the number of sessions that each child had. smt. Differences in terms of the number of sessions are due to adaptations to the procedure that were made (see section 6.2.3). "smt." means sometimes.

ID	Age	Sex	Ses	Condition (ICD-10)	CARS	KABC	Autistic Behaviour	Digital Knowledge	Other
1	13	M	3	Atypical Autism (F841)	30	MPI-56-68	Looking at himself, talking alone	Strong	Calm
2	12	M	10	Autistic Disorder (F840)	47	NVI-49	Hand flapping, tiptoeing, echolalias, hyperventilation	Little	Shy, strong relationship with OD
3	11	M	6	Autistic Disorder (F840)	42.5	MPI-53-68	Little repetitive behaviours	Little	Calm
4	12	F	6	Other childhood dis-integrative disorder (F843)	39	NVI-35-49	Looking at oneself, being very tactile	Medium	Calm
10	10	M	7	Autistic Disorder (F840)	41.5	MPI-35-47	Echolalias (e.g., to cover other sounds)	Strong	Shy, taste for digital tools
12	10	M	6	Other childhood dis-integrative disorder (F843)	41.5	NVI-47-61	Echolalias, sorting things	Little	
13	10	M	6	Atypical autism (F8411)	32	NVI-72-86	Echolalias in some contexts	Strong	Calm (smt. in a rush)

Sessions take place in a large room and last between five minutes (minimum) and twenty minutes (maximum) depending on children's acceptability, practitioners' evaluation of their experience, and unexpected events (e.g., child being late). Their duration is expected to increase over time in line with children's acceptability. Every week, several children's sessions occur successively, spaced by a fifteen-min break to clean the equipment and air the room according to COVID security rules. Four investigators are present, i.e., two psychologists, one psychology intern, and myself. Educators can also come if interested or for reassurance, following usual clinical practices. At the start, psychologists introduce the setting to the child and propose them to wear the headset. Children are not forced to wear it, and can remove/wear it at will. Children then experience a free-play time. Practitioners can interact with them (verbally or non-verbally) while monitoring what they perceive through the monitor. Session can end up in two ways: the child expresses that they want to stop (e.g., removing the headset) or time runs out. In this latter case, practitioners warn about the session's ending (verbally and by triggering a gong sound) and suggest to do one last thing. Children then remove the headset or practitioners help them

Table 6.2: Design choices and expected children’s AR experiences. “im.”: images.

ID	Music(s)	Image(s)	Expected behaviours	Expected support
1	Rap - <i>Medicament</i> (Niska); Folk Rock - <i>In the death car</i> (Iggy Pop & Goran Bregovic);	Basic im.	Being autonomous, hitting things, enjoying, speaking a lot, maybe getting bored over time	Little support
2	Lullabies - <i>Une souris verte, meunier tu dors, promenons-nous dans les bois</i> ; Basic music	<i>Mr. Men and Little Miss</i> (5 im.)	Displaying some anxiety, trying to remove the headset, enjoying the recording bubble	To wear HMD and initiate actions
3	Soundtrack - <i>Let it go</i> (The Snow Queen)	<i>Mr. Men and Little Miss</i> (5 im.)	Being autonomous, wanting to wear HMD alone	Little support
4	Pop - <i>Magic in the Air</i> (Magic System feat. Chawki); Basic Music	Basic im.	Being passive, displaying sensorimotor difficulties (e.g., to catch the bubbles)	To wear HMD and initiate actions
10	Pop/Rock - <i>Me gustas tú</i> (Manu Chao)	Basic im.	Being autonomous, potentially struggling to wear the headset at first	To wear HMD at first
12	Tradional pakistani music (2 songs); French song - <i>Aline</i> (Christophe); Basic music	<i>Paw Patrol</i> (4 im.)	<i>Unknown</i>	To wear HMD
13	Rap - <i>Medicament</i> (Niska); Folk Rock - <i>In the death car</i> (Iggy Pop & Goran Bregovic)	Basic im.	Being autonomous, with difficulties to stop, quickly exploring	Little support

to do it. Children are finally invited to draw using pencils if they want to, being told that their drawing would be included in the AR scene the week after.

After the child leaves, the psychologists answer a questionnaire about their experience. A semi-structured focus group interview follows, during which the psychologists and the intern are asked for further insights. Educators are then asked if they noticed anything unusual after the activity compared to before it. Yet, the day hospital agenda prevented us from discussing weekly with the educators.

Pol  this Ethics Research Committee of Paris-Saclay University approved procedures with reference 226.

6.2.3 Adaptations to the procedure

Due to the clinical context of the study and children’s specific needs, we had to adapt the protocol. As ID2 needed four sessions to wear the headset, his protocol was extended to ten sessions. ID10 also did a seventh session due to bugs occurring during session six (s6). Moreover, when the psychologists deemed that it could be beneficial, some sessions were added: ID2 did fourteen sessions (switching to actor condition at s11), ID4 did s7 as actor, and ID12 did s7 as actor. To compare children with respect to protocols of similar lengths, in the analysis, these sessions added to be beneficial are only considered to provide complementary insights. At last, as ID1 had an epilepsy crisis one week after s3, although such risks were unknown by the clinical team, and was thus excluded from the protocol after s3.

6.2.4 Data collection

As most children could not answer self-report questionnaires, various data sources were collected to mitigate the bias associated with each source and get closer to the child's view. They include practitioners' observations (questionnaire and interviews), video recordings (two cameras and a recording of the child's AR view), and children's drawings. As no validated questionnaire to be filled by practitioners existed, we used the semi-directed questionnaire that we devised for our pre-tests (see chapter 5). The semi-directed focus-group interviews targets fun, reassurance, and readiness to start another activity when leaving. After six sessions, inquiring about *holding* was preferred over reassurance, to match psychologists' language [334] (see again section 2.2.2.4 for a definition). To elicit more answers, we questioned differences between the session's start and end, and critical incidents (e.g, moving moments), following Flanagan [83]' critical incident technique.

6.2.5 Data analysis

Qualitative and quantitative analysis were used to examine children's actions with respect to their underlying processes, e.g., relationship with practitioners' actions [63]. To that end, the *grounded theory* inductive qualitative approach enabled to analyze all data apart from the videos that were only used to double check data in case of doubts: practitioners' observations (interviews and comments from the questionnaires), educators' observations, and children's drawings [48, 109] (see description of the method in section 3.2.1.3). At the end of the process, to confirm the emerging theory, questionnaires' answers were analyzed quantitatively, except for items about presence (Q18-Q21). Indeed, once these questions were answered, we realized that externally assessing children's feeling of presence through practitioners' quantitative ratings was not reliable enough. Grounded theory and the quantitative analysis were respectively performed with the software *MaxQDA*² and with the *matplotlib*³ python library. Children's views were considered, but practitioners' interpretations prevailed as children were minimally verbal.

6.3 Results

This section first presents how we constructed the grounded theory from the analysis of children's experiences with *Magic Bubbles* AR environment. This categorization is then used to synthesize the findings, with three main subsections accounting for the three main categories, along with examples of key incidents. Each subsection starts by summarizing the main properties of a category and their relationship with environmental conditions. Before to examine them more in depth, the structure of each subsection is explained, as it differs for each category.

We differentiate between events happening during discovery (i.e., two first

²MaxQDA software: <https://www.maxqda.com/>

³Matplotlib python library: <https://matplotlib.org/>

sessions when children wear the headset) and after discovery (i.e., from the third session with the headset on), due to autistic children's difficulties with novelty. Despite common ways of reporting the findings with the grounded theory approach [48], we included the number of phrasings, percentages, sessions, and children in the text, to allow the reader to be aware of the data supporting our analysis, and to align with existing conventions in computer science. They are written inside parenthesis as follows. X_p (X is a number) represents the number of phrasings. About percentages, $X\%/t$ indicate the percentage of phrasings with respect to the total number of phrasings in the grounded theory, and $X\%/c$ to the number of phrasings in a category. For concepts, percentages are often preferred over the number of phrasings for the sake of clarity. Session numbers are written with sX . $IDY-sX$ refers to a specific child and session (Y is the child identifier and X the session number). The number of children who fit in some concepts is indicated with $X/7ch$ (as seven children participated to the study). Moreover, as the names of the clinical psychologists who collaborated to our study are important for some findings, they are written using OD for Olivier Duris and CL for Charlotte Labossière.

6.3.1 Conducting the analysis

I performed the analysis process, while often checking with OD and CL. To do so, I first gathered all qualitative data, by transcribing observations made by the psychologists (interviews and questionnaires' comments) and educators, and scanning children's drawings. Figure 6.1 displays all children's drawings over time. Doing so, the psychologists were asked to clarify some misunderstandings or to correct their quantitative ratings when not matching their observations by looking at the videos. Initial concepts were then built through open coding, by focusing on critical incidents while staying close to initial wordings and keeping notes of first impressions in memos. Figure 6.2 displays four critical incidents that are discussed in the following subsections. Focused coding was then performed, by ranking the concepts with respect to their relative importance, while paying attention to negative experiences. Two strategies then helped to build advanced concepts: *axial coding* to explore the conditions, actions and consequences underlying each concept, and a comparison of our concepts with some of Glaser and Strauss [109]'s *theoretical codes* (e.g., identity-self, means-goal, reciprocity) to construct different properties. Diagrams were finally made to present the grounded theory and help to refine it. Grounded theory being a bottom-up approach, the names of subconcepts, concepts, and categories are close to practitioners' wordings.

Parallel to these last analytic stages, questionnaires' answers were analyzed by using descriptive statistics, due to the low number of children. Quantitative results are presented per child following the emerging categories, as the diversity of children's profiles prevented us from displaying them together. The analysis process considered children's personal difficulties, as reported by the clinical team. In particular, ID2, ID10, and ID4 faced challenging times, respectively between $s4$ and $s7$, $s2$ and $s4$, and $s6$ and $s7$. ID4 was unhappy against CL at $s4$, and ID12



Figure 6.1: Evolution of children's drawings over time. The abscissa axis refers to the session number and the ordinate axis for children's identifiers. Some boxes are left empty as children did not draw every week (only drawing if they wanted to). We can notice the following features: ID1 drew himself with the headset at s1, and on another boy's shirt at s3; ID3 drew the setting multiple times and gradually added elements to it, reflecting his exploration; ID4 added a red dot at s5 when being unhappy against CL; ID10 represented his relatives when undergoing a challenging time at s2, s3, s4, and maybe VB at s1 (after meeting him for the first time); ID13 may have represented himself at s2 and s6; ID2 just added himself a beard to look like OD on OD's drawing, reflecting a strong dyadic relationship; ID12 never drew.

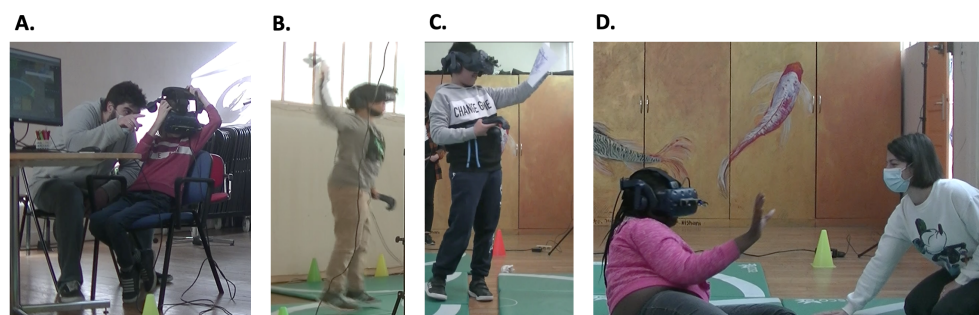


Figure 6.2: Photographs of critical incidents that illustrate the concepts and sub-concepts coming from the grounded theory analysis and are presented in the results' subsections: **(A)** ID2 managing to wear the headset alone at s5, **(B)** ID3 auto-stimulating by jumping at s5, **(C)** ID13 comparing his virtual drawing to the real practitioner's drawing at s5, **(D)** ID4 trying to reach practitioner's hand which was hidden by a virtual water pond at s2.

was tired when coming at s4 and s5, or scolded by his educator before s6.

6.3.2 The emerging categories

The overall grounded theory analysis comprises 2047 phrasings, and four main categories. Three interconnected categories relate to the child's experience: Encountering the AR setting (927p, 45%/t), Sharing experience over time (407, 20%/t), and Ways of getting secure (230p, 11%/t). A fourth category called Conditions supporting the AR experience (483p, 24%) concerns environmental factors influencing the child's experience. It has eight concepts: Therapeutic frame (22%/c), Caregivers' strategies (19%/c), Self-Regulation (14%/c), Time (13.5%/c), AR setting (11%/c), Child's state beforehand (11%/c), Contingencies (7%/c), and Actor vs. Spectator (2.5%/c). With respect to psychologists' terms, encountering the setting corresponds to any element being related to the interaction between a child and the AR setting (not only during the discovery). The AR setting corresponds to the virtual entities and the equipment, which also influenced children's experiences (e.g., weight of the headset). Although three children were assigned to the actor condition, and three to the spectator condition, practitioners rarely used the actor or spectator terminologies. Instead, they emphasized the influence of being able to interact on children's engagement, exploration, and agency. Figure 6.3 gives an overview of the grounded theory. The three categories about the child's experience are detailed in the three next subsections. Figures 6.4, 6.6, and 6.8 give an overview of these categories, and figures 6.5, 6.7A and 6.7B display the corresponding quantitative analysis. To present the findings from the grounded theory, we present the emerging categories, concepts, and subconcepts along with representative examples of children's behaviours. The evolution per child over time is out of the scope of this study and will be examined in the future. A video presentation which displays some critical incidents that happened during this research is also available at this link: <https://valentinbauer.com/research/doctorat/>.

6.3.3 The category called Encountering the AR setting

Encountering the AR setting is the most reported category (927p, 45%/t). It has three main concepts, namely, getting engaged (30.7%/c), qualities of exploration (31.3%/c), and becoming agent (19%/c), and two minor concepts, namely, qualities of understanding (10.9%/c), and qualities of acceptability (8.1%/c). In particular, the concept called becoming agent is larger than the actor and spectator conditions, as it covers all aspects related to the child's ability to intentionally act. We define that children accepted the setting when they accepted to wear the headset. Moderate acceptability corresponds to only briefly looking inside it (between five and twenty seconds). We also define that children explored when they did not stay still and tried to interact. The terms "qualities of" are used when referring to exploration, understanding, and acceptability, as they depend on many factors, as detailed through their subconcepts.

Three encountering profiles were built which correspond to quick (profile 1 - ID1, ID3, ID10 and ID13), gradual (profile 2 - ID2, ID4), or difficult encoun-

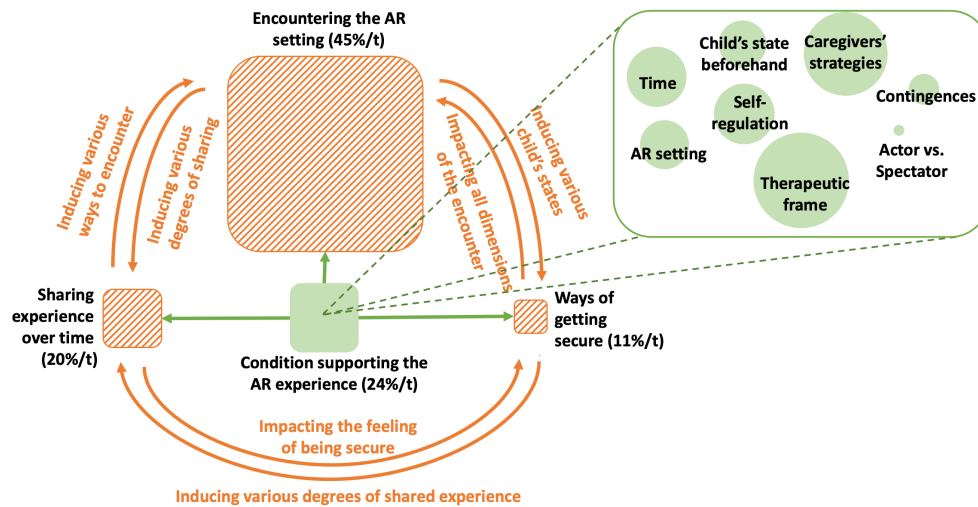


Figure 6.3: Overview of the four emerging categories of the grounded theory: categories related to the child's experience are displayed by using rectangles filled with orange stripes, and environmental conditions influencing the experience with a rectangle filled with green. Their sizes represent the percentage of phrasings that they gather with respect to the total number of phrasings in the grounded theory (/t). Arrows indicate the main influences that categories have over others. The rectangle on the right connected with dash lines to the category about environmental conditions gives an inside-view of this category by displaying its concepts. Concepts are represented with circles. Their sizes correspond to the percentage of phrasings that they gather with respect to the number of phrasings in the category.

ters (profile 3 - ID12). Concepts' properties vary depending on these profiles. For instance, practitioners' ratings related to acceptability, usability, agency, and engagement vary accordingly, as shown on figure 6.5. About subconcepts, enjoying (179p) is primarily reported (as children must enjoy to benefit from the experience), followed by exploring various interactive spaces (118p) and getting autonomous (102p). None of them belongs to qualities of acceptability, as practitioners stop mentioning acceptability as soon as the setting is accepted. Five main conditions influenced the encounter: caregivers' strategies (69p), time (63p), therapeutic frame (63p), AR setting (34p), and self-regulation (33p). For the encountering profiles two and three, caregivers' strategies include physical and verbal guidance (e.g., wearing the headset before the child). The therapeutic frame means that the dyadic relationship supported exploration. Figure 6.4 summarizes this category. The five next subsections detail its five concepts.

6.3.3.1 Qualities of acceptability

Most children (6/7ch) accepted the setting, 5/7ch directly and 1/7ch gradually (ID2 wore the headset from s5), but ID12 accepted it moderately. Direct acceptability relates to excitement and feeling secure during discovery. For instance, at

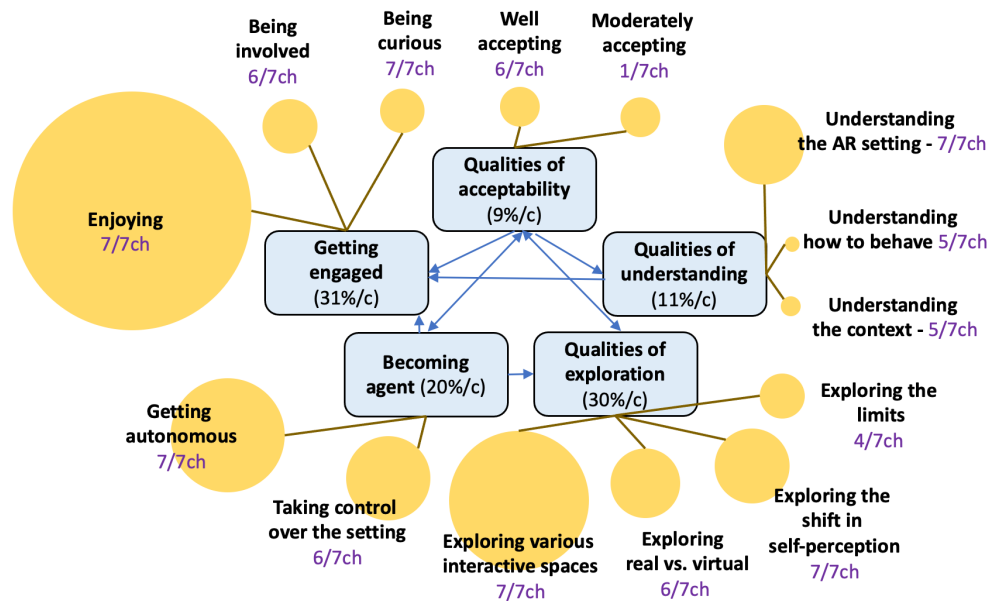


Figure 6.4: Overview of the concepts (rectangles) and subconcepts (circles) in the category called Encountering the AR setting that emerges from the grounded theory analysis of children’s experiences. The lines show an “inside-view” of the concepts by displaying their respective subconcepts. The arrows between concepts display their respective influences. The size of the circles represents the respective importance of subconcepts with respect to the number of phrasings in the category.

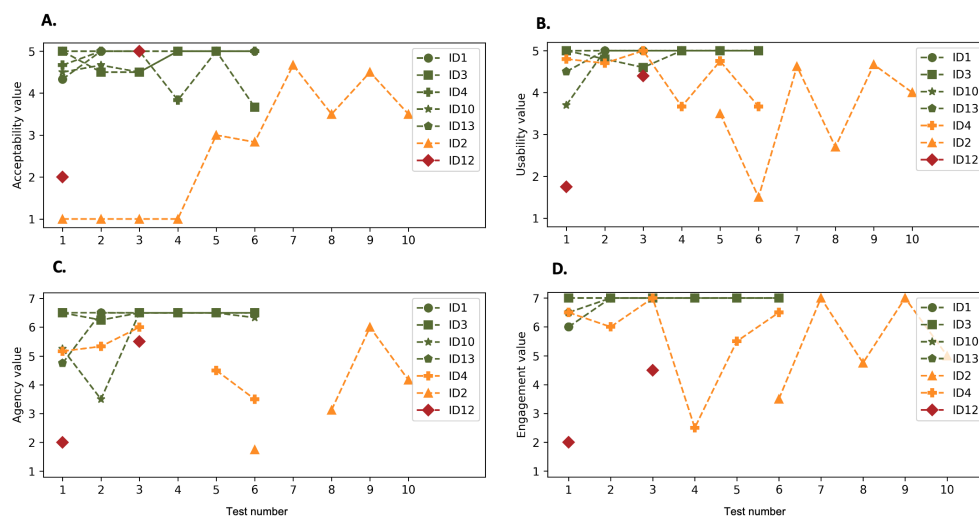


Figure 6.5: Quantitative answers from the questionnaire being related to the emerging category called Encountering the AR setting, about **A** Acceptability, **B** Usability, **C** Agency, and **D** Engagement.

s1, ID13 jumped towards the headset, whereas for ID2 and ID12 the novelty was anxiety-provoking. Moreover, despite their limited verbal abilities, ID2 and ID12 could express when refusing the headset (verbally or non-verbally). For instance, ID2 sang the lullaby *Promenons-nous dans les bois* (s5), as in this lullaby children are afraid by the wolf. Six main conditions influenced acceptability: caregivers' strategies (52p), the overall context (35p), the AR setting (28p), the child's state beforehand (15p), contingencies (5p), and time (4p).

Caregivers' strategies include wearing the headset while the child looks at the monitor (helpful for ID2) or using guidance (verbal, physical). Segmenting tasks also supported ID2's acceptability at s5: suggesting to get closer to the monitor, introducing the music, and then proposing the headset. Moreover, after s4, ID2 agreed to stay and observe ID10's session. According to OD, this was a key acceptability step, as "ID10 enjoys" and there "is no expectations towards ID2 when ID10 wears it", contrary to the practitioners. Guidance was also used with ID12: switching off the monitor at s4 allowed him to wear again the headset.

The overall context supported ID2 and ID12's acceptability, in particular due to the dyadic relationship (ID2, ID12), and to the understanding that they were not forced to wear the headset (ID2). ID2 accepted it after OD created a holding space at s5 (whispering, being physically close). ID2 expressed it by adding himself a beard on OD's drawing to look like OD (s6) (see figure 6.1). ID12 was first worried without his educator, e.g., only wearing it when he was nearby (s3). He then largely refused it from s5, but came alone at s6, which still indicated some interest. Practitioners hypothesized that ID12 may have required a longer protocol, and that it may have better worked by including more his educator.

About the AR setting, the content had a positive influence, e.g., ID12 wore the headset after seeing the individualized image (s1). The headset was well-accepted, despite some physical discomfort for ID3 and ID10 (scratching their nose), and ID2 (s7-s8) and ID12 (s7) who sometimes struggled to wear it and hold the controllers.

The child's state beforehand impacted acceptability. Indeed, ID4 refused the activity when unhappy against CL at s4. ID12 refused it when arriving in a bad mood and displaying repetitive behaviours at s5 and s6 (e.g., closing the windows).

Time played a major role, although less reported as obvious for practitioners. In particular, ID2 went through five stages: being in the room (s1), touching the headset and controllers (s2), controllers and cones⁴(s3), controllers (s4), and wearing the headset (s5). Ritualization over time was particularly helpful. For instance, it allowed ID12 to wear the headset without his educator at s4.

6.3.3.2 Qualities of exploration

ID1, ID3, ID10, and ID13 directly explored (encountering profile 1), ID2 and ID4 relied on their caregivers to then explore (profile 2), and ID12 hardly explored

⁴Activity cones are often used by psychomotor therapists. They are here used to highlight the limits of the virtual AR space.

due to acceptability difficulties (profile 3). Children explored four main aspects, with differences depending on their profiles: interactive spaces (42%/c), the shift in self-perception (23%/c), the real vs. virtual (21%/c), and the limits (14%/c).

Three spaces described by Lheureux-Davidse [173] with terms from psychology were explored: the body (until 10cm away), the grip (arm's length), and the locomotion (arm's length to the room's limits). Children also explored the monitor, as a window over AR. 5/7ch engaged their whole body, mainly after discovery. ID2 did it more than usual from s6: "It's incredible, when I said 'we can move', I did not believe in it" (CL, s7). ID3 and ID13 often auto stimulated (e.g., jumping). About the grip, 6/7ch tried to touch real and virtual objects, from (ID2, ID4, and ID13) or after (ID3, ID10, and ID12) discovery. ID2 manipulated a lot the equipment before to accept it. About locomotion, ID2, ID4, ID12, and ID13 observed a lot. The monitor was used by ID2 and ID12 as a gradual way towards AR.

Four main behaviours accounted for an exploration of what is real and virtual. First, 6/7ch children tried to touch real and virtual objects (e.g., ID2 and ID4 held the practitioners tight). Second, 5/7ch often wore/removed the headset during discovery. Third, 3/7ch covered the camera, with their face mask (ID4-s1) or hands (ID2-s6, ID13-s4). Fourth, ID2 hyperventilated and scraped his throat to feel that his body was real (s7, s9).

In AR, children may have perceived a shift in their self-perception, prompting them to explore their body in different ways. Indeed, 3/7ch had a different gait (ID2, ID4, and ID12). ID4 (s1,s2) and ID2 (s5) mainly remained on the floor at first, and then gradually stood up and moved in space. Others expressed this shift. For instance, ID10 said "I want my voice in my mouth" (s2). Others drew themselves with (ID1-s1, ID3-s2) or without (ID13) the headset (see figure 6.1). 6/7ch also wanted to see themselves, asking to be photographed (ID10-s1, ID12-s1) or to look at the mirror (ID4-s4, ID13-s6).

6/7ch children explored four types of limits. First, 4/7ch checked the limits of the physical space (e.g., ID4 went behind the table), and 4/7ch of the virtual space (e.g., ID3 went behind a virtual drawing). Then, 2/7ch explored advanced interactions, e.g., ID13 hit bubbles with his head (s2). After that, 2/7ch looked for artefacts, often for the *mise en abyme* phenomenon: ID1 drew himself on a child's shirt (see figure 6.1) and ID13 generated it by looking at the monitor with the headset on. ID13 also tried to trigger some bugs by looking at the mirror.

Four conditions prompted exploration: Time (40%/c), Self-regulation (22%/c), Caregivers' strategies (20%/c), and the Therapeutic frame (11%/c). ID3 showed the impact of time by drawing the setting from s2 to s6 and gradually adding what he explored (see figure 6.1). Self-regulation enabled to stay secure while exploring. The more exploration was observed, the more the acceptability and agency.

6.3.3.3 Becoming agent

The concept called becoming agent has two subconcepts that are detailed below, i.e., Getting autonomous (58%/c) and Taking control over the setting

(42%/c). Three agency profiles were built, corresponding to the three encountering profiles (see figure 6.1C): getting agent (4/7ch, profile 1), moderately agent (2/7ch, profile 2), and not getting agent (1/7ch, profile 3). Children with profile 1 were agent from s3, profile 2 were always moderately agent (as in real life), and profile 3 were not agent due to acceptability issues.

Getting autonomous concerns initiative-taking about the setting (e.g., wearing the headset alone) or others (i.e., initiating shared play). For instance, ID2 sometimes asked again for the headset. Children with profile 1 first asked when needing something (e.g., cleaning the drawings) and then took more initiatives over time. In particular, practitioners were struck when they made contextual requests, e.g., ID3 asked for a new music where the singer talked about being in a bubble (s6).

Taking control over the setting first concerns the content. To that end, seeing their new drawings every week gave children a form of control, in turn supporting self-confidence. Indeed, ID13, ID10 and ID3 often looked at all of them, and left the last one visible. Controlling the content increased over time, as being related to usability (see figure 6.5B). Moreover, 5/7ch children took control over the session's unfolding. In particular, ID3 and ID13 performed sessions in two parts at the beginning of the protocol: first being excited and then being calmer. ID2, ID4 and ID12 sometimes also left the room when needing to.

Four factors influenced agency: time (46%/c), contingencies (23%/c), care-givers' strategies (15.5%/c), and the therapeutic frame (15.5%/c). Agency increases over time, 89% of its phrasings being reported after discovery. About the therapeutic frame, ID2 and ID4 got agent after relying on their practitioners. At last, the more agency the better the child's experience, about acceptability, reassurance, exploration, engagement, and social interaction.

6.3.3.4 Getting engaged

Engagement is the most reported concept (287p), with three subconcepts: Enjoying (71%/c), Being involved (16%/c), and Being curious (12%/c). Its phrasings mainly appear after discovery (83%/c).

Enjoying largely emerged, concerning all children, with four properties: having fun (36%/c), not wanting to stop (33%/c), being happy to come (17%/c), and being excited (14%/c). Having fun relates to laughing and smiling (6/7ch, except ID12), dancing (ID3-s6, ID4-s6, ID13-s3), drawing the setting (ID3 from s2 to s6), or being happy to see their drawings in the AR scene (especially ID3, ID10, and ID13). Moreover, 5/7ch children (except ID4 and ID12) did not want sessions to finish after discovery. ID1 and ID3 also came back three times after the protocol ended to express that they missed the activity. Most children were also happy to come after discovery: coming alone (6/7ch, except ID2), stopping their activity to come (ID2, ID3, ID13), or directly smiling or communicating (ID1, ID2, ID3, ID10). At last, being excited largely appears, mainly concerning ID3 and ID13 during discovery, e.g., ID13 said "oh a headset !" and jumped towards it at s1.

All children but ID12 were personally involved in the sessions, five more than

usual (ID1, ID2, ID4, ID10, ID13). For instance, ID10 was involved at s4, although facing personal difficulties leading to not be engaged in other activities at the day hospital. ID13 was calmer than usual at s2 (e.g., not mumbling). ID2 and ID4's involvement depended upon their agency levels, i.e., involvement came up when "authorizing themselves" (after discovery) or when first testing the actor condition (s11 and s7). Similarly, ID12 spent more time in AR when being actor (s7). Moreover, while 5/7ch were directly interested (ID1, ID3, ID4 ID10, ID13), 2/7ch were intrigued but somewhat worried (ID2, ID12). For instance, ID12 quickly wanted to leave at s2, and then came back and asked to try again. Yet, he may have been disturbed by having to stop his previous activity in order to come. At last, we observed that AR and children's involvement did not hinder social interaction.

Four main conditions influenced engagement: therapeutic frame (34%), being actor (32%), contingencies (26%), and being agent (6%). The therapeutic frame mainly concerned the encountering profiles two and three, e.g., relying on their practitioners to get engaged. Being actor was also positive: ID4 (spectator) may have been bored from s4, but ID2 and ID4 were excited when being first actor (at s11 and s7). For instance, ID2 unusually vocalized his pleasure (s11). About contingencies, ID3 and ID4 wore again the headset after the activity ended, leading to enter a dark world with stars (i.e., the Steam welcome screen). Yet, they really enjoyed it: ID4 unusually vocalized a lot and smiled (s6), and ID3 asked to "look at the stars" at the end of every following session. At last, the more engagement the more agency, as leading to "be happy in their actions" (OD).

6.3.3.5 *Qualities of Understanding*

Qualities of understanding has three subconcepts: understanding the AR setting (71%-7/7ch), the context (17%-5/7ch), and how to act (12%-5/7ch).

Understanding the AR setting mainly consists in describing the setting (ID4-ID10-ID3). For instance, ID3 drew it from s2 to s6 and gradually added the new elements that he understood (see figure 6.1). Other children uttered context-related sounds, e.g., sounds of the bubbles (ID2-s6). 2/7ch children named the activity when explaining it to their educator: ID3 named it the "Snow queen" after his individualized music, and ID10 called it "video games". 6/7ch understood what the monitor represents. 3/7ch identified bugs (ID3, ID10, ID13), sometimes trying to fix them by imitating what the investigator had previously done (ID13-s7).

Understanding the context concerns ID2, ID3, ID10, ID13. Children connected sessions by looking at their drawings. Some of them understood when the protocol ended (e.g., ID3 hugged everyone). ID3 identified the adults' roles, asking for help to the adult in charge of technical aspects when identifying a bug: "I find it incredible: it bugs and he comes to you" (CL-ID3-s5). 2/7ch understood that other children used *Magic Bubbles*, e.g., ID13 imitated ID4 when seeing her drawings. ID1, ID4, ID12 are not mentioned, maybe due to ID4's minimally verbal condition, ID12's acceptability issues, and as ID1 only had three sessions.

Understanding how to act mainly relates to understanding the interactions. It

mainly concerns children being actor and quickly learning the interactions (ID1, ID2, ID4, ID10). Children being spectator had less understanding of it, maybe because the setting did not afford these possibilities.

Understanding increases over time, being positively influenced by exploration, caregivers' strategies, and contingencies. Caregivers' strategies consist in explaining how things work and confirming interrogations (e.g., OD said "yes the headset is real" when ID2 held it at s6). Contingencies are unexpected bugs which clarified that children interacted with a machine.

6.3.4 The category called Experience sharing over time

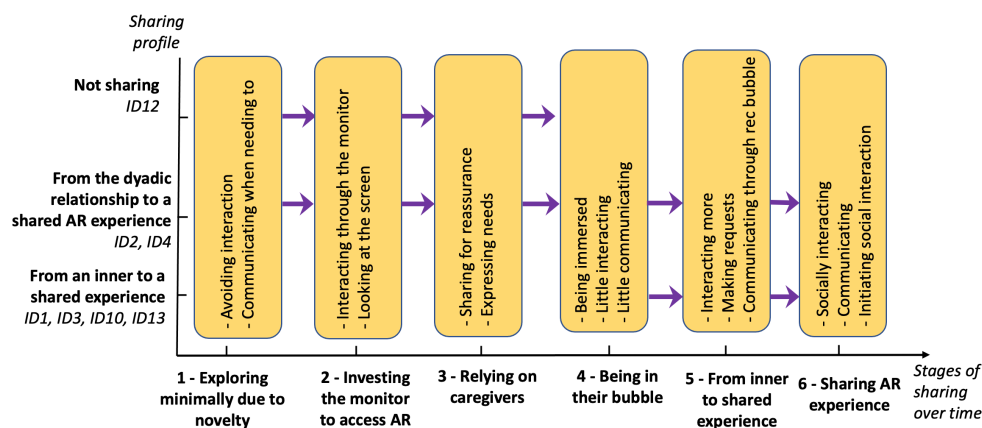


Figure 6.6: Overview of the category called Sharing experience over time emerging from the grounded theory analysis of children's experiences. The six concepts corresponding to stages of sharing over time are represented over the abscissa axis. The three sharing profiles that appeared are represented over the ordinate axis, corresponding to different ways of sharing over time. Arrows mark the evolution from one stage to another, and the first stage and last stage that children experienced according to their sharing profiles.

The category sharing the AR experience largely emerged (927p, 20%/t). Indeed, for practitioners, the key feature is the "evolution of the dyadic relationship" (OD). Moreover, it complements other day hospital activities, by happening *within* a "shared world" (CL, OD), rather than *between* a child and a practitioner.

Three sharing profiles appeared: from an inner to a shared experience (profile 1, ID1, ID3, ID10 and ID13), from the dyadic relationship to a shared AR experience (profile 2, ID2, ID4), and not secure enough to share (profile 3, ID12). They respectively correspond to the three encountering profiles. They were also confirmed by questionnaire's answers about communication (see figure 6.7A): profile 1 relates to communicating more over time, profile 2 to communicating at first (due to relying on practitioners), at the end, but less in-between, and profile 3 to hardly communicate. The profiles evolve differently over time through six stages that are profile-specific. For instance, stage 5 ("Towards a shared experience")

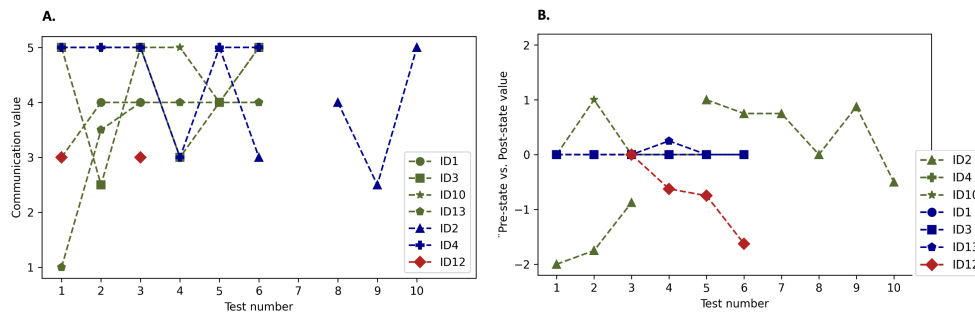


Figure 6.7: Quantitative rating from the questionnaires corresponding to the emerging categories called sharing experience over time and ways of getting secure. **(A)** Evolution of communication over time; **(B)** Pre vs. Post Child's state.

consists in requesting various aspects for profile 1 but mainly in wearing again the headset at the end for profile 2. Although with different profiles, ID4 and ID13 were the children who interacted the most. Figure 6.6 gives an overview of this category. The three next subsections present the three sharing profiles.

Sharing was mainly influenced by caregivers' strategies (11p) and contingencies (11p). Strategies mainly consist in initiating social interaction for profile one, and leveraging the dyadic relationship to prompt shared exploration for the others. Contingencies are unexpected bugs prompting interaction, e.g., ID10 gave the controller to practitioners at s2 because it was buggy, thus generating shared play.

6.3.4.1 From an inner to a shared experience

These four children (ID1, ID3, ID10 and ID13) were first calm, "in their bubble", gradually shared more, and finally initiated interactions: "first you focus on yourself. Then, you want to have fun with the adults" (OD). For instance, ID1 first "did his own thing", but was not bothered when practitioners tried to interact and even laughed about it (s2). ID3 expressed this "inner thing through his drawings" (OD), by representing himself alone (s2 to s6). All children gradually shared more by making requests. Two of them (ID1, ID10) started to communicate through the recording bubble, by repeating what was said (ID10-s3) or directly talking (ID1-s1, ID13-s2). For instance, ID1 teased OD at s1, saying "well done!". Over time, most children socially interacted more than unusual. For instance, ID10 played with all the adults at s7, saying: "The four of you must stop!". ID13 initiated shared play by drawing in AR and regularly checking that OD who was also drawing imitated him well (s5, s6). ID10 also managed to express personal difficulties by drawing his relatives, although he never did it before with his educators (s3, s4) (see figure 6.1).

6.3.4.2 From the dyadic relationship to a shared experience

The way ID2 and ID4 shared their experience significantly varied over time. At first, ID2 was somewhat intimidated, and ID4 remained still due to the setting's

novelty. ID2 made a first eye contact through the monitor (s5) then allowing him to accept the headset (stage 2). As ID4 was “more interested in the human than in technology”, and less intimidated, she directly went to stage 3. At stage 3, they both relied on their practitioners, e.g., holding their hand to move around (ID2-s6). For instance, OD said about ID4: “I felt her strength to bring it [my hand] back to her. The other had to exist” (s3). From that point, children had an inner experience: ID2 avoided to touch others and ID4 got stiller. Then, they interacted more again. For instance, ID2 asked to wear again the headset (s6, s7, s9, s10) or said that he wanted to stop (s6). At last, children shared a lot. For instance, ID4 said “hello” with eye contact (s5), or non-verbally asked practitioners to get closer (s6): “she stopped to chit chat and stared at me like... you come back” (s6). Moreover, ID2 talked more than during his usual therapy sessions (s10).

6.3.4.3 Not sharing

After minimally exploring due to novelty (e.g., quickly wearing the headset at s1), ID12 accessed AR by looking at what his educator through the monitor. He then relied a lot on him when present. Finally, he displayed an inner experience, e.g., accepting to wear again the headset when the monitor was off (s4). He then refused the activity from s5, thus not getting to the next stages.

6.3.5 The category called Ways of getting secure

The category called ways of getting secure (927p, 11%/t) has two concepts: getting secure (80%/c) and getting insecure (20%/c). These concepts depend on the children’s encountering and sharing profiles. They can be analyzed through four time windows: during versus after sessions, and during versus after discovery. For instance, regarding the evolution of the child’s state between before and after sessions as displayed on figure 6.7B, ID2 and ID10 got more secure (even during challenging times), ID1, ID3 and ID13 remained secure, and ID12 got insecure (due to acceptability issues). Observing the evolution between during and after discovery also suggests that ID2 gradually got more secure after overcoming the setting’s novelty. ID4 also felt better despite undergoing a hard time at s6 (not visible on figure 6.7B). Figure 6.8 gives an overview of this category. The two next subsections present its two main concepts.

Four main conditions influenced reassurance: Therapeutic frame (41p), Self-regulation (34p), Child’s state beforehand (38p), and the AR setting (20p). The therapeutic frame corresponds to the holding environment induced by practitioners and the overall context (e.g., carpets). Self-regulation is analyzed in the two next subsections with respect to the two main concepts. The child’s state largely influenced how sessions unfolded, e.g., ID2 hyperventilated a lot at s6 as going through a personal hard time. The AR setting may be holding in itself, due to the equipment and content. For instance, practitioners hypothesized that the headset could be holding for ID1, ID2, ID3 and ID10, as heavy, holding the head, and inducing a visual shrinking. They also suggested that *Magic Bubbles* could complement

Snoezelen by offering a holding space with free play rather than relaxing activities.

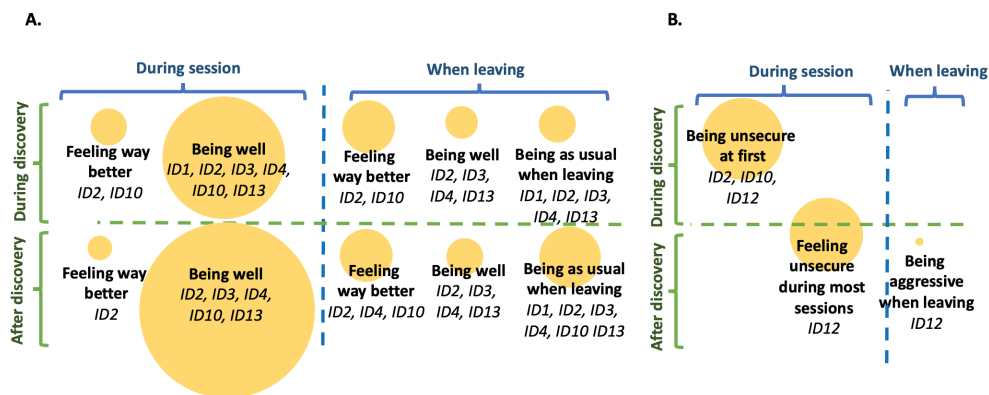


Figure 6.8: Overview of the category called ways of getting secure emerging from the grounded theory analysis of children's experiences. Its two concepts called getting secure and getting insecure are respectively represented on subfigures A and B. Subconcepts are displayed with yellow circles. Their sizes illustrate their number of phrasings with respect to the total number of phrasings in these two concepts. The two subfigures are organized following four time windows: during sessions (left part), after sessions (right part), during discovery (top part), or after discovery (low part).

6.3.5.1 Getting secure

Being Well (58%/c) is the most reported subconcept, followed by feeling way better (26%/c), and being as usual when leaving (16%/c). Phrasings are sorted as feeling way better rather than being well, if children felt unwell when starting the session. They fit in being well rather than being as usual when differences were observed regarding children's usual behaviour (e.g., communicating more). These subconcepts have three similar properties with various proportions: getting calm, handling well contingencies, and being ready for other tasks when leaving. Concepts are described below following these properties.

About getting calm, during and after discovery, 4/7ch children had less stereotypes, and ID2 and ID10 sometimes felt way better. In particular, ID2 less hyper-ventilated (s6), walked with flat feet (s7, s9, s10, s11), or used less hand flapping (s9). ID1 always refused to look in the mirror in the room, saying that he would never do it again at s3, although very common for him. He was also less tactile (s2). ID1 (all sessions), ID10 (s2), and ID13 (s2, s4) did less echolalias, and ID2 did not do any at s2. Moreover, 4/7ch adopted new self-regulatory behaviours. Indeed, ID1 did repetitive gestures with the column to get secure after socially interacting or exploring, as he confirmed at s3: "As soon as ID1 interacts with us, he then refocuses with the column, doesn't he?" (OD). "Yes I do" (ID1). ID3 and ID13 also auto-stimulated by moving a lot, maybe to induce vestibular stimulation, or visual blur, in turn enabling to better focus on the music. Other children focused on specific elements to shut out the surroundings, i.e., column (ID1 - all sessions),

panel (ID2 - s7), various objects (ID4 - s1), or the stars (ID3 - end of all sessions). Some children also got way calmer during (ID2, ID3) and after (ID2, ID3, ID13) discovery. ID4 also often lied on the floor, indicating relaxation (s1,s2,s3,s5).

Handling well contingencies mainly consists in being able to wait without frustration for the application to start or to be restarted (ID3, ID4, ID10, ID13). Such behaviour was unusual for ID13 at s3: "It's very rare. It actually never happened" (CL). ID3 could also "handled well his frustration" (CL) at s3 although eager to do the activity. According to his educator, ID3 could wait as knowing what he can get from the activity. Yet, children only waited if meaningful. For instance, ID13 did not do it at s4 when being told to wait for OD, as OD entered the room at the same time. Then, children could also tolerate unexpected bugs (ID10, ID3): "it's great that ID10 was not disturbed by the bugs" (CL - s6). Moreover, ID3 and ID13 more easily stopped the activity over the course of the protocol.

Practitioners stressed that ID2 (s4, s5, s7, s10) and ID10 (s2, s3) were sometimes calmer than usual, and more ready to start other tasks by the end. For instance, ID2 did less echolalias than usual after s3, and ID2, ID3, ID4, ID13 often easily started activities after leaving. Moreover, the fact that ID3 could express that he wanted to go to the toilets right after s6 was striking for OD and CL.

6.3.5.2 Getting unsecure

ID2 and ID12 were both somewhat unsecure at first: ID2 due to novelty and ID12 due to being overwhelmed by too many stimuli. Whereas ID2 gradually got secure (from s5), ID12 did not. Indeed, ID12 refused the headset during most sessions, and showed anxiety: repeating "I want to go to he cantine" (s5), sorting everything (all sessions), or wanting to leave (s5, s6). Yet, which element was actually anxiety-provoking was hard to identify (e.g., too many people around). Yet, according to the practitioners, ID12 still displayed a positive evolution, as he quickly wore the headset alone at s5 and s6 and came alone at s6.

6.4 Discussion

The objective of this study was to examine if *Magic Bubbles* could be reassuring for autistic children with SLN (RQ1), could prompt the child-practitioner relationship (RQ2), and to assess the overall quality of their experiences with *Magic Bubbles* (RQ3)? Four categories were built from our grounded theory analysis of children's experiences: encountering the AR setting, sharing experience over time, ways of getting secure, and conditions supporting the AR experience (see again figure 6.3). Below, we first discuss these four categories, which enables to address our three research questions. After that, limits to this study are outlined, and perspectives are drawn.

6.4.1 Children's AR experiences with Magic Bubbles

Most children (6/7ch) got secure, either from the start (4/7ch), or after discovery with practitioners' support (2/7ch). This finding matches practitioners' initial expectations (see table 6.2), and validates our first research question (RQ1). ID2 and ID10 sometimes even felt better after using *Magic Bubbles* although going through personal challenging times. Reassurance enabled 6/7ch to gradually become more agent (e.g., authorizing themselves), engaged (e.g., having fun), and to explore more (e.g., moving in space). Reassurance pertains to a large category called ways of getting secure which is summarized on figure 6.8.

AR *Magic Bubbles* environment also encouraged social interaction, thus validating RQ2. Indeed, according to the psychologists, it "created some relationship". Three sharing profiles emerged, related to different time evolutions (see figure 6.6). With profile one (4/7ch), children directly explored alone and then gradually shared with others. Profile 2 (2/7ch) consisted in three steps: first relying on practitioners, then exploring alone, and finally sharing their experiences. With profile 3 (1/7ch), ID12 was often worried and refused to share. Though, it may have been different if his educator had been around during all sessions. *Magic Bubbles*'s potential to bond with each other complements previous findings from studies using digitally-augmented multisensory spaces [95, 204, 227, 248]. Moreover, in light of our positive findings, practitioners expressed that it could complement the *Snoezelen* approach, by focusing more on free-play engaging aspects than on relaxation.

To account for the quality of children's experiences [251], and thus answer RQ3, a dense category called encountering the AR setting was built ⁵ (see figure 6.4). Three encountering profiles were constructed, with close ties with the three sharing profiles: profile 1 (4/7ch) consists in easily encountering the setting from the start (e.g., exploring), profile 2 (2/7ch) in largely relying on practitioners and then encountering the setting, and profile 3 (1/7ch) in facing encountering issues (e.g., acceptability issues). Although with profile 3, ID12 still displayed a positive evolution: coming alone at s6 and quickly wearing the headset alone at s5 and s6. This category subsumes five interconnected concepts: getting engaged and qualities of exploration largely appear, followed by becoming agent, qualities of understanding, and qualities of acceptability⁶. The significance of engagement and agency echo the findings from our interviews with autism stakeholders (see chapter 3) and from Spiel et al. [291]'s co-design experiment as part of the *OutsideTheBox* project.

Children's experiences were largely influenced by the overall setting, with the therapeutic frame and caregivers' strategies playing a major role. This observation confirms that analyzing autistic children's experiences with AR requires using methodologies that take into account the overall context, to understand the reasons underlying their actions, as previously reported by Spiel et al. [294] and in chapter 3.

⁵See definition in section 6.3.2.

⁶See definition in section 6.3.3.

6.4.2 Limits of the study

Though, this study still displays some limits. First, the analysis mainly reflects practitioners' interpretations, as children were minimally verbal. Despite efforts to mitigate this bias (e.g., asking children to draw), new methodologies should be devised to better account for their views [230, 291]. Then, since no previous study to our knowledge focused on such AR sensory and mediation objectives, our research questions were intentionally quite broad. While enabling to raise new insights, they prevented us from digging into precise aspects. The low number of children also limits the generalization of our findings. Future studies should thus include more children, and further examine new concepts that emerged (e.g., real-virtual understanding). At last, practitioners' preferences for the actor condition may also have influenced children's behaviours.

The qualitative analysis may contain inaccuracies due to misunderstandings or preconceptions, despite strategies used to mitigate them. Various aspects of children's experiences were uncovered but their causes often remain uncertain. For instance, the respective influence of ritualization, time, and *Magic Bubbles* on children's feeling of reassurance has yet to be explored. Investigating this issue may shed light on why and when children went from one sharing stage to another.

6.4.3 Perspectives

While the context, content, and equipment have contributed to secure children, two other aspects deserve more investigation: the visual shrinking induced by the AR headset, and physical features of the headset (e.g., size, weight). This visual shrinking may also be related to another form of shrinking: the use AR to remove real elements potentially inducing over arousal, as previously suggested in our interviews. Exploring if and which headsets could be reassuring also echoes Newbutt et al. [217]'s study about autistic children's acceptability, where children said that they would like to use headsets to feel calm.

Children's self-regulatory behaviours call for more investigation regarding three aspects. First, future research has to distinguish between behaviours accounting for anxiety and others used to calm down after performing actions (e.g., exploration). For instance, in our study, one child confirmed using repetitive behaviours for the latter. Such identification could help to better spot and decrease anxiety levels, while authorizing self-regulatory behaviours if not leading to isolation, as previously suggested [227]. Second, some children focused on elements as "blinkers" to shut out the surroundings (e.g., closely observing the column). Thus, future AR studies should include self-regulatory areas where children could actively go to calm down.

Children's immersion and co-immersion call for more research, through three main avenues. First, devising methodologies to assess the perceived immersion of minimally verbal children could help to go beyond the sole use of practitioners' interpretations. Second, children's understanding of real and virtual elements, and what it means to them, could be further examined. To do so, parallels could be

drawn with Winnicott [334]'s concept of *potential space*⁷. Third, parallels could be drawn between *immersion* and the *mise en abyme* phenomena, which appeared in drawings or when children looked at the screen. Checking if this phenomena accounts for immersion, exploration, or a will to disappear is worth examining.

The exploration of the shift in self-perception, of the real versus virtual, and of the limits indicated a possible feeling of presence. While the findings were not analyzed under this angle, as our measures targeting presence were not adapted for autistic children with SLN, the feeling of presence should be further explored with respect to its influence over all other aspects of children's experiences. Indeed, to our knowledge, previous studies targeting presence focused on autistic individuals with MLN who could answer self-report questionnaires [320], which was impossible in our case. To pursue such endeavours, other methods of inquiry must be devised, so that to collect and compare multiple data source, for instance coming from observations, interviews, or physiological data.

Many findings relate to a perceived shift in self-perception. Indeed, many children were interested in their body image (e.g., asking to look in the mirror). Conversely, one child refused to look in the mirror although usually doing it very often. Others also adopted a different gait than usual (e.g., walking with flat feet). Examining what actually caused this shift (e.g., equipment, AR) is worth investigating, as it may open new research avenues for AR to work on self-perception.

At last, the positive influence of unexpected features over children's experiences could be more explored (e.g., bugs). Such studies would need to draw links with usual interventions, as practitioners usually introduce unexpected elements within a structured setting to prompt exploration (see chapter 3).

6.5 Conclusion

This study had three main research questions regarding the use of *Magic Bubbles* AR environment for autistic children with SLN, related to the possibility to secure them (RQ1), to strengthen the therapeutic alliance (RQ2), and understand the overall quality of their experiences (RQ3). To address these questions, a long-term field study was conducted with seven autistic children. Multiple data sources were collected: practitioners' observations (questionnaires, interviews), children's drawings, and educators' observations. They were analyzed using a grounded theory approach, in addition to descriptive statistics. Findings first confirmed that most children got secure (RQ1), and could interact with the practitioners (RQ2). In particular, some children directly got secure, others gradually got secure over time, and one child remained unsecure, maybe due to the absence of his educator. A gradual evolution over time was identified, from an inner experience when children accept the setting, towards a shared experience with the practitioners. Four categories were built which provide a detailed account of children's experiences,

⁷See definition in section 4.4.1.2.

in relation to environmental factors (RQ3): encountering the AR setting, sharing experience over time, ways of getting secure, and conditions supporting the AR experience. This theoretical contribution could inform future XR research focusing on autism or neurodevelopmental conditions in general. Moreover, this study has a methodological contribution, being one of the first AR study intended for autistic children to our knowledge that uses mixed methods of inquiry largely relying on the grounded theory method. At last, directions for future research were drawn, particularly related to children's immersion, self-regulatory behaviours, the exploration of a potential shift in self-perception, and of what is real and virtual. Findings from such research could have implications for clinical psychology, fundamental aspects of autistic perception, and future autism XR research.

This chapter closes the second part of this thesis which focused on the design, development, and field testing of the AR multisensory mediation environment called *Magic Bubbles*. This project aimed at encouraging children's self-expression, strengthening the child-practitioner relationship, and securing them. While this last goal implied to tailor the environment to children's sensory profiles by removing stimuli being potentially over-arousing, this individualization process still remains challenging. Yet, it would enable to work with more children and thus to potentially generalize our findings. In particular, current auditory assessments are ill-suited to capture the auditory lived experiences of autistic children, especially in the case of SLN, even though most of these children display an Atypical Auditory Functioning (AAF) (see again section 2.1.3.2). The next part of this thesis thus investigates the possibility of using AR to better assess the autistic AAF. The creation of such AR tools may in turn facilitate the individualization of XR environments for autistic children as well as the adaptation of everyday spaces to accommodate for their auditory needs.

Part III

Using Augmented Reality to Assess the Autistic Atypical Auditory Functioning

Abstract

The third part of this thesis aims at leveraging the AR multisensory and interactive capabilities to increase the ecological validity of current auditory assessments intended for autistic children with SLN as well as the control that these children have over these auditory assessments. This objective seeks to overcome the current limits of auditory assessments which do not fully capture the everyday listening experiences of autistic children. It stems from the findings from our interviews with autism stakeholders that were presented in the first part, and attempts to complement the findings from our field AR experiments that were reported in the second part. Indeed, developing such auditory assessments could help to further tailor *Magic Bubbles* AR environment that was previously developed to the specific sensory profiles of autistic children. To investigate this objective, three studies were conducted. First, a systematic literature review was performed to create a taxonomy being representative of the everyday listening of autistic individuals, in terms of their common positive and negative experiences (see chapter 7). Second, the taxonomy was presented to 68 autism stakeholders through an online survey to see if it matched their lived experiences (see chapter 8). Findings enabled to validate and improve the initial taxonomy. Moreover, its items were ranked in terms of their relative significance over the positive and negative experiences of individuals, with discrepancies between the answer distributions of autistic and non-autistic participants (relatives and practitioners). Third, an AR auditory assessment informed by our taxonomy and an experimental protocol were designed in collaboration with a psychomotor therapist to perform future auditory assessments with autistic children (see chapter 9). These designs now have to be validated and refined through a participative design process involving autistic individuals, to ensure that they are representative of their views.

7 - Building a sound taxonomy being representative of autistic auditory perception

7.1 Introduction

Autistic people often display an Atypical Auditory Functioning (AAF), involving a Decreased Sound Tolerance (DST) towards specific everyday sounds (e.g., toilet flushing) and atypical sound preferences (e.g., pink noise) [132, 225, 297, 331]. Both DST and sound preferences can negatively impact their everyday life, for instance leading to social isolation or stigma. To help them cope with these issues, various adaptation strategies can be used (e.g., noise-cancelling headphones). However, adaptations are sometimes hard to provide due to unknowns surrounding autistic AAF [331] and to the limits of current auditory assessments which do not fully capture their everyday listening experiences (see details in section 2.1.3.2). In particular, assessments are limited to non-ecological conditions, in terms of context (e.g., clinical settings) and content (e.g., sinus waves). They also largely rely on third-hand accounts (e.g., from relatives) for children being minimally verbal or with ID, leading to potential inaccuracies [297]. Thus, more ecological auditory assessments should be devised that allow autistic children to express themselves.

We hypothesize that an AR setup with spatial audio capabilities could be used to achieve this objective. Indeed, AR is promising to enhance the ecological validity of clinical studies [231] and to complement sensory interventions (see chapter 3). Furthermore, spatial audio has already been used for various clinical purposes (see section 2.4.1.2), and could provide more ecological conditions by presenting various sounds semantic contexts (e.g., school) and parameters (e.g., intensity). However, to create the most comprehensive XR auditory assessment as possible, sound semantic contexts and parameters being representative of autistic AAF must first be identified. Indeed, so far, to our knowledge, no advanced sound taxonomies accounts for the everyday listening of autistic people.

To verify our hypothesis a threefold process was conducted. First, a systematic literature review was performed to create a sound taxonomy being representative of autistic AAF (see this chapter). Second, to validate and improve the taxonomy with respect to autistic people's experiences, it was presented to stakeholders through an online survey (see chapter 8). Third, an AR auditory assessment informed by our taxonomy was designed in collaboration with a therapist, along with a protocol intended to conduct future testing with autistic children. This chapter reports on the first step of this process. Two research questions are addressed:

RQ1 Which semantic sound contexts often induce negative or positive experiences for autistic individuals?

RQ2 Which sound parameters often induce negative or positive experiences for autistic individuals?

After reporting on the everyday listening of autistic people, the method used to conduct the literature review is presented, followed by the findings. Findings are then discussed and future perspectives for autism research are drawn.

7.2 The everyday listening of autistic people

Despite unknowns regarding the causes of autistic AAF [331], five possibilities exist: hyperacusis, misophonia, phonophobia, enhanced perceptual functioning, or a combination of them (see detail in section 2.1.3.2). Yet, current assessments do not address them all, nor their interplay, making it hard to identify what precisely causes discomfort [297]. On the one hand, auditory exams (e.g., speech audiometry) target hyperacusis by measuring loudness discomfort levels with respect to synthetic sounds (e.g., pure tones) [153, 164, 261]. Yet, results are poorly reliable due to using non-ecological sounds [6, 80, 297]. On the other hand, sensory profiles [27, 72] rely on questionnaires, observations, and interviews, to pinpoint situations being over-arousing, in the light of multiple aspects (e.g., child's history) [297]. Yet, observations remain limited to non-ecological contexts (e.g., clinical settings) and to reactions to a small set of sounds being heuristically chosen by therapists.

To overcome these shortcomings, auditory assessments could first consider the relationship between a sound source produced in a certain way in a specific place and the listener's experience [98]. While this holistic perspective has been studied by the field of *acoustic ecology* for more than twenty years [98], only neurotypical listeners have been addressed to our knowledge with studies attempting to classify environmental sounds [123], assess the environmental sound quality [120], or investigate cognitive sound representations [71, 108]. Only two studies describe sounds being representative of autistic AAF [213, 274], but they are limited to negative accounts [213, 274], do not rank the reported sounds [213, 274], or overlook sound parameters [213]. Hence, the holistic perspective adopted by the field of acoustic ecology could inform the design of new auditory assessments for autistic users that target various semantic sound contexts and sound parameters.

To improve the validity of auditory assessments, more control could also be given to autistic children. Indeed, so far, practitioners often struggle to conduct auditory assessments with autistic children with SLN who are minimally verbal or with ID (see chapter 3). As children's answers can be hard to collect and interpret, therapists often rely on second or third-hand accounts which are sometimes misleading. For instance Stiegler and Davis [297] report the case of the mother of an autistic child who thought that her child refused haircuts due his hyperacusis, although refusals came from socio-emotional causes. To allow children to express themselves, AR interactive capabilities could be leveraged to offer alternative ways of answering, e.g., simple interfaces with direct action-reaction relationships. This

aspect will be investigated in chapter 9.

7.3 Method

We performed a systematic literature review to build a taxonomy of sounds being representative of autistic AAF, drawing upon the PRISMA guidelines [226]. The methodological framework involved four stages: (1) defining the research questions (RQ1, RQ2) (2) identifying relevant studies with a three-step literature search, (3) gathering, summarizing, and reporting the results, and (4) reviewing the findings by one clinical expert in the field who did not take part in stages 1–3.

7.3.1 Search strategy

Online searches were conducted from June to September 2021, from various electronic databases and registers that aimed at covering a large part of the literature: PsycNET (PsycINFO), PubMed, Scopus, World Of Science, Google scholar, and Journal of Autism and Developmental Disorders and Autism. Online queries used were inspired by keywords used in different reviews [20, 225, 296, 297, 331]: ((autism OR ASD OR autism spectrum disorder OR asperger OR autistic) AND (child OR children OR paediatric)) AND (audio OR auditory OR audio sensitivity OR hyperacusis OR misophonia OR phonophobia OR sound tolerance OR tinnitus OR sound OR noise OR acoustic) AND (questionnaire OR classification OR clinical profile OR assessment OR evaluation OR treatment OR intervention OR training OR rehabilitation OR strategy).

To complement these online searches, and identify new papers fulfilling our inclusion/exclusion criteria, two approaches were used from July 2021 to July 2022: backward and forward snowballing sampling techniques (see section 7.3.2). Backward snowballing consists in examining the reference lists of the papers being identified. This technique was used iteratively until no new relevant paper could be found, i.e., the references from the papers being found through reference lists were also checked. Forward snowballing consists in searching for papers citing the papers being already identified, for instance using Google Scholar engine.

At last, a psychomotor therapist being expert in Sensory Integration Therapy and autism provided us with the auditory sections from five clinically validated sensory profiles (two of them being only in French): the Sensory Profile 2 [72], the Adolescent/Adult Sensory Profile [36], the Sensory Profiles Checklist (Revised) [27], "Évaluation Sensorielle de l'Adulte avec Autisme" (ESAA) [64], and "Evaluation des Altérations du Comportement Auditif de l'enfant et de l'adolescent avec TSA" [81].

7.3.2 Inclusion and exclusion criteria

Searches were limited to four types of peer-reviewed studies, focusing on: (1) auditory evaluation/rehabilitation of semantic auditory contexts being perceived as positive or negative, (2) environmental auditory parameters being perceived as

positive or negative, (3) first or second-hand accounts from children, parents, or caregivers about auditory contexts or/and parameters, and (4) sensory questionnaires for autistic children. As numerous studies appeared from our queries, and since most auditory autism research has been conducted during the last decade [331], we excluded studies not primarily focusing on auditory issues, only included publications from 2008, and studies in English (except for the questionnaires provided by the therapist). The following types of contributions were not considered: reviews, abstracts, notes, protocols, letters, editorials, reports, and master thesis.

Children had to be aged from 4 to 18 years old and have a confirmed autism diagnosis, according to one of the main standardized tests, i.e., International Classification of Diseases (ICD-10) [222], the Diagnostic and Statistical Manual of Mental Disorders version 5 [5], the Autism Diagnostic Observation Schedule version 1 or 2 (ADOS-2) [175], the Revised Autism Diagnostic Interview [176], or Childhood Autism Rating Scale version 1 or 2 (CARS) [277]. Studies focusing on evaluation/rehabilitation had to include at least 50% of the autistic individuals (except for control groups) and to display positive outcomes. As autism auditory research often reports on use cases without control groups, we also considered studies without controls. Studies focusing on environmental auditory parameters had to include at least 30% of autistic individuals (as acoustic designs are often devised for neurodevelopmental conditions in general). At last, since Sinha et al. [287]'s systematic literature review reported no positive evidence supporting the approach called Auditory Integration Training, we excluded it.

7.3.3 Screening process

I searched and reviewed all the studies. For both database and snowballing searches, the title of the studies were first screened following our inclusion criteria. If relevant, the abstract was then screened, followed by a full-text screening. The study was then included if fulfilling the predefined inclusion criteria. This process was repeated until all the data were considered.

7.3.4 Rationale for building the taxonomy

For each study, we extracted the variables corresponding to sound contexts and parameters being representative of autistic AAF. Hence, we gradually built the taxonomy by using deductive content analysis complemented by inductive content analysis [75]. Moreover, to give account of the contextual nature of autistic AAF, we decided to build domain-based categories, which would then comprise concepts based on the types of sound events. Deductive analysis was first used to classify variables following already existing categories being reported in our selected papers. Studies being excluded from the review could also be used if suggesting classifications pertaining to similar topics (e.g., hyperacusis in general, not limited to autism). When the extracted variables did not belong to already existing categories, inductive analysis was used to build new categories. This process stopped when reaching data saturation. At last, to validate and refine the emerging taxon-

omy, the psychomotor therapist who participated to the search strategy reviewed the classification.

7.4 Findings

Findings are presented in three steps. First, the review selection process is introduced, and summarized in figure 7.1. Second, we report on the types of sound variables being mentioned in the selected records (see table 7.1). At last, the taxonomy that we constructed is introduced, and summarized in table 7.2.

7.4.1 Study selection

The search yielded 36 articles: 8 studies about evaluation/training, 17 studies about environmental auditory parameters, 7 first-hand accounts, and 4 auditory items sections from sensory questionnaires. Figure 7.1 presents a flow diagram of the selection process. After removing the duplicates, 1121 titles remained. Of these, after removing the article types not fulfilling our inclusion criteria (e.g., notes, reviews) and performing title screening, 42 titles remained. These records were subjected to full-text screening. As 22 records did not meet the inclusion/exclusion criteria, 23 papers left (including the references sent by the psychomotor therapist). From there, forwards and backward snowballing techniques were used, which led to identify 38 new studies, 13 of which were kept after full-text screening. In total, 36 records were identified.

As it described negative contexts and parameters, Fodstad et al. [86]'s study was kept, even if being criticized by the autism community about its methodology [29]. Koegel et al. [160]'s study was included even if earlier than 2008, as being frequently cited in the records that we identified. Coelho et al. [55] and Rosenhall et al. [261]'s studies were excluded even if often cited, as not exclusively focusing on autism, or using pure tones as rehabilitation strategies. Stiegler and Davis [297] and Bettarello et al. [23]'s studies were only considered for their case studies (not their reviews). Brown and Dunn [36] and Degenne et al. [64]'s clinical questionnaires suggested by the psychomotor therapist were excluded as only focusing on adults. Nagib and Williams [214]'s study was removed as their findings regarding sounds were similar to the ones of their last study which used a similar protocol [213].

7.4.2 Study characteristics

Table 7.1 summarizes three types of variables that were extracted from the papers: negative sound contexts, positive sound contexts, and sound parameters. When variables accounted for both sounds contexts and parameters, they were classified in both of them. For instance, "clock ticking"2 mentioned by Ashburner et al. [8] was set as a negative context and as a parameter (repetition parameter). As visible in the table, nearly twice as much studies report on negative contexts (n=25) in comparison to positive contexts (n=13).

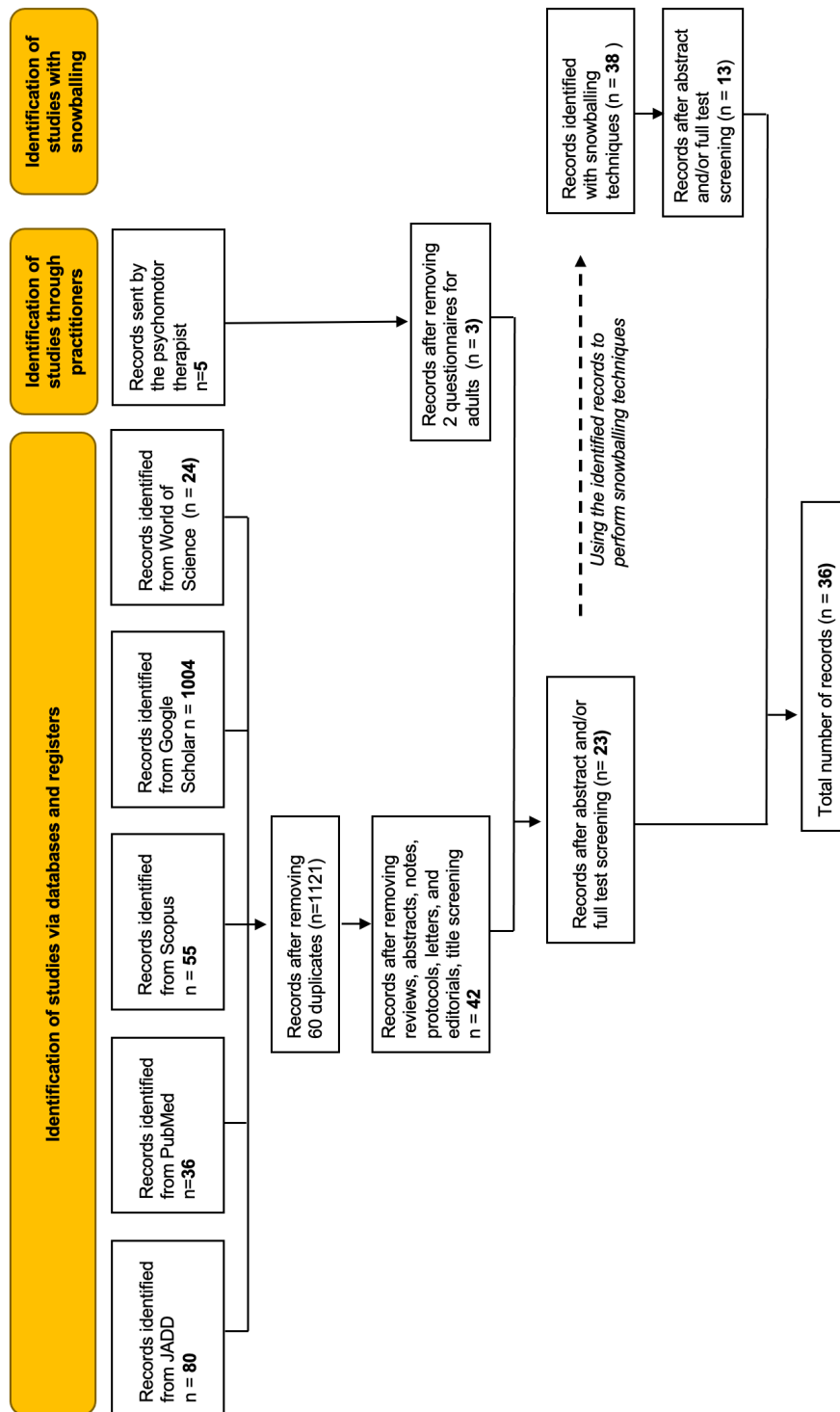


Figure 7.1: Flow diagram of the review selection process.

Table 7.1: Summary of selected contributions (n = 36). **Context:** Semantic sound context, **Params:** Sound parameters, **P:** the study mentions positive sound contexts, **N:** the study mentions negative sound contexts, **A:** the study evokes sound contexts or parameters but precise examples are absent.

Paper (n = 36)	Context	Params
Evaluation/rehabilitation of auditory contexts (n = 8)		
Fodstad et al. [86] (2021)	N	X
Johnston et al. [141] (2020)	N&P(A)	
Cibrian et al. [53] (2018)	P	X
Amir et al. [6] (2018)	N&P	X
Zakari et al. [337] (2017)	N	
Gilbertson et al. [107] (2017)		X
Bhatara et al. [24] (2013)	P	
Koegel et al. [160] (2004)	N	
Influence of environmental auditory parameters (n = 17)		
Irish [137] (2022)	N	X
Garner et al. [94] (2022)	N	X
Caniato et al. [43] (2022)	N	X
Bettarello et al. [23] (2021)		X
Nagib and Williams [213] (2017)	N	X
Kanakri et al. [144] (2017)	N	X
Kanakri et al. [145] (2017)	N	X
Nazri and Ismail [215] (2016)		X
Fernández-Andrés et al. [79] (2015)		X
Mostafa [207] (2014)		X
Mcallister and Maguire [194] (2012)		X
Kinnealey et al. [156] (2012)		X
McAllister [193] (2010)	N	X
Tufvesson and Tufvesson [316] (2009)	X	
Scott [280] (2009)		X
Friedlander [90] (2009)	N	
Mostafa [206] (2008)	N&P	X
First-hand accounts (n = 7)		
Scheerer et al. [274] (2021)	N	X
Pfeiffer et al. [236] (2017)	N	X
Howe and Stagg [133] (2016)	N	X
Kirby et al. [158] (2015)	N&P	X
Ashburner et al. [8] (2013)	N&P	X
Preece and Jordan [242] (2010)	N	
Dickie et al. [70] (2009)	N&P	
Sensory questionnaires for autistic children (n = 4)		
Filipova et al. [81] (2022)	N&P	X
Dunn [72] (2014)	N&P	X
Egelhoff and Lane [74] (2013)	N&P	X
Bogdashina [27] (2005)	N&P	X

7.4.3 Taxonomy coming from the literature

To construct the sound taxonomy, a deductive analysis process was conducted based on categories reported by Amir et al. [6] and Scheerer et al. [274] that were identified during the selection process. It also drew upon Potgieter et al. [241]'s review about hyperacusis in children, as being a valuable resource even if not autism-focused. Our code names were constructed by using similar wordings than the ones used in the selected papers. When the classification became stable, a psychomotor therapist deemed it representative and precised two aspects. First, he highlighted that shouts/cries of

children or babies are most commonly reported. Then, he added two positive contexts, that were absent from our review: Autonomous Sensory Meridian Response (ASMR) sounds¹ (including white noise), and pushing on one's ears to create inner sounds. Table 7.2 presents the emerging taxonomy, being divided into negative and positive sound contexts, and sound parameters. Elements evoked by the therapist are indicated within parenthesis as [PT].

Negative sound contexts split into eight categories: human-produced sounds, school environment, crowded spaces, hairdresser, city, home, nature, and music. Each of them subsumes various subcategories. For instance, the category human-produced sounds subsumes mouth noises, cries, human voice, and human presence. Positive context have seven categories: music, repetition, low, ASMR, nature, auto-produced, and other. Not enough positive sounds were reported to divide them into subcategories. At last, eight sound parameters were identified: intensity, pitch, duration, repetition, combination, unexpected, social, and reverberation. While intensity and combination mainly refer to negative accounts, other parameters relate to both positive or negative accounts depending on individuals.

7.5 Discussion

This study focused on the creation of a sound taxonomy being representative of autistic AAF based on a systematic literature review, and its validation and refinement with a psychomotor therapist. The resulting taxonomy comprises detailed concepts and categories related to semantic negative and positive sound contexts and sound parameters. Thus, it extends previous works by Nagib and Williams [213] and Scheerer et al. [274] which did not provide advanced categorizations [213, 274], only focused on negative experiences [213, 274], overlooked sound parameters [213], or were bounded to the home environment [213]. While some concepts were previously reported by Scheerer et al. [274], we constructed new overarching semantic categories. For instance, *rattling of dishes*, *TV*, *vacuum cleaner*, and *washing machine* previously pertained to four distinct categories, whereas we grouped them in the *home* category, through different concepts (e.g., *household appliances*).

7.5.1 Limits

While our inclusion criteria were adopted for practical reasons, they may have led to exclude potentially relevant papers. In particular, we only considered papers related to children. Future works should thus extend this classification by refining the categories with respect to age differences (e.g., school environment is not relevant for adults). The fact that I was alone in

¹ASMR: Relaxation technique consisting in listening to soft sounds with attention (whispering, blowing, brushing, etc.) in order to give a pleasant tingling feeling.

Table 7.2: Presentation of the sound taxonomy for autistic AAF with respect to negative sound contexts, positive sound contexts, and sound parameters. PT stands for the types of sounds suggested by the psychomotor therapist. Mc: Music.

Cat Subcat		Sounds being identified from the literature
<i>Negative sound contexts</i>		
Human-produced	Mouth noise	People eating (e.g., chewing) [6, 274], breathing [6, 8], snoring [6], sniffing [274], whistling [8, 274], humming [274], squealing [8], coughing [70]
	Cries	Baby/children crying/yelling/shouting/screaming [6, 8, 70, 74, 86, 133, 141, 242, 274, 337, PT]
	Voice	People laughing/nagging [6, 274], singing [81, 141, 274], surrounding voices [8, 43, 74, 158, 213, 274], voice from relative (e.g., high/low pitch [81]) [81, 213]
	Presence	People typing on a computer [8], audible steps [81]
School	Bell	School bell [6, 94, 274, 337], alarms (e.g., fire alarm) [6, 70, 274]
	Classroom	Classroom [6, 274], rustling paper [337], air conditioning/blow heater [72, 90, 144, 145, 193], plumbing (e.g., radiator) [94, 242]
Crowded space	Venues (sport, concert)	Applause [337], whistle [158], buzzer [274], score board [158], acoustic feedback [70], swimming pool [86], ballgames (e.g., bowling alley) [86]
	Human density	Party, assembly [6], voices in corridor [81] shopping/mall [86], restaurant [297], crowd noise [274], church [297], within public transport (e.g., school bus) [242]
	Alerts	Alarms [213]: Checkout till [337], phone ringing [8, 72]
	Background music	Background music at the hairdresser/shops [94]
Hairdresser	Electric	Hair dryer [6, 72, 274], razor [27], hair clipper [27, 297]
	Others	Scissors [27]
City	Explosion-like	Fireworks [6, 70, 86, 158, 236, 337], gunshot (e.g., at state fair) [158], inflated balloon bursting [158], hands clapping [70], other impacts [43]
	Traffic	Traffic noise [6, 8, 81, 145, 213, 274, 337], plane [8], car engine [6], train [337]
	Construction	Drilling [274], hammering [274, 337]
	Sirens	Fire engine, police, ambulance, etc. [6, 72, 81, 86, 141, 236, 274, 337]
Home	Household appliances	Various appliances [213]: robots, kettle whistle, vacuum cleaner [6, 70, 74, 158, 160, 213, 274], washing machine, dishwasher [6, 274], blender [6, 94, 158, 160, 274], hand-mixers [160], lawn mower [6], leaf blower [274],
	Toilets	Hand dryer [6, 8], toilet flushing [70, 74, 158, 160, 274]
	Background sounds	Background sounds [81], devices being on [81], lamps/neon lights [81, 90, 94, 137, 206, 213], branches on windows [8], clock ticking [8, 72, 81, 94], far church bell [81], fridge humming [72], line tapping against a metal flagpole outside [90], diverse rumbling sounds [43]
	TV/Radio	TV programs [6, 8, 72, 74, 274], such as commercials [70]
	Sound toys	Toys making sounds [72, 236]: animals [160], cars [81], objects with triggers [81]
	Other	Door slamming [337], furniture moving [81], rattling of dishes [90, 274, 337], door ringing [213]
	Elements	Thunder [27, 86], water flowing (e.g., waves) [27, 53, 274], rain [213], wind [53],
Nature	Animals	Sounds/calls [27, 43]: dog barking [70, 72, 86, 274, 337], birds [53, 81, 337]
	Mc.	Music [274], loud music [158], piano [8], other (instrument, singing toy) [81]

<i>Positive sound contexts</i>	
Music	Music [24, 206]: cello or clarinet melodies [53], classical music [24], favorite song [8, 70, 86] (e.g., from movie [8]), other objects (e.g., music box, maracas, tambourine, flute, guitar, rainstick, game with triggers, soap bubbles) [81]
ASMR	Various ASMR sounds [PT]: paper torn apart/rustling [72], white noise [6, PT]
Nature	Water flowing (e.g., brook, sea waves), birds, woods, rain [6]
Auto-produced	Inner sounds [72] (e.g., pushing on one's ears [PT])
Repetition	Some repetitive sounds [27] (e.g., heart beat [6])
Low	Low-pitch sound vibrations [27] (e.g., car roaring [158], cello at a low-pitch [53])
Other	Specific sound objects (metallic, plastic, wood), e.g., school material (e.g., pencils) [72, 74, 81], hit/slammed doors [27], traffic, crowd, or other sounds/noises
<i>Sound parameters</i>	
Intensity	Loud sounds perceived more negatively than quiet sounds: Noise level [43, 72, 74, 79, 94, 133, 137, 144, 145, 158, 193, 206, 207, 213, 215]: Loud sound [6, 27, 70, 72, 74, 81, 86, 158, 236, 274] (e.g., music [158]), quiet sound [72, 81, 274]; perceived neutrally [74]
Pitch	High pitch perceived more negatively than low sounds [8, 53, 274] (e.g., harsh/shrill sounds [274])
Duration	Long sounds perceived negatively or positively [81]
Repetition	Repetitive sounds perceived negatively [8, 274] or positively [6, 27]
Combination	Perceived negatively: Ambient noise (e.g., different layers of sound) [43, 79, 94, 144, 193, 194, 206, 207, 236, 274, 316],
Unexpected	Perceived negatively: Disturbed by unexpected sounds [8, 70, 72, 74, 94, 133, 158, 213, 236, 274, 280], unfamiliar [274], unpredictable noise [79], infiltrating noise [94, 145, 193, 194, 215, 316]; Perceived positively: Interesting in sudden sounds (specific objects, songs, voices, intonations) [81]; Neutral perception Egelhoff and Lane [74]
Social	Social sounds perceived more negatively [86], or non-social sounds being preferred [81]; Social sounds perceived positively (e.g., intonations can increase children's interests) [107]
Reverberation	Perceived negatively: disturbance due to echoes and reverberation [43, 94, 137, 144, 145, 156, 206, 207, 213, 215, 280] (e.g., due to hard floor, high ceiling, metal furniture); Perceived positively: sounds in the kitchen or bathroom [27], auto-stimulation with echoes or reverberation [206]

performing the literature review may also have generated inaccuracies due to my preconceptions. Though, this bias was mitigated by the review of the taxonomy by an external psychomotor therapist.

Then, as categories account for the most frequently reported auditory experiences, which often relate to specific contexts, they mainly correspond to domains, or sometimes to sound-producing events. Thus, our categories are not mutually exclusive, making it possible to hear the same sound in different categories (e.g., a phone could be heard in a crowded space or at home). Yet, this taxonomy answers well our primary objective which was to propose a first classification of the sounds linked with autistic AAF. Although it may contain inaccuracies, it encourages future autism research to revise and develop it. Moreover, this new taxonomy is a first intent to draw links

with the field of *acoustic ecology* [98], being situated in a recent connected field that could be called *autism acoustic ecology*.

7.5.2 Perspectives

In our view, our taxonomy has two main potentials: inform future auditory evaluation/rehabilitation strategies, and help autistic individuals and families to put words on their auditory experiences. Though, before to pursue these objectives, future research should focus on two main aspects. First, the taxonomy has to be validated and/or adjusted with autism stakeholders (autistic individuals, families, practitioners). Such a study will be reported in the next chapter, through an online survey. Second, the concepts and category must be ranked to give account of their respective influences, preferably by autism stakeholders. The study presented in the next chapter also focused on this aspect.

Then, while a consensus seemed to appear about a negative perception of loud sounds or a sound combination, other parameters were experienced either positively or negatively depending on individuals. Variations may be explained by individual differences, such as their idiosyncrasies (e.g., ways of reacting to external events) or emotional state (e.g., stressed, scared) [274], with respect to the overall presentation context. Thus, three main research avenues would be worth exploring: if negative or positive patterns of perception exist for autistic individuals regarding sound parameters, if some parameters are correlated, if some sound parameters are responsible for the negative/positive perception of others.

At last, many sounds parameters mentioned in other fields such as acoustic ecology or spatial audio are absent from our review. For instance, studies in acoustic ecology mention parameters such as harmonicity, spectral spread, periodicity, or envelope modulation [123], and spatial audio studies [141] evoke sound positioning, sound movement, and sound distance. While some of the parameters that we identified relate to such aspects (e.g., shrill sounds mentioned by Scheerer et al. [274] relates to harmonicity), future studies should assess if these parameters have really no impact, and why they are nearly absent from autism research.

7.6 Conclusion

In this chapter we have presented a sound taxonomy being representative of autistic AAF, accounting for both negative and positive experiences related to sound contexts and parameters. To build the taxonomy, a systematic literature review was first performed, leading to identify 36 papers. These papers were then analyzed using inductive and deductive methods. The taxonomy was then reviewed, completed, and validated by a psychomotor

therapist. The resulting taxonomy could inform the creation of future auditory assessment and training strategies, benefit to future research focusing on the everyday listening of autistic individuals, and potentially help autistic individuals to better understand their own auditory experiences. Yet, to confirm and generalize these statements, the taxonomy has now to be reviewed, validated, and enhanced by getting insights from more autism stakeholders, including autistic individuals, relatives, and practitioners. The next chapter describes such a process, that was conducted through an online semi-directed questionnaire addressed to various stakeholders.

8 - Validation of the Sound Taxonomy with Autism Stakeholders

8.1 Introduction

The previous chapter reported on the creation of a sound taxonomy being representative of autistic Atypical Auditory Functioning (AAF) based on a systematic literature review. To check if this taxonomy actually matches the lived experiences of autistic children with SLN, a questionnaire was addressed to autism stakeholders, including autistic individuals, relatives, and practitioners. In particular, two main research questions were explored:

RQ1 Would autism stakeholders validate this taxonomy? If not, how to enhance it?

RQ2 How to rank the items of this taxonomy with respect to their respective significance over autistic AAF?

To answer these questions, we presented the taxonomy to 68 autism stakeholders through an online semi-directed questionnaire that we created. This chapter reports on this process. After presenting the method that was used, findings are successively described according to sound contexts and parameters that often induce negative and positive experiences. Limits to this study are finally outlined and perspectives are drawn.

8.2 Method

After presenting the development of the questionnaire, the recruitment process is outlined, followed by the data collection and analysis process.

8.2.1 Development of the online questionnaire

The semi-directed questionnaire is short, taking around ten minutes to complete. It is accessible online to reach a large number of participants with various experiences. It comprises six sections: (G0) informed consent, (G1) sound parameters, (G2) negative sound context, (G3) positive sound context, (G4) demographics, and (G5) ending. After reading the aim of the research and agreeing to participate (G0), participants are asked about the influence of sound parameters (G1), negative (G2) and positive (G3) sound contexts. These three sections start by displaying of the corresponding parts of the classification, through diagrams. They use 1-5 Likert-type scales (from no impact to very significant impact) and optional free-text comments. Answers of the type "I don't know" are not used as the center of our scale is already

expected expected to play a neutral role [142]. In (G4), participants are then asked what “unexpected sounds” meant for them, as this term often appeared in the literature review (see chapter 7) without a clear definition. The questionnaire was posted on *LimeSurvey*¹ (a commercial survey hosting tool) in French, to facilitate further in-situ investigations. Table 8.1 summarizes it.

After the first version of the questionnaire was built, it was sent to six participants from different backgrounds for potential improvements: one research project member who did not participate to its initial construction, two adults without expertise in autism, and three with such expertise. These three experts include one clinical psychologist, a psychomotor therapist, and one medical director. In particular, the psychomotor therapist noted that some audio parameters were too advanced for some participants. Therefore, we created audio files being representative of each sound parameter that they could listen to at the beginning of (G1) if needed². Moreover, the psychologist suggested to add a negative category related to rhythmic music. Thus, the initial music category presented in chapter 7 was broken down into: loud music, high-pitch music, and rhythmic music. Apart from that, participants spotted potential misunderstandings due to specific wordings that we fixed, then allowing us to send the questionnaire. These answers only informed the design and are not considered in the final results.

Table 8.1: Semi-directed questionnaire answered by autism stakeholders about autistic atypical auditory functioning. cmt: comment.

Section	Question	Answer
Go - Consent	–	–
G1 - Sound parameters	Q1 - Rank the sound parameters	1 (no impact) - 5 (very significant impact)
	Q2 - Say if they are representative	yes/mod/no + cmt
	Q3 - Say if some parameters are missing	yes/no + cmt
	Q4 - Describe what “unexpected” means	cmt
	Q5 - Add optional comments	cmt
G2 - Negative sound contexts	Q1 - Rank the negative categories	1 (no impact) - 5 (very significant impact)
	Q2 - Say if they were representative	yes/mod/no + cmt
	Q3 - Rank the negative subcategories	1 (no impact) - 5 (very significant impact)
	Q4 - Say if they are representative	yes/mod/no + cmt
	Q5 - Say if elements are missing	yes/no + cmt
	Q6 - Add optional comments	cmt
G3 - Positive sound contexts	Q1 - Rank the positive categories	1 (no impact) - 5 (very significant impact)
	Q2 - Say if they are representative	yes/mod/no + cmt
	Q3 - Add optional comments	cmt
G4 Demographics	See Table 8.2	See Table 8.2
G6 - Ending	Q1 - Write overall comment (optional)	cmt
	Q2 - Leave email to hear about the results	cmt

¹LimeSurvey: <https://www.limesurvey.org/fr/>

²The sounds can be found at the following link: https://drive.google.com/drive/folders/1YQitPyWJ4kGAoG6NvHLR3YYqPNbefp_6?usp=share_link. They will be made publicly available as soon as the study is published.

8.2.2 Recruitment process

Recruitment was made with purposive sampling through online emails to reach a large number of participants. The study targeted autistic children (4-18 years old) with SLN. As many of them could not express their inner experiences, we focused on three groups of stakeholders: individuals self-identifying as autistic, relatives, or autism professionals. This sampling method was deemed to be adapted in order to provide a global picture, despite inherent limitations, as relatives and professionals could only give interpretations, and autistic individuals with severe communication impairments could not answer it. As practitioners know many children, they were asked to answer by thinking about one of their patients. Moreover, since autism stakeholders can be hard to reach, snowball sampling techniques were used, by inciting participants to tell others, if fulfilling our inclusion criteria.

In total, 461 emails were sent to: 295 associations representing autistic individuals and relatives (e.g., support groups for autistic individuals and families, or organization networks), 160 healthcare structures specialized in autism and neurodevelopmental conditions, six autism resource centers, and three autism professionals. Most contacts were found through autism resource centers' webpages. Emails stated the project rationale, and the importance of collecting accounts from autistic people, relatives, and practitioners. While the number of times the questionnaire was redirected remains unknown, 17 people informed us about such redirections: 14 relatives to their networks (emails and social networks), one autistic person to a LinkedIn support group, one psychomotor therapist to a Facebook group specialized in sensory integration therapy, and one autism resource center to their social networks.

8.2.3 Participants

In total, 68 autism stakeholders participated: 21 autistic people, 35 relatives, and 12 practitioners. Some autistic participants self-identified as having MLN ($n=3$)³, having an autistic child ($n=2$), or displaying significant auditory and olfactory over-sensitivities ($n=1$). Most relatives reported having a child with SLN ($n=19$), MLN ($n=10$), atypical autism ($n=1$)⁴, or ID ($n=2$). Some practitioners answered while thinking about a specific autistic child with SLN ($n=2$). "Mixed profiles" appeared: autistic practitioner ($n=2$),

³Two participants defined themselves as "Asperger". It refers to a diagnosis previously used that corresponds to social interaction difficulties and restricted interests, being close to the mildest forms of interaction and communication difficulties in autism. For the sake of clarity in this chapter, it was sorted as MLN.

⁴"Atypical autism" was a diagnosis previously used to classify children who had some, but not all, of the autism features. It is now part of the umbrella term "Autism Spectrum Condition".

autistic parent (n=1), and a parent being also a practitioner (n=1)⁵. Participants mainly include females (51/68), followed by males (12/68), and five autistic participants who did not self-identify as male or female. Most autistic individuals aged between 18 and 30, relatives are equally distributed over all age ranges, and most practitioners are between 45 and 60. Surprisingly, autistic people often report a low to significant knowledge of their auditory perception. Conversely, relatives and practitioners tend to report a moderate to significant knowledge, with relatives counting the most experts (n=5). About highest diplomas, autistic people are equally distributed between mid school and master, relatives are between high-school and master, and most practitioners hold masters. Table 8.2 summarizes the demographics.

The low response rate was not surprising according to a professional working in an autism center who diffused the questionnaire. Indeed, this population is often over solicited for research purposes, but rarely knows about the research outcomes. On the long term, this situation has discouraged many individuals, making them feel like “guinea pigs”. Thus, we can assume that people who answered were interested in the issues being raised.

Table 8.2: Demographics. mod: moderate.

	All (n=68)	Autistic (n=21)	Relative (n=35)	Practitioners (n=12)
Gender - male/female/other/do not say	12/51/3/2	5/11/3/2	7/28/0/0	0/12/0/0
Age - 0-18/18-30/30-45/45-60/60+ years old	9/11/20/24/4	1/8/8/3/1	8/1/10/13/3	0/2/2/8/0
Knowledge of autistic auditory perception - none/low/mod/significant/expert	2/7/30/20/9	0/5/8/5/3	2/2/13/13/5	0/0/9/2/1
Highest diploma - Mid school/high school/bachelor/master/doctorate/do not say	7/14/16/22/3/64/5/4/6/0/2	3/8/10/10/1/3	0/1/2/6/2/1	

8.2.4 Data collection and analysis

Data were anonymized with identifiers such as IDX (where X is the participant number). As written in the informed consent (G0), no information leading to identify the participants was collected, apart from email addresses when they wanted to be updated about the findings. Doing so, we tried to comply with ethical standards, as stated by the *Declaration of Helsinki* [9].

To analyze the quantitative data, descriptive statistics are used, as well as more advanced statistics to compare the answers from the three participant groups. As the data collected are non parametric, statistical tests include

⁵Mixed profiles are only considered in the qualitative analysis to complement our understanding of the participants' answers. For the sake of clarity, participant groups were separated in the statistics. Hence, since we were focused on everyday life experiences, participants with mixed profiles being autistic were classified as autistic, and those being simultaneously relative and practitioner were classified as relative.

the *Pearson's chi-squared test* to analyse the yes/no or yes/moderate/no answers, and the *Mann–Whitney U test* or the *Kruskal-Wallis test* to analyze the distribution of the participants' rankings. Qualitative data are analyzed using *MaxQDA* software⁶. Both deductive and inductive approaches are used, to sort the phrasings into already existing concepts from the literature, while still enabling to create new concepts and categories by using an inductive approach close to the *grounded theory* [48, 109] (see again chapter 3).

8.3 Findings

Findings are presented following four main subsections. Quantitative answers related to the validation of the taxonomy are first presented. We then describe how the participants ranked the different items of the taxonomy. After that, enhancements to the taxonomy are introduced, drawing upon a qualitative analysis process and the quantitative findings previously stated. Other insights that emerged during the analysis process are finally described. For the three first subsections, findings are structured in three parts, corresponding to negative and positive sound contexts, and sound parameters.

8.3.1 Validation of the classification

8.3.1.1 Negative sound contexts

Most participants found that the categories of negative sound contexts were representative of autistic AAF (G2-Q2): 56(82.5%) said yes, 9(13%) moderately, and 3(4.5%) no. Participant groups answered differently ($\chi^2(4, N=68) = 10.00, p = .04$). Post-hoc chi-squares tests were thus conducted with three paired comparisons (Bonferroni-adjusted significance level of 0.017). They revealed that autistic participants answered differently than relatives ($\chi^2(2, N=68) = 8.21, p = .016$) and practitioners ($\chi^2(2, N=68) = 8.21, p = .016$). Indeed, all autistic participants answered yes ($n=21$), contrary to relatives who answered yes ($n=24$), moderately ($n=8$), and no ($n=3$), and to practitioners who said yes ($n=11$) and moderately ($n=1$).

For most participants, negative concepts were representative (G2-Q4): 56(82.5%) said yes, 6(9%) moderately, and 6(9%) no. All participant groups answered similarly ($\chi^2(4, N=68) = 4.41, p = .35$).

Most participants found that no category or concept was missing (G2-Q5): 52(76.5%) said no and 16(23.5%) yes. All groups answered similarly ($\chi^2(2, N=68) = 3.42, p = .18$).

8.3.1.2 Positive sound contexts

Most participants answered that categories of positive sound contexts were representative: 54(79.5%) answered yes, 5(7.5%) moderately, and

⁶<https://www.maxqda.com/>

9(13)% no. All groups answered similarly ($\chi^2(2, N=68) = 4.27, p = .37$).

8.3.1.3 Sound parameters

According to most participants, categories of sound parameters were representative (G1-Q2): 55(81%) answered yes, 3(4%) moderately, and 10(15%) no. All groups answered similarly ($\chi^2(4, N=68) = 4.79, p = .31$). Most participants found that no parameter was missing (G1-Q3): 53(78%) answered no and 15(22%) yes. All groups answered similarly ($\chi^2(2, N=68) = 1.62, p = .44$).

8.3.2 Ranking the sound taxonomy

8.3.2.1 Negative sound contexts

a) Categories of negative sound contexts

The most reported categories of negative sound contexts (G2-Q1) are *crowded space* (1st), *school* (2nd), and *city* (3rd). The least reported are *home* (7th) and *nature* (8th). A Kruskal-Wallis test reveals that participant groups answered differently ($H(2) = 68.6, p = 1.24e-15$). A post-hoc Dunn's pairwise test (Bonferroni-adjusted significance level of 0.017), indicates significant differences between autistic and relatives ($p < .001$), and practitioners and relatives ($p < .001$). Thus, figure 8.1A presents categories separately for the three groups, being sorted according to the number of reported "strong" and "very strong" ratings.

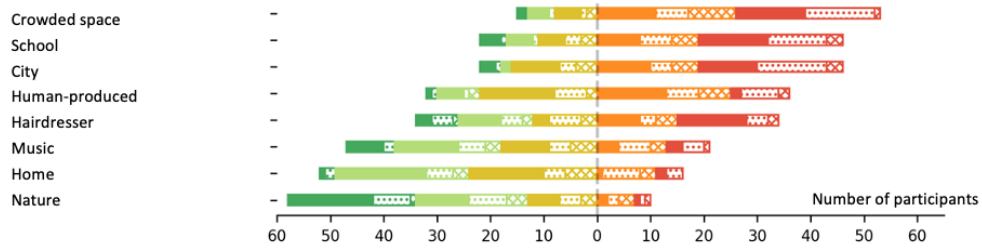
To examine where differences come from, Kruskal-Wallis tests were used for each category. While differences emerged for *crowded space* ($H(2) = 6.72, p = 0.03$) and *nature* ($H(2) = 6.95, p = 0.03$), post-hoc Dunn's pairwise tests (Bonferroni adjustment) revealed no significant differences.

b) Concepts of negative sound contexts

The most reported concepts of negative sound contexts (G2-Q3) are *cries* (1st), *human density* (2nd), and *explosion-like* (3rd). The least reported are *elements* (27th) and *toilets* (28th). A Kruskal-Wallis test reveals significant differences between how participant groups answered ($H(2) = 41.2, p = 1.15e-9$). A post-hoc Dunn's pairwise test indicates significant differences between autistic people and relatives ($p = 9.28e-10$), and practitioners and relatives ($p = .005$). Thus, figure 8.1B displays the concepts separately for the three groups, being sorted according to the number of reported "strong" and "very strong" ratings.

To examine where differences came from, Kruskal-Wallis tests were conducted for each concept. Differences emerged for *presence* (in the category called *human-presence*; $H(2) = 9.64, p = .008$), *playground* (in *school*; $H(2) = 6.08, p = .047$), *traffic* (in *city*; $H(2) = 8.30, p = .016$), *background sound* (in *home*; $H(2) = 13.51, p = .001$), *television* (in *home*; $H(2) = 6.48, p = 0.039$), sound toys (in *home*; $H(2) = 10.85, p = .004$),

A. Categories of negative sound contexts



B. Concepts of negative sound contexts

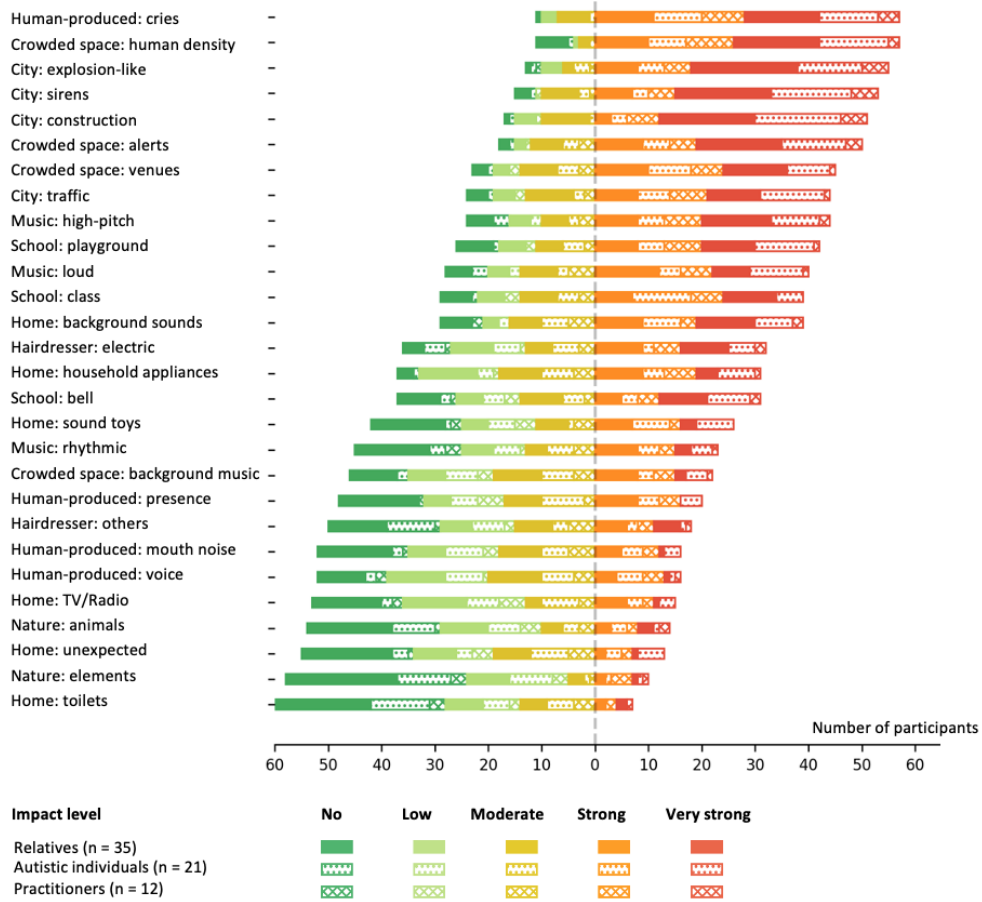


Figure 8.1: Participants' rankings related to the relative impacts of negative sound contexts over autistic AAF. **(A)** Categories of negative sound contexts. **(B)** Concepts of negative sound contexts. The order of presentation of the participant groups within each impact level (e.g., low, moderate) has no relevance over the ranking. Concepts and categories are sorted according to the number of strong and very strong ratings.

and *elements* (in *nature*; $H(2) = 6.46$ $p = .040$). Post-hoc Dunn's pairwise tests revealed significant differences between autistic individuals and relatives for *presence* ($p = .006$), *background sounds* ($p = .001$), *sound toys* ($p = .004$),

and between relatives and practitioners for *elements* ($p=.04$). Details about these discrepancies are displayed on figure 8.2.

When sorting parent categories with respect to the ranking of concepts (G2-Q3), the following classification emerges: *city*, *crowded space*, *school*, *music*, *human-produced*, *hairdresser*, *home*, and *nature*. As this classification differs from the one coming from (G2-Q1), it means the association between categories and concepts remains unclear for the participants, even though they agree on the categories (G2-Q2) and concepts (G2-Q4) being used. This insight calls for refining the taxonomy, as done in the next section.

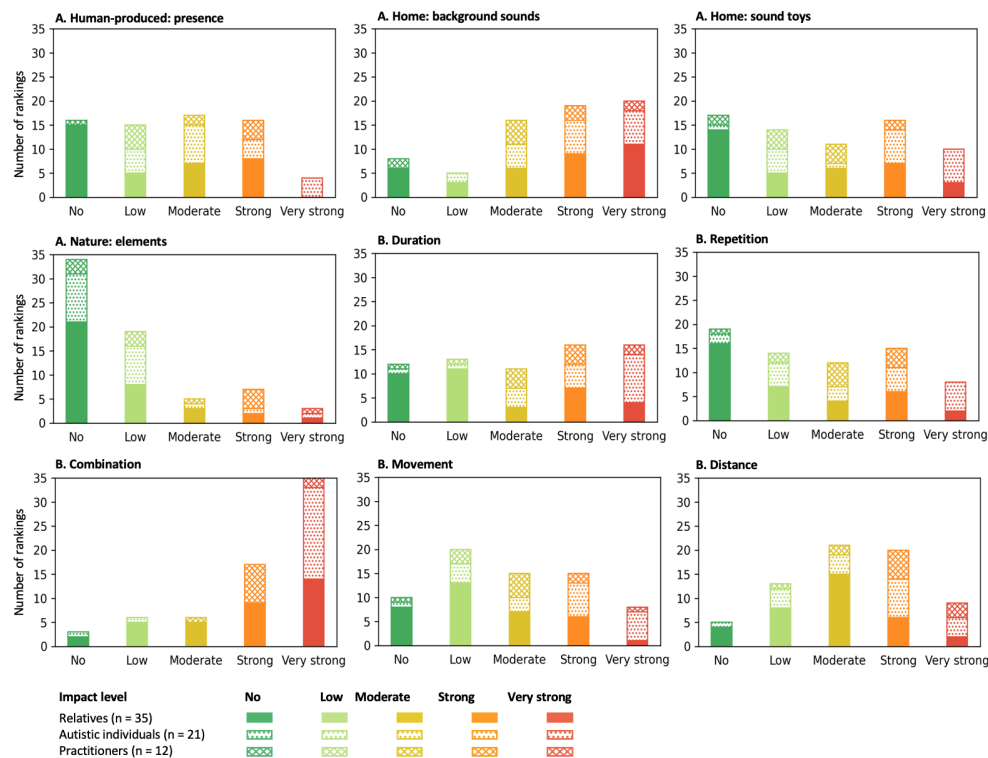


Figure 8.2: Concepts and categories for which a significant relationship was observed between participants groups and the rankings. **(A)** Concepts of negative sound contexts. **(B)** Categories of sound parameters.

8.3.2.2 Positive sound contexts

The most reported categories of positive sound contexts (G3-Q1) are *melodies* (1st) and *repetitive* (2nd). The least reported are *low-pitch* (6th) and *auto-produced* (7th). A Kruskal-Wallis test reveals that participant groups answered differently ($H(2) = 17.31$, $p = 1.74e-4$). In particular, a post-hoc Dunn's pairwise test (Bonferroni adjustment) shows a significant difference between practitioners and relatives ($p < .001$). Thus, figure 8.3

displays the categories separately per participant group, being sorted according to the number of reported “strong” and “very strong” ratings.

To examine where differences came from, Kruskal-Wallis tests were conducted for each category. Statistically significant differences only emerged for *auto-produced* ($H(2) = 6.47, p = .04$). Post-hoc Dunn’s pairwise tests revealed no significant difference.

8.3.2.3 Sound parameters

The most reported categories of sound parameters are *unexpected* (1st), *combination* (2nd), *intensity* (3rd), and *pitch* (4th). The least reported are *positioning* (11th), *repetition* (10th), and *movement* (9th). A Kruskal-Wallis test indicates a significant differences between the participant groups’ ratings ($H(2) = 65.4, p = 6.4e-15$). A post-hoc Dunn’s pairwise test (Bonferroni-adjusted significance level of 0.017) reveals significant differences between autistic and relatives ($p < .001$) and practitioners and relatives ($p < .001$). Thus, figure 8.4 displays the categories separately for the three groups, being sorted according to the number of reported “strong” and “very strong” ratings.

To examine where differences came from, Kruskal-Wallis tests were conducted for each category. Statistically significant differences emerged for: *duration* ($H(2) = 14.7, p < .001$), *pitch* ($H(2) = 6.08, p = .048$), *repetition* ($H(2) = 10.9, p = .004$), *combination* ($H(2) = 12.5, p = .002$), *social* ($H(2) = 6.91, p = .03$), *positioning* ($H(2) = 8.75, p = .013$), *movement* ($H(2) = 11.9, p = 0.003$), and *distance* ($H(2) = 10.4, p = .005$). Post-hoc Dunn’s pairwise tests (Bonferroni adjustment) revealed significant differences between autistic and relatives for *duration* ($p < .001$), *repetition* ($p = .005$), *combination* ($p = .002$), *movement* ($p = .002$), and between relatives

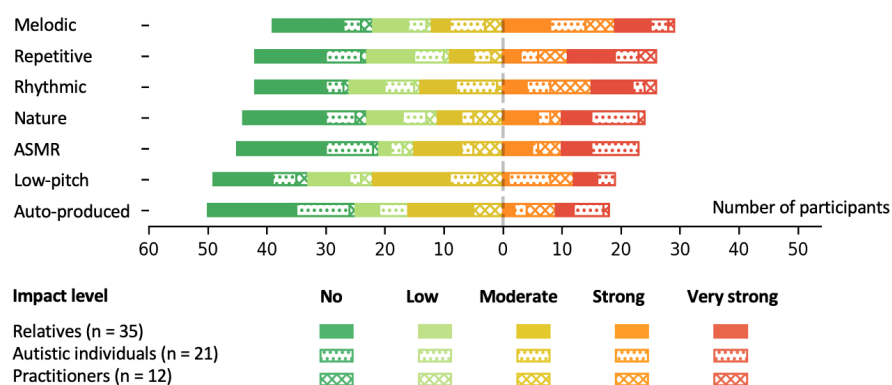


Figure 8.3: Participants’ ranking related to the relative impacts of the positive sound contexts over autistic AAF. The order of presentation of the participant groups within each impact level (e.g., moderate) has no relevance over the ranking. Concepts and categories are sorted according to the number of “strong” and “very strong” ratings.

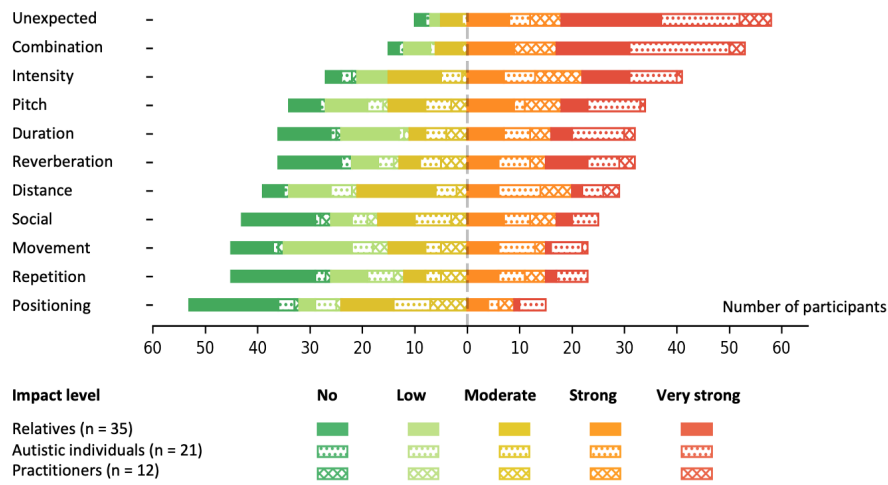


Figure 8.4: Participants’ rankings of the impact of the different categories of sound parameters. The order of presentation of the participant groups within each impact level (e.g., low, moderate) has no relevance over the ranking.

and practitioners for *distance* ($p=.009$). Details about these discrepancies are displayed on figure 8.2.

In particular, overall, *unexpected*, *combination*, *intensity*, and *positioning* were respectively ranked in 1st, 2nd, 3rd, and last position. Yet, autistic people sorted *duration* and *movement* in 4th and 5th, contrary to relatives and practitioners who set them in 6th and 10th. Practitioners also granted more importance to *distance* (4th), than autistic people and relatives (8th).

8.3.3 Improving the classification

Given the final purpose of the taxonomy to facilitate auditory assessments with autistic children, it was refined to better give account of sound contexts and parameters often eliciting negative and positive experiences. To do so, free-text answers were qualitatively analyzed. A deductive approach was performed based on already existing categorizations in the field of acoustic ecology [108, 121, 122, 239, 273] or on studies focusing on hyperacusis in children [241]. An inductive process complemented it, with *semantic similarity techniques* to give account of situational (e.g., location) and semantic (e.g., information about a danger) properties, including the agent producing the sound (e.g., friend) [122]. This process led to built new concept and categories and to adapt existing ones. We mention these changes by writing “*added*” or “*changed*” between parenthesis. We do not write anything when concepts and categories were left unchanged. This process led to cross-classify some sounds into different categories (e.g., some alert sounds are found both in *city* and in *indicators*) to reflect basic human principles

of categorization [122], and to be understandable by various stakeholders. Changes about negative and positive sound contexts and sound parameters are successively presented.

8.3.3.1 Negative sound contexts

We extracted 101 phrasings (101p) for negative sound contexts, from autistic individuals (35p), relatives (62p) and practitioners (4p). They came from answers about negative sound contexts (51p), sound parameters (42p), and positive sound contexts (8p). Negative sound contexts include twelve categories: *city* (19p, *changed*), *human-produced* (17p, *changed*), *indicators* (15p, *added*), *crowded space* (14p, *changed*), *school* (11p, *changed*), *home* (9p, *changed*), *nature* (7p, *changed*), *music* (4p, *changed*), *cries* (2p, *added*), *medical settings* (2p, *added*), *workplace* (1p, *added*), and *hairstresser* (0p, *changed*). Participant groups report them similarly ($\chi^2(20, N=101) = 30.7, p = .06$). Figure 8.5 summarizes this new classification of negative sound contexts. The main insights are detailed below.

City concerns *traffic* (12p), *construction* (3p), and *explosion-like* (3p). *Traffic* splits into sounds experienced as a passenger (e.g., inside the bus) or a pedestrian (e.g., car roaring). *Construction* refers to noisy construction machines (e.g., jackhammer). *Explosion-like* refers to sounds like fireworks.

Human-produced relates to *presence* (10p) and *ASMR*⁷ (3p, *added*). *ASMR* was added to match positive categories, being sometimes negatively reported: “ASMR - annoying unpleasant”. (autistic individual).

Crowded space covers different activities, as their meaning influences perception (e.g., going to work or a concert). *Recreational* activities often appear (7p, *changed*) (this name draws upon Potgieter et al. [241]’s study), being derived from the previous concept called *venues* (*sport, concert*). *Journeys* (2p, *changed*) also appears (e.g., train station). *Human density* was moved into the *socio-emotional* category of sound parameters.

The new category *indicators* includes *alerts* (11p, *added*) (e.g., ringing, alarm clock) and *explosion-like* (3p, *added*) sounds (e.g., fireworks). It was inspired from Schafer [273]’s category called “sounds as indicators”.

The categories *school* and *workplace* can be used interchangeably for evaluation purposes depending on the age of the participant. *School* mainly comprises sounds heard at the *canteen* (5p, *added*): “He cannot bear the canteen since kindergarten, my son is now in high-school and it still makes him sick” (relative). No precise sound was reported for the *workplace*.

About *home*, most categories were kept, apart from the new concept called *technical facilities* (2p, *added*), which refers to domestic equipment such as heaters. The *unexpected* concept was also moved into *socio-emotional*

⁷ASMR: Relaxation technique consisting in listening to soft sounds with attention (whispering, blowing, brushing, etc.) in order to give a pleasant tingling feeling.

category of sound parameters.

About *nature*, the previous sub-categories called *elements* and *animals* were renamed *geophony* (5p, *changed*) and *biophony* (2p, *changed*) following Pijanowski et al. [239]'s classification. *Geophony* refers to sounds from the earth being often negatively perceived (e.g., thunder). *Biophony* refers to animal sounds being often negatively perceived (e.g., barking).

Regarding *music*, we drew a new distinction between *foreground music* (2p, *added*) and *background music* (1p, *added*). As an autistic participant expresses: "I distinguish between background music and music that I listen to and can control".

Cries (2p, *added*) became a category. It was removed from the *human-produced* category as being the most reported sub-context in G2-Q3. While less reported in the comments, participants may have chosen to not repeat themselves.

8.3.3.2 Positive sound contexts

We extracted 27 phrasings for positive sound contexts, from autistic individuals (10p), relatives (14p) and practitioners (3p). Phrasings came from questions about positive sound contexts (17p) and sound parameters (2p). Positive sound contexts comprise five categories: *atypical but known* (14p, *added*), *human-produced* (4p, *changed*), *music* (4p, *changed*), *nature* (3p, *changed*), and *silence* (2p, *added*). *Music* and *human-produced* were added to match negative categories. They respectively encompass the previous categories called *melodic* and *rhythmic*, and the categories *ASMR* and *auto-produced*. Participant groups report the categories similarly ($\chi^2(8, N=27) = 8.91, p = .35$). Figure 8.5 summarizes this new classification of positive sound contexts. The main insights are detailed below.

The category *atypical but known* includes sounds which vary between individuals, e.g, household appliances (3p) or traffic sounds (2p). For instance, a relative says that "traffic sounds can be perceived very positively". The category name was chosen as relatives referred to "atypical" sounds, with respect to established social norms. Though, autistic individuals often referred to them as "known" and "predictable", thus focusing on their *meaning*.

Human-produced gathers three aspects: *ASMR* (n=2, *added*), *storytelling* (n=1, *added*), and *auto-produced* (n=1). Individuals appraise *ASMR* sounds in different ways: "I don't like rustling sound and whispers, but I really enjoy sounds of scalp massages" (autistic individual). *Storytelling* refers to specific narratives told through podcasts or by parents reading stories.

Music gathers different music styles, being highly individual. The new concepts called *foreground music* (4p, *added*) was added to match the classification of positive sounds. It includes different music genres, instruments, and melodies. Preferences vary between individuals depending on sound pa-

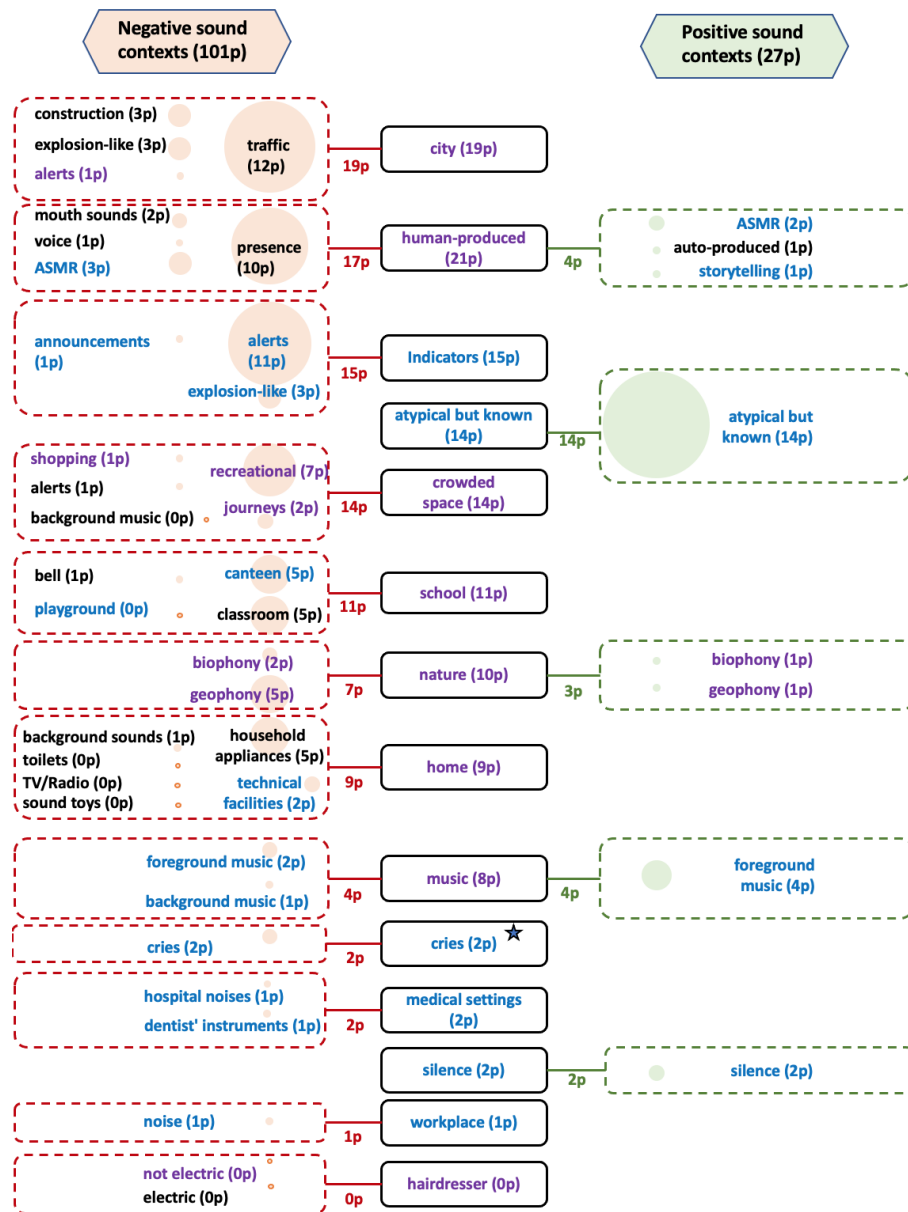


Figure 8.5: New classification of positive and negative sound contexts being representative of autistic AAF. Black rectangles with solid lines represent categories. Rectangles with dashed lines in red and green respectively delimit all the negative and positive concepts pertaining to a specific category. Circles represent concepts, their size being adjusted according to their number of phrasings. Number of phrasings are indicated with Xp (where X is a number). New concept or categories that emerged are written in blue. Concepts that derive from pre-existing ones are written in purple. Concepts left unchanged are written in black. The star displayed next to the category called *cries* signals that this category was the most reported negative sub-context in G2-Q3, even if it hardly appeared in participant's comments.

rameters such as repetition, low-pitch, and rhythm.

Nature includes two new concepts called *biophony* (1p, *added*) and *geophony* (1p, *added*) following Pijanowski et al. [239]'s classification, being added to match the classification of negative sound contexts. They include sounds being often positively perceived, such as bird chirping or rain falling.

8.3.3.3 Sound parameters

We extracted 89 phrasings (89p) about sound parameters, from autistic individuals (31p), relatives (42p), and practitioners (16p). Phrasings came from answers about sounds parameters (29p), and negative (46p) and positive (14p) sound contexts. Four new categories were built: *socio-emotional* (30p), *acoustic* (27p), *agent-related* (22p), and *multimodal* (10p). Participant groups report them differently ($\chi^2(6, N=89) = 14.6, p = .024$). Autistic individuals highlight *socio-emotional* (15p) and *multimodal* (6p), whereas relatives (respectively 9p and 3p) and practitioners (6p and 1p) mention them less. Relatives emphasize *acoustic* (19p), contrary to autistic individuals (5p) and practitioners (3p). Practitioners highlight *agent-related* (6p), contrary to autistic individuals (5p) and relatives (11p). Figure 8.6 summarizes this new classification. The main insights are detailed below.

Socio-emotional subsumes four concepts: *predictability* (17p, *changed*) and *control* (7p, *changed*), *expressive communication* (3p, *changed*), and *social meaning* (3p, *changed*). *Predictability* and *control* were derived from the initial concept called *unexpected*, and the two others from *social*. *Predictability* concerns sound anticipation, being positively perceived: "discomfort is stronger if combined with stress associated to the novelty of a place" (relative). Having no *control* over sound can be perceived negatively: "For a moto coming you expect a sound increase but you worry [...] as it's not controllable" (autistic participant). *Expressive communication* refers to understanding difficulties. *Social meaning* relates to the setting, the agent emitting the sound, and human density.

About *acoustic*, two new sub-categories were created, called *extrinsic acoustic parameter* (19p, *added*) and *intrinsic acoustic parameter* (9p, *added*). Extrinsic parameters include *sound density* (8p, *changed*), *pitch differences* (4p, *added*), *repetition* (6p), *reverberation* (1p), *positioning* (0p), *distance* (0p), and *movement* (0p). *Sound density* stems from the initial concept called *combination*. It refers to combinations of sound events (e.g., two sounds being heard simultaneously) or of sound parameters (e.g., one sound being both loud and high-pitched). This latter description was added following remarks from one autistic participant: "My preferred music format is MIDI -> neutral, flat. I like listening to known music in MIDI". *Repetition* is more often reported than in G1-Q1. *Pitch differences* accounts for autistic enhanced discrimination abilities. Then, intrinsic parameters includes *inten-*

sity (4p), *pitch* (3p), *timbre* (1p, *added*), and *duration* (1p). *Timbre* was added as autistic children express being sensitive to the harmonic content of sounds.

Agent-related gathers individual aspects, with five new concepts: *time-related* (9p, *added*) such as age; *state* (6p, *added*) such as cognitive load or stress; *medical condition* (4p, *added*) such as headaches; *taste* (2p, *added*) such as preferences for specific music styles; and *way of reacting* (1p, *added*) such as overreacting.

Multimodal accounts for a presentation of stimuli over several sensory channels at the same time. This category differs from the concept called *sound density* which relates to auditory-only presentations of sound events. *Multimodal* subsumes two concepts called *visuals* (8p, *added*) and *vibrations* (1p, *added*). *Visuals* relates to simultaneously seeing and hearing stimuli, and *vibrations* to feeling and hearing them. These multimodal impact varies depending on individuals: “a car engine is annoying due its noise and to the vibration [...] shaking the body” (autistic individual).

8.3.4 Other insights

Most participants were enthusiastic about the study: 14 phrasings account for it, 39 participants left their email addresses to know about the research outcomes (13 autistic, 18 relatives, and 8 practitioners), and two associations and one autistic individual emailed us about it. Nine participants stressed its importance, one autistic participant precisising: “if only it could reach decision-makers, particularly regarding urban planning!”. Two participants wrote that they could be contacted again for further information.

Many phrasings concerned *societal possibilities* to better include autistic individuals (n=9), and consider their everyday auditory listening (n=8). The former relates to constructing a more inclusive society (n=6), by making social adjustments. For instance, two participants advise introducing more silent hours in public places, as is already done in some supermarkets (n=2). A call towards more agency was also made, with autistic people wanting to be called “autistic” rather than “individuals with autism” (n=2), or a relative who calls for including more autistic people in research endeavours (n=1). The latter concerns well-being issues related to autistic individuals (n=7) and families (n=1). A parent reports: “noise sensitivity engenders fatigue, one of the main reasons for adaptation difficulties of my children in society”.

Several participants (2 autistic individuals, 3 relatives, 3 practitioners) had difficulties in answering. This was due to answering for a child (n=5), as practitioners “only see them once in a while and in the same setting”, and relatives “can observe strong impacts, [but] nuances are harder to perceive”. Two participants found that categories were bit too heterogeneous, as always dependent on individuals’ idiosyncrasies (n=4). Two regretted the use of forced answer choices, and not having the ability to say “I don’t know”.

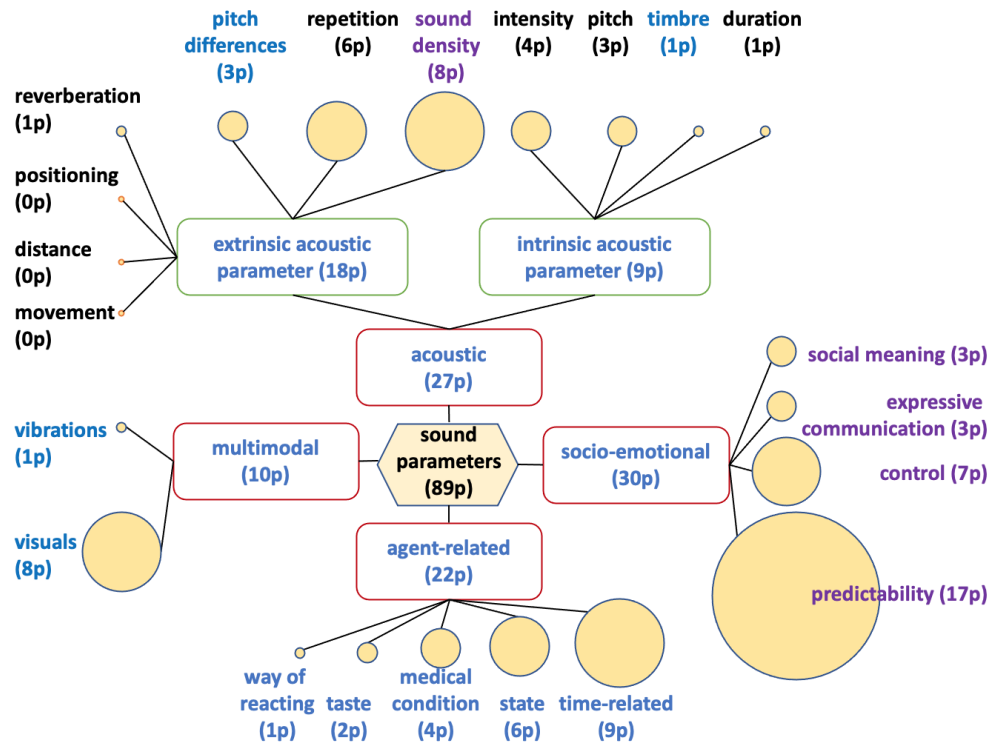


Figure 8.6: New classification of sound parameters being representative of autistic AAF. Red and green rectangles respectively represent categories and sub-categories of sound parameters. Circles represent concepts, their size being adjusted according to their number of phrasings. Number of phrasings are indicated with Xp (where X is a number). New concept or categories that emerged are written in blue. Concepts that derive from pre-existing ones are written in purple. Concepts left unchanged are written in black.

At last, a speech therapist highlighted the difficulty to conduct sensory evaluations with non-verbal children: “sounds can come from a barely audible thing and it is not easy to identify it when the autistic person is non-verbal”.

8.4 Discussion

Participants validated the relevance of our previous sound taxonomy which intended to be representative of autistic AAF and was reported in chapter 7. They ranked the relative impact of negative and positive sound contexts and sound parameters in different ways, with significant discrepancies between the answers from autistic and non-autistic individuals (especially relatives). This insight complements the findings from previous research [43, 297]. Indeed, Caniato et al. [43] stated that assessments of sensory-induced discomfort largely differs when conducted by parents or prac-

titioners. Stiegler and Davis [297] also reported differences between autistic people and relatives, through the case of the mother of an autistic child who was convinced that her child's fear of haircuts came from hyperacusis, although it came from socio-emotional causes. These differences prompt to better include autistic individuals in the design of future auditory assessment strategies [230], to ensure that they are adapted to their specific needs.

The analysis of participants' comments led to construct new concepts and categories and to adapt others. The parts of the new resulting taxonomy related to sound contexts and parameters are respectively displayed on figure 8.5 and 8.6. In particular, new negative (indicators, cries) and positive (atypical but known) sound contexts were built, as well as new categories of sound parameters (e.g., multimodal). About parameters, extrinsic parameters (e.g., sound density) were largely reported, although the literature mainly refers to intrinsic acoustic parameters (e.g., intensity), apart from the findings from Scheerer et al. [274]'s study. Participants also precised that some categories of sound contexts or parameters (e.g., atypical but known) can be positively or negatively experienced depending on individuals and on the presentation context. For instance, a mother of an autistic child expresses that "repetitions are positive but can lead to self-stimulatory behaviours."

8.4.1 Differences with the literature

Discrepancies appear between the importance given by stakeholders and by the literature to specific sound contexts and parameters.

About negative sound contexts, participants barely report toilet sounds, whereas the literature often mentions it (see again table 7.2).

As little research currently focuses on the positive auditory experiences of autistic children to our knowledge, this study provides one of the first categorization of such experiences based on participant's answers.

About sound parameters, stakeholders deemed *reverberation* and *distance* to have a significant impact over autistic AAF, although they are rarely considered in current auditory assessments. Future studies should thus investigate the influence of diverse aspects of reverberation, such as first reflections, late reflections, or room size. Moreover, while auditory exams often focus on intrinsic acoustic parameters, the most reported concepts of sound parameters are *predictability*, *time-related*, *sound density*, and *visuals*. In particular, *visuals* accounts for a multimodal presentation of stimuli over several sensory channels. *Sound density* refers to a combination of sound events (e.g., two sound stimuli) or parameters (e.g., one loud and high-pitch stimuli).

Regarding other insights, the call that participants make towards more agency (e.g., participants wanting to be called autistic, and to take more part in research endeavours) reminds of the fourth wave HCI (see section 2.3.1).

8.4.2 Limits

This study also displays some limits. Whilst the inclusion and exclusion criteria were adopted for practical reasons, it could have led to exclude potentially relevant papers. Then, as this study was performed online, findings are subjected to the bias of people willing to participate who may be not representative of all stakeholders. The online experimental context also prevented us from understanding the context in which people answered (e.g., physical, emotional) and from collecting detailed answers. As remarked by some practitioners, stakeholders answered differently: autistic participants referred to their own lived experiences, parents spoke for their own child, and practitioners may have answered while thinking of a patient with significant auditory particularities (instead of autistic patients with more usual sensory profiles). Then, some participants may have been confused when answering: speaking of contexts in questions related to parameters and conversely. Some participants also regretted to have to pick an answer instead of being able to say “I don’t know”. Future studies may include a preliminary training to clarify what is meant by sound parameter and context, and the possibility to use an answer of the type “I don’t know”. At last, many participants started answering the questionnaire but stopped half-way, their answers not being collected. While reasons for such droppers remain unknown, they may have stopped due to thinking that the questionnaire was too advanced for them, or due to the absence of an “I don’t know” answer.

8.4.3 Future perspectives

To explain the underlying causes of autistic AAF, three theories were proposed in the literature [225, 297, 331], physiologic, psychoemotional-behavioural, and enhanced perceptual functioning (see section 2.1.3.2). The work reported in this chapter also suggests the impact of *multimodal* aspects (e.g., vibrations, sounds with visuals) over autistic AAF. Being little explored in the literature to our knowledge, this issue deserves further investigation.

The four categories of sound parameters which appeared (i.e., acoustic, co-modalities, socio-emotional, agent-related) seem to have close ties. For instance the sound of a high-pitch sound at home during a pleasant family gathering may be experienced differently than the same sound heard in a crowded place outside home. Future studies should thus investigate how these parameters relate to each other. Moreover, such parameters may influence the perception of sound contexts. For instance, an unknown or known voice may be perceived in different ways. The difference between how foreground and background music are perceived may also refer to the control parameter (within *socio-emotional* category). This aspect calls for more investigation regarding the mutual influence of sound contexts and parameters.

As age largely influences everyday sound perception [122], the taxonomy

provides a basis that needs to be precised following different age-groups (e.g., children often experience school sounds whereas adults do not).

8.5 Conclusion

This study had two main research questions regarding the possibility to validate and enhance the sound taxonomy related to autistic AAF that was previously built and is presented in the previous chapter (RQ1), and to rank its items according to their respective significance (RQ2). To address these questions, an online semi-directed questionnaire was devised and answered by 68 autism stakeholders, including autistic people, relatives, and practitioners. Statistics were used to analyze quantitative answers, added to inductive and deductive qualitative methods to analyze participants' comments. Regarding RQ1, findings validated the relevance of our previous taxonomy. Comments then enabled to adjust it by creating or adapting categories and concepts. Participants also pointed out that some sound contexts and parameters can induce positive or negative experiences depending on individuals. Figures 8.5 and 8.6 summarize the final state of the sound taxonomy. About RQ2, participants ranked the different items of the taxonomy (see again figures 8.1, 8.3, and 8.4), with answers differing between autistic and non-autistic individuals (particularly with relatives).

To overcome the common challenges that practitioners face when working with autistic children with SLN, a new AR auditory assessment for such children can now be designed based on the sound taxonomy that was created. The objective is to leverage the AR potential to provide more ecological conditions while making children more agent. The next chapter reports on this process, with the design of the AR application called *ASD_AudioEval*, and of an experimental protocol intended to conduct future testing with autistic children in collaboration with a psychomotor therapist.

9 - *ASD_AudioEval*: An AR Application to Assess the Auditory Perception of Autistic Children with Severe Learning Disabilities

9.1 Introduction

A sound taxonomy being representative of autistic AAF was previously built based on a systematic literature review (see chapter 7) and an online questionnaire addressed to autism stakeholders (see chapter 8). This chapter reports on the design of an AR auditory assessment strategy for autistic children with SLN based on this taxonomy, which intends to increase the ecological validity of existing auditory assessments while making autistic children more agent. This design process is driven by two main hypotheses:

- H1** : Using a spatial audio AR application could increase the ecological validity of the auditory sections of sensory profiles conducted by practitioners with autistic children with SLN, and in particular of the *Sensory Profile 2* [72]. More specifically, this application could support the assessment of Decreased Sound Tolerance (DST) and atypical sounds preferences towards various semantic contexts (**H1a**), intrinsic acoustic parameters (**H1b**), and extrinsic acoustic parameters (**H1c**).
- H2** : Providing autistic children with SLN with more control over the auditory assessments could increase the validity of their results.

To design such an AR auditory assessment drawing upon H1 and H2, a user-centered design process was conducted with a Psychomotor Therapist (PT). This process led to design the AR application called *ASD_AudioEval* and the first version of an experimental protocol intended to pursue future testing with autistic children. A preliminary step first consisted in creating auditory stimuli being representative of autistic AAF. This led to build the soundbank called *ASD_SoundBank* based on our taxonomy. Due to time-constraints during the thesis, in particular related to the development of the taxonomy, the development of *ASD_AudioEval* is still ongoing. When it will be finished, a participate design process involving autistic individuals will need to be conducted to refine the design of the application and protocol before to conduct field testing with autistic children.

After presenting the creation of *ASD_SoundBank*, the design of *ASD_AudioEval* is presented, followed by our experimental protocol. At last, we discuss this work and draw future perspectives.

9.2 Creation of the soundbank *ASD_SoundBank*

The soundbank *ASD_SoundBank* was created based on the sound taxonomy being representative of autistic AAF that was constructed in chapters 7 and 8. It contains sounds often eliciting negative or positive experiences, and pertaining to various semantic contexts (e.g., traffic) and parameters (e.g., pitch). Each sound item is associated with multiple sound files, to minimize potential habituation effects for the child when *ASD_SoundBank* is used as part of auditory assessment strategies.

Sounds were collected or created through various ways. I gathered some of them heuristically based on my personal experience as a professional sound engineer from publicly available resources or research datasets being referenced in previous works in acoustic ecology [51, 122]. Such resources include *freesounds.org* (as in [141, 337]), the *Urban Sound Datasets*¹ [268], and *BBC Sound Effects*². I also recorded some sounds, and recreated others by using the procedural audio system called *Nemisindo*³, the software called *Soundpaint* with the “ASMR sound library”⁴, and the *Logic Pro X* digital audio workstation for music melodies.

After sorting sounds into folders according to our taxonomy, I performed four actions. First, audio files were shortened to ten, five, and one second files based on their original duration. Short and similar durations were chosen to facilitate future comparisons during auditory assessments. Second, background noise was partially removed from the audio files so that they can then be used in actual audio assessments with autistic individuals. Third, all files were normalized to -20dBFS. Fourth, all files were exported to a separate folder with the same structure than the initial folder. To perform noise reduction, the *noisereduce 2.0.1* python library was used [266], which employs spectral gating noise reduction. Other processes were performed using the python libraries called *pydub* and *scipy*.

To keep track of audio files, an excel document was created which contains all metadata about sound properties (e.g., name), contexts (e.g., location), parameters (e.g., intensity), and common appraisal (e.g., enjoyable). To be usable in our application *ASD_AudioEval* and in future applications, an XML file was generated which describes how the files are organized. This file was built using the python libraries *openpyxl* and *yattag*.

The resulting soundbank *ASD_SoundBank*, and all the scripts above-mentioned, can be found at this link: https://drive.google.com/drive/folders/1e90jrV7rhwwVXaSCyvGiMPN-3tYZaMNo?usp=share_link⁵.

¹Urban Sound Dataset: <https://urbansounddataset.weebly.com/>

²BBC Sound Effects: <https://sound-effects.bbcrewind.co.uk/>

³Nemisindo: <https://nemisindo.com/>

⁴Soundpaint software: <https://soundpaint.com/>

⁵This link will be replaced by a public github link as soon as the study is published.

9.3 Design of *ASD_AudioEval*

The AR application *ASD_AudioEval* intends to deliver more ecological auditory assessments for autistic children with SLN in comparison to current auditory assessments, while making them more agent. A user-centered design process was conducted with a PT to decide on a first version of the environment, interactions, and activities, that are successively presented below. Before to actually be used with autistic children, they will need to be refined through a participate design process involving autistic individuals, as discussed in section 9.5.2.

9.3.1 Environment

The child sees an AR neutral individualized visual stimuli at the sound position through a tablet (e.g., loudspeaker). AR is preferred over VR based on the findings from our interviews (see chapter 3), to allow children to see and hear their real environment and practitioner, as well as virtual audiovisual elements. Doing so, we aim at minimizing the potential bias associated with the setting novelty, for instance related to distress or over-arousal. Thus, a tablet is used rather than a headset, as many children already know what a tablet is. Moreover, AR seeks to present multisensory stimuli in more ecological conditions than traditional auditory assessments. Sounds are represented by a neutral individualized image to prevent from inducing potential fearful reactions. Other soothing visuals are visible depending on activities (see below), inspired from *MagicBubbles* (see chapter 4): soap bubbles, individualized image (e.g., cartoon character). The AR setting is displayed on figure 9.1A.

ASD_AudioEval uses binaural audio rendering (see section 2.4.1.2), to allow children to hear sounds in the 3D real space and to prompt them to localize them by using the tablet, by looking for their corresponding AR image. Sounds come from *ASD_SoundBank* to cover various semantic contexts (e.g., school) and intrinsic acoustic parameters (e.g., pitch). They are automatically selected depending on activities. Various extrinsic acoustic parameters are available. They include three distinct reverberations, which intend to cover situations being commonly reported in the answers to our questionnaire about autistic AAF (see chapter 8): reflective large room (e.g., canteen), reflective small room (e.g., bathroom), and “neutral” space (e.g., office). Moreover, AR capabilities afford to adjust 3D sound positioning and movements, inspired from our taxonomy. This enables to account for situations where sounds are both heard and seen, or only heard (e.g., front, left, right, back), as well as to check how sound movements affect autistic users (e.g., idle, slow, fast). Sounds can be heard alone or in combination with others.

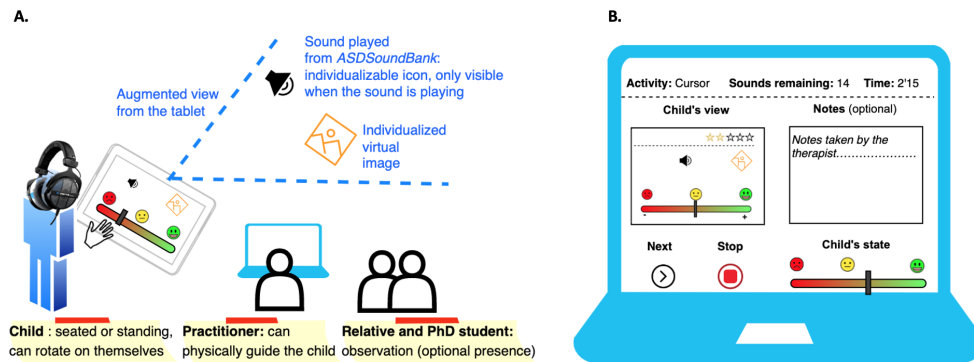


Figure 9.1: Diagram of the environment and interactions in *ASD_AudioEval*. **(A)** AR view seen by the child when manipulating the tablet (example of the cursor activity). **(B)** Therapist's interface on a computer to monitor and control the activities' unfolding (example of the cursor activity)

9.3.2 Interactions

The child interacts with a cursor or buttons on the tablet depending on activities. To be understandable for children with ID, simple action-reaction relationships are used, as well as smileys at the ends of the cursor to represent extreme emotional states. To precisely adjust the sound distance and positioning with respect to the child, *ASD_AudioEval* is intended to be used at a fixed position in space. Though, the child can either sit or stand, as they wish. Moreover, they are encouraged to look for the sounds being heard by rotating on themselves.

Practitioners manipulate a user interface on a computer to: (1) select activities; (2) manage the activities' unfolding to match the child's pace; (3) monitor what the child perceives in real-time; (4) assess the child's experience through note-taking, questionnaires, ratings of the child's pleasantness; (5) stop everything if needed (e.g., over arousal) (see figure 9.1B).

9.3.3 Activities

ASD_AudioEval includes three successive activities inspired from usual sensory profiles [27, 72, 81]: *free-play*, *cursor*, and *executive*. The three activities are represented on figure 9.2.

9.3.3.1 Free-play activity

Free-play intends to get the child used to the AR setting in terms of stimuli and equipment. Various stimuli are displayed: image representing the sound, soap bubble, and individualized image. The practitioner can support exploration (e.g., physically) and adjust the activity duration accordingly.

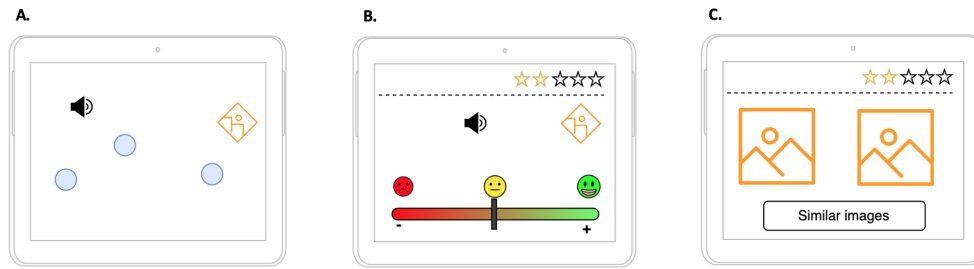


Figure 9.2: Diagram of the activities in *ASD_AudioEval*. **(A)** Free-play activity: this activity intends to get the child used to the AR setting. **(B)** Cursor activity: this activity seeks to assess sound pleasantness and thus to rank the child's preferences and difficulties in terms of semantic contexts, intrinsic parameters, and extrinsic parameters. **(C)** Executive activity: this activity seeks to assess the influence of semantic contexts, intrinsic parameters, and extrinsic parameters over the child's attention.

9.3.3.2 *Cursor activity*

The *cursor* activity seeks to assess sound pleasantness and thus to rank the child's preferences and difficulties through three successive tasks focusing on semantic contexts (cur.1), intrinsic parameters (cur.2), and extrinsic parameters (cur.3). Children use a cursor to rate their perceived pleasantness, so that to collect dynamic insights, inspired from previous studies in the field of acoustic ecology [10]. This method was preferred over the four following methods. First, rating their preferences with likert-type scales as in Zakari et al. [337]'s study would have only provided static accounts. Second, using head turns to infer the child's preference as in Dawson et al. [61] and Paul et al. [233]'s studies would not give control to the child. Third, interactive button press to trigger sounds based on children's preferences as in Gilbertson et al. [107]'s study only affords using a limited number of sounds. Fourth, using brain-computer interfaces as in Cibrian et al. [53]'s study is bulky and possibly not tolerated by some children.

After each sound is heard, the therapist also rates their interpretation of the child's pleasantness using a cursor, and can add comments. They then trigger the next sound when the child is ready. If meaningful, they give the child a star after five sounds, the goal being to collect five stars when finishing a task. The three tasks are as follows:

- cur.1 *Semantic sound contexts* (6mn): 36 sounds are randomly selected among the 18 most reported concepts of sound contexts from our taxonomy, based on our questionnaire's answers, so that each context can be heard with two different sounds. In this set: 28 sounds are expected to be experienced negatively, and eight positively. A comfortable audio level (expected to be around 50-60dB) is set by the practitioner in agreement with the child and their relative (see section 9.4.2). The task starts with a training over two neutral stimuli (outside the set).

- cur.2 : *Intrinsic acoustic parameters* (5mn): Four sounds assessed as neutral during *cur.1* are heard: two being high-pitch, and two low-pitch. Each sound is heard multiple times with a gradual intensity-increase of 5dB steps, starting from a low level (40dB). This process aims at addressing hyperacusis, inspired from common audiology practices [67, 153]. It stops when the therapist observes some discomfort, when the child expresses it, or beyond 90dB, to remain below the acoustic risk threshold.
- cur.3 : *Extrinsic acoustic parameters* (8mn): Three stimuli assessed as neutral in *cur.1*, and differing from *cur.2* are heard with various parameters: three reverberations, four positions, and three movements. They are then heard simultaneously. Presentation order is randomized, the sound level being the same as in *cur.1*.

9.3.3.3 Executive activity

This activity seeks to assess the influence of semantic sound contexts (ex. 1), intrinsic acoustic parameters (ex. 2), and extrinsic acoustic parameters (ex. 3) over the child's attention. Drawing upon Wetzel et al. [328]'s study, the child's reaction times is measured when completing a simple visual discrimination task in the presence of sound distractors. Two images are visible which change every four seconds. Children are told to perform fast and correct button presses only when images are similar while ignoring sounds. Distractors start 500ms before the images change. They are selected based on the findings from the *cursor* activity. Children get a star if they answer correctly within a two-second window. Otherwise, the therapist can still decide to give them one to motivate them. The activity starts with a one-minute training without distractors, followed by one of the following tasks:

- ex.1 *Semantic sound contexts* (7-8mn): Fourteen sound distractors corresponding to various semantic contexts (liked-disliked; long-short) are used. Liked sounds are first heard to prevent from inducing a saturation effect. Then, to avoid generating over-arousal, an enjoyable sound is heard between every three disliked sounds.
- ex.2 *Intrinsic sound parameters* (7-8mn): Four sound distractors previously assessed as "neutral" and displaying various intrinsic sound properties are used: two being high-pitch, and two low-pitch. Only neutral sounds are used to make sure that children's reactions to the sounds are only caused by variations of intrinsic parameters. Intensity is gradually increased as in *cus.2*.
- ex.3 *Extrinsic sound parameters* (7-8mn): Three sound distractors previously assessed as "neutral" are used, while modulating reverberation,

sound positioning, and movement. Only neutral sounds are used to make sure that children’s reactions to the sounds are only caused by variations of extrinsic sound parameters.

9.3.4 Data logs

After each task, the therapist rates their perception of the child’s pleasantness, and can write additional observations. They also complete short questionnaires that we devised based on common sensory profiles [27, 72, 81]: *ASD_AudioEval_QInter* after each task and *ASD_AudioEval_QEnd* at the end of the *executive* activity. Questionnaires are summarized in tables 9.1 and 9.2. Answers consist in five-point Likert-type scales (never, rarely, sometimes, often, always) and optional comments. Results are logged in csv files, being human-readable to facilitate future analysis.

Table 9.1: Questionnaire *ASD_AudioEval_QInter*. Under: Under-sensitivity. Over: over-sensitivity, Ref.: References, Cat.: Category, Seeking: Sensory Seeking, I: item.

Index	Ref.	Cat.	Question
QInt1	[27, I66], [64, under],[72, EN8]	Under	Looking for an increase of auditory feelings by making noise by themselves (e.g., shouting, grinding teeth).
QInt2	[27, I59],[64, over]	Over	Trying to avoid/decrease auditory stimulation (e.g., pushing one’s ears, making noise to cover other sounds).
QInt3	[27, I67]	Pain	Getting angry towards specific sounds.
QInt4	[27, I68]	Pain	Trying to destroy/break sound objects.
QInt5	[27, I69]	Seeking	Getting fascinated with some sounds.

Table 9.2: Questionnaire *ASD_AudioEval_QEnd*. Under: Under-sensitivity. it.: items.

Index	Ref	Category	Question
QEnd1	Chapter 5	State before	The child looks tired.
QEnd2	Chapter 5	State before	The child looks anxious.
QEnd3	Chapter 5	State before	The child looks in good shape.
QEnd4	Chapter 5	State before	The child looks happy.
QEnd5	[64, under it.], [72, SE6-7]	Under	The child looks non reactive to sounds.
QEnd6	–	Other	Are there some elements missing? If yes, which ones?

9.3.5 Apparatus & Development

The child uses a tablet *Samsung Tab S7*. To facilitate binaural externalization, the open-back headphones *beyerdynamic DT-990 Pro* are used [210], as well as the Bluetooth head-tracker *WitMotion BWT901CL* to adapt the auditory scene based on the child’s head movements [259] while avoiding physical discomfort. The therapist runs the application from their personal computer. This setup is chosen to be quickly mounted/dismounted and affordable, in line with clinical constraints observed during my previous studies at the day hospital and conservatoire, or mentioned in previous works [230].

ASD_AudioEval is being developed with *Unity3D* software. Audio rendering is handled by *Wwise*. Spatial audio capabilities are handled by *Google Resonance Audio*.

9.4 First version of an experimental protocol

To validate our two main hypotheses, the first version of an experimental protocol was devised in collaboration with a PT. It is presented below. Before to actually be used with autistic children, it will then need to be refined and validated through a participative design process involving autistic individuals, as well as validated by the ethics committee of our university, as discussed in section 9.5.2. This participative design process is of primary importance to check if autistic individuals would agree with the research choices being made, and to better adjust the protocol according to the needs and wills of autistic people, relatives, and practitioners.

9.4.1 Intended participants

Pre-tests include six non-autistic children and six autistic children with MLN without ID (minimum). Tests include twelve autistic children with SLN (minimum). For the pre-tests, autistic participants and neurotypical peers are recruited per email. For the tests, autistic children are recruited by the PT among his patients, or through autism associations he takes part of, or through messages on social networks through others groups of parents (e.g., Facebook). Several inclusion criteria are used: children must have a confirmed autism diagnosis (e.g., ADOS-2 [175]), be older than nine years old to prevent risks linked with exposition to screens, and present an atypical auditory functioning. A 3:1 male to female ratio is used to match the ratio being observed in the overall autistic population [174]. Children with features possibly hindering the conduct of the experiment are excluded, e.g., severe over-sensitivity other than auditory (e.g., to light). Participants are not paid for their participation.

9.4.2 Protocol

9.4.2.1 Before the experiment

PT will present the protocol and objectives to the child and relatives. The child (if possible) and their relative will complete a consent form. To support the child's understanding and ability to give or not their consent, explanations will be adapted based on their communicational abilities, by using an Augmentative and Alternative Communication (AAC) system (e.g., pictures, gestures). To do so, several versions of the consent form using different AAC systems will be prepared in advance through participative design sessions with autism stakeholders mainly including autistic individuals (see section 9.5.2), as well as preliminary discussions with the child's relatives.

After agreeing to participate, children's evaluations about autism "severity" will be made visible to the investigators (e.g., ADOS-2). If not recent enough according to the PT or absent, a new evaluation will be performed. The PT will then conduct Dunn [72]'s sensory profile to serve as a comparison point for our study, and ask about an individualized appealing image to include in the application. Before the first pre-test, a 45-minute presentation of *ASD_AudioEval* will be given to the PT.

9.4.2.2 During the experiment

The experiment will consist of one session with each child led by PT. A relative knowing well the child will be present, to secure the child and help in assessing their state. Sessions will take place at the PT's usual workplace (e.g., medical office). Though, if potentially inducing too much distress, alternate solutions will be offered, e.g., conducting sessions in a more familiar environment (e.g., at home). This issue will be discussed through future participative design sessions involving autistic individuals (see section 9.5.2). In all cases, the setting will be previously cleared from any potentially distracting stimuli for the child (e.g., bright lights). The child's educator, a clinical intern, or myself may come to sessions, in accordance to common clinical ways of working, but only if the child agrees (or a relative knowing well the child).

At the start, PT will greet the child and relative, introduce the setting, and switch on the tablet. Then, the child will complete four tasks. To keep the session time below thirty minutes, the PT will make up three groups of children (grp1, grp2, grp3) of similar size (5 children minimum) and developmental age. First, the child will get used to the system with the *free-play* activity. After that, the PT, in agreement with the child and relative, will assess a comfortable sound level for the child. To that end, he will display a neutral sound for them (chosen with them beforehand) at a very low intensity and gradually increase its level by 5dB steps until the child indicates that a comfortable level has been reached (the level is expected to be between 50dB and 60dB, and will not exceed 65dB). If no sign is given, the level of 55dB will be used. Then, the child will perform the tasks cur.1, cur.2, cur.3, and one executive task (i.e., grp1 does ex.1, grp2 ex.2, and grp3 ex.3). Before each task, PT will explain how it works, by using a communication system being meaningful to the child (e.g., pictures). At any time, the child or relative will be able to ask questions or stop the experiment without providing explanations, as detailed in the consent form. During each task, the therapist will stop the stimuli as soon as he observes any sign of discomfort, or after any requirement made by the child or relative. After each task, the child, the PT, or the relative, will be able to ask for a short break without providing explanations, during which the child can do whatever they want without the tablet.

For the sake of our test, a fixed set 36 ten-second sounds will be used. Sounds are chosen to cover various semantic sound contexts and parameters being most often reported as negative or positive, which emerged from the analysis of our online questionnaire (see chapter 8). Sounds which appraisal often varied between individuals are excluded (e.g., voice, ASMR, and *atypical but known* category). This set of sounds is summarized in table C.1 in appendix. All sessions will be filmed if agreed on the consent form.

9.4.2.3 After the experiment

For pre-tests, after the PT completes the last questionnaire, a short semi-directed interview (less than ten minutes) will be conducted by myself with the PT, the relative, and the child. It will be recorded (if agreed on the consent form), and will aim to collect their insights so that to refine our application and protocol. In particular, four questions will inquire about: the usability of the application, its perceived efficiency, ethical considerations to minimize discomfort, and potential design improvements. A final question will ask about additional thoughts that the child, relative, or the PT would like to mention. After all sessions, in a second step, I will look at the videos to take notes of spontaneous reactions (verbal and non-verbal) from the child, relative, and PT.

9.4.3 Data collection and analysis

Multiple data sources will be collected to mitigate the bias associated with each source. They will include: the child's answers with the cursor and buttons, the child's reaction times, notes of spontaneous reactions from the child, relative, and PT (verbal and non-verbal), the PT's answers (questionnaire, cursor), the interview (for pre-tests), video recordings, movements of the tablet, and physiological data (heart rate variability) if the child accepts to wear sensors. Tracking the position of the tablet aims at pinpointing potential anxiety-related behaviours. To do so, an external camera will be used as well as data logs coming from the inertial sensors of the tablet. Then, collecting physiological data can bring additional insights when working with children being minimally verbal, in particular related to anxiety, as suggested by Van Laarhoven et al. [317]. To that end, little intrusive technologies will be used to not disturb children, as suggested by Sharma and Giannakos [284] and discussed with the PT. Previous research established the validity of the lightweight heart rate monitors *Polar RS800CX* (Polar Electro Oy, Kempele, Finland) for neurotypical individuals, consisting of a wireless wrist-band [243, 322]. As it is currently discontinued, we will use a more recent Bluetooth optical heart rate sensor from the same brand called *Polar verity sense*.

Mixed methods (quantitative and qualitative) will be used to analyze the data. All data sources will be considered apart from video recordings

which will only be used to check other data in case of errors. The overall analysis process will intend to take into account the following confounding variables. It will consider the child's emotional state before and after the session, as well as after tasks, through the questionnaire's answers. The PT will also take notes of potential delayed reactions towards stimuli (e.g., the child doing hand flapping ten minutes after the sound presentation) based on his expertise. Notes of spontaneous reactions from the child, relative, and PT, may also help to identify confounding variables. Moreover, using an AAC system to provide explanations to the child aims to minimize potential misunderstandings. Issues in the data will be spotted by comparing the answers from the child, relative, and PT (large differences could point at errors that should be checked by looking at the video recordings). Further details cannot be given at the moment, as to be meaningful, the analysis process will be refined when starting.

9.5 Discussion

This study presents first steps towards the creation an AR auditory assessment strategy which intends to perform more ecological auditory assessments for autistic children with SLN and ID while making them more agent. It has three contributions. First, a new soundbank being representative of autistic AAF called *ASD_SoundBank* was devised based on the sound taxonomy that was built and described in the two previous chapters. In addition to offering a meaningful basis for conducting future auditory assessments, *ASD_SoundBank* could be used by researchers and practitioners to work on auditory rehabilitation or on the understanding of everyday autistic perception. Second, the AR application *ASD_AudioEval* was designed through a user-centered process with a psychomotor therapist. *ASD_AudioEval* includes three main activities which seek to assess autistic AAF either directly, by targeting sound semantic contexts, intrinsic and extrinsic sound parameters, or indirectly, by measuring children's reaction time in the presence of sound distractors. While the development is still ongoing, researchers, designers, and autism stakeholders could adapt this design for other contexts, within or beyond clinical contexts (e.g., at home). Third, the first version of an experimental protocol was devised which intends to conduct field testing with autistic children with SLN in collaboration with a therapist. After highlighting the limits of the work presenting in this chapter, perspectives will be presented. I will first discuss the need to conduct participative design sessions with autism stakeholders, mainly including autistic individuals, to validate and refine the design of *ASD_AudioEval* and of the protocol in relation to their needs and wills. Then, potential future uses of *ASD_AudioEval* and extensions of the soundbank *ASD_SoundBank* will be

mentioned.

9.5.1 Limits

Our work displays some limits. In particular, our user-centered design process was only conducted with one therapist, without consultation of autistic individuals or relatives. To take this issue into account, participative design sessions must now be conducted with autism stakeholders, mainly involving autistic individuals, but also relatives and practitioners being representative of different therapeutic orientations, as detailed in the next subsection. Most existing auditory assessment strategies that informed our design processes are driven by the medical model of disability, with a main focus on training and “fixing” autistic individuals, rather than on well-being in the first place. Although bringing useful insights, they may have led to over emphasize the views from non-autistic individuals, in comparison to autistic individuals. Conducting participative design sessions will thus be of primary importance to ensure that all voices are represented in this study.

9.5.2 Next design iterations with autism stakeholders

Last year, in 2021, Fodstad et al. [86] presented a case study consisting of the assessment and treatment of noise over sensitivity, and involving a 16-year-old autistic teenager. After publication, the study was largely criticized in the autistic and research communities through Botha et al. [29]’s commentary. Many ethical concerns were raised, related to dangerous sound volumes, masking of native responses indicating distress, dehumanization, lack of consent, or lack of consultation with autistic expertise. While the overall intent of our study seems close to the one expressed by Fodstad et al. [86], our ultimate goal differs: we want to enable children and relatives to better spot auditory stressors in their environment so that to adjust it accordingly and in turn increase well-being, whereas Fodstad et al. [86] tended to focus on short-term outcomes by using performance measures (e.g., decrease in the number of native distress responses). Though, we must build on the criticisms that were expressed to make our research process more ethical. In particular, Botha et al. [29]’s remarks call for conducting participative design sessions with autistic individuals to validate and refine the design of our application and protocol before to conduct any testing with autistic children.

Participative design sessions will aim to take into account the various needs and concerns of autism stakeholders, so that to adjust our design accordingly, in line with recent recommendations in autism research [84, 230]. They will involve autistic individuals, but also relatives and practitioners being representative of various therapeutic orientations. The topics discussed will for instance include all ethical issues raised by Botha et al. [29], but also the ethical principles stated by the Declaration of Helsinki [9] (e.g., related to the precautionary principle). These sessions should be conducted with at

least seven people, mainly including autistic individuals, to allow for different views to emerge. They will take place every month or two months to leave me enough time to make the changes being proposed to the application and protocol. During each session, the design of *ASD_AudioEval* and the experimental protocol will be presented, and participants will be able to test *ASD_AudioEval*. Alternatives to these research endeavours will also be evoked to spur discussions (e.g., using AR to remove auditory elements rather than to add distressing elements). Various methods will be used to collect participants' views, such as brainstorming techniques, or post-it notes as in Parsons et al. [230]'s study. I expect this process to last between six months and one-year, due to the time needed to recruit participants, prepare the sessions, analyze the data, and adjust our designs accordingly. At the end of this process, the final version of the protocol will be submitted to the ethics research committee of our university for consideration.

9.5.3 Future perspectives

Future works first consist in finishing the development of *ASD_AudioEval* so that to then conduct participative design sessions as above-mentioned. In the future, *ASD_SoundBank* could also be extended to perform auditory training with respect to various sound contexts and parameters. This use could benefit from AR capabilities to show and hear stimuli in bimodal conditions (audio and visuals) or unimodal conditions (audio or visuals). Indeed, Taffou et al. [302] previously suggested that these conditions induce differences in terms of arousal in relation to aversive stimuli in VR.

ASD_SoundBank could be improved by including spatial audio stimuli coming from other research datasets. This addition could then be included in *ASD_AudioEval* so that practitioners could propose audio stimuli on top of spatial audio backgrounds. Such datasets for instance include *EigenScape* [114] (previously used in [141]), *ARTE* [326], or *STARSS22* [240]. Moreover, other publicly available sounds could be added to *ASD_SoundBank* to offer more alternatives for each sound item. Such sounds could come from the datasets above mentioned, or others, such as the *British Library Sound Archive* ⁶, *AudioSet* ⁷[101], or from open sound maps such as the *Montreal sound map* ⁸, *London Sound Survey* ⁹, or *LOCUSTREAM* ¹⁰.

⁶*British Library Sound Archive*: <https://sounds.bl.uk/>

⁷*AudioSet*: <https://research.google.com/audioset/>

⁸*Montreal sound map*: <https://www.montrealsoundmap.com/>

⁹*London Sound Survey*: <https://www.soundsurvey.org.uk/>

¹⁰*LOCUSTREAM*: <https://locusonus.org/wiki/index.php?page=Locustream.en>

9.6 Conclusion

This study presents the design of an AR application called *ASD_AudioEval* which intends to provide practitioners with more ecological conditions when conducting auditory assessments with autistic children with SLN and ID, while making children more agent. This design process, that was conducted in collaboration with a psychomotor therapist, involved the creation of a new soundbank called *ASD_SoundBank* being representative of autistic AAF based on the sound taxonomy that was previously built and was reported in the two previous chapters. An experimental protocol was also devised for conducting future field testing with autistic children in collaboration with a psychomotor therapist. These three contributions could inform the design of future autism research regarding the creation of new auditory assessments or the study of the everyday listening of autistic children. Before to conduct testing with autistic children at the therapist's office, a participative process involving autistic individuals and practitioners is planned to validate and refine our designs.

10 - Conclusion and Perspectives

Several studies were presented in this dissertation, which intended to better support autism stakeholders¹ by complementing existing sensory interventions through the creation of multisensory XR environments.

This thesis was structured in three main parts. First, we examined if the focus of existing autism XR research matched autism stakeholders' needs and views through a literature review and interviews with stakeholders, mainly including practitioners. Our findings drove the second and third part of this thesis. In the second part, we examined the use of a free-play creative multisensory AR environment to secure autistic children and reinforce the child-practitioner relationship. In the third part, we used AR to develop more ecological auditory assessments for autistic children with Severe Learning disabilities and complex Needs (SLN) as well as Intellectual Disability (ID). The various contributions from this thesis are summarized in section 10.1. Perspectives for future autism XR research are presented in section 10.2, drawing upon limits to our work and new insights that emerged.

10.1 Summary of the contributions

This thesis started from a simple observation: while sensory issues have been more and more studied in autism research since their inclusion as a core autism feature in the *DSM-5* ten years ago [126], they remain under-explored in autism XR research. Indeed, this research field mainly addresses socio-emotional abilities through the recreation of everyday social situations (e.g., interacting with students in a classroom), thus excluding many autistic people who cannot directly work on them. Moreover, this focus prevents from generalising the current research findings to the autism spectrum as a whole. Therefore, our first objective was to check if the current focus of autism XR research aligned with stakeholders' views. To that end, a literature review was conducted, as well as semi-directed interviews with autism stakeholders, mainly including practitioners. The grounded theory analysis of the interviews, being informed from our literature review, yielded four main insights. First, it confirmed the presence of discrepancies between the focus of autism XR research and stakeholders' needs. Then, a categorization of existing autism interventions without and with digital tools was built, as well as a set of XR use cases and a set of XR design guidelines intended for future autism research. In particular, stakeholders advised focusing more on sensory

¹By "autism stakeholders" we refer to autistic people, relatives, and practitioners with experience in autism.

and mediation issues. They also confirmed our initial assumption that AR seemed more suited than VR for autistic children with SLN and ID, due to allowing them to keep contact with the physical space and with their usual practitioner. These findings drove the two next parts of this thesis, which are described below.

The second part of this thesis explored the possibility of using AR to secure autistic children and reinforce the child-practitioner relationship. To that end, an AR environment called *Magic Bubbles* was designed based on the findings from our interviews and then adapted for a clinical setting in collaboration with clinical practitioners. Being inspired from existing sensory approaches, such as Snoezelen, it consisted of free-play soothing sensory activities promoting self-expression. After validating its acceptability among a clinical team through testing with eleven practitioners, acceptability and usability testing were performed with ten children with a neurodevelopmental condition and ID. Findings revealed a positive acceptability and usability with practitioners' support, thus enabling to start a five-month field study with seven autistic children with SLN. For that purpose, a specific methodology was devised, involving diverse measures (e.g., children's drawings), and mixed methods of analysis largely relying on the grounded theory qualitative method. Findings suggested that children experienced a similar evolution over time, starting from an inner experience when accepting the headset, and then gradually sharing more. More specifically, some children communicated more about their AR experience than what they usually do at the day hospital during other activities. According to the practitioners, *Magic Bubbles* could complement existing sensory interventions such as Snoezelen, by offering an alternative virtual intermediary space for bonding with each other. A categorization of children's AR experiences was also built that takes into account many contextual aspects and could inform the design of future XR studies. It includes new insights related to self-perception and the exploration of what is real and virtual, which deserve more research.

In the third part of this thesis, we argue that AR could help to increase the ecological validity of auditory assessments for autistic children with SLN. This hypothesis stems from our interviews' findings, and the need to better tailor the AR *Magic Bubbles* environment to the specific sensory profiles of autistic children. Indeed, current auditory exams are ill-suited to account for the variety of autistic people's lived auditory experiences. This research endeavour was carried out in collaboration with a psychomotor therapist. To create the most comprehensive AR auditory assessment as possible, we first had to build a taxonomy being representative of autistic atypical perception, in terms of sound contexts (e.g., school sounds) and parameters (e.g., intensity). To do so, a first taxonomy was derived from a systematic literature review, and then validated and improved through an online semi-directed

questionnaire answered by 68 stakeholders. Findings also highlighted discrepancies between the answers from autistic people, relatives, and practitioners, related to the respective significance that they gave to the different sound items. Based on this taxonomy, a soundbank called *ASD_SoundBank* was created. Then, the design of the AR application *ASD_AudioEval*, which intends to perform more ecological auditory assessments for autistic children, was conducted. An experimental protocol was also devised to conduct future field testing with autistic children. Experiments are planned at the therapist's office following a participative process involving autism stakeholders, mainly including autistic individuals.

10.2 Discussion and Perspectives

To our knowledge, the work carried out in this thesis constitutes one of the first XR research endeavours using headsets that focuses on the sensory perception of autistic children with SLN for well-being and assessment purposes. Several contributions of this thesis could benefit to autistic individuals, families, practitioners, as well as researchers in HCI and XR. In particular, the XR use cases, XR design guidelines, and the categorization of autistic children's experiences with AR *Magic Bubbles* environment that were built could inform future XR autism research. The methodologies that we used could also be reused or extended by future works to better include autistic children with SLN and better assess their holistic experiences. Our positive acceptability and usability findings related to AR for autistic children could also inspire more XR research collaborations between researchers, clinical institutes, autistic people and families, thus helping to devise meaningful approaches for all stakeholders. The sound taxonomy and the soundbank *ASD_SoundBank* that were constructed could inform future works led by researchers and practitioners when focusing on auditory rehabilitation. Moreover, as expressed by two autistic individuals in their answers to our online questionnaire, they could also benefit to autistic people to better understand their lived experiences.

While we answered several research questions, new questions were raised based on challenges that we faced and new insights that appeared. We discuss them below as directions for future research, followed by reflections about methodologies intended to better include children from the entire spectrum.

10.2.1 Directions for future research

Magic Bubbles AR environment that was developed in this thesis mainly relied on audio and visuals, and used some controllers' vibrations. Drawing upon the findings from our AR experiment, future work could explore the use

of tangible manipulations, and haptics in general, to further support autistic children's understanding of what is real and virtual. In particular, mapping physical objects commonly used in interventions (e.g., sensory balls) to virtual AR entities could extend what we proposed by drawing links to the real space. Possible use cases could consist of sending a real ball to the therapist to trigger actions in AR, so that to work on action-reaction relationships while bonding with the therapist. Triggering actions in AR could also have impact on real objects in the room (e.g., changing the color of the lights).

New research avenues emerged from our AR experiment with *Magic Bubbles*, that could benefit to researchers in XR and HCI and autism stakeholders. First, the overall categorization of children's AR experiences could be validated and/or extended through testing with more autistic children in AR. Future studies could also investigate if this categorization could be applied to understand the experiences of autistic children with VR. To devise new XR approaches aiming to complement clinical sensory interventions (e.g., about postural issues), future studies could also investigate the process underlying two new AR insights related to a perceived shift in children's self perception and their understanding of what is real and virtual. Moreover, discussions with psychologists revealed similarities between *Magic Bubbles* AR space and the *potential space* psychology construct [334]: an intermediate space for playful experiences situated between the inner reality and the external physical reality. Exploring this parallel may inform future autism XR research. Exploring if similar findings to the ones obtained in our AR study could be reached with VR, or other non-digital (e.g., Snoezelen room) and digital mediums (e.g., projection screen) also calls for more research. The question of how children experience the real-virtual transition when wearing the headset also remains unanswered, although important for future autism XR research. To investigate it, a possible use case could consist in assessing the differences in terms of acceptability between not perceiving any AR element when wearing a AR headset (only perceiving the real space) but gradually introducing them, and directly perceiving AR elements when wearing it. The platform used for developing the *Magic Bubbles* AR application is appropriate to undertake such studies, in particular due to its see-through capability which affords to precisely handle the proportion of real and virtual elements.

This dissertation only explored some of the research questions that were raised in the analysis of our interviews. In my opinion, two other XR approaches would be worth examining: XR "derivatives of stereotypes" and AR approaches to make non-autistic people more aware of autism perception.

About "derivatives of stereotypes", the goal is to replace stereotypes that often induce stigma with individualized XR alternatives offering self-reassurance. For that purpose, lightweight AR glasses may be worth explor-

ing, as potentially more easily socially accepted, such as the Google Glass[©] which was previously successfully used in classrooms [324], or more recent devices such as the Spectacles^{©2}. Potential use cases may consist in displaying additional soothing AR elements or filtering out real elements inducing over-arousal. Such use cases raise many issues related to individualization, object detection, what *filtering* actually means, and *how* to perform it. For instance, about the former, if a child tends to often spin objects at school, displaying an AR spinning object, such as a top, may be reassuring while decreasing stigmatizing behaviours associated with spinning objects. About the latter, filtering could consist in filtering sounds by *blurring* them, e.g., adjusting their pitch or frequency range. Such use cases could be inspired by “sound halos” as in the *SoundTorch* project [131], that were used to only hear sounds in a specific space direction. At last, mixed approaches could also be explored, by adding stimuli while removing others. To that end, machine learning may help to adjust specific stimuli on the fly based on users’ verbal or text prompts, drawing upon visual creations performed with *DALL-E API*³. This project requires adopting specific methodologies to prevent risks of habituation and favour inclusion.

Regarding the use of XR to make non-autistic people more aware of autistic perception, the objective is to decrease assumptions about autism. By better understanding how autistic people experience the world, the final goal would be to make neurotypical children approach their autistic peers in “autistically appropriate” ways [187, p. 6]. This objective would enable to shake common practices which usually consist in teaching autistic people how to interact in “appropriate” ways with their neurotypical peers. To that end, AR could be used to enable for quick comparisons between how neurotypical users perceive their environment versus autistic individuals. Challenges for instance concern the real-time audiovisual rendering and its adaptation to the level of sensory issues being experienced.

Future development is needed to finish the AR *ASD_AudioEval* application intended to increase the ecological validity of current auditory assessments. Before to conduct field testing in collaboration with a psychomotor therapist, a participative design process must be carried out with autism stakeholders, and more specifically autistic individuals. The objective is to validate and refine the design of our application and experimental protocol, and thus ensure that they align with stakeholders’ needs and wills. Then, the findings from field testing with autistic individuals relying on *ASD_AudioEval* could open up doors to new assessment and training strategies, that could benefit from the AR capability to see and hear stimuli at the same time or separately. Our work also pinpointed a dearth of research about the everyday

²Spectacles[©] AR glasses: <https://www.spectacles.com/fr/>

³DALL-E API and project: <https://openai.com/publications/>

listening of neurodiverse populations, as many studies in *acoustic ecology* focus on the everyday listening of non-autistic people [98]. This observation calls for more studies in this direction in a potential new sub-field that we could call *autism acoustic ecology*.

10.2.2 Towards new methodologies targeting the entire spectrum

The analyses of our AR field experiment mainly reflected practitioners' and researchers' interpretations, as autistic children were limited verbally and had associated ID, and despite efforts to mitigate this bias (e.g., using children's drawings). Therefore, the question of how to capture and analyze children's holistic experiences must be pursued further to consider multiple perspectives, including children's views, as also expressed by Spiel [292]. This also implies to find new ways of assessing fundamental XR concepts, such as perception of immersion, presence, awareness, realism, affordances, as well as XR drawbacks (e.g., cybersickness), since current assessments usually target neurotypical individuals through self-report questionnaires. Devising such methodologies could enable future autism XR research to better include autistic children with SLN and associated ID, or a related neurodevelopmental condition, who are currently under-represented. Our categorization of children's experiences with *Magic Bubbles* AR environment may provide a basis for building such methodologies. Moreover, to be meaningful, all stakeholders must be better involved in this research process, through interdisciplinary and participative design approaches, as previously encouraged [84, 89, 230, 294].

I argue that conducting participatory research requires two main dynamics: making autistic people more agent in research processes, and going towards more interdisciplinary research. The former aspect somewhat comes from an incident that happened when diffusing my questionnaire about auditory perception. I was struck when people at the Autism Resource Center told me that autistic people are often reluctant to participate to studies because they are actually overwhelmed by research requests but rarely hear about the findings. In addition to making them feel like "guinea pigs" [68], this situation highlights existing social barriers and power dynamics between autistic and non-autistic people. To bridge this gap, we, as researchers, have a responsibility to give more agency to all autism stakeholders, and particularly autistic people, in the design and evaluation of research projects. This reflections echoes insights coming from the fourth HCI wave [89], that call for making users more agent, as well as insights from Critical Disability Studies (CDS) [187], which underline their current lack of agency while advising for a change. Yet, to perform such participative work, it has to be more interdisciplinary. In my view, interdisciplinary means spanning across several disciplines such as computer science, psychology, sociology, and anthropology. Indeed, the fourth HCI wave stems from various sociological and

philosophical trends and methods, such as *Actor Network Theory* [170] or *Critical Discourse Analysis* (CDA) [88, 143]. For instance, these two methods were used by Spiel et al. [293] to conduct an in-depth analysis of children's experiences with technology. Then, CDA also has roots in other fields, such as feminism, with for instance the work led by Judith Butler, who focused on marginalized people (transgender people in her case) to draw conclusions for everyone (gender theories) [40]. Therefore, I argue that taking ideas from different fields would help to better consider different viewpoints and thus design more relevant methodologies to work with autistic children.

A - Material Related to the Interviews with Autism Stakeholders

Appendix A presents the detail of the findings from the interviews that were constructed using a grounded theory approach regarding autism interventions without digital tools (see Table A.1) and with digital tools (see Table A.2).

Table A.1: Autism interventions without the use of digital tools mentioned by the participants

Category	Concept	Sub-concept	Examples / Details
Individualize interventions (n=33)	Start from the child's interests (n=32)	Create game depending on the purpose (n=10)	Game must depend on child's interests (n=4), skills (n=2), fears (n=1)
		Individualize rewards (n=16)	
	Individualize communication method (n=17)	Use alternative communication system (n=16)	Use pictograms / gestures, e.g., PECS (n=14) & Makaton (n=7) systems
		Communicate through mediation activities (n=4)	Use any game (n=3) or object (n=1)
	Individualize sessions (n=14)		Session has to depend on the child's state, e.g., fatigue (n=6)
	Build personalized project (n=13)		Set personalized long-term goals based on evaluations (n=13)
Assess the state of the individual over time (n=29)	Individualize care method (n=6)		No method suitable for every child exists (n=6)
	Assess child state on the long-term (n=28)	Conduct sensory evaluation (n=21)	Conduct sensory profiles (n=20), clinical observations (n=9), sensorimotor evaluation (n=4)
		Conduct psycho-developmental evaluation (n=18)	Assess development and autism severity (n=15), conduct clinical observations (n=5)
		Ask questions to parents (n=10)	Use discussions (n=7) and questionnaires (n=3)
	Assess the child evolution on the short term (n=21)	Carry out observation of sessions (n=18)	Take notes (n=3) of shared attention patterns (n=3), stereotypical behaviours (n=2), new interests (n=3)
		Assess child at different intervention times (n=8)	Carry out specific assessments (n=8)
		Discuss with people knowing the child (n=8)	Discuss with relatives (n=8), people at school (n=2)

Build and strengthen the therapeutic alliance (n=30)	Use individualized playful activities (n=27)	Use mediation activities (n=24), e.g., music (n=14), fine arts (n=5) Use any appealing games (n=12), e.g., video games (n=5) Use autistic interests: sensory stimulation (n=6), music (n=5), machines (n=4), geometric shapes (n=3), things that spin (n=3), bubbles (n=3)
	Adapt the practitioner's behaviours depending on the child (n=19)	Be slow and enveloping (n=12), e.g., adjust voice intensity (n=4), Do not over anticipate (n=3), Adopt the child's pace (n=2) Provide meaningful explanations (n=8) Understand the "autistic world" (n=8), e.g., Allow stereotypies (n=1)
	Create a secure relationship with the child (n=14)	Create a secure relationship (n=9); Enjoy the activity conducted (n=7)
Use playful activities (n=26)	Adapt game based on the intervention goal (n=25)	Goal can be social (n=13), cognitive (n=5), sensory (n=4)
	Entertain the child and widen his interests (n=4)	
	Increase the child's autonomy (n=2)	
Use behavioural strategies (n=26)	Use rewards (n=19)	Use sensory-based rewards (n=9), the token economy method ¹ (n=5), or verbal congrats (n=4)
	Gradually increase the challenge (n=18)	Gradually adjust sensory loads (n=13), helping strategies (n=3), number of elements (n=3), therapist place (n=1)
	The child imitates the practitioner (n=7)	
	Use physical prompts (n=4)	
	Set things available to prompt demands (n=3)	
Provide a sense of agency (n=16)		Give choice over a few tasks (n=16), offer possibilities to move (n=1)
Alternate activities (n=15)	Alternate types of activity (n=15)	Use challenging vs. appealing (n=13), known vs. unknown tasks (n=1) Often change activities (n=3)
	Alternate ways to work on activities (n=3)	Task can be done sitting (n=3), moving (n=3), outside (n=1)
Use compensation strategies to relax the child (n=14)	Make the child available for performing challenging tasks (n=12)	Use sensory stimulation (n=7), relaxing activity (n=4), start from stereotypical behaviours (n=2)
	Give daily strategies to prevent meltdowns (n=4)	Use derivatives of stereotypies (n=2)

Structure the intervention program (n=27)	Offer predictability of intervention program (n=27)	Offer time predictability (n=21)	Show visual planning at session start (n=6) and timers (n=4) Finish session with appealing activity (n=4)
		Offer space predictability (n=19)	Use clear learning areas (n=6), clean space before child arrives (n=3) Show pictures of activities before to start (n=2)
		Use routines (n=17)	Ritualize activities and their organization (n=14) Rehearse activities (n=6)
		Use same methods in all activities/spaces (n=9)	Provide parental advice (n=9)
	Structure intervention over different periods (n=11)	Observe individual to detect his interests (n=8)	
		Build the relationship with the child (n=7)	
	Do not overstructure the environment (n=6)	Prepare for real life unpredictability (n=4)	
		Overstructured environments can prompt ritualization (n=3)	
Face difficulties in interventions (n=27)	Face difficulties working with autistic individuals and their families (n=21)	Find the suitable individualized intervention approach (n=15)	Some sensory channels remain hard to stimulate (n=7) Assess the impact of the intervention (n=6) Help without stigmatizing (n=4) Make activities meaningful (n=2)
		Build the therapeutic alliance (n=9)	Understand the child's actions and feelings (n=6) Handle heteroaggressivity (n=3)
		Reassure parents regarding possible fears (n=8)	Fears of the methods used (n=6) and institution(n=4)
	Face difficulties due to the health-care system (n=20)	Face activity-related difficulties (n=14)	Health environment differs from daily life (n=9) Face difficulties linked with private/public work context (n=7) Healthcare equipment is often expensive (n=3), e.g., Snoezelen
		Face difficulties external to one's practice (n=12)	Sensoriality in interventions remains new (n=6) Face lack of specialized practitioners (n=6)

Work on sensoriality in intervention (n=26)	Work on sensory processing disorders (n=21)	Conduct gradual sensory habituation (n=15)	Gradually adjust specific sensory loads (n=13) Work in flexible multisensory environment (n=8)
		Modulate audiovisual information speed (n=7)	Use Logiral (n=6) [309] or Youtube (n=1)
		Use contrasted sensory elements (n=3)	Use environmental contrast in multisensory spaces (n=2)
	Provide multisensory environmental adaptations (n=20)	Offer sensory loads to regulate the child sensorimotor balance (n=13)	Give specific simulation based on child particularities (n=9) Work in adjustable multisensory environment (n=8)
		Use sensory protections (n=12)	Protections can be audio (n=12) (headphones), tactile (n=2), (smooth ground cover), visual (n=1) (sunglasses)
		Work in a neutral environment (n=11)	Limit environmental sensory information: visual distractors (n=6) (posters on walls. . .), Neutral colour of walls (n=3)

¹Token economy method can be situated within ABA methods. It uses systematic reinforcements of target behaviours, with “tokens” that can be exchanged for other rewards.

Table A.2: Autism interventions already using digital tools mentioned by the participants. AAC: Alternative and Augmented Communication; Act.: Activity; AT: Assistive Technologies; C: Desktop Computer; Cat.: Category; Cons: Video Game Console; Diag.: Diagnosis; Edu: Education; Ki: Kinect; Lang: Language; Med: Mediation; Narr: Narrative; Perc: Perception; NS: Non-specified; P: Tablet and/or Phone; PS: Projected Screen; R: Robot; Sens: Sensoriality; TI: Tangible Interface; Unders: Understanding.

Cat.	Sub-cat.	Content		Game name (when mentioned) & Medium	
				2D graphics	3D graphics / other
Social skills (38% n=13)	Social skills and emotions (n=4)	Video modeling (n=2)			Youtube or other applications (C/P, 3D, n=2)
		Social scenario (n=3)	Autimo (P, n=1)(Auticiel, 2015)		JeMiME (C,3D,n=1)[117] JeStiMuLE (C,3D,n=1)[282]
	Group activities (n=2)	Video game workshop (n=2)	Degrees of Separation (C/PS, n=1)(Moondrop, 2019)		Human Full Flat(C/PS,3D,n=1)(No Brakes Games, 2016) lco(C/PS,3D,n=1)(Sony Interactive Entertainment, 2011)
		Storytelling workshop (n=1)	NS		Research project (R, Other, n=1)[73]
AT (38% n=13)	AAC (n=12)	Tailored pictograms (n=12)	NikiTalk (P, n=3)(La Rocca, 2019) Snap Core (C/P, n=2)(Tobii Dynavox, 2021) LetMeTalk (P, n=1)(appNotize UG, 2014) Dis-moi! (P, n=1)(Caulavier, 2013)	Proloquo2Go(P,n=1)(AssistiveWare, 2013) Avaz (P, n=1)(Avaz, Inc., 2020) CommunicoTool (P, n=1)(C..Texdev, 2016) -	NS
	Daily planning (n=1)	Visual planning (n=1)	-	-	NS
Med & Well-being (29% n=10)	Rewarding activity (n=10)	Any appealing game	Application allowing users to burst balloons (P, n=1)		Youtube Channels (C/P, NS, n=1)
	Mediation (n=4)	Any appealing game	Angry birds (all,n=2)(Rovio,2009) Bumpy (Cons, n=1)(Loriciels, 1989) Théâtre de Minuit (C,n=1)(Dada Média, 1999) Various brick breaker games (T/C, n=1) Video game displaying an aquarium (C, n=1) Tetris (all, n=1)(Pajitnov, 1984)	MyPiano (P, n=1)(Trajkovski Labs, 2000) Real Drum (P, n=1)(Kolb Sistemas, 2012) Noogra Nuts (C/P, n=1)(Bengigi, 2012) Games based on « Simon Says » (all, n=1) Talking Ginger (P, n=3)(Outfit7, 2012) My Talking Panda (P, n=1)(Sofia_Soft, 2017)	MGTA Vice City (Cons, 3D, n=1)(Rockstar North, 2015)

Edu (24% n=8)	Cognitive remediation (n=8)	Programming workshop (n=2)	Rob'Autisme (C/R, other, n=1) [267]	Scratch Lang. (C, other, n=1)(Resnick, 2006)
		Appealing game, e.g., memory game (n=7)	Cognibulles (C,2D,n=1)(Virole and Wierzbicki, 2011) BitsBoard (P, 2D,n=1)(2021)	School (P, n=1, other)(LearnEnjoy, 2012) Watch'n'Learn (P, n=1, other)(Peters, 2018)
	Narr unders (n=1)	Storytelling work- shop (n=1)	Research project (R, n=1) [73]	NS
	Daily living skills (n=1)	Task: brushing teeth (n=1)	Ben le Koala (P, n=1)(Happy Moose Apps, 2017)	NS
Sens (24% n=8)	Multisensory Binding (n=6)	Slowing down videos (n=4)	NS	Youtube (Any, n=1, other) Logiral (C/P, n=3, other)[309]
		Auditory unders task (n=1)	NS	Application for doing sound lotos ² (NS, n=1, other)
		Audiotactile task (n=2)	NS	Tangible allowing users to play music (TI, n=1, other) Theremin instrument (TI, n=1, other)
	Sensorimotor disorders (n=2)	Act. for fine mo- tor skills (n=1)	NS	-
		Act. for gross motor skills (n=1)	NS	Just dance (Ki, n=1, 3D)(Ubisoft, 2009) Bowling application (Ki, n=1, 3D)
	Body perc (n=1)	Storytelling work- shop (n=1)	NS	Rob'Autisme (C/R, n=1, other) [267]
	Diag. (6% n=2)	-	Sensory profile (n=1)	NS
Assessment of lang. unders (n=1)			NS	-

²Sound lotos are listening games which consist in trying to identify daily noises (e.g. objects, animals).

B - Material Related to the Validation of the Sound Taxonomy

Appendix B presents the online questionnaire directed towards autism stakeholders to validate and enhance the sound taxonomy that was previously derived from a systematic literature review. The questionnaire was written in French language.

Quels sons pour évaluer la perception sonore d'enfants avec autisme dit modéré à sévère ?

Durée : ~10mn.

But du projet de recherche : Identifier et classer les contextes sonores (Par ex. : milieu scolaire) et paramètres sonores (Par ex. : intensité sonore) qui impactent fortement la perception sonore d'enfants avec autisme dit modéré à sévère (sons gênants ou appréciés). Ce questionnaire est un prérequis à une étude qui visera à évaluer la perception sonore d'enfants avec autisme dit modéré à sévère.

Contexte du projet de recherche

L'autisme concerne environ 1/100 personne dans le monde. La majorité des individus présentent des particularités sensorielles, qui sont souvent sonores. La perception sonore qui en découle implique une Tolérance Sonore Réduite (TSR) à l'égard de certains sons gênant leur qualité de vie quotidienne (ex. : chasse d'eau), et des préférences sonores atypiques (ex. : se frotter les oreilles). La TSR peut dépendre d'aspects physiques (par ex. : intensité sonore) ou contextuels, tels qu'une irritation à l'égard de bruits de bouche ou une peur à l'égard de certains sons. Pourtant, l'interrelation de ces aspects reste peu explorée par les profils sensoriels cliniques et examens audiologiques.

Créer un outil qui permette d'évaluer la perception sonore d'enfants avec autisme dit modéré à sévère selon ces différents critères perceptifs est donc nécessaire. Cependant, ceci demande un pré-requis : identifier et classer les contextes et paramètres sonores susceptibles d'être gênants ou appréciés d'enfants avec autisme. Ce questionnaire en ligne vise à remplir ce pré-requis.

Une revue de la littérature scientifique existante a permis d'établir une première classification de ces contextes et paramètres sonores, qui a ensuite été confrontée à l'avis de professionnels de terrain, puis réajustée. Cependant, les retours de personnes avec autisme, de leurs proches, et de praticiens, sont essentiels pour l'améliorer. Le questionnaire ici proposé vise à réunir de tels retours.

La participation à ce questionnaire étant volontaire, aucune indemnisation n'est prévue pour y participer.

Structure du questionnaire : (1) contextes sonores susceptibles d'être gênants, (2) contextes sonores susceptibles d'être appréciés, (3) paramètres sonores susceptibles d'avoir un fort impact, et (4) aspects démographiques.

Vos droits de vous retirer à tout moment : Après votre participation vous pouvez décider de supprimer les données collectées en contactant Valentin Bauer (valentin.bauer@limsi.fr).

Vos droits à la confidentialité et au respect de la vie privée : Les données collectées sont anonymes et traitées de manière confidentielle. Toutes les données seront archivées et seuls le responsable du projet et les chercheurs adjoints y auront accès. La durée d'archivage est de 5 ans. Enfin, en cas de demande de votre part et conformément aux dispositions de la loi Informatique et Libertés, vous pourrez exercer vos droits d'accès et de rectification ou suppression des données collectées auprès du responsable du projet.

Bénéfices de l'étude :

1. Mieux comprendre la perception sonore d'enfants avec autisme dit modéré à sévère.
2. Construire une banque de sons représentative de cette perception, utilisable dans le cadre d'outils d'évaluation sonore.

A terme, ces deux aspects visent à améliorer la qualité de vie quotidienne des enfants et de leurs familles, par une meilleure compréhension de leur perception permettant de mettre en place des aménagements plus adaptés.

Diffusion :

Les résultats de ce questionnaire seront diffusés dans des colloques et/ou publiés dans des actes de colloque et des articles de revues académiques.

Consentement à la participation :

En cliquant sur suivant, vous certifiez que vous avez lu et compris les renseignements ci-dessus, en particulier le fait que vous pouvez contacter le doctorant responsable du projet après avoir rempli le questionnaire si vous désirez vous retirer de l'étude et supprimer les données vous concernant.

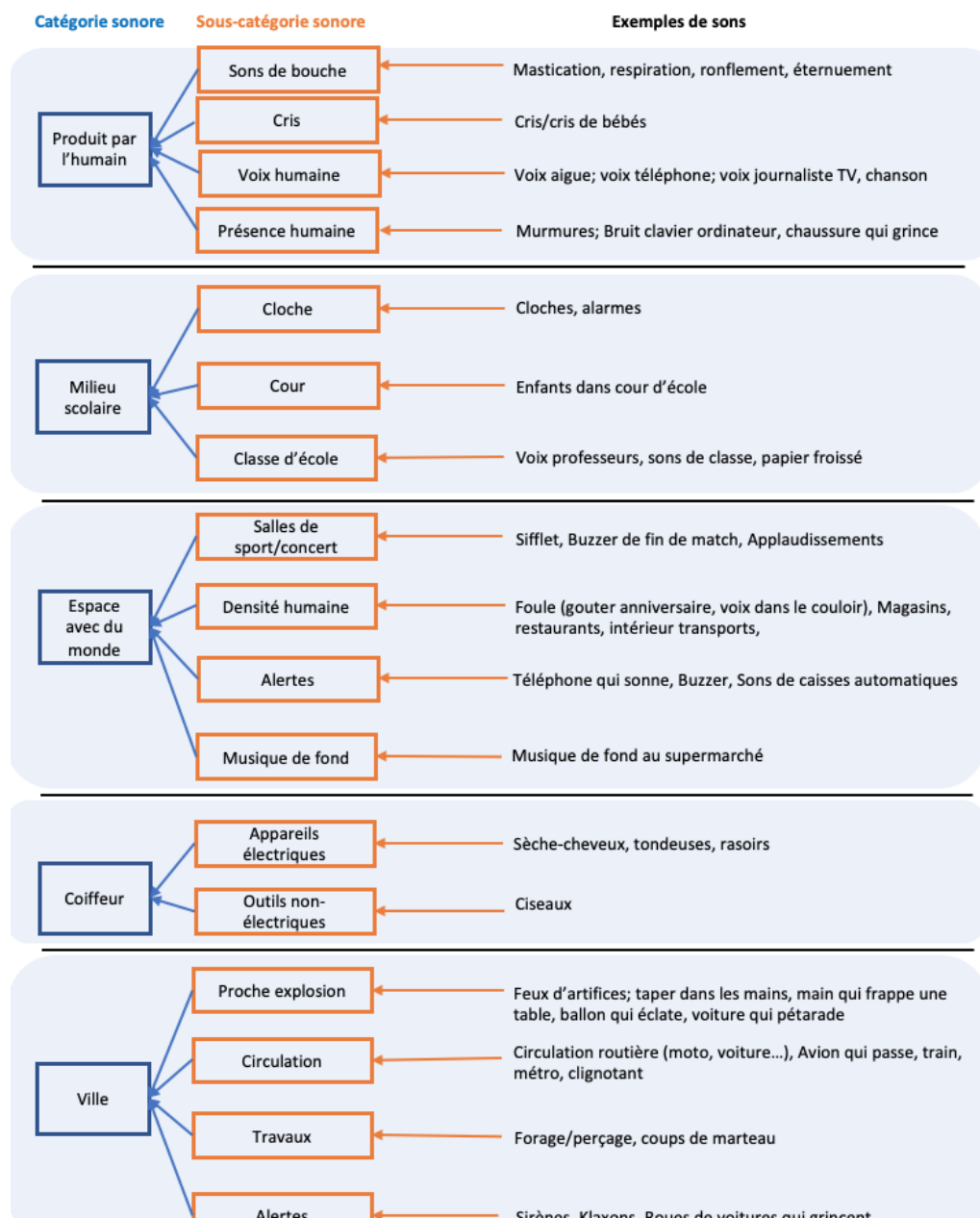
Doctorant responsable du projet:

Valentin Bauer, Doctorant, valentin.bauer@limsi.fr, 0609763689, Université Paris-Saclay, CNRS, LISN (Laboratoire Interdisciplinaire des Sciences du Numérique), équipe VENISE - Campus universitaire bât 507, Rue du Belvédère, F - 91405 Orsay cedex

Il y a 21 questions dans ce questionnaire.

Sons pouvant amener une expérience négative

La figure 1 ci-dessous présente la classification des sons qui peuvent induire des expériences négatives chez des personnes avec autisme. Elle a été construite à partir des articles scientifiques internationaux publiés sur le sujet, puis validée par un psychomotricien professionnel. Les questions suivantes visent à obtenir votre point de vue par rapport à celle-ci, afin de la critiquer / améliorer.



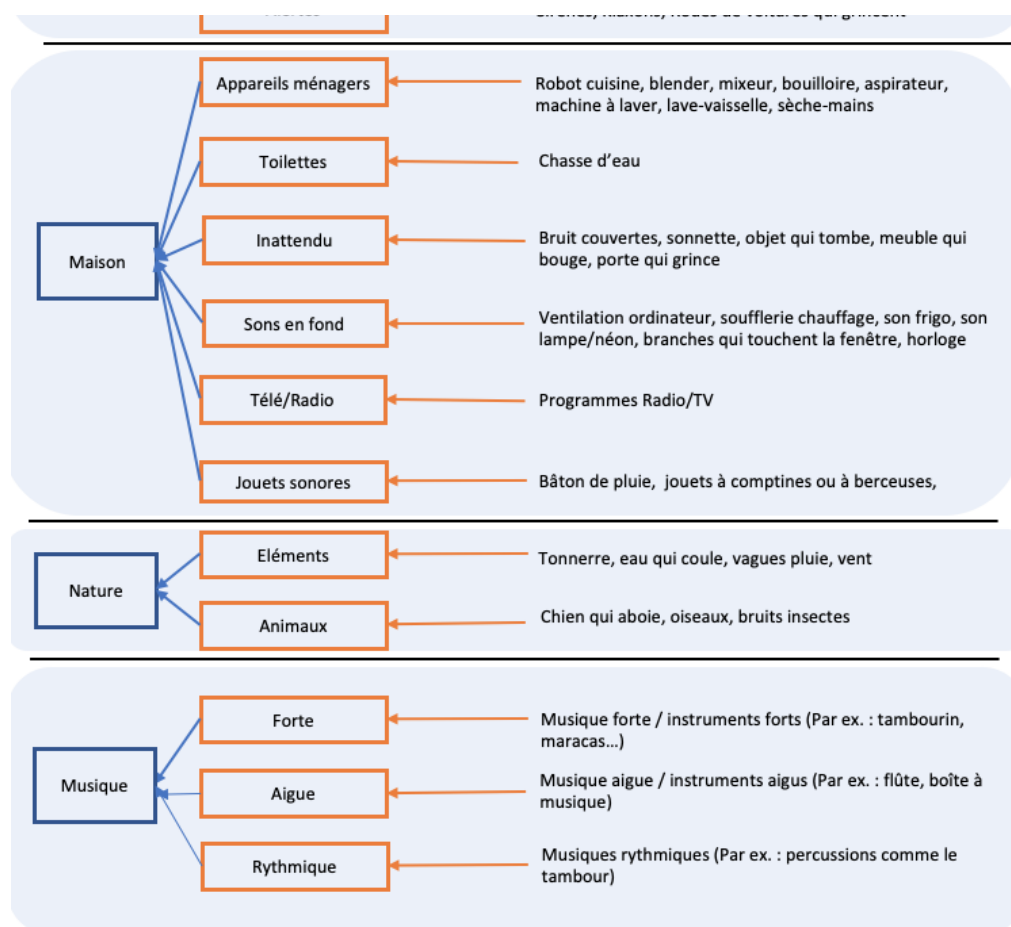


Figure 1 : Classification sonores pouvant induire des expériences négatives chez des personnes avec autisme.

L'impact sur la perception sonore correspond à la propension de ces catégories sonores à déclencher des réactions d'inconfort (Par ex. : grimaces, cris, fuite, pleurs, mettre les mains sur les oreilles pour se protéger des sons). Cet impact évalue l'importance de ces comportements, et tient compte du fait qu'ils sont individuels. Par exemple, une grimace peut manifester une grande réaction d'inconfort pour une personne ("impact très important") et une réaction légère d'inconfort pour une autre ("impact léger").

Si vous êtes une personne avec autisme : Notez ces 8 catégories sonores selon leur impact sur votre perception sonore (si possible lorsque vous étiez enfant).

Si vous êtes un proche d'enfant avec autisme : Notez ces 8 catégories sonores selon leur impact sur sa perception sonore.

Si vous êtes un praticien : Notez ces 8 catégories sonores selon leur impact sur la perception sonore d'enfants avec autisme dit modéré à sévère avec qui vous avez travaillé.

PS: La description des catégories est présentée sur la Figure 1 en haut de la page.

*

Choisissez la réponse appropriée pour chaque élément :

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important
Nature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ville	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Coiffeur	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Espace avec du monde	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Milieu scolaire	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Produits par l'humain	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Musique	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Selon vous, ces catégories sont-elles représentatives des contextes sonores ayant un possible impact négatif sur la perception sonore de personnes avec autisme ?

- **Oui** : avez-vous des suggestions d'amélioration ?
- **Moyennement / Non** : pouvez-vous préciser pourquoi et comment les améliorer ?

*

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Moyennement
- ☐ Non

Faites le commentaire de votre choix ici :

L'impact sur la perception sonore correspond à la propension de ces sous-catégories sonores à déclencher des réactions d'inconfort (Par ex. : grimaces, cris, fuite, pleurs, mettre les mains sur les oreilles pour se protéger des sons). Cet impact évalue l'importance de ces comportements, et tient compte du fait qu'ils sont individuels. Par exemple, une grimace peut manifester une grande réaction d'inconfort pour une personne ("impact très important") et une réaction légère d'inconfort pour une autre ("impact léger").

Si vous êtes une personne avec autisme : Notez ces sous-catégories sonores selon leur impact sur votre perception sonore (si possible lorsque vous étiez enfant).

Si vous êtes un proche d'enfant avec autisme : Notez ces sous-catégories sonores selon leur impact sur sa perception sonore.

Si vous êtes un praticien : Notez ces sous-catégories sonores selon leur impact sur la perception sonore d'enfants avec autisme dit modéré à sévère avec qui vous avez travaillé.

PS: La description des sous-catégories est présentée sur la Figure 1 en haut de la page.

*

Choisissez la réponse appropriée pour chaque élément :

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important
Musique -> Forte	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Nature -> Animaux	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Nature -> Eléments	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Jouets sonores	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Télé/Radio	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Sons en fond	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Inattendu	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Toilettes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Maison -> Appareils ménagers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ville -> Alertes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ville -> Travaux	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ville -> Circulation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ville -> Proche explosion	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Coiffeur -> Outils non- électriques	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Coiffeur -> Appareils électriques	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Espace avec du monde -> Musique de fond	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important
Espace avec du monde -> Alertes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Espace avec du monde -> Densité humaine	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Espace avec du monde -> Salle de sport/concert	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Milieu scolaire -> Classe d'école	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Milieu scolaire -> Cours d'école	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Milieu scolaire -> Cloche	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Produit par l'humain -> Présence humaine	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Produit par l'humain -> Voix parlée	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Produit par l'humain -> Cris	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Produit par l'humain -> Sons de bouche	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Musique -> Aigue	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Musique -> Rythmique	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Selon vous, ces sous-catégories sont-elles représentatives des sons ayant un possible impact négatif sur la perception sonore de personnes avec autisme ?

- **Oui** : avez-vous des suggestions d'amélioration ?
- **Moyennement / Non** : pouvez-vous préciser pourquoi et comment les améliorer ?

*

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Moyennement
- ☐ Non

Faites le commentaire de votre choix ici :

Selon vous, une/des catégories ou sous-catégories manquent-elles? Si oui, laquelle/lesquelles? *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

☐ Oui

☐ Non

Faites le commentaire de votre choix ici :

Avez-vous d'autres commentaires à ajouter par rapport aux sons pouvant amener une expérience négative?

Veuillez écrire votre réponse ici :

Sons pouvant amener une expérience positive

La figure 2 ci-dessous présente la classification des sons qui peuvent induire des expériences positives chez des personnes avec autisme. Elle a été construite à partir des articles scientifiques internationaux publiés sur le sujet, puis validée par un psychomotricien

professionnel. Les questions suivantes visent à obtenir votre point de vue par rapport à celle-ci, afin de la critiquer / améliorer.

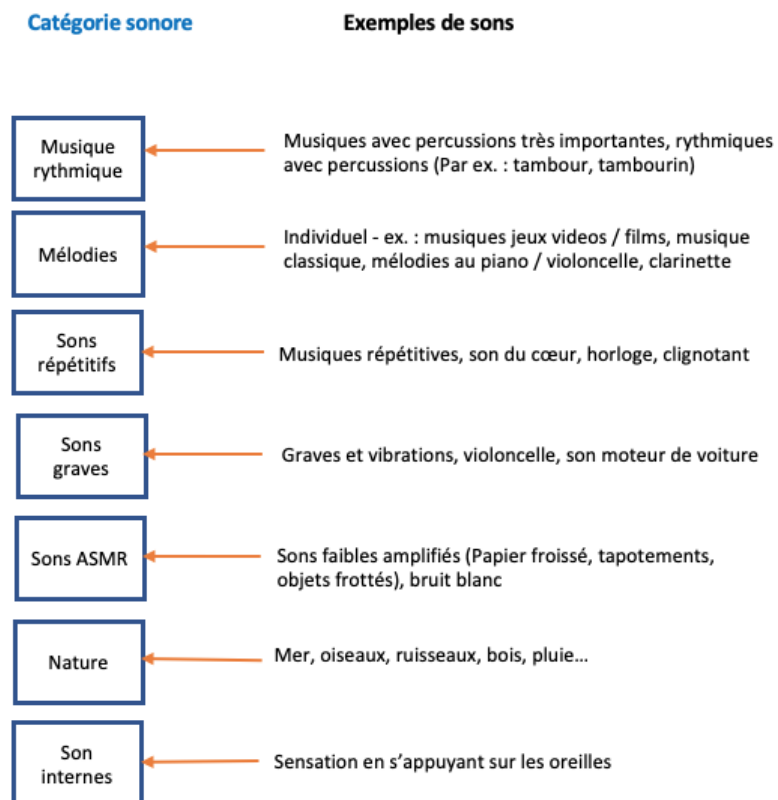


Figure 2 : Classification de sons pouvant induire des expériences positives chez des personnes avec autisme.

L'impact sur la perception sonore correspond à la propension de ces catégories sonores à faire qu'un son est apprécié (Par ex. : se coller au son, l'écouter en boucle). Cet impact évalue l'importance de ces comportements, et tient compte du fait qu'ils sont individuels. Par exemple, redemander plusieurs fois à écouter un son peut manifester qu'il est très apprécié par une personne ("impact très important") ou légèrement apprécié par une autre ("impact léger").

Si vous êtes une personne avec autisme : Notez ces 6 catégories sonores selon leur impact sur votre perception sonore (si possible lorsque vous étiez enfant).

Si vous êtes un proche d'enfant avec autisme : Notez ces 6 catégories sonores selon leur impact sur sa perception sonore.

Si vous êtes un praticien : Notez ces 6 catégories sonores selon leur impact sur la perception sonore d'enfants avec autisme dit modéré à sévère avec qui vous avez travaillé.

PS: La description des catégories est présentée sur la Figure 2 en haut de la page.

*

Choisissez la réponse appropriée pour chaque élément :

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important
Sons internes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	1 - Aucun impact	2 - Impact léger	3 - Impact modéré	4 - Impact important	5 - Impact très important
Nature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons ASMR [ASMR : technique de relaxation consistant à écouter des sons de faible intensité avec attention (tapotements, papier froissé, objets frottés...) dans le but de procurer des frissons / un bien-être.]	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons graves	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons répétitifs	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mélodies	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Musique rythmique	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Selon vous, ces catégories sont-elles représentatives des sons ayant un possible impact positif sur la perception sonore de personnes avec autisme ?

- **Oui** : avez-vous des suggestions d'amélioration ?
- **Moyennement / Non** : pouvez-vous préciser pourquoi et comment les améliorer ?

*

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Moyennement
- ☐ Non

Faites le commentaire de votre choix ici :

Avez-vous d'autres commentaires à ajouter par rapport aux sons pouvant amener une expérience positive ?

Veuillez écrire votre réponse ici :

Paramètres sonores

Cette section concerne les paramètres sonores susceptibles d'avoir un fort impact sur la perception sonore d'enfants avec autisme. 11 paramètres sont considérés : hauteur du son, intensité sonore, longueur du son, répétition, combinaison de plusieurs sons, son inattendu / soudain, son social / non-social, position par rapport à soi, mouvement du son, réverbération, et distance du son à soi.

Pour mieux comprendre à quoi les paramètres sonores correspondent, des exemples sonores sont donnés ci-dessous. Vous n'êtes pas obligés de les écouter si les paramètres sont clairs pour vous. [Pour écouter ces sons : utiliser deux enceintes, ou un casque audio/des oreillettes en mettant les deux écouteurs].

Hauteur du son

Son aigu

0:00 / 0:04

Son grave

0:00 / 0:04

Intensité sonore

Son faible

0:00 / 0:04

Son fort

0:00 / 0:06

Longueur du son

Son continu et long

0:00 / 0:10

Son bref

0:00 / 0:01

Sons répétitif

Tic tac d'une horloge

0:00 / 0:08

Clignotant de voiture

0:00 / 0:18

Combinaison de plusieurs sons

Personne qui parle dans un bar et ambulance au loin

0:00 / 0:07

Son inattendu / soudain :

Sirène d'ambulance inattendue

0:00 / 0:14

Son social / non-social

Cour d'école

0:00 / 0:10

Personne qui parle

0:00 / 0:02

Exemple non-social (cours d'eau)

0:00 / 0:10

Position par rapport à soi

Son venant de la gauche

0:00 / 0:04

Son venant de devant

0:00 / 0:04

Son venant de la droite

0:00 / 0:04

Mouvement du son

Ambulance qui passe

0:00 / 0:06

Son musical qui va de gauche à droite

0:00 / 0:04

Réverbération

Aucune réverbération

0:00 / 0:03

Petit espace réverbérant

0:00 / 0:03

Très grand espace

0:00 / 0:04

Distance du son à soi (Par ex. : proche, éloigné)

Même voix avec 4 distances différentes (très proche, 3mn, 10mn, 15mn)

0:00 / 0:08

Papier froisé à 3 distances différentes (très proche, 1m, 3m)

0:00 / 0:13

L'impact sur la perception sonore correspond à la propension des paramètres sonores à déclencher des réactions d'inconfort (Par ex. : grimaces, cris, fuite, pleurs, mettre les mains sur les oreilles pour se protéger des sons) ou au contraire à apprécier un son (Par ex. : se coller au son, l'écouter en boucle). Cet impact évalue l'importance de ces comportements, et tient compte du fait qu'ils sont individuels. Par exemple, une grimace peut manifester une grande réaction d'inconfort pour une personne ("impact très important") et une réaction légère d'inconfort pour une autre ("impact léger").

Si vous êtes une personne avec autisme : Notez ces différents paramètres sonores selon leur impact sur votre perception sonore (si possible lorsque vous étiez enfant).

Si vous êtes un proche d'enfant avec autisme : Notez ces différents paramètres sonores selon leur impact sur sa perception sonore.

Si vous êtes un praticien : Notez ces différents paramètres sonores selon leur impact sur la perception sonore d'enfants avec autisme dit modéré à sévère avec qui vous avez travaillé.

*

Choisissez la réponse appropriée pour chaque élément :

	1 - pas d'impact	2 - impact léger	3 - impact modéré	4 - impact important	5 - impact très important

	1 - pas d'impact	2 - impact léger	3 - impact modéré	4 - impact important	5 - impact très important
Longueur des sons (Par ex. : ventilation qui fait du bruit en continu vs. sons brefs émis d'impacts)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons répétitifs (Par ex. : clignotant de voiture)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Combinaison de plusieurs sons à traiter en même temps (Par ex. : dans un restaurant avec du brouhaha, des bruits de couverts, de la musique, une personne qui parle en face de soi)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons inattendus / soudains	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sons sociaux / non- sociaux (Par ex. : personne qui parle ou son synthétique)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Réverbération (Par ex. son qui se résonne dans une cathédrale, dans une cantine/piscine/gymnase, dans une salle de bain/cuisine)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	1 - pas d'impact	2 - impact léger	3 - impact modéré	4 - impact important	5 - impact très important
Positionnement du son dans l'espace (Par ex. : on entend un son à sa gauche, derrière soi, sa droite, devant soi)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Hauteur des sons (Par ex. : sons graves vs. aigus)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Intensité sonore (Par ex. : sons forts, faibles)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mouvement du son (Par ex. : statique, lent, rapide; son de voiture qui se déplace, son de mouche qui vole autour de soi)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Distance du son à soi (Par ex. : très proche, 3m de soi, 10m de soi, 20mn de soi)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Selon vous, ces paramètres sonores sont-ils représentatifs des paramètres sonores ayant un possible impact positif/négatif sur la perception sonore de personnes avec autisme ?

- **Oui** : avez-vous des suggestions d'amélioration ?
- **Moyennement** : pouvez vous préciser pourquoi ? et comment les améliorer ?
- **Non** : Détaillez pourquoi selon vous, et comment les rendre plus pertinents.

*

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Moyennement
- ☐ Non

Faites le commentaire de votre choix ici :

Selon vous, un/des paramètres sonores manquent-ils à cette liste ? Si oui, lequel/lesquels ? *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

☐ Oui

☐ Non

Faites le commentaire de votre choix ici :

Le paramètre "inattendu" apparaît souvent dans les témoignages mais recouvre beaucoup de notions. Selon vous, à quoi correspond un son inattendu ? (Par ex. : causes, situations)

*

Veuillez écrire votre réponse ici :

Avez-vous d'autres commentaires à ajouter par rapport à ces paramètres sonores ?

Veuillez écrire votre réponse ici :

Critères démographiques

Situation *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Personne avec autisme
- ☐ Proche de personne avec autisme (si possible, préciser en commentaire: autisme léger/modéré/sévère, âge, garçon/fille/autre)
- ☐ Praticien (préciser en commentaire: métier, années d'expérience)
- ☐ Autre (préciser en commentaire)

Faites le commentaire de votre choix ici :

Sexe *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Homme
- ☐ Femme
- ☐ Autre
- ☐ Ne veux pas dire

Age *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ 0-18
- ☐ 18-30
- ☐ 30-45
- ☐ 45-60
- ☐ 60+

Comment qualifiez-vous votre connaissance de la perception sonore d'enfants avec autisme ? Pouvez-vous expliquer pourquoi ? *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Aucune connaissance
- ☐ Peu de connaissances
- ☐ Connaissances modérées
- ☐ Connaissances importantes
- ☐ Expert

Faites le commentaire de votre choix ici :

Plus haut diplôme obtenu *

❗ Veuillez sélectionner une réponse ci-dessous

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Brevet
- ☐ Bac
- ☐ License
- ☐ Master
- ☐ Doctorat et +
- ☐ Ne veux pas dire

Merci beaucoup d'avoir pris le temps de répondre à ce questionnaire !

Pour toute question, n'hésitez pas à contacter le doctorant Valentin Bauer par mail (valentin.bauer@limsi.fr) ou téléphone (06 09 76 36 89).

Avez-vous des commentaires à ajouter ?

Veuillez écrire votre réponse ici :

Veuillez inscrire votre email dans la boîte texte ci-après si vous voulez être tenus au courant de la suite de l'étude.

Veuillez écrire votre réponse ici :

C - Subset of Sounds Selected for the AR Application *ASD_AudioEval*

Appendix C presents the set of sounds that were selected to perform the experimental protocol based on the AR application called *ASD_AudioEval* that is described in chapter 9.

Table C.1: Set of sounds being used in the experiment. Cat.: Category; Subcat.: Sub-category.

Sound	Cat.	Subcat.	Value
Cry 1	Cries	Baby crying	Neg.
Cry 2	Cries	Baby crying	Neg.
Restaurant 1	Crowded space	Recreational	Neg.
Restaurant 2	Crowded space	Recreational	Neg.
Tube 1	Crowded space	Journeys	Neg.
Tube 2	Crowded space	Journeys	Neg.
Canteen 1	School	Canteen	Neg.
Canteen 2	School	Canteen	Neg.
Over a bridge 1	City	Traffic	Neg.
Over a bridge 2	City	Traffic	Neg.
Hammer	City	Construction	Neg.
Hammer	City	Construction	Neg.
Keyboard typing 1	Human-produced	Presence	Neg.
Keyboard typing 2	Human-produced	Presence	Neg.
Eating 1	Human-produced	Mouth sounds	Neg.
Eating 2	Human-produced	Mouth sounds	Neg.
Siren 1	Indicators	Alerts	Neg.
Siren 2	Indicators	Alerts	Neg.
Shaver 1	Hairdresser	Electric	Neg.
Shaver 2	Hairdresser	Electric	Neg.
Blender 1	Home	home appliances	Neg.
Blender 2	Home	home appliances	Neg.
Fridge 1	Home	technical facilities	Neg.
Fridge 2	Home	technical facilities	Neg.
Dog Barking 1	Nature	Biophony	Neg.
Dog Barking 2	Nature	Biophony	Neg.
Bird 1	Nature	Biophony	Pos.
Bird 2	Nature	Biophony	Pos.
Thunder 1	Nature	Geophony	Neg.
Thunder 2	Nature	Geophony	Neg.
Brook 1	Nature	Geophony	Pos.
Brook 2	Nature	Geophony	Pos.
Cello 1	Music	Melody	Pos.
Cello 2	Music	Melody	Pos.
Pink noise 1	Atypical but known	Atypical but known	Pos.
Pink noise 2	Atypical but known	Atypical but known	Pos.

D - First Steps Towards XR Music Therapy for Autistic Children

D.1 Introduction

In chapter 6 we described a long-term field study that investigated the use of AR *Magic Bubbles* environment with autistic children. AR was chosen over VR based upon the findings from our interviews (see chapter 3) and our design process (see chapter 4), to secure children as well as some practitioners who were initially concerned about VR potential risks of isolation. In light of our positive findings, the psychologists mentioned being also interested in trying the use of a multisensory VR environment with self-expressive capabilities. To provide complementary VR insights to the AR insights and XR guidelines previously reported in part I, and thus confirm them or raise new issues, this appendix reports on two preliminary studies exploring this VR research avenue. They sought to extend another creative sensory intervention: Music Therapy (MT).

MT comprises a wide range of approaches which vary depending on children's abilities, the setting, the intended outcomes, and the therapist [104, 190]. Some of them focus on relational aspects by focusing on the music performance (e.g., child's technique), while others focus on the music dialogue no matter the instrument (e.g., turn-taking). However, such approaches display challenges, in terms of potential social anxiety, limited flexibility, and multisensory capabilities. While VR could overcome these different issues, it still remains under-explored so far [140].

This appendix presents two VR MT applications which seek to extend different MT interventions, respectively focusing on the music performance and music dialogue. They were created at Paris-Saclay music conservatoire in collaboration with a music therapist, and at the day hospital André Bouloche with psychologists (hereafter called the "conservatoire" and the "hospital"). They stem from two main hypotheses, that were evoked in previous technology-based MT studies [140, 245]:

- H1** Creating VR replicas of existing instruments could facilitate the music performance during MT sessions by better suiting autistic children's needs.
- H2** Creating VR-only instruments could lead to generate novel MT techniques and strengthen the child-practitioner relationship.

These two projects were led in collaboration with the *Multisensory Experience Lab* (ME-Lab) at Aalborg University Copenhagen, based on pre-existing

designs that were previously created there. User-centered design approaches were conducted to adapt these designs to the specific contexts of the conservatoire and hospital, and address **H1** and **H2**. The design process of the VR-only instrument was published at the *Sound and Music Computing 2022* Conference (Saint-Etienne, June, 2022), under the title “Exploring the Possibilities of Music Therapy in Virtual Reality: Social Skills Training for Adolescents with Autism Spectrum Disorder”. After presenting related work about MT, digital tools, and XR, two subsections describe the design, development, and preliminary testing of the two applications.

D.2 Music therapy and XR

D.2.1 Music therapy practices with digital tools

Digital tools are promising to overcome the limits of MT autism interventions, due to their specific affordances (see section 2.3), which enable to create appealing and accessible instrument interactions [3, 140, 245]. They can be sorted in four categories (with some technology overlaps) [245]: *Game Simulations*, *Interactive Multimodal Systems* (IMS), *Robots*, and *XR environments*¹. Game simulations use motivating gamified narratives to facilitate the training of target abilities. For instance, *BendableSound* [52] relies on a music fabric-based interactive surface with space-like animations on top of it (e.g., planets). Testings with 24 autistic children were positive in terms of attention and sensory rehabilitation. IMS affords music creation through multimodal approaches. For instance, with *Soundbeam*, children make gestures to create sounds, with potential to prompt imitation between the child and practitioner [87]. Robots are also used to prevent social anxiety by removing social cues from the therapists. For instance, playing the xylophone with a NAO[®] robot can help to train cognitive abilities [305].

However, these three categories have limits: practitioners’ presence may still induce social anxiety, environmental stimuli may lead to over-arousal, and immersive capabilities are often lacking. As using multisensory stimuli may improve the quality of the music experience [140, 245], XR may be promising to extend them.

D.2.2 XR music instruments

With its multisensory embodied capabilities, XR may overcome the limits of current MT practices with or without technology. Indeed, it allows children to: perform MT from the social safety of their home, safely share experiences, and get access to flexible multisensory MT resources. Yet, MT

¹While Ragone et al. [245] grouped game simulations and XR together, we chose to separate them due to differences in terms of immersion and multisensory capabilities.

XR research remains largely unexplored [3, 140]. Only two VR studies exist to our knowledge [39, 283], and no AR studies. Shahab et al. [283] created a VR environment allowing a child to play the xylophone with a robot avatar. Testing with five children were positive in terms of music ability and cognitive skills. Bryce et al. [39] exposed four children to a 360° video of a children's choir, but findings were inconclusive.

Existing MT VR studies intended to recreate existing MT techniques, in line with **H1**. Though, Serafin et al. [281]'s recent review about VR music instruments advised designing VR instruments with both "magical interactions" (not possible in real life) and "natural interactions" (close to real life), in order to create compelling user experiences. They also suggested to design novel experiences: "in line with Lanier's thoughts (see [130]), immersive technologies enable new musical experiences that extend beyond those offered by traditional musical instruments. "[281, p.23]. Being close to **H2**, this vision remains unexplored in the autism field.

D.3 First XR Music Therapy Use Case

This study addresses **H1** through several questions:

- RQ1** Could autistic children accept the virtual instrument? How does it compare with the real-world counterpart?
- RQ2** Could autistic children easily play with the virtual instrument? How does it compare with the real-world counterpart?
- RQ3** Would autistic children prefer playing in VR or real life?
- RQ4** How collaborative VR music play affects the dyadic relationship?

To answer them a user-centered design process was conducted with the music therapist (hereafter referred to as the "therapist"). An exploratory testing was also conducted in collaboration with her, with three autistic children. After presenting the VR instrument and experimental design, preliminary findings are outlined.

D.3.1 User-centered design: VR balafon

The therapist has more than six years of professional experience in autism care, at the conservatoire with children with special needs, and in other clinical settings. When starting the design process, we first inquired about her needs and objectives about the use of VR with autistic children in her class at the conservatoire. Two questions first asked about what instrument would be most or least relevant to recreate. We then inquired about the usual duration of MT sessions, the condition of the children in her class, and her motivation for the study.

Based on her answers, we decided to recreate a VR balafon ². Indeed, she expressed that: (1) it sounds good whatever you play, (2) its soft sounds are often appealing, (3) it enables collaborative play (side by side, or face to face), (4) it affords easy interactions with a limited number of notes and interactions (hitting a key to make a sound). Conversely, string instruments were the least relevant, due to common difficulties in terms of playability. Usual MT sessions last thirty minutes. Children are autistic with SLN. The therapist's motivation was twofold. First, she was interested in the differences in terms of children's interest between the real and VR balafon. Second, she wondered if first using VR could then facilitate the access to the real instrument. This second aspect could not be investigated at the time of the study since children already knew the real balafon. It was thus postponed to perspectives.

D.3.1.1 Design of the balafon

The VR balafon was visually recreated with *Blender* software, based on photographs of the real instrument. Both instruments are displayed on figure D.1. To make the VR balafon sound like the real one, it uses audio recordings of the keys of the real instrument with three intensities (low, medium, high) that were performed by sound engineers at the conservatoire. The mapping between hitting a key and the resulting sound intensity was adjusted by ear.

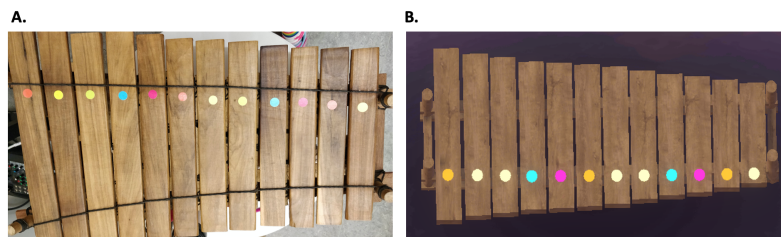


Figure D.1: Design of the Virtual Balafon. **(A.)** Real Balafon, **(B.)** Virtual Balafon.

The therapist and child can play together in a VR neutral room, being represented by simplified avatars holding virtual sticks (see figure D.3.A). The room and avatars come from a pre-existing VR prototype that was created at the ME-Lab with a user-centered approach. Using simplified avatars follows the guidelines that emerged from our interviews (see chapter 3). A video of the project is available at <https://valentinbauer.com/research/doctorat/>.

²The balafon is an instrument pertaining to the xylophone family, coming from Mali.

D.3.1.2 Apparatus

To make the VR setting easy to be used by the therapist at the conservatoire, two *Oculus Quest 2* standalone VR HMDs are used. Multiplayer and networking issues are handled by Normcore API³.

D.3.2 Preliminary experimentation

D.3.2.1 Participants

The therapist recruited three autistic children with SLN, or related traits, from her class: Axel, Ben, and Chris⁴. To do so, she explained the protocol to their legal tutors and collected their informed consent. Indeed, according to her, children were not capable of completing an informed consent by themselves. Recruitment was made on a voluntary-basis.

Axel is a non-verbal nine year old boy with SLN. He often relies on gaze to communicate. While being often up for MT activities, his MT preferences remain unknown. Ben is a verbal nine year-old boy with moderate autism who goes to school. He tends to speak a lot, and often needs to be channeled by the therapist as he also displays attention deficit / hyperactivity disorder. He usually first refuses activities (for the sake of refusing), and then accepts them, being pretty flexible. He has no particular issues about playing with the balafon. Chris is a nine year old boy with moderate autism, with minimal verbal abilities. He has access to digital tools at home. At the time of the study, all children have played with a real balafon for one year in the MT class at the conservatoire.

The low number of children is imposed by our inclusion criteria: SLN according to common criteria (e.g., ADOS-2 [175]) or therapist's expertise (if no criteria was available), be older than nine (to prevent risks with exposition to screens)⁵. Children also had to not display epilepsy or behaviours potentially hindering the conduct of the experiment (e.g., severe sensory issues).

D.3.2.2 Development of the semi-structured questionnaire

At the time of our study, no validated VR MT questionnaire existed. Moreover, children were not capable of directly answering existing MT self-report questionnaires. Thus, we devised a questionnaire to be filled by the therapist and the child for specific questions, drawing upon: our previous AR study (see chapter 5), Aruanno et al. [7]'s study, and self-report questionnaires [7, 34, 150, 308, 335]. It comprises four sections and takes five to ten minutes to complete. After inquiring about the child's state at the session's beginning and ending, two sections compare the child's experiences with the

³Normcore: <https://normcore.io/>

⁴Children's names were changed for anonymity reasons

⁵<https://www.csa.fr/Proteger/Protection-de-la-jeunesse-et-des-mineurs/Les-enfants-et-les-ecrans-les-conseils-de-l-Arcom>

real and VR balafon in terms of usability and of relationship with the therapist. A last section finally asks children (with therapist's support) if they enjoyed the real and virtual balafon, using smileys next to photographs of the instruments (see figure D.2). Questions use five-point Likert-type scales and optional comments, being summarized in table D.1.

Enfant : _____ Date : _____

As-tu aimé jouer avec cet instrument ?



Beaucoup aimé





Pas aimé

As-tu aimé jouer avec cet instrument ?




Beaucoup aimé





Pas aimé

Figure D.2: Part of the music therapy VR questionnaire to be answered by the autistic child with support from the therapist.

D.3.2.3 Protocol

a) Sessions

Each child participated to two weekly thirty-minute sessions conducted by the therapist at the conservatoire. The duration was adapted if the child needed more time to accept the HMD. They were not never forced to wear it. To compare the effect of playing in VR and in real life, the child started

Table D.1: Questionnaire addressed to the therapist (as well children for the last section) about children’s experiences with the real and VR balafons. In the column called “References” the letter “I” next to literature references refers to the items of the questionnaires being reported in these references that inspired our questions. “pres” stands for “presence”.

Section	Medium	Questions	References
Child’s state	State before session	Q1 - Fatigue Q2 - Anxiety Q3 - Happiness	[B]
	State after session	Q4 - Fatigue Q5 - Anxiety Q6 - Happiness	[B]
Interactive experience	VR	Q7 - Lots of things to learn before to use the system Q8 - Level of Exploration Q9 - Level of attention Q10 - Emotional participation (e.g., laughing)	[34, i10] [308, iEFI] , [308, iEFI] [308, iEFI]
	Real	Q11 - Lots of things to learn before to use the system Q12- Exploration Q13 - Attention Q14 - Showing emotions (e.g., laughing)	[34, i10]
	VR	Q15 - Cybersickness	[150]
Dyadic relationship	VR	Q16 - Negative behaviours against therapist (e.g., refusal) Q17 - A music dialogue starts Q18 - The child takes initiatives in the music dialogue	[244, i4] [244, i6] [244, i7]
	Real	Q19 - Negative behaviours against the therapist (e.g., refusal) Q20 - A music dialogue starts Q21 - The child takes initiatives in the music dialogue	[244] i4 [244, i6] [244, i7]
	Real/VR	Q22 - The child interacts more with the therapist in VR	[335, i12-pres]
Enjoyment	VR	Q23 - Did the child like to play with this instrument?	[7, i9-10]
	Real	Q24 - Did the child like to play with this instrument?	[7, i 9-10]

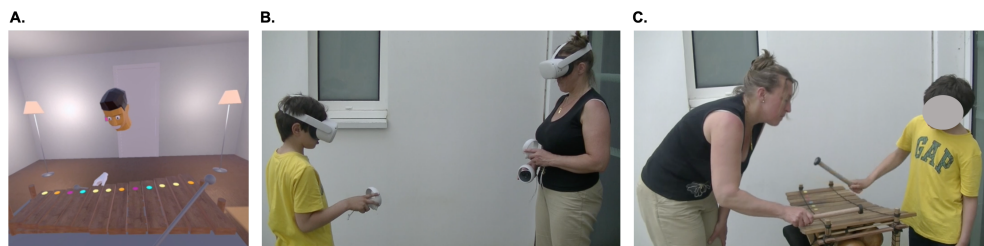


Figure D.3: Ben playing with the real and virtual balafon at session 2. **(A.)** Music play with the virtual balafon (VR view)). **(B.)** Music play with the VR balafon (real view). **(C.)** Music play with the real balafon.

in VR, and finished in real-life. This structure was adopted due to children’s previous experience with the real balafon. All sessions were filmed with two views: a video camera and a recording of the therapist’s VR view. Due to unexpected organizational events at the conservatoire, the first and the

second sessions took place in different spaces (the second one being unknown by children). Figure D.3 shows moments when the child and therapist played together with the VR and real balafon.

At the start, the therapist welcomes the child, introduces the VR setting, and helps the child to wear the HMD. Then, the session is freely structured by the therapist, as she usually does during her MT sessions. At the end, they play a goodbye song together on the real balafon (i.e., a routine that children already know). If able to understand it, children are asked about their engagement, with support from the therapist. They then leave the room, and the therapist completes the questionnaire. Any risk detected for the child would lead to stop the experiment and withdraw them from the protocol.

b) Subsequent elaboration with the therapist

In addition to the questionnaires, a semi-directed interview with the therapist was needed to collect further insights. Thus, I created new videos per session by synchronizing and displaying together the therapist's VR view and the camera view. Based on them, I conducted a pre-analysis to identify critical incidents [83] and to prepare a set of questions organized in different themes. To construct the themes, descriptive content analysis was used drawing upon our questionnaire and our categorization reported in chapter 6. This process was complemented by inductive analysis for incidents not fitting into preexisting themes. Thirty critical incidents were identified and six themes were built: attention (e.g., gestures to keep the child's focus), music performance (e.g., music dialogue), relationship (e.g., looking for the therapist), self perception (e.g., looking at oneself), influence of the overall setting (e.g., room), and engagement (e.g., exploration).

A few weeks after the last session, the therapist was confronted to the videos through four stages to elicit further insights about the course of actions occurring during sessions [311]. First, she looked at all the videos while verbalizing her thoughts, following the think-aloud technique. Second, details were asked about the critical insights being previously identified. Third, I inquired about the six themes previously pinpointed. The overall therapist's view was finally addressed, in terms of use, possible design adjustments, and additional comments. This process was audio recorded. Notes were also taken about key incidents.

D.3.2.4 Data analysis

Due to time-constraints during this thesis, I mainly analyzed the semi-directed questionnaire (see section D.3.2.2). Descriptive statistics were used due to the low number of children, and understood through the lens of the therapist's comments. In the future, qualitative methods will be used to analyze the post interview. Videos were only used to double check question-

naire's answers in case of doubts. Data were previously anonymised using identifiers.

D.3.3 Findings

All children wore the headset, with a positive evolution between the start and the end of sessions, as shown by answers to questions 1 to 6 (Q1-Q6) (see figure D.4A). Tiredness (Q1, Q4) remained low with no observable change between the start and the end. Some children were slightly worried when starting but they all gradually got secure by the end (Q2, Q5). For instance, Ben was first a bit disturbed due to not seeing his therapist during session 1 (s1), Axel was first disturbed due to being in new room at session 2 (s2), and Chris was first agitated at s1. All children happy during sessions (Q3, Q6). Their happiness levels grew during s1 and remained high during s2. For instance, Ben said "I look forward to wearing the headset" before coming to s2. Children also enjoyed more playing with the virtual balafon (Q23, Q24), as shown on figure D.4B⁶

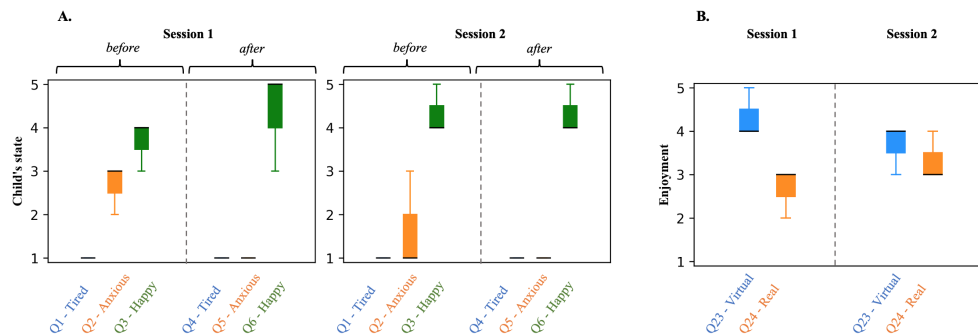


Figure D.4: Questionnaire's ratings. **(A.)** Evolution of the child's state between the beginning and the end of sessions. **(B.)** Difference in terms of enjoyment between playing with the virtual and real balafon. QX stands for Question X (where X is a number).

Answers about children's interactive experience (Q7-Q15) are summarized on figure D.5. Children did not need to learn many things before to play with both instruments as they already knew the real balafon (Q7, Q11). Yet, they were somewhat disturbed in VR by the possibility to go through the balafon with the sticks, which induced a different way of playing. While exploration levels of both instruments were similar at s1 (Q8, Q12), the VR balafon was more explored at s2. This higher VR exploration, associated with intents to understand the VR space distracted children from the VR

⁶Ratings about enjoyment were finally reported by the therapist after orally asking children about their preferences. Indeed, time constraints did not allow her to make children complete the questionnaire.

balafon at s1 and s2 (Q9, Q13). Indeed, the therapist had to get children back on the VR balafon more often than in real life. She specifically “struggled to catch” Ben, who asked a lot of questions about the VR space at s2 (e.g., about the room) and struggled to play his piece (s2) due to being “everywhere at the same time”. The lack of eye tracking also distracted Axel who usually “relies on gaze to communicate” (s1). Then, children expressed their emotions similarly in both cases (Q10, Q14). Axel expressed that he preferred the VR balafon at s1, Ben smiled when wearing the headset at s2, and Chris hardly showed his emotions as usual. Yet, the therapist found it difficult to read children’s emotions with the headset. At last, no child had cybersickness (Q15), which is not surprising as children did not have to move a lot to play with the VR balafon.

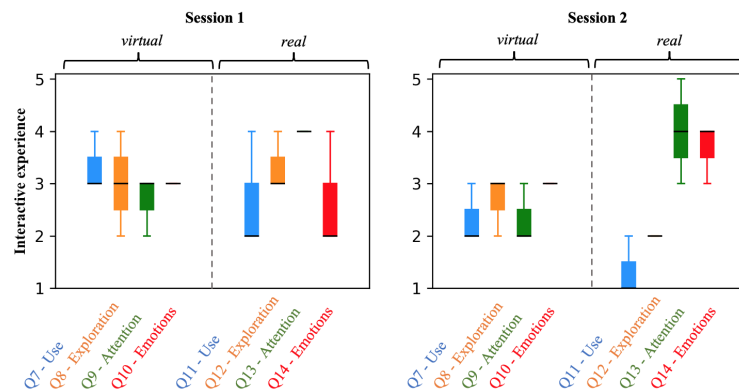


Figure D.5: Children’s interactive experience with the virtual and real balafon. QX stands for Question X (where X is a number).

Answers related to the dyadic relationship (Q7-Q22) are summarized on figure D.6. While children behaved slightly more negatively in VR at s1, no negative behaviours were observed at s2 (Q16, Q19). Chris’ agitation at s1 may be due to the fact that children usually do not only play with the balafon during MT sessions. The therapist reported that music dialogue was more developed in real life during both sessions (Q17, Q20). For instance, Alex (s1) and Chris (s2) sometimes experiencing an inner experience in VR. Alex “explored and played for himself but not for the relationship” (s1), in particular by going through the balafon with the stick (s1, s2). Chris “was absorbed, leading to less music dialogue”, but explored various gestures on the instrument (e.g., sliding between different keys (s1, s2)). Yet, Ben and Axel physically looked for the practitioner at s1, by trying to touch her. Conversely, Chris managed to imitate the therapist in real life, and Ben to play his piece. Children took little initiatives during session (Q18, Q21) even if slightly higher in real life at s2. Though, this is usual for them, e.g., Chris

usually “struggles to leave imitation”. As a result, children socially interacted more in real life (Q22). According to the therapist, this finding is mainly due to the possibility to “go through the VR balafon which changes the instrument”, the impossibility to see the physical therapist, and the lack of eye contact.

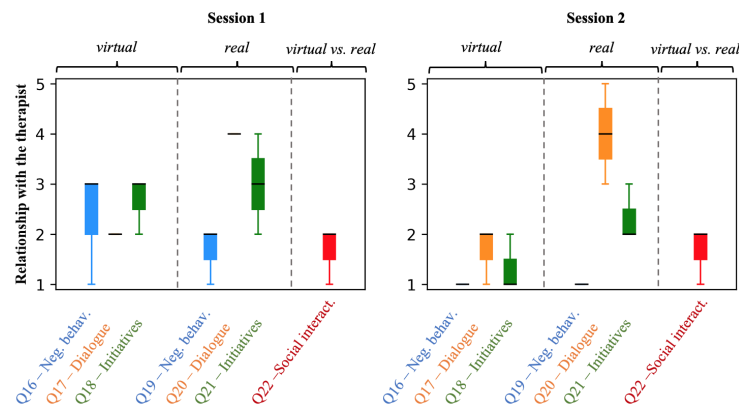


Figure D.6: Children’s relationship with the therapist with the virtual and real balafon. QX stands for Question X (where X is a number). “Neg. behaviours” stands for negative behaviours. “Q22 - Social interact.” was a question asking if children interacted more in virtual than in real life.

D.3.4 Discussion and Conclusion

A user-centered design process was conducted with a music therapist at a music conservatoire, intended for autistic children with SLN. A virtual balafon was created, which aimed at replicating a real balafon that the therapist already uses. An exploratory VR MT study was carried out with three autistic children to observe differences between the real and virtual balafon regarding in terms of acceptability, music play, children’s preferences, and dyadic relationship.

All children easily accepted the HMD. They were all calm by the end of sessions, even if sometimes worried at first due to the setting’s novelty. Children explored more in VR. Yet, this sometimes made them loose their focus on the music play. Attention loss was also caused by the fact that children could go through the VR instrument (all children), not see the real therapist (two children), and not make eye contact (one child). Children preferred playing in VR, but more social interactions were observed with the real balafon. As a result, children had an *inner* experience in VR. Given that with *Magic Bubbles*, children had an inner experience after accepting the AR headset, but then gradually shared more over time (see chapter 6.3), a longer VR MT study may unveil a similar evolution.

D.3.4.1 Limits

During this exploratory study, organizational issues at the conservatoire made us change of room for the second session, which disturbed one child. Moreover, the low number of sessions and children prevent us from generalizing our conclusions to many children. This observation calls for longer testing with more children and the presence of a control group. However, our preliminary findings may still benefit to future VR MT studies in terms of design and methodology.

D.3.4.2 Perspectives

As one child was disturbed due to not being able to make eye contacts in VR, future VR MT studies should include eye tracking capabilities. More generally, this raises the question of how to convey relevant social music cues during VR MT sessions. While this aspect would of course differ between therapeutic practices, studying if a common ground actually exists may inform future studies. For instance, conducting interviews with professional music therapists and filming MT sessions may enable to generate a repertoire of MT gestures being most commonly used. Adapting this repertoire into VR could then make VR more suited to complement current MT practices. Moreover, this question involves sub questions, for instance related to how the therapist could better perceive the child's emotions in VR, so that to better adapt the session accordingly.

Most children were disturbed by the possibility to go through the VR balafon. This finding calls for further research focusing on the use of tangible interfaces, and in particular light-weight systems affording passive haptic feedback, in order to make VR experiences more compelling. Moreover, to complement the haptic feedback provided by light tangible interfaces, we could use a pseudo-haptic rendering based on a visual illusion of the haptic feedback [182].

At last, given that children accepted the VR balafon, and were engaged while still communicating with the therapist, further testing should explore if using VR from the moment when children discover a MT instrument could speed up the access to the real instrument. This hypothesis aligns with the initial music therapist's concerns, but could not be tested in our study, since children already knew the real balafon when starting the experiment. Validating this hypothesis could have a positive impact on current MT programs with autistic children or children with a similar neurodevelopmental condition.

D.4 Second XR Music Therapy Use Case

While the previous section reported on the design and preliminary testing of a VR instrument which aimed to replicated a real one, this section presents the creation of a VR-only instrument which affords both natural and magical interactions. Our design process was driven by the following research question:

RQ How to create a VR-only instrument that could extend typical MT practices by offering alternate ways to develop the child-practitioner relationship?

To address this question, a user-centered design process was conducted with the two clinical psychologists who had participated to the design and testing of Magic Bubbles AR experiment. Given that a pre-existing VR project at the *ME-Lab* which I participated to design caught psychologists' attention, particularly due to its 'magical' affordances, we tried to adapt it for their specific context at the day hospital. Below, I describe this overall process.

D.4.1 Initial use case

D.4.1.1 Environment

The initial VR environment created at the *ME-Lab* consists of a music looper⁷ looking like a train looping over rails that a child and therapist can play with together. The train is used as being often appealing for autistic children, as reported in a previous technology-based intervention based on the application called *the Transporters*, where real emotional faces are displayed on top of trains to teach emotion recognition to autistic children [110]. It lays on a virtual table (around three by two meters) within a virtual classroom (e.g., with a backboard, shelves). Sounds are triggered with an associated visual feedback (music notes rising) when it goes through bridges. Bridges have different sound modes, being represented by icons on top of them: marimba, drums, 'magical' sounds (e.g., whistle, whooshes).

Users can interact with four objects on a control panel reminding of the train controls. First, moving a lever adjusts the speed of the train. Second, pushing the +/- buttons changes the overall sound volume. Third, turning a knob shifts the overall sound pitch. At last, blowing the whistle triggers a horn sound. These objects are supposed to display clear action-reaction relationships and strong affordances as autistic children often like trains. They are visible on figure D.7.A.

The child and practitioner can see each other through iconic-looking avatars, with only two hands and a head (see figure D.7.B). This choice was

⁷A music looper is an electronic music instrument enabling to record audio sources to then play them back in a loop.

made to limit the amount of information [31], following Newbutt [218] who reported that realistic avatars could be intimidating for autistic children.

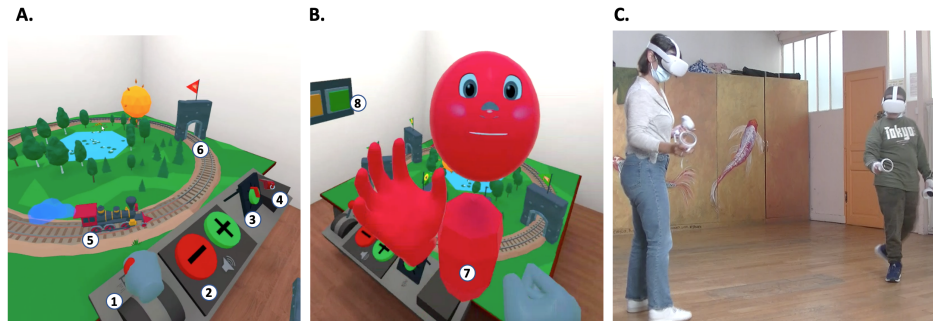


Figure D.7: Design of the VR Train. For the elements that were added or adjusted during the design process we respectively write *(added)* and *(changed)*. **(A.)** Child's VR view of the VR train crossing bridges while manipulating the lever – Content: 1 lever; 2 +/- volume buttons; 3 pitch knob; 4 whistle; 5 train; 6 bridge; 7: flag on top of bridges *(added)*. **(B.)** Avatar of the therapist greeting the child. – Content: 8: avatar of the therapist *(changed)*; 9: colour button *(added)*. **(C.)** Child and therapist playing together in the room (ongoing testing).

D.4.1.2 Apparatus

The application was developed using Unity 2019.4.19f1, with the SteamVR plug-in, and the multiplayer framework Normcore. Audio is heard through the earphones of the HMD.

D.4.2 Adaptation for a day hospital setting

D.4.2.1 Method

This adaptation of the initial use case for the day hospital setting was conducted with two clinical psychologists. It consisted in three online meetings when they could remotely see the VR application and comment on it. This user-centered design process intended to adapt the design to their needs, and to validate the use of the VR application at the hospital. Below, psychologists' insights are grouped into several themes that emerged from the interviews, in turn leading to several design adjustments.

D.4.2.2 Findings

The psychologists suggested to make the avatar look more expressive, and to clarify the contributions from each user. Hence, two eyes and a nose were added, as well as the fact that the colour of the flag on top of bridges would change depending on who interacts with it. Users could also change their avatar colour by pushing colour buttons on the wall.

To keep children focused, psychologists asked for simplifying the space. This remark led to only keep five interactive objects: the colour buttons, the

bridges, the railroad, the control panel, and the train. Given autistic common sensory difficulties, the size of all objects was also increased, as well as the weight of bridges so that to not tip over.

About the sounds being used, high-pitched sounds were removed, and replaced by sounds from low-pitch instruments (e.g., marimba, drums, and Rhodes).

While the development platform remained similar, we replaced the HTC Vive HMD by a standalone *Oculus Quest 2* to increase its portability and simplify its use at the hospital.

D.4.3 Ongoing experiment

After the design and development ended, we started an experiment at the day hospital in collaboration with the psychologists and the clinical team. This experiment includes seven autistic children with SLN from the day hospital, as well as other children with similar neurodevelopmental conditions. Similar to our previous AR experiment with *Magic Bubbles* (see chapter 6), children experience a free-play time, followed by a questionnaire addressed to practitioners, as well as interviews. This experiment is still ongoing, and therefore the analysis will be conducted in the future. In particular, we are interested in investigating if the categorization of autistic children's experiences with AR *Magic Bubbles* that we built and reported in chapter 6 could be applied to understand aspects of autistic children's MT experiences in VR. A video of the current state of the project is available at <https://valentinbauer.com/research/doctorat/>.

D.5 Conclusion and Perspectives

This appendix described the creation of two VR MT applications that aimed at complementing two types of MT approaches for autistic children: a VR balafon to support therapists when focusing on the music performance, and a VR-only instrument looking like a train to generate novel MT techniques and strengthen the child-practitioner relationship. Two separate user-centered design processes were conducted, with a music therapist at Paris-Saclay conservatoire, and psychologists at the day hospital André Bouloche. Exploratory testing of the VR balafon with autistic children suggested positive outcomes in terms of acceptability and exploration. Though, usability issues were observed due to the possibility to go through the instrument, and VR exploration sometimes led to attention loss. Testing of the VR train is still ongoing and will be analyzed in the future.

The VR issues that arose from our preliminary testing, and particularly related to attention loss, seem to confirm that AR is more suited than VR for working with autistic children with SLN. Indeed, by allowing children to keep

visual and auditory contact with the real space and their usual therapist, the issues related to not seeing the therapist may not have arisen. Moreover, the therapist may more easily rely on her usual gestures to convey music and social cues, and to catch the child's attention, while being less limited by her XR personal experience and the available movements of the avatar. Children may also be less tempted to explore the virtual space, as corresponding to their familiar environment, and in turn focus more on the music play. These observations are in line with our choice to use AR for *Magic Bubbles* environment reported in chapter 4, and our initial assumptions based on our interviews with autism stakeholders reported in the discussion of chapter 3. Given that the initial use of VR aimed at offering a safe space for autistic children to play music with a precise control of environmental stimuli, future research should instead focus on the use of Mixed Reality (MR) environments, to precisely handle the proportion of real and virtual stimuli. For instance, a MR environment may consist in adding a virtual balafon onto the real space, while removing disturbing environmental stimuli (e.g., sound echoes, images). Such work also entails issues related to the individualization of the real-virtual proportion of elements depending on autistic children, which remain unexplored to our knowledge.

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