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Fig. 1. JamaicAR is an inclusive version of the Jamaica board game using both handcrafted fixes done by professionals of board game adaptations, as well as interactive augmentation through SAR. A) PapArt hardware [31] and Jamaica board, B) projection of areas detecting pawns with a color-depth camera. Areas are touch sensitive and trigger audio feedback, C) a tactile memory aid of the spatial layout of the board, D) people with visual impairments playing JamaicAR.

Board games allow us to share collective entertainment experiences. They entertain because of the interactions between players, physical manipulation of tokens and decision making. Unfortunately, most board games exclude people with visual impairments as they were not initially designed for players with special needs. Through a user-centered design process with an accessible game library and visually impaired players, we observed challenges and solutions in making existing board games accessible through handcrafted solutions (tactile stickers, braille labels, etc.). In a second step, we used Spatial Augmented Reality (SAR), to make existing board games inclusive by adding interactivity (GameARt). In a case study with an existing board game considered as not accessible (Jamaica), we designed an interactive SAR version with touch detection (JamaicAR). We evaluated this prototype in a user study with 5 groups of 3 players each, including sighted, low vision and blind players. All players, independent of visual status, were able to play the Augmented Reality game. Moreover, the game was rated positively by all players regarding attractiveness, play engrossment, enjoyment and social connectivity. Our work shows that Spatial Augmented Reality has the potential to make board games accessible to people with visual impairments when handcrafted adaptations fall short.

CCS Concepts: • **Human-centered computing** → **Scenario-based design**; **User studies**; *Interaction devices*; **Accessibility systems and tools**.

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1 INTRODUCTION

Entertainment is an important social and developmental activity. It should be considered as fundamental as access to any other type of information and service [24]. Among entertaining activities, playing a game has a social impact [10]. In particular, board games usually involve multiple players and promote social interactions, which largely contributes to the user experience. An interesting aspect of board games is their tangibility since players physically manipulate boards, dice, cards, tiles or pawns. However, because all these elements must be identified, located, picked up and placed at the right location mainly based on visual cues, board games are per se not accessible for people with visual impairments (VI), i.e. people who are low vision or blind. In the accessibility domain, many games are serious games and exergames [48], i.e. have a purpose of training. Many accessible versions of existing board games and accessible games in general, are digital games (without any physical tokens to handle) and limited to one player [59]. Thus, they do not promote inclusion and entertaining experience for players with special needs the same ways as board games do. Interestingly, at the intersection of research on Augmented Reality (AR) and gaming, some works show that AR fosters the interactions between multiple players [11] and the manipulation of physical tokens [33]. Similarly, Spatial Augmented Reality (SAR) has been used to make pedagogical tactile media inclusive through adding interactivity [56]. SAR has the advantage that it allows the use of physical material that is accessible to VI people through touch combined with audio feedback. However, little work has been done on transferring these results to the domain of inclusive board games. We suggest that multimodal interaction and SAR may provide an opportunity to improve game accessibility and to support inclusion of multiple players with or without VI.

We have followed a participatory design approach with the Accessijeux accessible games library. In a first step, we have observed game challenges and how members of Accessijeux fix them using handcrafted solutions. However, not all challenges can be resolved using handcrafted solutions. We therefore present how SAR can be used to fix remaining challenges (GameARt). Finally, we present a concrete use case (creation of JamaicAR based on the inaccessible Jamaica game) and its evaluation. Our work provides the following contributions:

- The identification of issues in playing board games for people with visual impairments and possible handcrafted fixes. We highlight fixes that are not possible with mainstream tools and techniques, and which would benefit of Spatial Augmented Reality.
- GameARt: a framework (edition and play modes) for generic adaptations of board games based on a SAR toolkit called PapARt [31] for touch detection and for multimodal feedback.
- Application of this framework to the Jamaica Board Game as a Use Case (a board game identified as not playable and not adaptable by expert stakeholders), and the development of a working prototype called JamaicAR.
- Evaluation of the prototype in 5 inclusive gaming sessions with visually impaired and sighted players.

2 RELATED WORK

2.1 Accessible Games, Inclusive Games, Playing Together

Research on accessibility and gaming is not new, and has focused on different topics such as exercises for people with motor impairments [1, 20, 53], activity of older adults [19], social relationships of children with autism spectrum disorder [7], respiration exercises for children with ADHD [54], developing braille skills [38, 39] or navigation skills for people with VI [34, 50, 51]. All these examples take advantage of interactivity for improving both accessibility and enjoyment in learning. These games are accessible, i.e. can be played by people with special needs. However, because they are designed with specific target users in mind, they are not inclusive, i.e. can not be played jointly by people with and without special needs. Besides these examples, educational games, frameworks for digital games [4] and video games have been proposed. *TAMPOKME* [18] is a cooperative and competitive audio game, accessible to people with visual or motor impairments, as well as people without any impairments. It is a reflex game where each player should press a key on a keyboard whenever a specific sound is played. The players collaborate in a team, and try to increase individually their score. Interviews and questionnaires conducted during this project indicate that players are in demand of accessible multiplayer games [18]. During the iterative design cycles, the authors highlighted the challenges in order to design inclusive games : it is important to think about all users' needs, whether they are sighted or VI [18]. Even though sighted people could play a non-visual game, they prefer visual feedback [14, 18]. This work highlights additionally the difficulty to balance the game difficulty.

Most of the previous accessible games for people with VI were not designed for or evaluated by people with and without VI playing together. As one of the exceptions, *Kinaptic game* [23] is an asymmetric pursuit game where the player with VI must catch the sighted player digging a tunnel. In this work, the asymmetry is used to enable a fair game by providing different interfaces for sighted players (virtually digging) and VI players (catching the other player) . The interface for people with VI provided haptic feedback, wind, sonar, acoustic and ambient sound. Haptic and acoustic feedback were rated as most useful. The game was evaluated as usable and fun by people with and without VI, and it supports various strategies for the different types of players.

As another example of inclusive gaming, Metatla et al. [37] have applied a co-design approach to design games for VI and sighted children in mainstream schools. These games were based on the use of small robots. In co-design workshops with children and educators, different games were developed, including robot races, space travel or finding robots in the building. The user study showed group dynamics conducive to collaborative learning experiences, including shared goal setting/execution, closely coupled division of labour, and interaction symmetry.

From the previous works, we note that multiplayer games are inclusive if they have been specifically designed for people with and without VI. The existing works describe two accessible approaches: 1) non visual games, and 2) games with specific interfaces and roles depending on vision status of the players (e.g. a visual interface for the sighted and an audio interface for VI players). These approaches are accessible, but highlight limitations for inclusion: 1) sighted players prefer playing games with visual feedback, and 2) when specific roles are attributed this can be less flexible in terms of team composition (a specific number of profiles is required to play). It is challenging to improve accessibility, while balancing difficulty and preserving gameplay. We believe that games could foster even more inclusion through the sharing of a common pop-culture if existing and mass market multiplayer games were made accessible [18, 35, 60].

2.2 Adaptation of existing multiplayer games

Existing multiplayer video games, such as Wii and Kinect sport games, have been used to promote inclusion and perform physical activities for people with VI. Two examples are *VI-tennis* [40] and *VI-Bowling* [41]. The authors identified social limitations (finding exercise partners or sighted guides), safety concerns (by the person, or their relatives), and self barriers (choice of physical activities considered as unfeasible with VI, fear of being mocked during exercises) which prevent VI people from practicing sports [40–42]. Exergames provide solutions to these limitations: no need for partners, playable at home and limiting the risk of injuries.

Thirteen children participated in the user study of *VI-Tennis* [40] playing two versions of VI-tennis against the computer, with audio-tactile feedback or with audio feedback only. As results, the primary visual cues (e.g. the ball bouncing) should be substituted by non-visual cues, and some game mechanisms (e.g. modifying the ball speed) or secondary cues (score, serving player) may be modified or removed to ensure playability without visual feedback.

In *VI-Bowling*, the remote controller vibrates more or less continuously depending on its horizontal direction : the vibration is continuous if the remote points exactly to the target. Once the players located the target orientation for a strike, they can swing the remote along the body to end up pointing the targeted orientation [41]. Participants suggested to add spatialized audio to locate the pins, and to add environmental sounds in particular for successful trials. Although these games were initially intended as multiplayer games, this option was not implemented in the accessible adaptations and participants pointed out multiplayer gameplay as a possible improvement [41].

The same research team proposed to adapt existing games from *Kinect Sport* at run time [42]. In this approach, the video output of the game is processed to detect the game state. The system identifies specific events, and provides a sensory substitution (haptic or audio). For instance, the system triggers if an obstacle is coming (the player will have to jump on place when the obstacle is at the right distance) [42]. The average rate of success showed no difference between three groups : commercial version by twelve sighted players, adapted version by sixteen sighted players, adapted version by seven players with VI. The major difference concerns the types of errors: players tend to react too late with the commercial version, but too early with the adapted version.

AuditoryPong [28] is a version of pong that is playable both with and without visual interface. The ball is located with a continuous sound, so the player can infer the distance, the speed and the location of the ball. Another sound represents the bounce of the ball. Multiple inputs and output devices are described within the paper, such as a joystick or a tangible slider. Three thousand people informally manipulated *Auditory Pong* as a demonstration and described it as fun and playable with and without vision [28]. *King Pong* [52] is an alternative accessible version of Pong, where different types of feedback can be provided: audio, haptic and visual. The game can be played in multiplayer mode but was evaluated in mono-player mode, by one player with VI.

The games *Guitar Hero* and *Rock Band* were adapted as *Blind Hero* [61] and *Rock Vibe* [3]. *Blind Hero* [61] transforms visual cues in haptic cues. To keep an enjoyable experience, Blind Hero is played with four guitar buttons instead of five buttons in the original versions. The players wear gloves with a vibrating motor on four finger and should hold the corresponding button when a motor is vibrating. Evaluations show similar performance for Blind Hero between three groups of three players (expert blindfolded sighted, novice blindfolded sighted and novice blind players) [61].The authors noticed a significant difference between the novice sighted players playing **with** vision (more than 70% of accuracy) and the novice sighted players playing **without** vision (less than 35% of accuracy) [61]. Removing vision affects the experience of people who rely on visual capabilities.

Rock Vibe [3] adapted a drum game through a design process with interviews and focus groups. In the prototype, vibrating motors are fixed with Velcro straps on the upper arms (external drums), on the lower arms (internal drums) and on the ankle (kick drum) [3]. Audio feedback plays the sound of the drums in case of successful hits (i.e. correct time and drum), and a click sound in case of incorrect hits (too early, too late, wrong drum). The user study shows a positive learning effect. The lessons learned indicate that the feedback should be balanced (warnings, intensity, annoyance) and/or customized [3].

Finally, an adapted Domain of *Discworld MUD* allows to navigate in a representation of an area of the game (called *Death's Domain*) [55]. *Discworld MUD* is initially a text-based game. The game had two adaptations : egocentric mode of the navigation in the dungeon (left, right, backward, forward), or allocentric mode (west, east, south, north). The results of the user study suggest that players with VI prefer egocentric navigation, and sighted player allocentric navigation, in line with what has been shown in prior studies [9]. Thus, the spatial tasks and the spatial representations have an effect on the usability and the experience of a game.

Some board games are accessible with few or without any adaptations [26, 27]. Board games that are not initially accessible, can be adapted with handcraft techniques. Da Rocha Tomé Filho et al. [12] proposed guidelines on how to modify existing board games in order to make them accessible in line with universal design guidelines (such as adding braille labels). But these handcrafted techniques may not be sufficient to provide VI users with access to the board's spatial layout and game mechanics. When handcrafted techniques do not allow to make an existing game accessible, interactive systems can be alternative solutions. A few board games with multiple players have been adapted. Computer based chess games involve two players and present both pros and cons for people with VI compared to physical chess boards [5]. Indeed, the pieces cannot be knocked down (as would be the case for a physical chess board), but the cognitive load for remembering the positions is very high in the absence of the tangible board. *Othello* [25] and *Tic-Tac-Toe* [15] are other multiplayer board games that have been adapted. The accessible *Othello* [25] relied on a tactile device to mix up the experience of a physical board game with a computer. It provided both audio and tactile feedback about the game state. Although they were inclusive, these two prototypes were evaluated by people with VI or blindfolded participants playing against the computer and not a sighted human. *AudioBattleship* [49] is a multiplayer adapted version of a battleship game that was developed to foster collaboration between blind learners. This game integrates balanced difficulty levels for playing with sighted people to ensure fairness (the same probability of winning independently of visual status). It was evaluated by people with VI in a multiplayer condition.

To sum up, even though there is work on games which are inclusive (i.e. games that are playable "by all") and which integrate a multiplayer setting, existing games have mostly been evaluated by people with VI in groups, or even in a monoplayer setting. Moreover, it has been shown that accessibility is not enough, but the user experience (e.g. fun) is important and that some compromises in the gameplay should be made if it ensures a better playability.

2.3 Augmented Reality and Inclusive Gaming

The perception of figurative and spatial material (maps, graphics, drawings, etc.) is a key research question in non-visual accessibility [16]. In addition to multimodality [13, 58], interactivity can foster accessibility of complex layouts for people with VI. For instance, previous work with people with VI has shown that interactive maps are more efficient and satisfactory to use than tactile maps with Braille [8], and that interactive 3D models better support memorization of text and geographic elements [21]. SAR has also been used to make maps and graphics accessible thanks to audio-tactile feedback [2, 56]. Based on these different results we suggest that SAR can be a powerful tool to improve the accessibility of board games because: 1) it can make board games interactive, 2) this interactivity improves spatial perception and spatial memory without vision, even for complex layouts.

Regarding games in general, and not specifically accessible ones, AR is already used to foster multiplayer interactions. By definition, board games support social interaction via physical artifacts, which is particularly appropriate for AR games [44]. *TARBoard* [33] is a tabletop game that uses tangible interaction and AR to preserve the affordance of physical elements while adding digital visual feedback. In *ARQuarke*, the authors aimed to provide physical rendering of digital information, with a see-through display and haptic feedback of virtual elements [57]. More precisely, the player moves in the real word, collects virtual objects, fights virtual monsters and completes objectives. The AR game *Augmented Groove* [47] was proposed for collaborative jam sessions, with and without musical instrument, using cards. In a set of three AR games called *Touch-Space* [11], two players help a princess trapped in the witch's castle, by finding maps, reaching the castle and fighting a witch. The game takes place physically in a real room. *TankWar* [44] is an adaptation of a tabletop game using a head-mounted display. By sharing the same tabletop and manipulating tangible pawns, the players can follow other players' actions. *Pirates!* [6] was designed to use the real-world as a board game with a multiplayer gameplay. All these works show that AR is a solution for keeping the imaginative play while focusing on human interactions and preserving the freedom of movement [11].

Two research works proposed an Augmented Reality approach to make board games accessible. Noble et al. [45] studied the benefits of projected augmented reality for accessibility. The interactive prototype was not evaluated, but they demonstrated that SAR was promising. Recently, Johnson and Kane proposed *Game Changer*, a system providing audio and tactile feedback on top of existing board games [29]. A camera tracks the pawns and the cards in order to add audio feedback on three commercial games (*SORRY!*, *Monopoly* and *Chutes and Ladders*). Tactile markers could be added manually on the board. This work was tested by seven people with VI, playing one by one against a sighted player. Participants found the game more accessible with the Game Changer additions, appreciated being able to follow the gameplay and to play independently and expressed their interest to use Game Changer to augment other games. This work is closest to our work presented in this paper. However, it differs in that it does not make use of additional visual feedback for sighted players and does not propose an editing mode for new games. Moreover, our work builds upon the know-how off an accessible games library for creating physical adaptations (such as tactile markers and digital dice) integrated into our prototype.

2.4 Summary

Based on the analysis of existing work, we make the hypothesis that SAR can help to go beyond the existing limitations of handcrafted adaptations to design inclusive multimodal and multiplayer games. Interactivity can give access to the layout of the board and the gameplay by augmenting visual information with audio feedback, while maintaining the visual layout for sighted players. As shown above, only few approaches enrich the original game to make them accessible (adaptation), instead of re-implementing the game or creating a new one. Our work aims to fill this gap.

3 TOWARDS MAKING ACCESSIBLE BOARD GAMES

3.1 Objectives and Approach of our work

Previous work has proposed various adaptations of specific games. However, (i) it is not clear how these adaptations overcome the limits of existing handcrafted adaptations, and (ii) how well such adaptations can be generalized for inclusive gaming. The main existing techniques and remaining challenges for making the games playable, in a generalizable way, are not well established. In our work, we addressed the following research question: can AR be used to overcome the inaccessibility of board games, and foster inclusion of sighted gamers and gamers with VI? We investigated whether AR can be used as a generic tool to make an existing board game accessible and inclusive. We evaluated a game played by people with and without VI. Our objectives were **O1**: to identify the criteria that would make the adaptation of games easy or hard, according to experts of game adaptation, **O2**: to identify the interactive features of a generic adaptation framework to make games accessible when handcrafted-only adaptation fails (GameARt), and **O3**: to apply this framework to a specific use-case (JamaicAR) and evaluate the prototype regarding accessibility and inclusion during game sessions.

3.2 Participants

This work was conducted in close collaboration with Accessijeux, Paris, FR which is a non-profit organization, officially recognized as a public service organization, holding an accessible game library. It offers more than 160 games that have been adapted to be accessible to people with VI. In 2018, Accessijeux participated in 31 games festival and sold 900 adapted games. The organization has 240 members, half of them with visual impairments. Since 2015, Accessijeux adapts board games to be accessible to people with VI of all ages, based on two mantras: 1) not to change the original aspect of the game in order to preserve the enjoyment for sighted people and people with low vision, and 2) using handcrafting techniques for fixes to limit the amount of work and be able to sell the adapted games for a similar price than the original one. For these adaptations, many different materials are used, such as tactile stickers, Cerne relief, pinch, magnets or metal pieces, which we describe later in this paper. In addition, they recently designed a smartphone application to provide digital dice, and access to texts (e.g., game rules, cards and descriptions).

During the observation of board game adaptations with Accessijeux we worked with two visually impaired and 3 sighted members of Accessijeux. During the adaptation of the board game using SAR techniques, we worked with six visually impaired players. Pretests were done with two VI people and one blindfolded sighted person. The actual user study was conducted with eight sighted and seven VI people in 5 groups of 3 players each. Details are provided in the sections below and in table 2.

4 OBSERVING HANDCRAFTED ADAPTATIONS FOR MAKING BOARD GAMES ACCESSIBLE

In this section, we describe the analysis of game adaptation techniques used by a non-profit organization with the objective of highlighting the main techniques, criteria and challenges for game adaptations.

4.1 Participants and Method

In order to observe adaptations undertaken by Accessijeux, we organized a three day observation, working with the president of Accessijeux (male, 45 years old, tunnel vision, visual acuity 1/10 on the best corrected eye, blind in dark conditions), one employee (male, 42, low vision, able to see in the 20 cm range), and three game adapters (1M and 2F, sighted, 18 to 25). In addition, we observed two nights of inclusive gaming organized by Accessijeux. The participants from Accessijeux first selected and demonstrated a sample of 24 adapted games representing all different types of adaptations they apply [1]. These games were initially not or only partially accessible to people with VI, but once adapted these games were playable (we define "playable" as the adaptation succeeded, or in other words the game after adaptation is accessible). Another set of games was hard or impossible to play even after adaptation (the adaptation failed)[2]. Finally, one game (Nyctophobia) is generally played blindfolded, and hence does no not require adaptations. This corpus provides an important empirical feedback about successful and failed handcrafted adaptations, played by sighted, low vision and blind players of the organization. We discussed games that the experts consider as not adaptable because of the game mechanics (we define a game as adaptable if there are existing approaches for making it accessible such as described below), or with poor playability

[1]Arboretum, Cartagena, Citadels, Colt Express, Rat trap, CuBirds, Unmöglich!?, Decrypto, Draftosaurus, Hanamikoji, Intrigue, Jaipur, Keep cool, Kingdomino, Linko, One Night Ultimate Werewolf, One Night Werewolf Daybreak, Luminos, Mascarade, Noah, POK, Quarto, Saboteur, Sushi Go!

[2]including but not limited to Ticket to ride, The Werewolves of Millers Hollow classic, Jamaica, Around the World in 80 Days, Scotland Yard.

after adaptation based on their own experience (e.g. due to a cognitive load that is too high, or unfair for players with VIs).

Based on these observations, we proposed a heuristic table that allows to predict the adaptability of board-games. It reports: (1) the identified challenges to be adapted, (2) the adaptation techniques, (3) the complexity (material and cost) of the adaptation techniques, and (4) the remaining challenges that cannot be resolved. People working at Accessijeux read the document to verify that the reported challenges, techniques, cost and remaining challenges are consistent with their expertise and knowledge. This report is now used as an internal document, and transmitted to the game editors working with Accessijeux. The heuristic table (see table 1) was run on the set of games. We computed two simple scores: the *non-adaptability* (NA) score (i.e. how many remaining challenges exist for each game according to the criteria), and the *adaptation effort* (AE) score. The *AE* score was computed as follow: +1 for each simple adaptation, +2 for each medium adaptation. We asked Accessijeux to annotate the **adapted** games as playable (Unmoglich!?!, Hanamikoji, Intrigue, Keep cool, One Night Werewolves, POK, Skull, Sushi Go), playable with limited fairness due to a higher workload or a difference of information in the accessible version (Apagos, Darftosaurus, Decrypto, Jaipur, Kingdomino, Linko, Mascarade, Quarto, Rat trap 3 and 4 players, The Mind, Werewolves Daybreak), not playable due to unfairness or a high cognitive workload (Citadels, Colt Express, Schotten Totten) and impossible to play (Arboretum 2 and 4 players, Cartagena, Cubirds, Noah and Saboteur). The playable games have an AE score under 4, and a NA score under 2. The games playable with limited fairness have an AE score under 8, and a NA score under 3. The unplayable games have an AE score under 5, and a NA score under 6. Finally, the impossible games have an AE score over 4 and up to 10, and a NA score over 3 and up to 7. These results illustrate that games with higher remaining challenges and adaptation effort scores have a lower playability.

4.2 Observed adaptation techniques

According to Accessijeux, many game mechanics are accessible. For instance, the mechanics of card games consist in choosing, distributing and memorizing cards in a deck. These games are accessible because the cognitive load is not too high. Players know their own cards, make guesses about the other players' cards, and the situation evolves step by step. Negotiation games (e.g. Intrigue) mechanics are accessible because most of the elements are shared among players (each player knows about the others' situation). Yet, other game mechanics are inaccessible. For instance, it is hard to adapt silent collaborative decision-making (e.g. Werewolves of Miller's Hollow) where a team must decide whether or not to eliminate one player without talking (e.g. using gestures and grimaces). It is also very complicated to adapt games where the spatial layout of the board is essential, especially in the following situations: 1) The board configuration or state is changing depending on players' actions; 2) The visual layout of the board game has an important impact on the gameplay, e.g. in Arboretum, the score is computed as the longest paths between two identical trees on a grid; 3) The size of the board is very large or evolving. For instance, in Saboteur each player adds a tile, which increases the board size of one box at each turn, virtually infinitely in any directions. In all these situations, systematic and extensive exploration movements are mandatory (eventually at each turn) to understand the board configuration. These "spatial" games are not essentially hard to adapt (e.g. adding tactile stickers on tiles), but they require too much work to be adapted for tactile exploration (e.g. creating a holding system for the pawns or tiles) or they are considered as non-playable even after adaptation because of the high cognitive load, or the recurrent manual exploration of the board needed to play the game.

Estimating the adaptability of a game before performing the adaptation is an important requirement for Accessijeux. It presents two main interests:

Description	Simple	Medium	Remaining	Fixes and possible remaining issues
Dice				
A. Dice with numbers	x			Tactile dice or Smartphone app
B. Dice where faces are not numbers		x		Blank dice with tactile stickers or Tactile dice with correspondence table or Smartphone app
C. More than one dice		x		Tactile dice of various sizes, or Smartphone app
Cards, tiles, tokens, coins and paper money				
D. Cards or tiles that are oriented (top, bottom, left, right) or printed on both sides (recto-verso)	x			Perforation or tactile stickers at the same location on each card (prevent sighted players from recognizing cards)
E. Different types of cards, tiles, coins or paper money having the same shape	x			Tactile stickers or perforations
F. Cards or tiles: 1 or 2 pieces of information required to decide the next action (e.g. color and value on a card)	x			Tactile stickers and/or perforations at 2 different locations
G. Cards or tiles: 3 pieces of information to decide the next action (e.g. type, coast and attack points on a card)		x		Tactile stickers and/or perforations at 3 different locations
H. Cards or tiles: 4+ pieces of information to decide the next action		x	x	Adapt the gameplay to work with 3 pieces of information instead of 4 (managing more is possibly too complex, remaining issue to be resolved).
Pawns and figurines				
I. Different pawns with the same shape	x			Pedestals (wood, cardboard, 3D printed, etc.) with different shapes or tactile stickers
J. Location of other players' pawns required to decide next action (with 3+ players)		x	x	Magnetic pedestal and metal pieces on the board (medium fix) but possible cognitive load issue (remaining issue to be resolved).
Boards made of boxes, tiles or cards				
K. Up to 25 specific areas drawn on the board (e.g. boxes, cards areas, etc.)	x			Tactile stickers to indicate the areas
L. More than 25 specific areas on the board (empirical limit, also mentioned in [17])	x		x	Stickers to indicate the areas (simple fix) but possible cognitive load issue (remaining issue to be resolved).
M. Different types of specific areas	x			Different tactile stickers (in addition to items K and L)
N. Tiles used to build the board on a non-delimited area		x	x	System to attach the tiles (e.g. Velcro®, magnet) but possible cognitive load issue (remaining issue to be resolved).
O. Multiple paths and junctions on the board	x		x	Tape on the board (simple fix) but possible cognitive load issue (remaining issue to be resolved)
P. Specific area on the shared board can change value (with 3+ players)			x	Ensure tactile exploration (c.f. J and N fixes) but possible cognitive load issue (remaining issue to be resolved).
Text				
Q. 1 to 7 textual elements presented at the same time		x		Tactile stickers (or Braille stickers for braille readers). Game is accessible in a mixed setting (at least one sighted player to tell the elements) or with an app
R. 8+ textual elements presented at the same time		x	x	Tactile stickers. Possible working memory issue.
S. Textual elements hidden to other players			x	Non-playing sighted person or custom application to assist.
Decision making				
T. Knowledge of the board layout required at each turn if strategy must be hidden		x	x	Propose a way to get the information without asking questions, for instance with a memo or a generic way to describe the board state. Possible cognitive issue due to spatial complexity
U. Knowledge of the board layout required at each turn to win points (e.g. Arboretum, Cubirds)			x	Possible cognitive issue due to spatial complexity
V. Decision based on spatial memory of his/her own board			x	Possible cognitive issue due to spatial complexity
W. Decision based on spatial memory of the shared board	x		x	Make sure that each player verbally describes his/her own actions in particular sighted players. Possible cognitive issue due to spatial complexity
X. Silent decisions (e.g. based on gestures) in a group (e.g. The Werewolves of Millers Hollow classic)			Impossible	Impossible to play depending on vision abilities
Y. Knowledge of the board layout required at each turn to plan 3+ successive actions in combos (e.g. Noah)			x	Possible cognitive issue due to spatial complexity
Total of simple fixes, medium fixes and remaining issues:	10	9	13	

Table 1. Summary: criteria with easy or medium fixes and remaining challenges, validated by the adaptation experts of Accessijeux.

- Estimating the number of fixes to perform as well as the required techniques and materials. It is directly linked to the time spent and final cost. The simple fixes require limited time, costs, materials and expertise to fully solve the accessibility issues. The medium fixes require higher times, costs, materials, and handcraft expertise to fully solve the accessibility issues
- Estimating if the game will be playable by people with VI once all the fixes have been performed, which means being able to decide if the adaptation will be successful or not. The remaining issues are the identified cases without adaptation fully solving the issues.

To sum up, we observed the following challenges and handcrafted solutions (see also Table 1) :

(1) **Written text** is not accessible to people with VI. This includes game rules and text on cards, tiles, boxes, names and descriptions of characters, objects, special powers, etc.
Handcrafted fix: Confidential text which is not to be shared with others, can be read with an assistive tool or sent by SMS (the assistance of a sighted person may be sufficient) and read by text-to-speech on the phone. Braille transcription can be used, written with a Perkins device on paper or transparent stickers (however, it must be noted that less than 20% of VI people read braille [43]). QR codes and a phone application with voice synthesis or CD can provide better access to text than braille labels.
(2) **Cards** display numerous visual features such as type and variations (e.g. species, sex, age of characters), values, properties, etc. Correct orientation (top-bottom, left-right, recto-verso) can be important.
Handcrafted fix: Cards, bank notes, etc., can be punched with different tactile patterns, in order to indicate orientation, value, type, etc. Transparent stickers with tactile codes can also be used. Values, numbers or shapes can be added as tactile codes. In addition, the position of the sticker on the card can be used to enhance the code and indicate orientation, e.g. with the same sticker located on the left/right or bottom/middle/top.
(3) **Dice** are difficult to find and read. Special dice (other than numbers from 1 to 6) can contain colors or visual patterns.
Handcrafted fix: Transparent stickers with tactile markings can be stuck on dice. A smartphone application can replace physical dice.
(4) **Dynamic boards**: in some games the **board** is built by **assembling cards or tiles**.
Handcrafted fix: It is possible to stick transparent tactile tape on the board, or use hot glue to create tactile paths or tactile stickers to indicate the location and identity of boxes on a board game.
(5) The **board** contains visual information that **describes a specific spatial layout**. It may be complicated to memorize this spatial information and to update it as players move along the board.
Handcrafted fix: The first strategy is to describe the board and attribute meaningful nicknames to special locations. For instance, a place on the board where nobody wants to go can be called “the toilets”. A known layout (e.g. the Braille cell) can be used to talk about the board layout. For instance, using the Braille cell layout can help to locate three boxes on the left (1,2,3), three boxes on the right (4,5,6), as well as boxes on top (1,4).
(6) **Pawns and figurines** may have similar shapes and can be hard to distinguish by touch alone.
Handcrafted fix: Add a pedestal with a specific shape.
(7) When exploring the board by touch, **pawns can be pushed** out of position, or fall.
Handcrafted fix: The pedestal can contain magnetic material. Magnets can then be positioned at specific locations under the board, to attract the metallic pedestal of the pawns and keep them stable, at the right location.

(8) The players must **find and manipulate the other players' pawns or cards**.
Handcrafted fix: Define a specific area where such tokens are positioned for all players, for instance on a playing mat.

4.3 Remaining issues that handcrafted adaptations cannot solve

From the summary table (Table 1), we identified the following remaining issues that cannot be solved by handcrafted adaptations:

- H. More than 4 pieces of information per card or tile
- J. Locations of the players' pawns are required to decide the next action
- L. More than 25 specific areas on the board
- N. Tiles used to build the board on a non-limited area
- O. Multiple paths and junctions on the board
- P. Specific area on the shared board can change value (when more than 3 players)
- R. More than 8 textual elements presented at the same time
- S. Textual elements hidden to other players
- T. Knowledge of the board layout required at each turn for strategy
- U. Knowledge of the board layout required at each turn to win points
- V. Decision based on spatial memory of one's own board
- W. Decision based on spatial memory of the shared board
- X. Silent decisions (e.g. based on gestures) in a group (e.g. The Werewolves of Millers Hollow classic)
- Y. Knowledge of the board layout required at each turn to plan 3+ successive actions in combos

Many of these issues are related to knowing and updating the knowledge of the layout of the board and its states: J, L, N, O, P, T, U, V, W and Y. As a consequence, making the board itself more accessible (its layout and its state) is a major issues.
The accessibility of the text is another major issue (R and S). The particularity here is to provide individual and private information to each player, which has been done by Accessijeux through braille adaptation or the use of a smartphone app and flash-codes on the cards. For group feedback, the framework can provide textual information in an audio format. The issue H can only be solved by adapting the gameplay. It is very difficult, to solve issue X.

Based on these findings, we suggest that Spatial Augmented Reality could be used to solve the remaining issues. As presented above, audio-tactile augmented reality has been used to make spatial representations accessible in the context of tactile maps and drawings (see section 2.3) and consequently is promising for enabling the same in the context of board games. SAR also allows to add audio feedback and thus provide access to textual elements.

5 FRAMEWORK IMPLEMENTATION: GAMEART

5.1 SAR Implementation of GameARt

Based on the prior work of making maps and graphics accessible to people with visual impairments [2, 56], we decided to use a Spatial Augmented Reality approach to create accessible games from existing board games. We used the PapARt AR toolkit (Figure 1A) [31] which comprises hardware, API and applications. A depth-color camera tracks fingers and objects. PapARt includes a microphone, which allows saving on-the-fly verbal and audio feedback [56]. A projector augments the working area with visual projection, while audio feedback is provided through loudspeakers.

Fig. 2. A blind person playing JamaicAR. The combination of touch and interactive audio feedback provides accessible features and preserves the user playing experience (manipulating the tokens, reading the game rules, and possibly cheating, etc.). From left to right: the person (1) finds by touch the red pawn, (2) counts the spaces by touch relying on the varnish relief, (3) keeps the left hand on the space, and grasps the pawn with the right hand, (4) verifies the space number and the zone launching the audio feedback, and (5) pays resources.

In order to propose a generic adaptation framework GameARt, we suggest to implement two modes: 1) a play mode to use during game sessions, providing the adaptations to the players such as audio feedback, and 2) the edition mode, in order to set up the adaptation for any game. The latter can be used during the design process to augment the physical game board with interactive areas (similar as in [56]). Visual cues were used during the edition mode to visualize the created interactive areas on the augmented board. Augmented games could be saved and reloaded.

To summarize, the interactive features of our SAR game are: (1) input: touch detection by color-depth camera tracking fingers and objects, (2) output: interactive zones providing audio descriptions, and 3) visual cues for edition mode. In this section we will generally introduce GameARt play mode and edition mode, before providing details about the implementation of JamaicAR as a use case in more details in the following section.

5.1.1 Play mode: playing the game. In Play Mode, interactive zones on the board trigger visual and audio feedback (Figure 2). The following features make the game accessible in play mode:

- Input: detects the position and colors of the pawns, detects a simple touch and a long touch on the interactive areas.
- Output: verbal description of the game state (pawn locations) or the type of any space on the board (e.g., sea, harbor, treasure, cost), launching the dice and repeating the last values. Ambient sounds can be added to increase the user experience (e.g. birds, fighting, waves).

These features answer the following remaining issues identified above (Table 1):

- J ("Locations of the players' pawns are required to decide the next action"): When a player touches a pawn its name is spoken. The position of all pawns can be detected and provided.
- L ("More than 25 specific areas on the board"), N ("Tiles used to build the board on a non-limited area"), O ("Multiple paths and junctions on the board"), V ("Decision based on spatial memory of his/her own board"), W ("Decision based on spatial memory of the shared board"): The framework provides audio-information on touch to access information on demand, thus enhancing the exploration of complex layouts as well as their memorization.
- P ("Specific area on the shared board can change value (when more than 3 players)"), T ("Knowledge of the board layout required at each turn for strategy"), U ("Knowledge of the board layout required at each turn to win points"), Y ("Knowledge of the board layout required at each turn to plan 3+ successive actions in combos"): The prototype provides an audio and generic description of the board state on demand, the proposed framework helps to indicate the state of the game, without indicating a strategy to the other players.

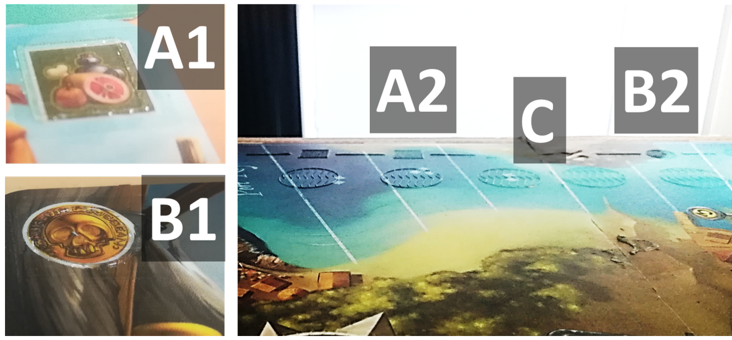

Fig. 3. Adaptation of the board with transparent tactile cues. The tokens and the tactile stickers on cards representing food are square (A1). A tactile square on the board (A2) represents the sea. Round tokens and the tactile stickers on cards represent gold (B1). A tactile square on the board (A2) represents harbors. Interactive zones are represented by the nearby wavy tactile area (C). The tactile straight lines between the spaces indicate the path on which pawns can travel throughout the board.

Additionally, interactive dice zones (picking randomly a value) or deck zones (shuffle a list of values, then picking the value of the *top of the virtual deck each time*) make dice and decks accessible. This allows to repeat the last value, or to pick a new one.

5.1.2 Edition mode: making digital adaptations. The edition mode allows users to make their own adaptations to different board games and works similarly as the prototype in [56]. The first step is to draw the outline of the board to limit the interactive area. To do so, the user moves the finger on the table along the shape of the physical board. Then, he or she can draw the areas of the board with the finger, and register audio captions related to each area with the microphone (see the highlighted zones in Figure 1A and B). The areas can have different behaviors:

Interactive area: audio description of spaces on the board. During the game, the descriptions are triggered by a simple finger touch. It makes sense to additionally highlight these zones with tactile information. For instance, in the case of JamaicAR, we indicated these digital areas with a physical "wavy" tactile pattern Figure 3C.

Pawns location area: audio-description of the game state on demand. The users can ask for a standardized description of the game state at any time. The pawns are detected by the color-depth camera when they are inside a predefined zone. Each pawn's location corresponds to an recorded audio label that is played during the audio description of the board state. E.g., when playing JamaicAR, the game will play the audio feedback "Player {blue} is on {space 4}, Player {red} is on {space 12} and Player {green} is on {space 13}". All information between brackets has been recorded in the edition mode, i.e. the name of the pawns (here the color) and the description of the spaces (here the space number). They correspond to the entire space of the physical board (see Figure 1B). Conversely to the interactive areas, they are triggered by pawns (vs touch with finger for the areas), they do not have the same information (e.g. the space number vs the cost), nor the same interactive zone (the entire space or a part of the space). The pawns are positioned on specific areas during the calibration, where a name is associated to image recognition of the pawn.

Dice or Deck area: corresponds to the dice simulator (A1 and B1 in Figure 4). When creating the dice area, the user registers the audio feedback corresponding to each dice face (e.g. "1" to "6" for a regular dice, or "food", "sword", "shield", etc. for a custom dice). The dice areas can be modified to create an interactive card deck instead, by not repeating a previous value, or by maintaining a virtual pool of values not yet picked. If necessary, multiple virtual dice can be associated to a dice area, generating one, two or more random values if there are one, two or more dice associated with this area. A short touch input repeats the last value(s) (simulating a glance), and a long touch input provides a new random set of values (simulating the launch of the dice).

The whole interactive layout can be saved and relaunched later on.

5.1.3 Technical implementation.

Framework data: PapARt framework provides positions of touches and objects at any time on a surface (either from finger detection or color detection). Coordinates are in millimeters and in 3D relatively to the surface (here the game board).

Creating a new area: We generate an interactive area by "drawing" it with the finger directly on top of the boardgame in edition mode. By doing so, we obtain the touch positions, and save them as a chained list of touch positions. This list constitutes the border of the created area. Once a new area is created, we simplify the shape by removing points when the distance (Hausdorff) between the two shapes (with and without the point to remove) is under a threshold. This threshold is defined by the programmer from the scale of the interactive area, and the computation power allowed to detect a touch inside a given area or not. If shapes are convex, all points with an angle equal or over 180°(oriented in direction of the center of the figure) can be removed. From the list of the points defining the area border, we generate a svg-like file in Json format. Each area is described as a set of points to generate a closed path [3]. Each shape is associated with a sound recorded at the time of the shape creation using a microphone. The name of the sound to play is associated with the area in the Json file. A new area is added on top of the existing area. A parameter enables to reverse the order of the area (the last area created is on the bottom of the existing areas).

Displaying the areas and detecting a touch inside the areas: We display the interactive areas (projection) as convex or concave areas, and detect the touch inside the drawn shapes. A touch can trigger several areas, then the sounds are played successively from the "top" area to the "bottom" area. The interactive areas are triggered by a finger touch, while the Pawn areas are triggered by a Pawn. The pawn detection associates the color detection and the height of the pawn (to distinguished color from the board and from the pawns). Each pawn is detected by its color, and each color is associated with a pawn name.

Dice and deck areas: the deck and the dices are launched when touching a deck or dice area. These areas are linked to a set of sounds using a Json file. Each touch plays a new sound. A dice area plays randomly one of the sounds in the set. A deck area shuffles the list of sounds, and plays the first one. Depending on the deck type, this sounds is moved to the last position ("under the deck"), or is removed from the playable sounds ("drop").

5.1.4 Verification of the compatibility of the edition mode with multiple games. We designed the edition mode to be usable for any game. To verify that it is the case, we selected 6 board games in the top 50 best sellers of an online store : Monopoly, Catan, Cluedo, Parcheesi, Trivial Pursuit, Risk and Pandemic. We reviewed the rules and the physical tokens to propose adaptation with our prototype (the details are provided as supplementary material).

We adapted Monopoly with GameARt as a demonstrator for Accessijeux organization. We then ran the heuristic table (table 1) for Catan, Cluedo, Parcheesi, Trivial Pursuit, Risk and Pandemic. For each identified remaining adapation, we analyzed if GameARt proposes adaptation features. We found that the edition mode is compatible with the majority of the games (Monopoly, Catan, Cluedo, Parcheesi). With a minor modification only (association between questions and responses),

[3]https://www.w3.org/TR/SVG/paths.html#Introduction

Fig. 4. Board adaptation and memo. Top: The original Jamaica board. Middle: JamaicAR Board with the transparent relief (in red on the picture for better visibility), and the "wavy" transparent tactile pattern for the interactive zones (in black on the picture). The visual dice areas (A1 and B1) are transcribed as the interactive area for launching the dice of the morning and night action (A2) and the fight dice (B2). Bottom: the memo (A5 size) presents an overview of the paths on the board. The relative position of the dice areas are represented with the same relief symbols (A2/A3 with a “play” triangle and B2/B3 with the target). Triangles are engraved every 5 spaces to facilitate counting the number of the spaces. The alternative paths are represented (C1, C2 and C3) for a better layout overview.

Trivial Pursuit would be adaptable as well. The adaptation of Risk and Pandemic required further modifications:

Player deck: a player deck can be added. It can be entirely virtual, but it can also consist in augmented physical cards identified by markers. The card description can be played by simple touch (see interactive objects in [56] and cards in [22]). This solution was relevant only for a high number of different cards (e.g. 48 cities in Pandemic). Otherwise, simple tactile stickers can be used to handcraft the cards.

Hidden deck: in some games, the deck has to be hidden from other players. If a simple card fix with tactile sticker is not possible, an interactive solution can be implemented. The SAR system can be connected to the players' smartphones (using socket APIs for Java in the current prototype). The hidden deck can be described with earphones to remain private.

Split deck: the deck could be split into subdecks. The characteristics can be: active deck (the cards are picked from this deck), size of the active deck, status "pickable cards" from the active deck (once picked, the cards are no more pickable until the condition to put them back on the active deck is fulfilled), reserved deck (where to pick the cards when the active deck is empty), and a trash deck.

One challenge which we identified concerns the description of the board when the spatial organization does not have a direction. Several games (Monopoly, Parcheesi) have a board with a direction, start and end point. However, maps have typically no directions, for instance the world map of Risk. In case of spatial information with a direction, it is possible to describe the board in a meaningful order, e.g. who is ahead of me, with a description from the start to the arrival. The description of the game state, for a spatial organization without a direction is not a problem when there is no need to know where the other pawns are to play (Cluedo, Monopoly). It is a challenge when it is necessary to know all pawns' positions to play, and if there are a lot of token positions to describe (e.g. Risk, where all 42 territories are occupied). This should be explored more in the future.

This adaptation feasibility study verified that games are adaptable, however does not verify if the resulting adapted games are playable and fun which we therefore decided to investigate in a separate user study presented below.

6 MAKING THE JAMAICA GAME ACCESSIBLE THROUGH SPATIAL AUGMENTED REALITY

6.1 The Jamaica Game Rules

Jamaica[4] is set as a boat race around an island in the ocean. The board shows one main path and three alternative ones (50 spaces in total, see Figure 4). At every round, the players decide before anybody is playing, which action they will do first ('morning action') and second ('evening action') at their turns. These actions are chosen from the players' cards, and can be: "take food", "take coins", "move forward", or "move backward". Each card shows combinations of morning and evening actions. Numbers of morning and evening actions (number of food units or coins taken, number of moves forward or backward) are the same for all players in each round. They are determined by the morning and evening dice (M and E values). If two players end on the same space, they will fight with cannon tokens and a special cannon dice. The order of actions is as following:

- **Starting player P1** launches the morning and evening dice (values of M and E determined)
- **All players** pick the card they will play. The card has one morning and one evening action.
- **Player P1's turn**: M*P1's morning action, then E* P1's evening action

[4]https://www.asmodee.co.uk/manufacturer/Asmodee-Editions/Board-Card-Games/Board-Card-Games/ASMJCA01Ml_Jamaica

- **Player P2's turn**: M*P2's morning action, then E* P2's evening action
- **Player P3's turn**: M*P3's morning action, then E* P3's evening action
- **P1 becomes the last player and P2 becomes the starting player** and launches the dice
- **Etc.**

Depending on the spaces on which players land, optional actions are possible, such as taking coins or fighting between two players on the same space. To win, it is mandatory to assess the actions and consequences of the other players' moves during the phase called **"All players"**, including for instance : "where are the other players likely to go?", "what will be their position if I play before them?", "will the treasures be taken by another player?", etc.

6.2 Justification of adapting Jamaica

According to the Accessijeux organization, Jamaica is a recent and enjoyable game. However, Accessijeux considered that Jamaica would require a high adaptation effort, and once adapted, there would be many remaining issues. More concretely, Jamaica presents the following adaptation challenges: 1) three dice (Morning and Evening actions, Cannon), including one special dice with symbols (Cannon) (A to C in Table 1); 2) many cards with visual information on it (morning and evening actions) (D to H in Table 1); 3) a board with fifty spaces displaying five different visual cues (harbor, gold taxes, sea, food cost, treasures) (L & M in Table 1); 4) a board with three junctions, combined with the possibility to move backward and forward (O in Table 1); and 5) the spatial organization of the ship hold to organize the resources (coins, food, cannons) (M,T,U,W in Table 1), 6) the actions depend on other players' location and estimation of their future actions (T,U,W in Table 1).

We chose this game for our work since it could not be easily adapted with handcrafted solutions. We made the hypothesis that Spatial Augmented Reality (and more precisely GameARt) could be used to solve these accessibility issues.

6.3 Participatory design process for the adaptation

As for the first part (analysis of the adaptation techniques described above), we collaborated with the Accessijeux game library. As a first step, six participants helped us to create and iterate on a handcrafted and interactive adaptation of the game "Jamaica": the president and one low vision employee of Accessijeux (see section 4.1), two volunteer players recruited during a game night organized by the organization (both blind, we did not ask for any further personal characteristics), and two people recruited through the network of our research group (one blind participant without light perception, and one participant with low vision). We made fixes for the five adaptation issues that we observed when studying the Jamaica use-case as mentioned above. Over three months, including one week on site, we adapted the board game and the tokens with the handcrafted techniques used by the organization (e.g. tactile stickers). The above mentioned visually impaired people evaluated the handcrafted adaptations and provided feedback. When the handcrafted adaptations were not sufficient to be playable with visual impairments, we augmented them with interactive features using GameARt.

We identified three important challenges for players with VI after handcrafted adaptations: 1) understanding the layout of the game board; 2) knowing where the players' pawns are; 3) knowing and keeping in mind the dice values. All these challenges are due to the game play which is based on spatial strategies. These spatial strategies are based on the board layout (possible junctions, moving backward and forward), players' actions (battle if moving on a space with another player, collecting treasures, racing), and on the dice values which are the same for all players. The analysis is quite easy to perform visually: a glance at the dice values, looking at the pawns on the board

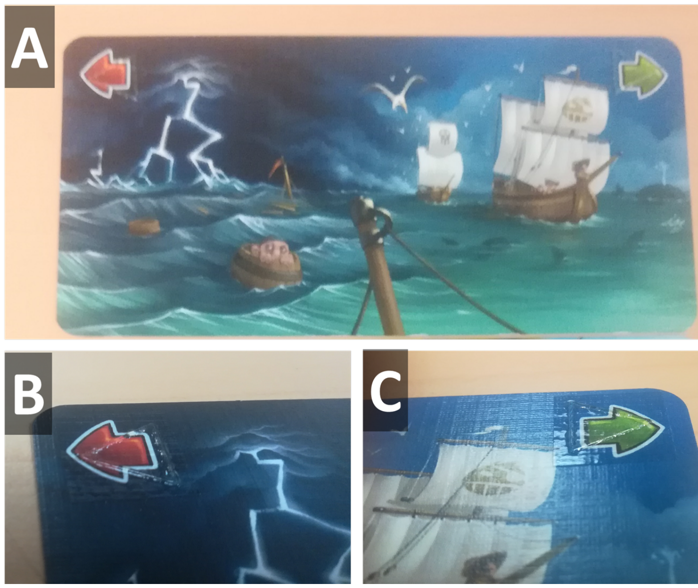

Fig. 5. A: adapted card of Jamaica. B: detail of the tactile sticker "move backward": a tactile triangle pointing to the left superposed on the red arrow. C: detail of the tactile sticker "move forward": a tactile triangle pointing to the right superposed on the green arrow. The tactile stickers were placed on the top of the cards, to disambiguate morning and evening actions.

and calculating where the pawns can land moving forward and backward; then, looking at the cards and deciding the actions from there. However, in the absence of vision this is difficult. An important observation was that asking questions about the layout and/or pawns position can reveal the player's strategy and is thus not a viable solution.

6.4 Adaptations

6.4.1 Cards. The handcrafted fixes included stickers at the top of the cards, as illustrated in Figure 5. They were used to disambiguate the morning (top left) and evening (top right) actions. The tactile stickers were chosen to have as much signification as possible (e.g. arrows indicate directions). They were transparent to avoid visual modification of the game for the sighted players. This handcrafted fix was judged sufficient by players with VI and thus no interactive adaptation was needed.

6.4.2 Layout. Stickers on the board indicate harbors, sea, treasures, junctions, and dice zones. We applied varnish onto the board to create tactile cues to indicate the position and the type of the spaces, as well as the different paths (Figures 3 and 4). However, indicating the food and gold taxes for each space represented too much tactile information on the board. Following iterations and tests with people with VI during the participatory design process, we decided to provide this information with audio feedback.

6.4.3 Dice. Managing the three dice was another challenge, even with tactile stickers on them. We designed two throwing zones on the board to throw virtual dice using PapARt. These zones correspond to the dice zones drawn on the original board. A simple touch on these zones repeats

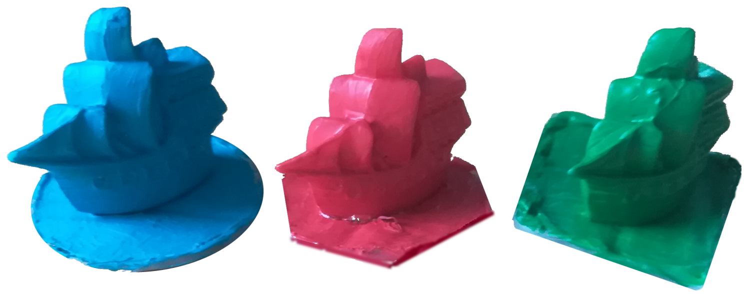

Fig. 6. Adaptation of the pawns. We added pedestals with different shapes (circle, square, polygon) to distinguish different players' pawns. Using a color camera we could identify the pawns and track their locations.

the last value, while a long touch launches the dice. The first zone launches two dice (morning and evening dice), while the second launches the cannon dice.

6.4.4 Locating the pawns. A first important step to be able to follow the game state and plan ahead is to identify the pawns and their locations. It is mandatory to know the positions of the pawns on the map because they trigger important decisions such as being the first at a treasure, fighting if two players land on the same space, catching up with the first player, etc. The original pawns have the same shape but with different colors. We added a pedestal with different shapes to each pawn (Figure 6). As it is very difficult to verify the pawns' locations by touch at each turn (risk of pushing the pawns as observed in previous work [36]), we also added a digital fix using text-to-speech feedback: the camera of PapARt was calibrated to track the color of the pawns. It could then detect the position of the pawns on the board and describe on demand with a touch on the dedicated interactive zone on the board the positions and state of the board game in a standardized manner.

6.4.5 Memo board. In order for the player to better understand the global layout of the board, and to explore the board layout without pushing away the pieces, we designed a memo board (technique already used by Accessijeux for adapting another game). We improved the memo in an iterative process (see Figure 7). The memo was tested by three blind people, and two people with low vision. During one of the pre-tests, one player with VI was even able to do a complex series of actions (moving forward on the main path, then backward on the alternative junction to get a treasure). From his own words, he would not have been able to identify this possibility without the memo.

6.5 Audio-feedback

Audio feedback for the description of the game state and for the pawns is identical to the one reported in section 5.1.2. The morning and evening dice values are {one}, {two}, {three}, {four}, {five}, {six}. The cannon dice values are {two}, {four}, {six}, {eight}, {ten}, {(explosion sound)}. The dice areas repeat the last values with a simple touch ("glance at the dice values"), and launch a new roll with long touch. To signify this roll, a sound of rolling dice is played.

7 USER STUDY

As presented above, we designed JamaicAR as an accessible augmented version of the board game Jamaica. This was intended a case study to assess if Spatial Augmented Reality can help to adapt a

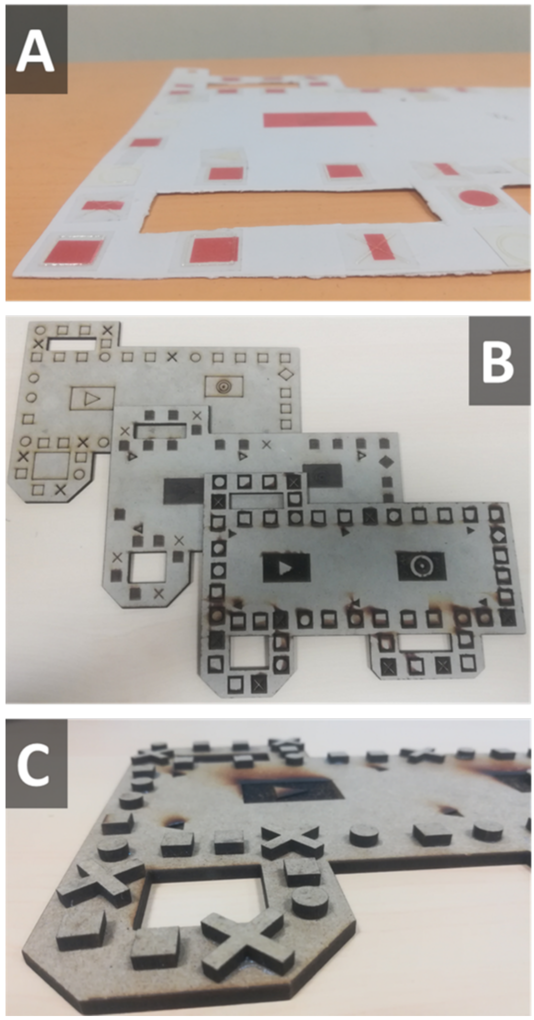

Fig. 7. The iterative design of the memo. A: the first mock-up (paper version with tactile stickers). The spatial representation and the size was defined at this stage. B: three different laser cut mock-ups (contour engraved, inner shapes engraved, and outside area engraved to mimic relief) used for evaluating tactile readability. C: finally the two millimeters relief was chosen for good readability. From our tests, the relief shapes are easier to perceive than the engraved ones (test B). For learning purposes, the relief shapes correspond to the stickers and visual shapes (square for food, circle for coins, cross for treasures). Moreover, all the locations are equidistant to each other to facilitate spatial encoding.

board game that was considered as not adaptable to people with VI by Accessijeux. We identified three research questions:

RQ1: Is a complex board game (considered as not adaptable) playable once augmented with AR?

RQ2: Is such AR board game accessible for people with VI?

RQ3: Is such a game inclusive (i.e. preserving the gaming experience for sighted players and being accessible to VI players)?

7.1 Evaluation Method

We organized game sessions with JamaicAR each with three players, who were either sighted, low vision or blind. As Jamaica is not playable by people with VI, we could not run a comparative study with the original board game as has been done in some of the prior studies.

To answer RQ1, we used the GUESS questionnaire [32, 46]. It consists of 55 items with 9 subscales, and generally takes around 5-10 minutes to complete. The subscales include Usability / Playability, Narratives, Play Engrossment, Enjoyment, Creative Freedom, Audio Aesthetics, Personal Gratification, Social Connectivity, and Visual Aesthetics. We measured the User Experience with the User Experience Questionnaire (UEQ [30]). To answer RQ2 and RQ3 in a more qualitative way, we added three open questions related to accessibility (for people with VI) and acceptability (for sighted people). For people with VI, the questions were: "What are the pros / cons of the system?", and "What can be improved?". The questions for the sighted participant were "What are the pros / cons of the system for playability?", and "Did some elements of the system bother you?". We asked these questions in order to evaluate if the game was acceptable for sighted players with the modifications, and hence truly inclusive.

7.2 Participants

We performed a pretest with two people with VI (one blind person without light perception and one low vision participant) and with a blindfold sighted person. This pretest aimed at verifying the prototype was usable and to test the experimental protocol. Participants in the pretest did not participate in the main study. Blindfolded participants cannot replace people with visual impairments in evaluations. While we decided to include a blindfolded person in the pretest, none of the participants was blindfolded during the actual test.

Eight sighted and seven people with VI participated in the game sessions which was the actual user study (see Table 2). Their age ranged from 21 to 66 years (Mean=41, SD=14.1). Players were divided in 5 groups of 3. Each group was mixed-gender (in total 6 Females, 9 Males, 0 Other). Groups 1 to 3 included heterogeneous vision capacities. Groups 1 and 2 were composed of two sighted and one blind participant. Group 3 included one sighted, one low vision, and one blind person with light perception. Group 4 was composed of three legally blind participants. Group 5 (only sighted participants) aimed at verifying that the system was usable by sighted people as well. None of the participants had played JamaicAR before the test . However, one low-vision participant had participated both in the handcrafted adaptation as an expert transcriber (previous section) and in a game session during the user study. Another blind participant had been involved in the evaluation of the memo (whether it is readable or not by touch).

7.3 Protocol

The sessions were organized as follows:

- Introduction and signature of the consent form, which was sent in advance in electronic version so that blind people could read it with a screen reader (10 min);
- Familiarization with the interactive board game and the game rules (one game turn; 30 min);
- Game play, which was stopped after 45 min in order to not exceed the duration of the user study, except if the group wanted to continue (45 min);
- Replying to GUESS, UEQ and open questions. They were filled in online with a screen reader or by a sighted person if required by the participant. (15 min);

7.4 Results

In this section we present the results of our study for each research question described above.

Gender	Age	Vision	Board games knowledge
GR1:			
F	52	Blind without light perception (> 30 years)	played board games once or twice
M	66	Sighted	aware of board games but does not play
M	27	Sighted	played board games once or twice
GR2:			
F	63	Early blind (previously low vision)	played board games once or twice
M	21	Sighted	aware of board games but does not play
F	25	Sighted	plays once a month
GR3:			
F	54	Blind with light perception (for 2 years)	played board games once or twice
M	44	Low vision (tubular vision and blindness by night)	plays once a week
M	23	Sighted	plays once a month
GR4:			
F	47	Blind without light perception (evolutive from birth)	plays once a month
M	33	Blind without light perception	played board games once or twice
M	32	Low vision (legally blind, from birth)	plays once a month
GR5:			
F	43	Sighted	Plays once a week
M	42	Sighted	Plays once a week
M	43	Sighted	Plays once a week

Table 2. Details about group composition and participants.

7.4.1 ***RQ1:*** *Is a complex board game playable once augmented with AR?*

For answering the first research question, we analyzed feedback regarding user experience and playability. UEQ items oppose two adjectives on a scale between -3 (extremely bad) and +3 (extremely good). According to UEQ instructions of use, the scores between -0.8 and 0.8 are neutral, the scores under -0.8 are bad, and the score above 0.8 are good. In the following sections, we note respectively the mean scores for the group (M-all), the players with VI (M-VI) and the sighted players (M-S) in squared brackets. UEQ results (Figures 8, 9 and 10) showed that the attractiveness [M-all= 0.98, M-VI=0.97, M-S=1.00], the pragmatic qualities [M-all=-0.10, M-VI=0.13, M-S=-0.33] related to the activity (perspicuity [M-all=0.075 , M-VI=0.250, M-S=-0.100], efficiency [M-all=-0.375, M-VI=-0.050, M-S=-0.700] and dependability [M-all=0.00, M-VI=0.200, M-S=-0.200]), and the hedonic qualities [M-all=0.68, M-VI=0.15, M-S=1.20] (stimulation [M-all=0.500, M-VI=0.150, M-S=0.850] and novelty [M-all=0.850, M-VI=0.150, M-S=1.550]) were neutral or good for all participants, independently of visual status. The attractiveness was rated best (or almost best) for sighted and VI participants (around 1). A tendency of difference between people with VI and sighted people can be noticed for the hedonic values on the novelty score (people with VI=0.150; sighted people=1.550), even if we cannot compute if this difference is statistically significant due to the size of the (unpaired)

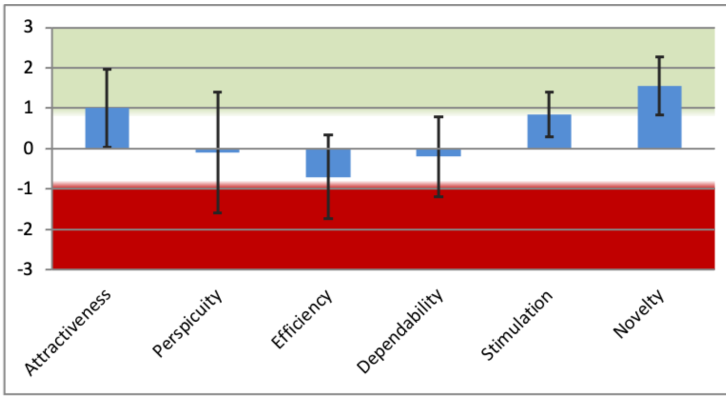

Fig. 8. UEQ results for sighted participants. Attractiveness, pragmatic qualities and hedonic qualities were neutral or good for sighted participants. Note: the UEQ questionnaire results are standardized. According to UEQ instructions of use, the scores between -0.8 and 0.8 (in the white area on the graphics) are neutral, the scores under -0.8 (in the dark red area) are bad, and the score above 0.8 (in the light green area) are good.

samples. We suspect that this difference occurs since VI players are more used to audio feedback during games than sighted people (i.e. what is new for the sighted is standard for VI people).

Similarly, the GUESS results (Figure 11) were between average (the average value for GUESS is 4) and good. In particular, the Play Engrossment [M-all=4.95 , M-VI=5.13, M-S=4.78], the Enjoyment [M-all=5.01, M-VI=4.97, M-S=5.04] and the Social Connectivity [M-all=5.05, M-VI=4.95, M-S=5.15] were positively rated, independently of the visual capacities. However, the difference in usability / playability score [M-all=3.85, M-VI=3.49, M-S=4.22] indicates that the game remains challenging to play without vision (rated better by sighted than visually impaired people).

The participants appreciated the physical adaptations. Players with visual impairments reported using the memo to decide on their next moves. The combination with the audio description of the board game state (position of the other players) makes it possible to plan moves and test game hypotheses. These two features (memo and descriptions) enable autonomous and "private" planning, which is fundamental for competitive game. Moreover, it is possible to actually play on the board (finding and moving pawns), with the visual and tactile perception of the boxes, augmented with audio-description. This shows that SAR fosters the playability of a complex game. The augmented audio description of boxes and game states provides an equivalence for the spatial and visual information when the tactile adaptation is not efficient enough. In addition, we observed that the interactive features require some learning to launch the feedback. Since the camera for touch detection is placed on the top of the board, some hand configurations are easier to detect and trigger feedback. The system provides visual feedback on the touch detection, which of course is not perceivable by VI players. The players not perceiving this feedback relied more on sighted player's feedback to learn how to launch touches. While this is a generally positive result, it also shows that there would be room for improvement to make the game even more enjoyable, especially for players with VI.

7.4.2 ***RQ2:*** *Is an adapted AR board game accessible for people with VI?* . With this question, we were more specifically interested in observations and in the qualitative feedback of visually impaired people regarding the AR game.

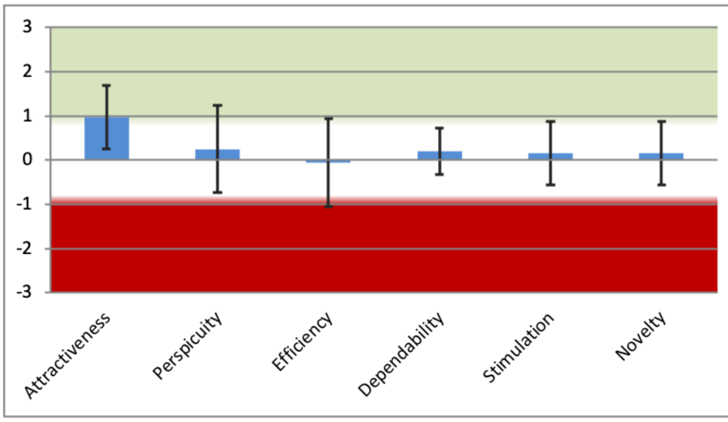

Fig. 9. UEQ results for the participants with visual impairment. Attractiveness, pragmatic qualities and hedonic qualities were average or good for VI participants.

All players, including blind participants, were able to find their pawn, move it to a desired position on the board, and obtain the instruction related to the space. We observed that both the handcrafted and the interactive adaptations were used for completing these tasks.

The players with VI from three groups mentioned that the memo of the board is helpful as it provides players with the spatial organization of the board and allows thinking about the strategy, while the board without memo "is too large to understand its structure" (P6). The tactile stickers on the board also enable players to find a space and move a pawn.

The GUESS results show that JamaicAR obtained a positive Audio Aesthetics score [M-all=4.54, M-VI=4.90, M-S=4.19] (Figure 11). The audio feedback on the board was appreciated because it provides additional information that cannot be represented with tactile stickers (e.g. the number of gold and food items to spend). The system also detects the pawns position and provides feedback about the game state. Participants said that the audio feedback was "good; the voice is clear" (P7). In the context of a game library, the audio level is crucial, as many players are playing at other tables providing a constant noise level which will make it harder to hear the audio feedback of the system.

Moreover, participants reported issues regarding collaborative play. Indeed, our game was played with multiple players, but the audio feedback is played only when one single touch is detected. For generic description, it did not come up as an issue, but when multiple players asked for a description of boxes, we observed two issues. First, the system does not launch audio feedback when two or more touches are detected. Second, if audio feedback is provided but several users have been touching the board, it is difficult to identify who triggered it. Therefore, the audio feedback related to a multiplayer configuration remains challenging due to (1) the triggering event that should be compliant with multiple players, and (2) the identification of the origin of audio descriptions.

As noticed by the participants, the system is not fully accessible, as the installation of the set up is currently not accessible with visual impairments. Indeed, authoring the generic adaptations (associating audio feedback to boxes on the boardgame for instance) requires visual feedback.This adaptation process could be automatized in future work to make it more accessible. Moreover, building the hardware and launching pre-registered adaptations with GameARt could be made accessible. To summarize, the entire process of adaptation, from building the adaptation material to

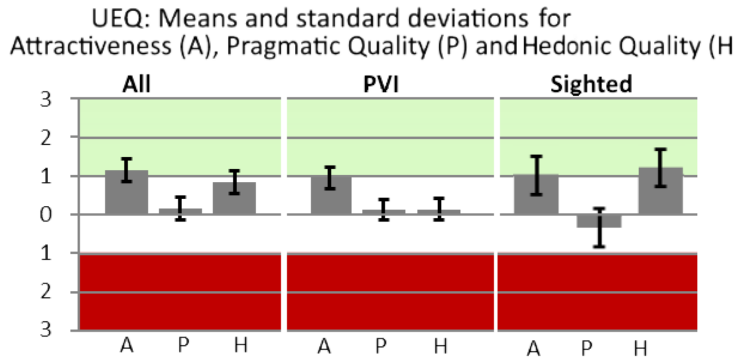

Fig. 10. Summary UEQ results. Diagram of the Attractiveness, Pragmatic Quality and Hedonic Quality for all participants, for people with visual impairments and for sighted people.

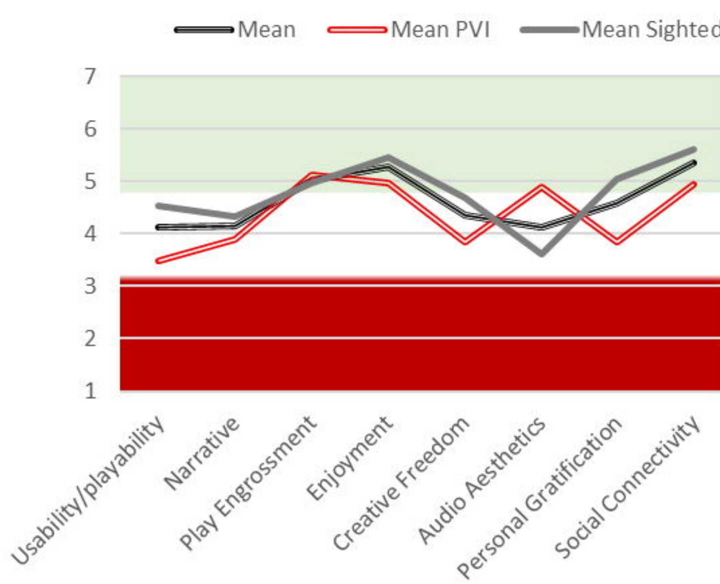

Fig. 11. Results of the GUESS questionnaire. Each dimension of GUESS questionnaire is the mean score of several questions related to this dimension, rated on a Likert scale from 1 (totally disagree) to 7 (totally agree). In particular scores for Play Engrossment, Enjoyment, and Social Connectivity, are similarly positive for all groups.

installing the hardware and launching the software is necessary to pretend to a fully accessible system.

7.4.3 ***RQ3:*** *Is an adapted AR game inclusive (i.e. preserving the gaming experience for both sighted and VI players)?* With this question we wanted to study how the adaptations made to the game were perceived by sighted players since to make the game inclusive, it needs to be playable both by sighted and VI people.

The UEQ results (Figure 10) show that attractiveness [M-all=0.98, M-VI=0.97, M-S=1.00] and hedonic values [M-all=0.68, M-VI=0.15, M-S=1.20] were rated positively by the sighted group and even more so than for players with VI. This may be due to the novelty effect as discussed above. On the other hand, sighted participants rated the pragmatic (i.e. task related value) [M-all=-0.10, M-VI=0.13, M-S=-0.33] including efficiency [M-all=-0.375, M-VI=-0.050, M-S=-0.700] more negatively. We suspect that the augmentation adds interactions which are perceived as unnecessary by sighted players who could play the original board game. Indeed, sighted participants stated that the electronic dice is not an added value, but can induce bugs. Sometimes the users had to touch the dice areas twice because the first touch was not long enough to launch the dice (it just repeated the values on a simple press).

Participants highlighted the possibility to play a game which is not accessible otherwise as a first inclusion lever. The game was not perceived as entirely fair regarding workload between people with and without impairments, but the conviviality was real, and it was possible to play together. Yet, the adaptation of challenging games, as we did with JamaicAR, may not convince competitive players. The second inclusion lever is the generic description of the game state (position of each players' pawns), where the contribution is two fold : (1) not relying on another player to get a description of the game, and (2) the generic nature of the description does not give information on one's strategy (in comparison to oriented questions addressed to a human co-player). So far, our system does not describe the resources owned by all players. While some players can just glance at others' resources, some need to ask ask. This is a limitation regarding equality of information access.

8 DISCUSSION

Our research was driven by the following objectives: **O1**) to observe challenges and solutions for making board games accessible to VI people, **O2**) to provide a framework for making board games accessible through the use of SAR (GameARt), **O3**) to identify interactive features to adapt in SAR from a concrete use-case (Jamaica board game), and **O4**) to evaluate the prototype (JamaicAR) regarding accessibility and inclusion during game sessions. We met all objectives in this paper.

We followed a participatory design approach including people with visual impairments, by collaborating with Accessijeux game library. In this work, we combine the advantages that Augmented Reality has for improving accessibility (e.g., supporting spatial representations [2]) with the adaptation techniques of board games (GameARt). In our prototype JamaicAR, we augmented a board game that has been considered inaccessible by Accessijeux with Spatial Augmented Reality. The inputs of classical game play (e.g. positioning a pawn on a space on the board) are inputs for the AR system which in return detects the pawns' positions and provides an audio overview of the game. Moreover, the system provides audio information on a space by touch detection for VI people, while sighted people can take a glance at the board. Our goal was to make a game that can be played by sighted and VI people together.

Yet, the current system can be improved. First, the current setting (PapARt prototype) is not easily portable. It would be interesting to build a system that could be more easily transported and adopted by different game libraries. Moreover, as in many AR systems there are issues related to image detection. The calibration and the finger tracking are sensitive to light, leading to some delay in detection. Sighted people have visual feedback about finger detection with the projector. On the other hand, people with visual impairments have so far no access to the the information "is my finger detected?" and "Where is my finger detected?". This would however be helpful feedback for debugging.

As discussed above, the collaborative use of the interactive features could be studied in the future. So far, only one participant at a time can launch audio feedback which currently creates conflicts in multi-player settings.

Moreover, we did not study the game play itself (occurrence of misunderstandings, errors, unintended moves etc.). This could have been useful additional information and is a perspective of this work. The UEQ and GUESS questionnaires may evaluate the regular Jamaica gameplay more than the JamaicAR adaptation. However, we did not find a possible way to separate evaluation of the original game from the adapted version since the players with VI could not play the original game. Our work is also limited by the relatively low number of participants which is due to the fact that it is complicated to recruit people with special needs for user studies. Yet, this hinders us from running statistics on the quantitative data collected through the questionnaires.

Our work is closely related to *Game Changer* [29]. However, some elements in the approach, system and evaluation differ. Regarding the approach, we decided to keep the original visual aspect of the board, as we does not modify the images (e.g. the cards) and we provide feedback through transparent tactile relief. In collaboration with an accessible games library we selected a game that was considered not adaptable with handcrafted techniques only, whereas other criteria were considered for *Game Changer*. Our system is not as portable as *Game Changer*, but since we use a SAR toolkit it provides supplementary features (distinguishing short and long press for different functionalities, projection of visual information). To our knowledge, this work is also the first one that studies a generic AR framework to adapt multiple board games to people with visual impairments.

Making existing games accessible has multiple advantages over designing specific games for people with special needs. It first introduces a new audience (people with disabilities) to existing media. This can help improve social interaction and awareness of others. It can also have an economic interest. Indeed, developing games is expensive and risky. It is more cost effective to develop an accessible game from scratch [61], but making the games already in the market accessible afterwards requires time, efforts and generates costs.

Interestingly, when making games accessible for VI people, physical adaptations based on the tactile modality (stickers, Braille) are used more than audio (speakers, bells), while audio is widely used for digital adaptations (text to speech, 3D audio) over tactile feedback (vibro-tactile, ultrasound haptic, shape changing devices). The advantage of our system is that it allows to combine tactile and audio feedback.

9 CONCLUSIONS

Board games are entertaining because of the interactions between players, physical manipulation of tokens, and decision making based on the rules of the games. Our work shows that with Spatial Augmented Reality it is possible to preserve the physical game elements of the original game, as well as existing adaptations mastered by the transcribers for people with VI. Existing adaptations mainly include tactile cues on cards, pawns, dice and the board. It is then very easy to augment these different elements with audio (verbal and non-verbal) instructions and feedback [10]. SAR can provide audio cues related to the current game configuration (e.g. the description of the pawns' positions) but also when game pieces are touched, without revealing any information on personal strategies, thus preserving the game mechanics.

In this work, we first presented a heuristic created from observations at an accessible games library which presents challenges for making board games accessible and possible handcrafted solutions. Then, we presented GameARt, a generic system to create interactive audio-tactile content for board games where handcrafted techniques are not sufficient. Interactive zones and dice systems can be registered on the fly, saved and re-loaded. This offers the opportunity to make games interactive for people with and without visual impairments. Then, we presented a use case study on the board game Jamaica which we analyzed and made interactive using both handcrafted adaptation fixes and a Spatial Augmented Reality prototype (JamaicAR). We specifically addressed the problem of inclusive adaptation (people with and without visual impairments playing together) and evaluated the game in sessions with players with mixed visual abilities. All players, independent of visual status, were able to play JamaicAR. Moreover, the game was rated positively by all players regarding attractiveness, play engrossment, enjoyment and social connectivity.

Our study shows that SAR can help to turn existing board games into accessible games for people with VI. It also shows that SAR can preserve the game experience for sighted players because it preserves the existing physical elements and the game play. Even if this should be further explored in future work, our system enabled VI players to play a game that would not be accessible otherwise. Three groups were mixed groups, regarding visual potential, suggesting that interactive adaptations could foster inclusive board-game sessions between sighted and VI players. We hope that our work will contribute to make more board games accessible and inclusive in the future.

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A APPLICATION OF THE FRAMEWORK TO OTHER GAMES

Monopoly: our system provides audio feedback for the names and cost of the touched spaces, the description of the hotels of the players on the entire board providing a good overview, and the modified dice area provides accessible virtual decks.

Catan: with our system, the dice can be launched, the deck can be simulated, each space can be associated to a number with the interactive areas. The pawn location zones can be a bit bigger than the visual spaces. In this case, the zone can overlap on the edges (where the pawns will be). It is possible to describe the board by describing "city of the red player is next to a zone '6- stone', '3-forest' and '11-clay'" etc.

Cluedo: the rooms, objects, and persons' decks can be handcrafted without adding any interactivity. The dice, the clue deck, and the board spaces can become interactive thanks to our system. The secret passages can be indicated when triggering the rooms description ("Conservatory, secret passage to the Lounge"). The techniques used to follow virtual lines described in previous work can be extended to redirect a player to the arrival of the secret passage without vision [2].

Parcheesi: the two dice can be simulated, the spaces can be associated to pawns zones.

Trivial pursuit: the dice can be simulated. The spaces can be interactive. It is possible to create one deck by color of questions, and the decks have to be slightly modified to associate a question with the answer. The deck picks first a random question of the given color (classical usage). At the second long touch input (modified usage), the deck area should play the answer of the previous question. The third long touch input picks a new question.

Risk: the defense and attack dice can be simulated. The player should launch once, twice or three times the attack dice, and once or twice the defense dice (depending of the game actions) to keep the best values in mind. The risk deck has two uses: (1) a public usage to 42 territories icons to start the game, and (2) a hidden usage of the three army type icons during the games to gain more armies, with bonus if the card is associated to a territory controlled by the player. As a consequence, it makes sense to simulate a virtual deck for the first usage, and to use handcrafted cards for the second usage. Indeed, the risk deck can be simulated to pick the 42 starting territories. To find these territories, a geographical indication can be added ("Siberia, north west"), or we can use the features to guide a finger on a map with audio to a location previously described in literature[2]. A first (imperfect) adaptation of the second usage would be not to use the territories to gain armies. In this gameplay adaptation, the cards can be adapted by adding only three different tactile stickers representing respectively infantry, cavalry and artillery. As it is not possible to represent each of the 42 territories by a unique sticker, a second adaptation would be to associate numbers to the countries and the continents (there is 4 to 11 territories per continent). The other deck, with the hidden missions, can be handcrafted: stickers to represent the army to destroy, stickers to represent the continent to conquest, or stickers to represent the numbers of territories to conquest. Each of the 42 territories of the board can be described by audio description when touched. However, the 42 territories have pawns on each of them at all times. It is then not efficient to describe all territories and all armies on them to get an overview of the game state. The description of the board states can be adapted to ease the game: the game can describe how many territories are controlled by each player, and the number of controlled territories by each player on each continent.

Pandemic: a virtual propagation deck is usable to start the game to pick nine of the 48 cities cards. The use of this virtual deck during the game would lead to some modifications. Indeed, the cards can go back to the deck during the game, and previously seen cards will always be seen first. The adaptation of the virtual deck can be done by having two pools of cards in this deck. When doing a long touch, the cards will be in priority picked in the pool of previously seen cards, randomly. If this pool is empty, the new card will be randomly picked from the unseen pool, and added as a picked card of the seen pool. A mechanism should put all picked cards back in the seen pool (unpicked) to simulate these cards are back to the top of the deck. To find the city mentioned on the picked card, the mechanism used to find a target with a finger as described in [2] can be used. The players' card decks should have pools as well to respect the distribution of epidemic cards. The picked cards go to the virtual player deck or the trash. As pandemic is a collaborative game, the cards have no need to be hidden. Using physical cards with fiducial markers (existing feature of PapARt), the virtual cards of the player can be associated to physical content that the player can manipulate, exchange and put virtual cards in trash deck (as in the educative CARDS project [22]). The board cities can be interactive, as well as the description of the position of the players and the infected cities with three, two and one blocks of contamination.

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