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Review

A Review of Accessibility and Sustainability in Augmented Reality Tabletop Gaming Experiences

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Abstract

Tabletop Gaming Experiences are a form of traditional gaming that traditionally requires either models, illustrations, or a vivid imagination to fully benefit from. Technology can be used to supplement this, such as mobile or tablet applications to help visualise aspects of gameplay content. Augmented Reality technology has the potential to further enhance Tabletop Gaming; however, there is little research into how it can be used in the areas of accessibility and sustainability, whether by reducing the carbon footprint of producing these games or by enabling wider participation. Our research aims to explore these topics and answer the following questions: How is Augmented Reality currently being used in Tabletop Gaming Experiences? How can it be used to assist with accessibility and make Tabletop Gaming Experiences more available to a wider range of audiences? Can Augmented Reality be used to lower the environmental impact of producing and distributing these games? This paper seeks to review the existing literature on this topic to identify how existing research has explored these issues, and how their findings may inform future Augmented Reality research on Tabletop Gaming experiences that are both inclusive and environmentally sustainable.

Keywords: augmented reality; accessibility; tabletop games; sustainability

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1. Introduction

Recreationally, Tabletop Roleplaying Games (henceforth abbreviated to TTRPGs) are used as a form of escapism, in which players can detach from reality for the duration of the play session to take on a new role, such as an army commander, a head of a nation, or more frequently, a fictional character within a new narrative setting, such as a wizard who fights dragons or a science fiction soldier defending their world from alien invaders. Tabletop Gaming Experiences have undergone a renaissance in the past decade within popular culture, moving from what was historically a niche interest typically associated with the Geek community to a hobby with more generalised societal adoption. Dungeons & Dragons (henceforth abbreviated to D&D) in particular has been a proponent of this due to productions such as Critical Role [1] (a web series featuring famous voice actors playing the game), its prominence in the plot of the popular television series Stranger Things and even a full Hollywood film, Dungeons & Dragons: Honour Among Thieves. Furthermore, computer game adaptations have also increased public interest in Tabletop Gaming franchises, such as Baldur's Gate 3 (an RPG game built on the D&D system) which sold 15 million copies [2], Space Marine 2 (an action game themed around Warhammer

40,000) which sold 4.5 million copies [3], and Pathfinder: Wrath of the Righteous (an RPG game built on the Pathfinder system) which sold 1 million copies [4]. These adaptations and uses within popular culture have renewed interest in Tabletop Gaming Experiences, with Hasbro alone reporting a 7% increase in revenue immediately following the release of Baldur's Gate 3 [5] and the release of Space Marine 2 reportedly resulting in additional customers in Warhammer stores [6]. Furthermore, the 5th edition of D&D, when released in 2014, utilised promotion of online content creators such as YouTubers, Influencers, and other online personalities to help promote the release of the edition, emphasising that it was beginner friendly and accessible to new players [7]

The synergy of computer games, television, web series, and films has been a boon to the Tabletop Gaming market, both in terms of sales and popular interest; however, this new interest raises potential concerns regarding the ecological sustainability of tabletop games, both in terms of the carbon footprint of the manufacturing/production of miniatures/paints, and with players 3D printing their own miniatures. Additionally, the surge of popularity coinciding with the COVID-19 pandemic that brought more players into the hobby via virtual tables, has prompted little in the advancement of accessibility within the various hobbies regarding Tabletop games. For example, a player with Aphantasia may be excluded from the hobby of Tabletop Roleplaying Games given the inherent reliance on imagined visuals as part of the experience. Unless a player group specifically adopts visual stimuli (such as miniatures, images, or other visualisation methods) as part of their experience, players with Aphantasia may be unable to participate or experience the full enjoyment out of the hobby.

Popularities of any hobby will wax and wane with time and interest; however, the renewed interest in TTRPGs presents both a possibility and a responsibility for the topics of sustainability and accessibility to be further explored using alternative mediums. The field of Augmented Reality may be well suited to this, as it creates new possibilities for visualisation methodologies within Tabletop Gaming for the depiction of both miniatures and visual effects. For example, rather than needing to manufacture two armies of miniatures for a tabletop strategy game, Augmented Reality (henceforth abbreviated to AR) can be used to 3D render them over the playable space, therefore removing the need to create plastic figures. Furthermore, AR could also be used to create additional visual effects that would otherwise be impossible to achieve, such as having animations on individual units for movement, projectiles that fire when weapons are discharged, or even sound effects that play during action sequences. The possibilities created using AR technology could revolutionise Tabletop Gaming, both for how the games are created and how they are played.

This is not a theoretical concept, and hobbyists are already using AR technology to enhance their gaming experiences. An example of this is the tabletop AR system known as Ardent Roleplay [8], a mobile application that allows players to set up adventures with a full range of 3D models, particle effects, animations, and terrain, along with interactable props and environmental pieces. These can be mapped to pre-made cards that are then physically moved around the table, with mobile devices handling the rendering of AR components over them, using the cards as marker-based trackers. Whilst this has the potential to create additional enjoyment for players, there have been critiques made of the implementation of the system. For example, an article published on Arkenforge [9] that discusses the logistical impracticality of having to look at the tabletop through a phone, along with the limitations imposed by device battery life and concerns regarding the heat generated by a mobile device when constantly using its graphical processing hardware. This demonstrates that whilst the technology exists and that some players are using it, there are still concerns regarding the practicality and limitations of using AR for tabletop games that could be explored further through research.

The purpose of this paper is to further explore the topic of AR for tabletop games and discover how AR is currently being used for Tabletop Gaming Experiences (furthermore abbreviated to TTGEs). What technologies and visualisation methods do existing AR products or projects use for TTGEs? How have accessibility requirements been addressed using AR technology? What are the ecological considerations of using AR over physical products? This information will be used to inform future research on the use of AR for TTGEs.

This review follows a narrative synthesis approach due to the heterogeneity within this topic. Sources were identified using the University of Staffordshire's Library search platform, which aggregates results from databases such as the ACM Digital Library, IEEE Xplore, ScienceDirect, and SpringerLink, along with open-access publications. Additionally, further searches were conducted via Google Scholar, along with general web search to capture grey literature and projects not yet published via indexed sources. Search terms included combinations of "Augmented Reality", "Mixed Reality", "Tabletop Games", "Tabletop Roleplaying Games", "Accessibility", and "Sustainability". Studies were included if they discussed the development of an AR or MR system within a Tabletop Gaming context, or if they were discussed in relation to accessibility/environmental sustainability in the contexts of AR or MR. Because of the limited amount of literature in this area, studies were not subject to any filtering based on the year of publication. The limited research in this area is also the reason why a narrative review design was selected over a systematic approach, as this allowed inclusion of studies and projects from adjacent fields or other areas of AR with translatable concepts to TTGEs.

Furthermore, we will be comparing existing studies against the Web Content Accessibility Guidelines (henceforth abbreviated to WCAG), version 2.1 [10]. These guidelines were designed for web-based content rather than AR specifically; however, as both are technology-based mediums with presentation of digital content at their core, the guidelines are applicable to AR content. These guidelines provide four major categories for accessibility:

1. Perceivable: Information and user interface components must be presentable to users in ways they can perceive.
2. Operable: User interface components and navigation must be operable.
3. Understandable: Information and the operation of the user interface must be understandable.
4. Robust: Content must be robust enough that it can be interpreted by a wide variety of user agents, including assistive technologies.

Each section contains a series of guidelines for accessibility to ensure adherence to these four categories along with testing criteria to identify how well each category is conformed to (rated as A, AA, and AAA, respectively, with AAA being the highest grade attainable). Whilst these are guidelines, they are often used in legislation, with different countries often requiring web-based content to achieve a minimum of AA ratings in each category. For the purposes of our review, we will be comparing how the use of AR would bring a project closer to compliance with the four principles of the WCAG, rather than evaluating if the study itself is fully WCAG complaint. This is because anything short of a comprehensive, consumer grade AR application would likely not meet all of the criteria.

The World Wide Web Consortium (W3C), the creators of the WCAG 2.1 guidelines, have also begun creating a document to assist with accessibility requirements for XR, or Extended Reality, which encompasses all immersive technologies including Virtual Reality, Mixed Reality and Augmented Reality. This document is called the XR Accessibility User

Requirements [11], or XAUR (and henceforth abbreviated as such). Unlike the WCAG 2.1 guidelines, however, the XAUR seeks to outline accessibility needs rather than drafting a set of guidelines. Consequently, it does not have a rigorous set of rules to follow to ensure compliance to a framework; however, it can be used in conjunction with the WCAG guidelines to identify how existing AR projects address accessibility.

2. Literature Review

2.1. Augmented Reality for TTGEs

Augmented Reality is a tool with many purposes; however, within the context of this paper, we are primarily seeking to explore how it has been used with tabletop games. Before even considering accessibility or sustainability, it is important to address ways in which it is being used for TTGEs and the reasons why players may wish to include the technology as part of their gameplay experiences. Such explorations are still relatively new, as consumer-grade devices capable of rendering AR have only become widely available in the last two decades and have varying capabilities. This was addressed in a study by Huynh et al. [12] in 2009, in which the authors acknowledged that the technology of the era was "barely up to the task", citing issues such as limited viewing areas, rendering capabilities issues with AR tracking, but still sought to utilise it to create an AR tabletop game called "The Art of Defense". Huynh et al. addressed this using a rigid marker-based structure for their game that utilised hexagonal tiles (similar to games such as Catan [13]), which provides a method for tracking and confines the rendering area to wherever the tiles are placed. The Art of Defense was designed as a cooperative Tower Defence style game, a genre that previously would not have been appropriate for tabletop due to the real-time nature of its gameplay. Players of this game would place a combination of tiles for the game board, and tokens that could be placed over them to build/upgrade towers. These tokens were then augmented with AR via the use of a Nokia N95 smartphone. Participants in this study who played the game were observed to cooperate with each other by communicating and coordinating their strategies to best cover the available space, such as multiple groups identifying a strategy to overcome the more limited rendering capabilities of the technology by dividing up the board and only placing towers on each other's sides when communicated by the other, thus requiring a measure of trust in the other player to successfully manage their own sides of the playable space. As a conference paper, limited results were published, but it did include some data on player feedback. It showed that players had enjoyed the game, but they had expressed frustrations at problems such as the AR rendering disabling when the device was moved, or players accidentally blocking each other by moving in front of the camera. With this study being an early adopter of AR for TTGEs, the technology used is now outdated, and alternatives such as Head-Mounted Devices (henceforth abbreviated to HMDs) with newer tracking algorithms could overcome the limitations encountered by this research. However, it does demonstrate that AR allows for gameplay elements previously unavailable in TTGEs, and that players do find enjoyment from playing tabletop games with AR enhancements made to them.

Further research subsequently explored other methods for the implementation of AR within boardgames, such as using AR to add new visualisations to existing boardgames rather than designing new ones around the technology. Such was the case in a 2010 study by Molla & Lepetit [14], in which the authors sought to use AR to add holographic elements to the game board. The authors of this study sought to build a system similar to the one used by Eye of Judgement, a 2007 AR game developed by Sony Computer Entertainment for the PlayStation 3. Players of Eye of Judgement had a physical playmat and cards, which they would place on the mat, and a PlayStation camera would then scan those into the game and use them to control the players' moves, similar to other popular trading card games of the era. Molla & Lepetit developed a similar system to implement AR over a game of Monopoly, using a camera pointed at the gameboard. The hardware used is not fully discussed, with the authors only mentioning that their configuration is displayed on a “computer screen”, which suggests that this setup was being run off a desktop PC or laptop. Players of this game interacted with it by moving coloured pieces around the board, all identical save for their colour, which the computer used to visualise a holographic character over. The system is also shown to render dice and houses/hotels (a key mechanic in the gameplay of Monopoly) but there is no discussion in the paper regarding how these were handled. As a conference paper, it is brief and demonstrates the proof-of-concept, but does not publish any testing results or player responses to playing this version of Monopoly. However, it is accompanied by discussion of technological limitations of the era, with the authors discussing that HMD’s were “still cumbersome” and that their implementation was only capable of outputting at “about 20 hz”—limitations that may have hindered development or engagement with such systems in 2010, but have since been overcome by the time of this review. The authors conclude with a note that AR could make boardgames more immersive, and that the use of it could reach larger audiences.

Existing boardgames are a point of interest for AR research, as a game that players are already familiar with can benefit from the addition of holographic content without the concern of teaching new rules or mechanics; instead, players can engage with the game whilst getting the full benefit of the new content. This was the case in a study by Rizov et al. [15], who used AR to add visualisation elements to the game known as Small Star Empires, a competitive board game in which players control interstellar empires that must expand across an expanding game board made of hexagonal tiles. Like the study by Molla & Lepetit [14], this project only added visualisations to the gameplay experience using a mobile application to render 3D models over parts of the game, in this case adding 3D visualisations over the physical Technology Cards that players use in the game. Details of the setup of this configuration are vague, only stating that other forms of AR had been considered and that mobile was the chosen method, with the web platform Augment [16] being used to host the AR content. Augment allows developers to upload 3D models and targets to their web server, which can then be loaded in from their native mobile application. Despite adding visuals to the gameplay cards, the authors of this study did not discuss the intentions behind adding AR, other than a statement about wishing to “enrich the game experience”, and the results only mention that interviewed participants found the AR experience to be interesting, but that they thought the experience would be better if the AR was also used for gameplay purposes. As a technical study, it shows an interesting approach for adding AR to an existing game, but the results do not provide enough context to fully inform future studies. Further research on using AR for gameplay elements would be required to explore this further.

Similar concerns regarding the logistics of HMDs for tabletop games have been a recurring theme through the history of AR for tabletop games, particularly considering that depending on the game being played, the headset may need to be worn for prolonged periods of time and if the design of the HMD makes it uncomfortable, that may negatively impact the user experience. This was addressed in a study by Nilsen [17] in 2005, who developed a tabletop AR game titled Tankwar—a game in which two players control holographic armies consisting of tanks, helicopters, and artillery units to compete with one another. This game utilised an HMD—the iO Display Systems i-glasses SVGA, and a Logitech 4000 Camera mounted to the front; however, limited discussion was provided regarding the full technical configuration of this setup, only that it utilised ARToolKit [18] (an opensource library for creating AR applications). This project was deployed at GenCon Indy 2005 [19] (a Tabletop Gaming convention) with participants collected from attendees of the convention. Limited results are published, but the author reports 230 participants provided questionnaire responses and provided feedback indicating that players had enjoyed the game and expressed they were interested in AR-based tabletop games. However, participants responses also stated that the headset was uncomfortable, difficult to fit on some head sizes, and that there was a disparity in the time required for players to learn the controls or operation of the AR system. This study predated the study by Molla & Lepetit [14], indicating the logistics of HMDs and user comfort has been a recurring trend. Results from this study also show another concern: user uptake, or the speed at which a user becomes proficient at using a system. Whilst it can be reasonably assumed that users would be quick to adapt to a system using technology they are familiar with (such as a smartphone application, a program running on a PC/Mac, etc.), the rate at which a user learns a more bespoke system, such as an AR application, will vary, and players may not be able to meaningfully engage with, or take enjoyment from, an application that they are still learning how to use. As such, future AR projects should seek to either use a streamlined design methodology that will reduce the learning curve for new users, or implement a tutorial of some kind to familiarise the user with the Human–Computer Interaction (henceforth abbreviated to HCI) requirements of the system.

It is not only boardgames that have benefitted from the implementation of AR technology, as other styles of tabletop game have also been the focus of research into how the technology can enhance their gameplay, such as tabletop strategy games. In this genre of games (Warhammer, Battletech, Trench Crusade, etc.), players will assemble their own squads or armies of toy soldiers and play a simulated tabletop battle against one another. Although the backstories of such games usually revolve around large spectacles, the reality of playing often depends on player imagination, and with many key mechanics revolving around measuring distances, determining if figures have a line-of-sight to their targets, and subsequent rolling of dice/consulting rules. This was addressed in a study by Dolce et al. [20], who sought to enhance the tabletop strategy genre with AR to automate the flow of gameplay and minimise the need to take notes or consult rules. The authors of this study developed a tabletop strategy game called ARmy, using simple blocks for terrain and plastic toy soldiers as units. ARmy could be played either traditionally using measuring tapes and rules, or an augmented version that would track rules, movement ranges, and the line-of-sight for each soldier. The AR version used an overhead camera to detect the objects, and a spatial AR projector to project the AR enhancements directly onto the gameplay table, which could even project textures onto the terrain pieces to make them look more visually interesting. Participants in this study played two rounds of this game, one with the AR functions and one without, in random order, with their gameplay data being the main focus of testing. The participants were provided with a questionnaire to determine which version of the game they enjoyed most, with the results indicating that whilst players enjoyed both versions of the game, the AR version was rated more positively. The gameplay data showed that combat rounds were faster in the AR version, as players did not need to manually measure distances, role dice, or keep track of which units had already moved during their turn. However, despite the benefits to efficiency, participants reported that the system could be slow to calculate at times, that blindspots with the camera forced players to simplify how terrain was laid out, and that the AR version had removed some player engagement as they were passively observing outcomes rather than experiencing the physical involvement of things like dice rolls. These findings contrast with the study by Rizov et al. [15], which indicated that participants would enjoy gameplay more if the AR components would automate gameplay. This study demonstrates a practical application of using AR for a Tabletop Strategy Game; however, it does also show that players may prefer the conventional methods of playing a game, even if they are slower and less efficient, which suggests that a full replacement may not be preferable to a system that could enhance the visuals without removing the gameplay elements that players enjoy.

It is important to distinguish that there are further studies that have been conducted on AR for bespoke tabletop games for educational purposes, including educating on nursing [21], chemistry [22], disaster preparedness training [23], and socialisation skills [24]. However, these are bespoke learning tools specifically created for teaching rather than for recreation. The focus of this review is specifically regarding recreational games and how AR may be used to improve accessibility and/or sustainability within games for entertainment. Unless the scope of these studies encompasses accessibility or sustainability, we will not be including them in this review. This is entirely to keep our scope defined and not bleed over into other areas of research that may not pertain to our review.

Augmented Reality for Commercial TTGEs

Outside the context of academic study, commercial games developers have also sought to include AR within their products as a means of adding novelty or new methods of interaction with the game experience. In some cases, such as Ardent Roleplay [8], the system itself is not a standalone game, but rather a tool designed to enhance existing ones. Such was the case for Mirrorscape [25], an AR application designed to allow players to create and play TTRPG games on a physical tabletop with the use of iOS and Android devices. Unlike Ardent Roleplay that made use of cards to track AR content, Mirrorscape instead uses a spatial system to track AR without the need for physical manipulatives. Additionally, it provides a range of tools to allow players to create modular 3D environments for players to explore, such as virtual castles, towns, and dungeons, which can include animations and controls so that players can open doors or spawn monsters mid-game. Furthermore, the game is also partnered with companies that manufacture miniatures, such as Hero Forge, Titancraft, and others, which allow players to purchase their miniatures virtually for use in Mirrorscape to further emulate the traditional TTRPG environment. Steam reviews of Mirrorscape are mixed, with players praising the mechanical aspects and functionality of the game, but critiquing the costs of purchasing models through the in-app store. This suggests that whilst players are welcoming of the idea of using augmented content in their TTPRG sessions, they perceive that the cost of gameplay pieces should be lower than their real-world counterparts, and so future AR developers may require further market research to identify what prices players would be content with spending for an AR TTRPG experience.

Both Ardent Roleplay and Mirrorscape rely on users having access to a mobile device or tablet to visualise AR content; however, there are alternatives to this. Tilt Five [26] is an AR system that instead uses a combination of a pair of head-mounted glasses and a bespoke gameboard to render AR content, that players can interact with via use of a controller called a "Wand". Users of this system deploy the board, connect it to a computer running Windows or an Android device, and then wear the glasses, with AR content then rendering over the game board. Rather than providing a set of pre-made tools for designing a TTRPG experience, Tilt Five instead provides developer kits for Unity, the Unreal Engine, and an SDK for the C programming language to allow creators to make their very own bespoke experiences. This allows for independent players, or developers, to create AR experiences for the platform, including board games, war games, or even games that would more closely align with computer games in their design, but be played via the tabletop.

Such was the case for The RPG Engine [27], a Virtual Tabletop (henceforth abbreviated to VTT) designed to virtually recreate the Tabletop Gaming experience. This includes similar functionality to previously discussed applications, such as being able to virtually create scenery with pre-fabricated assets, being able to add animations and interactions, along with some additional features such as fog effects, lighting, and several others. Where The RPG Engine diverges is that rather than being an AR application, it was designed for use on desktop PCs or laptops. However, The RPG Engine was also ported to Tilt Five, resulting in a version that becomes an AR TTRPG when used with the Tilt Five system and allowing players to augment their tabletop surfaces with full interactivity via the Wand peripheral. Steam reviews of The RPG Engine are "Very Positive" according to the store page, with many users praising the functionality of the software, and a few reviews criticising the monetisation model used.

Additionally, there are other applications that function on the Tilt Five for AR TTGEs. Tabletopia [28] is an application originally designed for Windows and Mac devices to allow groups of players to play tabletop games together, including TTRPGs and board games. This includes licensed official titles from designers and publishers to allow users to play official games (as opposed to community-created ones) inside the application, with the Steam store page claiming that there are over 2400 playable games. Tabletopia is also compatible with the Tilt Five, meaning that there is an extensive library of playable TTGEs all playable in AR. However, Tabletopia provides a sandbox that places virtual game boards and pieces with no scripted gameplay functionality, meaning that players are required to read rulebooks themselves and locate other players to play with. Other applications for the Tilt Five allow for scripted or programmed interactivity, such as Realm's Crossing [29], a virtual board game that includes gameplay features more typical of computer games, such as animations or particle effects. Realm's Crossing also allows players to play against a computer, meaning that it is entirely functional as a single player experience.

Whilst the Tilt Five and allow players to virtually engage with the tabletop experience in AR, there is a potential issue with the scalability of the setup. Unlike Ardent Roleplay or Mirrorscape, which function as independent AR applications on commonly owned smart devices, the RPG Engine, Tabletopia, and Realm's Crossing exclusively require the Tilt Five to play in AR mode. This is potentially costly for players, as the system is sold in different bundles depending on how many glasses/wands are purchased simultaneously. It is not possible to purchase glasses and wands separately; they must be purchased as part of bundle for the entire system. This means that should a group of five wish to play using this configuration (one storyteller/dungeon master and four player characters), the cheapest bundle combinations to achieve this would be $1198, making the Tilt Five system a very expensive investment compared to its alternatives. However, as there are a substantial number of playable games available for it via Tabletopia and The RPG Engine, it could be seen as an investment for players who wish to repeatedly play TTGEs in AR. Online, there is little discussion surrounding the released product, with the only dedicated online discussion space for the Tilt Five being a Reddit community [30] for the system that has not seen new posts made in over eleven months, indicating that interest in this system is niche or has declined since release.

2.2. Augmented Reality for Accessibility in TTGEs

AR as a medium can be used for all manner of accessibility purposes and can be useful for both general audiences as well as for those with accessibility requirements. For example, the Google Translate application [31] for mobile devices is used to translate text or audio from one language to another; however, the application also has an AR mode that, using the devices camera, can translate written text and superimpose a translated version over the top of the original using the device screen and allowing the user to read it in a language of their preference. Using the visualisation medium of the technology along with the computational power of the device facilitating the AR application, information or its presentation can be altered, transformed, or re-contextualised to become more accessible for audiences in ways that may be personally tailored to their preferences or requirements. When discussing accessibility, it is important to recognise that accessibility options can also benefit wider audiences by providing options that can be used to customise individual experience. Furthermore, it is essential to explore the way AR has been used to add accessibility options to existing TTGEs to analyse the options these provide and their potential uses, both to assist players who may otherwise be unable to engage in TTGEs, and how these options may have been used by other users.

Within the context of education, Roleplaying Games (henceforth abbreviated to RPGs) can be used as valuable ways to simulate scenarios or situations that prompt the leaner to explore various resolutions in a safe environment, as was the case in an AR RPG by Lee et al. [32] in which the authors built an AR RPG system for children with autism. This system was built using Vuforia and allowed participants to interact with the system by moving around a cardboard avatar containing a photograph of each participant, which the authors state reduces confusion for autistic children compared to using traditional non-identifying markers (such as QR codes, dot matrixes, etc.). When used, this system allowed participants (three children with autism) to play a series of scenario stories based on their everyday lives from school, their homes, or within their local community, such as being greeted by a stranger and needing to pick the appropriate social response. Participants were studied under observation by a therapist who was able to observe and evaluate each participants' response and then teach the participants the socially correct response. The study found that all three participants had a reduced rate of error for navigating social situations in the aftermath of the study and that the parents reported that after the study, their children were more frequently responding appropriately to social cues. This demonstrates that AR TTGEs have viable uses as simulation tools, particularly due to how these can be created as bespoke tools specific situations or audiences. The authors noted that the use of a physical manipulation was beneficial for children with autism as the existing literature on the topic [33] suggests that it helps to channel the children's attention whilst also providing context for interactable components.

Regarding AR accessibility for TTGEs, there is very little existing literature in terms of traditional TTGEs as many research studies into this area have instead sought to create a bespoke game for a specific purpose which may not translate into what players would traditionally expect from a tabletop game. These have been included to discuss their approaches and findings; however, it must be prefaced that the following studies may not directly translate to conventional TTGEs.

Autism appears to be a common topic of AR research, with many researchers focusing on how AR can be used to simulate tasks in a safe environment. An example of this is Tidd, an AR-based tabletop experience designed by Wu et al. [34] in a study on developing daily living skills for children with autism. This project was specifically developed for children with autism and with an emphasis on learning/practicing skills rather than playing a conventional gaming experience. The design of this system used an overhead projector to project the AR content onto the tabletop area, with a camera positioned adjacent to the projector to observe and record physical interactions on the tabletop. Participants in this study interacted with the system by moving physical objects around on the desktop surface. A camera would capture these movements and send them to a computer running Unity, which would process the interactions. The TTGE content included two exercises; one in which participants were taught to fold bedsheets, the other in which they were taught how to select appropriate clothing for each season, and each interacted with using miniaturised quilts and clothing examples that can be manipulated on the table. These both worked in four stages: participants were shown a demonstration, taught to perform the processes with AR visualisations, then had to replicate the methods with AR projection providing cues as appropriate. At the end, participants were then prompted to perform the demonstration on life-sized equivalents without any AR guidance. Results taken from this study were qualitative and relied upon both observations and feedback from therapists who were present throughout the testing process. The results indicated participants did not interact with the system as expected in some contexts, but they did respond well to the reward mechanism (an animation of fireworks that played upon a success). The therapists approved of the novelty of the project due to the interactivity of it. The therapists also reported that children with autism generally tend to prefer having someone demonstrate a task when it is performed for the first time, and that repeated demonstrations are important, rather than a single occurrence. Whilst these findings are no doubt useful for designing AR systems for children with autism specifically, it is unclear if these findings would be generalisable for adults with autism too, or if they only would only be appropriate for child audiences. Furthermore, the concept of a projector being used to augment the surface of the table itself is a novel concept that could be used in a TTGE to provide additional information or interactivity; however, considerations may need to be made for how it may also be obstructed by elements such as physical terrain pieces, character models, or dice.

Projectors as a tool for visualising AR content have been investigated in other forms of research, as with AR for tabletop games. In another study by Wu (et al., but with different co-authors than the previous study) on the use of AR TTGEs for children with autism [35], projectors were once again used as the method of rendering AR content. Unlike the previous study that was designed to teach mechanical operation, this study, titled MagicBLOCKS, instead sought to educate on a broader range of skills, such as toothbrushing, musical notation, and matching and sorting, whilst also facilitating social interactivity. This study utilised an overhead projector with a web camera, and included an air bar touch sensor to allow for finger-based inputs on the working area. This system included a variety of games, each controlled with either physical manipulatives such as blocks or cards, or by touching the playable area (via the touch sensor). Participants in this study, all children with autism, were given the opportunity to observe the system being used by researchers, and were then given blocks and physical cards to practice with prior to using the system themselves. Afterward, each participant was given time to play with the MagicBLOCKS system, with each participant playing for approximately 25 min. Results from this study found that participants enjoyed using the system, were more likely to practice their communication skills when playing with it (to their parents/therapists), and that when playing the games, the participants began to openly collaborate with each other to solve problems or keep gameplay elements moving. The technical setup for this system is novel as it demonstrates additional functionality for interacting with a TTGE via the touch sensor, and can allow for interactivity with the game area itself rather than just physical manipulatives. Regarding the accessibility aspects of this, however, this study was specifically designed to create a bespoke AR TTGE for children with autism, meaning that it did not seek to address adding accessibility to existing TTGEs but rather how to approach designing a game to foster development in a very specific audience. The findings regarding how playing the game encouraged communication and collaboration are very promising, but may not translate to adult audiences, particularly when the recreational aspect of this genre already requires communication and socialisation skills as pre-requisites for engaging with them.

2.3. Accessibility Tools in Virtual Tabletop Environments for TTGEs

Taking examples from the accessibility options for Virtual Tabletops (Henceforth abbreviate to VTTs) can help provide an insight into current working examples of digital accessibility functions and tools which can be used for future application into an AR environment. VTTs have become a larger space for roleplayers over the last decade, with the COVID pandemic instigating a huge rise in online roleplaying experiences. This rise in users has naturally sparked the need for more content, tools, and accessibility considerations.

Roll20, a free online Virtual Tabletop hosting company and website began an accessibility push in 2021 [36]. As the VTT is used through screens and monitors, a dark mode was created to allow users the option of having bright or dark screen space colours as well as a lowered colour contrast ratio of their user interface (UI). This helped combat eyestrain and support users with colour blindness. In 2017, Roll20 had initially outlined its plans for accessibility features such as additional language options, visual interpreters for the blind, and a colourblind mode [37]. However, these features were mentioned on an official Roll20 Blog which has since been taken down and the mentioned features are still not present in the current Roll20 Build online. When searching under the keyword 'accessibility' in the Roll20 Community forums [38], 160 results are found; however, most of these are in relation to accessing a tool or character sheet and not accessibility functions within the VTT. A user by the name of 'Dave' on the Roll20 forums, when discussing mod implementation for blind players said "Sadly, Roll20 is very, very accessibility unfriendly" [39]. When considering the use of AR, it is usually the case that more established digital spaces have already made steps towards making their websites and platforms more user-friendly. While Roll20 has fallen short on delivering this successfully, there is still space for it, and it would be hoped that these can be implemented in future versions.

Foundry VTT is another virtual tabletop, which offers substantially more player options and user customisation. Players can enable photosensitivity mode which is described on the tool tip as 'reducing the prevalence and intensity of flashing, fast-moving and repetitive animations and effects'. Users are able to customise the UI and can scale the interface and font individually to each other as well as enabling dark and bright modes for the same. This is all available prebuilt into the application without the need for plugins, webpage modifications, or additional paid content. Foundry has 165 translation and localisation free add-on modules as well as an Accessibility Enhancement module created by a user called 'Cora' in 2024 [40]. This enables drag-and-drop alternatives, audio feedback, and high-contrast character sheets. Foundry has more options for accessibility with the core VTT having more granular options for user customization. Foundry has more depth of options and user customisation both are primarily user-led decisions either petitioned for or user made with modules or add-ons. Having granular customisation allows each individual user to curate their space for their unique needs without the need for browser plugins, allowing for greater user control. With AR and digital tabletop experiences being similar in usage and application, AR could and should be aiming to provide as much user control as possible. The more the user can alter and edit their experience the more they can enjoy the provided platform. As tabletop experiences are usually long experiences that will surpass an hour of play, these options are necessary for not just accessibility of play groups but also comfort.

2.4. Augmented Reality for General Accessibility

Augmented Reality is a tool with great potential for accessibility purposes, as its nature as a transformational tool allows it to provide new information, new contextualisation, or new methods of engagement for users. Many studies have explored ways in which AR can be used to provide accessibility to users for a variety of purposes and for a wide range of topics including outside the context of AR TTGEs. Even though these studies may not directly relate to TTGEs, it is important to address how other AR studies have approached accessibility as the methods used could be applicable to other areas of AR. For example, a paper by Puyuelo et al. [41] sought to explore the usage of AR for augmenting a

UNESCO heritage site called the Lonja de la Seda, a gothic silk market building, for the purposes of making the building and its contents more accessible to all audiences. This motive is only alluded to in the abstract; however, the authors imply the reasoning for using AR is because of poor lighting and distance, which may make parts of the building or its contents difficult to see in normal circumstances. As the authors were working in a protected heritage site, they had limitations upon their working space as their design was required to be non-intrusive, and so they opted for a solution that included setting up a television alongside the exhibit with a camera mounted to it and letting participants use photographic hand-held markers to visualise AR content via the screen. By holding up markers, the camera and screen acted as a digital mirror with AR content overlaid over the marker, allowing participants to examine virtualised versions of the sites' architecture using a physical manipulative prop. The authors recruited 145 participants from site visitors in this study who were surveyed on their enjoyment of the application and how difficult it was to use. They found that the majority of participants enjoyed using the AR application and that it was considered easy or very easy to use. This method of AR implementation demonstrates that users respond well to the technology due to their perceived enjoyment of it; however, in this case, the primary purpose of the application was to make the site more accessible, something that the authors achieved whilst also increasing visitor enjoyment of their visits. This demonstrates that when the technology can be used to increase accessibility, it can make an experience more enjoyable for all audiences.

Navigation is another area that can be improved upon using AR to make locations more accessible to audiences, something that may be particularly useful to any person who struggles with directions, may not speak the local language of their current location, or those with anxieties regarding traveling. A study by Rocha & Lopes [42] explored this further by seeking to develop an application to assist users with navigating buildings, such as museums, airports, hotels, etc. Applications such as Google Live View [43] already enable this for outdoor exploration using AR to impose directional arrows over the users' local environment to direct them to their destination; however, this functionality is only available in specific countries and only works outdoors on streets, not inside buildings. The authors of this study sought to expand upon that using a mobile AR system to map out the inside of buildings and using a waypoint system to navigate the user to pre-determined destination nodes. The study also used a cloud database to store the navigation data of buildings (referred to as maps) that the application could download automatically by accessing the location ID of the building using the SSID of the building's Wi-Fi, meaning that users could automatically download location data for the app just by connecting to the building's Wi-Fi upon arrival and preventing the need to manually locate and download the files themselves. This study did not include any testing or results; however, as a proof of concept, it demonstrates a very functional and elegant method of improving navigational accessibility using AR, which may be useful for elements of TTGEs or even for full Live-Action Role-Playing (LARP) scenarios.

Using AR for navigation is one of many areas explored for developing Smart Cities; however, it is not the only application of the technology. Smart Cities AR research has also investigated how AR may be used to benefit users in wheelchairs, as was the case in a study by Rashid et al. [44] whereby the researchers sought to use the technology to help wheelchair users overcome limitations placed on their independence by the structure of modern society. Within the context of this study, the authors specifically examined supermarkets and the difficulties their structure imposes upon wheelchair users, due to items being placed on vertically stacked shelves that may not be accessible to them. To try to find a potential solution to this challenge, the authors created an application that would allow users to install an app to a mobile device that could scan RFID codes placed on shelves. Upon scanning the QR code, the user is then presented with a view of the shelves that can be navigated to browse the products stored upon them, which can then be added to a list for retrieval by an assistant whenever the user activates the assistance icon. The system also used a cloud database to update product information in real time based on location and presence, meaning that if items were removed or relocated, the application updated accordingly, preventing any scenarios where a user would be shown items on their device that are not present on the shelf. The study tested this application on nine participants who used wheelchairs and found that participants were satisfied with the proposed system, with participants expressing that they found the system to be beneficial and aided with gaining autonomy. The authors focused on the applications of this system for wheelchair users, but it would also benefit wider groups, for example users who were unable to reach high shelves for any reason (such as height, injuries, other medical conditions, etc.). It may be easy to compare such a proposed system to an existing one such as 'click and collect'—a common system used in shops to allow users to browse products online, place an order for them and then go to the shop to collect them. Whilst functional, 'click and collect' still excludes people from a conventional retail shopping experience, whereas the system proposed by Rashid et al. would foster a more inclusive experience.

2.5. Augmented Reality for Sustainability

In the context of AR for sustainability purposes, the literature on the topic is generally aimed towards how AR can be used to educate. The existing literature tends to lean toward how to teach learners about climate change by creating educational experiences [45–49], Serious Games [50,51], or even uses the technology to create visualisations via lidar scans to track the impact of climate change [52]. However, within the scope of using AR to improve sustainability in tabletop games, there is a distinct lack of literature on the topic, thus creating a niche area for future research to potentially explore.

The reason we sought to include this section is because of the carbon impact of producing and distributing tabletop games. These are often large, bulky, and produced with potentially climate damaging resources—paper, wood, plastic, and sometimes metal components are all common, and card stock is often covered in a chemical glaze which protects the gaming tools, but makes them less biodegradable. In addition, most TTRPGs and boardgames are manufactured away from the point of sale (most notably, China), and then shipped around the world. Furthermore, games are fragile in transit and elicit high shipping costs as they must be stored at the top of containers to avoid being crushed. They are also often covered in large amounts of protective packaging, which in itself is often environmentally unfriendly. The use of AR could be beneficial for reducing the overall carbon footprint of producing and shipping.

Each year, companies tend to (but do not always) publish sustainability/social responsibility reports for that fiscal year. These include summaries of carbon emissions generated by the company defined within three scopes [53]:

1. Scope 1: Direct Emissions produced by the company (e.g., fuel burned by company-owned vehicles, emissions from chemical reactions in manufacturing processes, etc.).
2. Scope 2: Indirect Emissions produced from electricity, steam, heating, or cooling purchased by the company. (e.g., electricity purchased to power lighting, refrigeration, air conditioning, etc.).
3. Scope 3: Indirect Emissions that occur in the company's value chain. (e.g., carbon costs of raw materials, packaging, shipping via land/sea/air, waste, etc.).

This framework is used by many companies to publicly report on their emissions, and many game manufacturers use them to highlight their efforts to reduce their carbon footprints. As such, these can be used as a benchmark to estimate the carbon impact of producing and distributing tabletop games (with numbers subject to variation to account for marketing, promotional materials, prototypes, etc.), as seen in Table 1. Furthermore, these companies do not exclusively produce tabletop games, meaning that these numbers can be used to form a generalised idea about emissions but not a precise set of figures (please note that emissions are rated in CO2e (Carbon Dioxide Equivalents)).

Table 1. Comparison of CO2e emissions from TTGE manufacturers.

Company	Year of Report	Scope 1 (CO2e)	Scope 2 (CO2e)	Scope 3 (CO2e)	Total (CO2e)
Hasbro [54]	2024	3880	4840	698,076	706,796
Mattel [55] *	2023	13,574	Location-Based: 146,790 Market-Based: 142,926	1,516,185	Location-Based: 1,676,549 Market-Based: 1,672,685
Games Workshop [56]	2023	484	2736	59,222	62,442
Spin Master [57]	2023	246	1339	78,109	79,694
LEGO [58]	2024	23,403	1	1,796,299	1,819,703

* Please note that Mattel reports Scope 2 emissions using Location-Based and Market-Based methodologies for calculating indirect emissions under the Greenhouse Gases Protocol [59], which is why both figures are presented.

Within the context of AR-based TTGEs, using AR does not remove the carbon impact of creating a game system for either the developer or for the consumer. If an HMD was being chosen as the solution for implementing AR, then the carbon impact would increase as HMDs are not commonly purchased devices by consumers. The most recent large-scale attempt to market an HMD to consumers, the Apple Vision Pro (marketed as a "spatial computer"), undersold compared to sales estimations and had its sales figures cut back [60]. Consequently, it can be reasonably assumed that consumers would need to purchase an HMD to engage with an AR-based TTGE, thus increasing the carbon impact of such a gaming configuration.

Mobile devices are also not without carbon impact, with studies reporting the carbon impact of consumers due to the frequency at which they replace their devices [61–63]; however, that is not the focus of this paper. Regardless of mobile device replacement habits, unlike with HMDs, it can be reasonably assumed that players of TTGEs already own a mobile device capable of rendering AR. As most consumers would not need to purchase a new device to participate in an AR TTGE, the carbon impact of developing, deploying, and playing such a game is theoretically far lower, with the carbon costs generally shifting toward energy consumption and server hosting.

This section of the review had been intended to explore this topic further and analyse how the existing literature has already addressed the climate impact of using AR for TTGEs; however, there does not appear to be any literature on this topic. Further research is required on this area to explore how the use of AR could potentially offset the emissions generated by TTGEs.

3. Results

Below in Table 2 is a summary of the referenced AR systems from the prior chapter. Please note that for studies that did not specify accessibility as a direct part of their study, but the created project could be used for accessibility purposes, we have designated their studies with an asterisk (*) in the accessibility considerations column as to further discuss how it may be applied to future studies on AR for accessibility. If data has not been provided for any areas, it has been recorded as N/A (Not available). Accessibility framework alignment is detailed in Table 3.

Table 2. List of reviewed studies.

Study	Project Title	AR Implementation	Tabletop Game?	Accessibility Considerations	Sustainability Considerations
Huynh et al. [12]	Art of Defense	Mobile Device	Yes—Original Game	Visualisation *	N/A
Molla & Lepetit [14]	No Title	Camera/Screen	Yes—Existing Game	Visualisation *	N/A
Rizov et al. [15]	No Title	Mobile Device/Server Driven	Yes—Existing Game	Visualisation *	N/A
Nilsen [17]	Tankwar	HMD	Yes—Original Game	None	N/A
Dolce et al. [20]	ARmy	Projector AR	Yes—Original Game	Visualisation, Cognitive *	N/A
Lee et al. [32]	Unnamed (but referred to as AR RPG)	Overhead Camera/Screen	Yes—Original Game	Visualisation, Cognitive	N/A
Wu et al. [34]	No Title	Projector/Screen	Yes—Original Game	Visualisation, Cognitive, Mechanical Operation	N/A
Wu et al. [35]	MagicBLOCKS	Projector/Screen/ Touch controls	Yes—Original Game	Visualisation, Cognitive, Mechanical Operation	N/A
Puyuelo et al. [41]	No Title	Camera/Screen	No	Visualisation, Situational accessibility	N/A
Rocha & Lopes [42]	No Title	Mobile Device	No	Visualisation, Navigation, Cognitive	N/A
Rashid et al. [44]	No Title	Mobile Device	No	Visualisation, Equity	N/A

Studies were also mapped against the four WCAG 2.1 principles defined in Chapter 1: Perceivable, Operable, and Understandable and Robust, with individual success criteria referenced where applicable. In addition, each study was evaluated in relation to the XAUR documentation which explores accessibility needs for immersive and spatial technologies. Table 3 presents this comparative alignment to address where existing studies or projects on AR adhere to WCAG 2.1 guidelines or XAUR considerations, along with discussion of how these were applicable.

Table 3. Alignment with accessibility frameworks.

Study	WCAG Adherence	XAUR Considerations
Huynh et al. [12]	Perceivable— 1.3.6 Identify Purpose 1.4.3 Contrast The AR content is programmatically determined over the physical markers, meaning it can be changed as required. The 3D models use contrasting colours to stand out from the physical environment.	4.3 Immersive Personalisation 4.6 Colour Changes The game pieces use symbol sets that can be used to communicate purpose to users. The colours used on 3D Models are brightly coloured and contrast with the game board.
Molla & Lepetit [14]	Perceivable— 1.4.3 Contrast The AR content uses bright and contrasting colours to differentiate it from the physical game board.	4.6 Colour Changes High-contrast colours are used to separate the AR content from the game board.
Rizov et al. [15]	None. AR elements are limited to 3D model visualisation only with low contrast levels.	None. The system only includes 3D model visualisation with no customisation. AR content requires physical objects to be moved around.
Nilsen [17]	None. No augmented content is shown in the study and descriptions are mostly of gameplay functionality rather than how content is presented to users.	4.5 Voice Commands 4.7 Magnification context and resetting Players can interact with the game with voice commands, and the design of the application allows the user to magnify and zoom where required.
Dolce et al. [20]	Perceivable— 1.3.4 Orientation 1.3.6 Identify Purpose 1.4.3 Contrast Operable— 2.5.1 Pointer Gestures Due to the projected nature, the content is not restricted based on view. The AR content uses bright and contrasting colours/projected textures to distinguish it from the playable space. Inputs can be operated with a single pointer (albeit with a finger tap rather than a mouse cursor).	4.6 Colour Changes The spatial projectors for managing AR use high-contrast textures to make the environmental pieces easy to distinguish from each other. Unit movement radiuses are also brightly contrasting with the game board.
Lee et al. [32]	None. Although this study used 3D AR content, it was presented over a brightly coloured game board, meaning that there was little contrast. The fixed board and camera positions also prevent customisation for individual users.	4.3 Immersive Personalisation The authors of this study designed the system to work with personalised markers for each user.
Wu et al. [34]	Perceivable— 1.4.3 Contrast The system used a projector to display AR content on a desk, with each AR item contrasting against the surface.	4.6 Colour Changes The projections have high-contrast levels with the surface area which would aid colourblind users in distinguishing projections from the surface.
Wu et al. [35]	Perceivable— 1.4.3 Contrast The system used a projector to display AR content on a desk, with each AR item contrasting against the surface.	4.6 Colour Changes The projections have high-contrast levels with the surface area which would aid colourblind users in distinguishing projections from the surface.

Table 3. *Cont.*

Study	WCAG Adherence	XAUR Considerations
Puyuelo et al. [41]	None. AR Content is designed to imitate real-world items/architecture and so the colours do not contrast with the background. Content can be resized based on proximity to the camera but WCAG only considers resizable text in its guidelines, not multimedia.	4.7 Magnification context and resetting Though not a full magnification tool, the static nature of this setup allows users to magnify content by holding markers closer to the camera as required.
Rocha & Lopes [42]	Perceivable— 1.1.1 Non-Text Content 1.3.4 Orientation 1.4.3 Contrast The application uses visual navigation arrows and text-based navigational instructions for users. Either landscape or portrait orientations can be used. The application also uses bright contrasting colours that are distinguishable from the background.	4.2 Motion Agnostic Interactions 4.5 Voice Commands 4.6 Colour Changes 4.13 Orientation and Navigation Users can interact with the system using touchscreen functions; motion is not required. Voice commands are available for interactions. Colours are bright and contrasting against the background. The system uses defined visual landmarks to assist with navigation.
Rashid et al. [44]	Perceivable— 1.4.3 Contrast The application uses contrasting tones/colours on the digital screen to identify the users selection in relation to where it is on the physical shelf.	4.2 Motion Agnostic Interactions 4.6 Colour Changes Users interact with the system via the touch screen. There is a handheld AR mode but it is not needed to operate the system. The UI uses bright colours to distinguish AR selections from the background.

3.1. What Technologies and Visualisation Methods Do Existing AR Products or Projects Use for TTGEs?

Existing exploration of AR for TTGEs has primarily utilised four approaches; Mobile/Tablet-based AR [12,15], HMD-based AR [17], Camera/Screen-based [14,32], and with use of Projectors [34,35]. Mobile/Tablet solutions are always popular as the technology is readily available at consumer grade level and can be effectively deployed with minimal technical logistical concerns, such as using existing applications/services to handle the deployment of AR content [15] or even bespoke tools designed specifically for TTGEs [8]. Research into these tools has generally been explorative purposes into the logistics of creating an AR TTGE rather than the benefits of using them (with the exceptions of the two studies by Wu et al., which focused on the benefits of using AR TTGEs to benefit children with autism), and has shown that there are possibilities of enhancing TTGEs with additional content, controls, or management of gameplay rules; however, these have not fully explored the range of possibilities for how it can be used to synergise with gameplay rather than just existing alongside it. Whilst it is clear that there is some interest in this area, it is still somewhat underdeveloped.

3.2. How Have Accessibility Requirements for TTGEs Been Addressed by the Use of AR Technology?

Within the context of how AR has been used in the exploration of accessibility features, the existing literature focuses on creating bespoke TTGEs for children with autism [32,34,35], but not for other requirements. Although AR has applications in aiding with accessibility for a variety of purposes, such as allowing for visualisations of content that may otherwise not be logistically possible [41], providing new means of navigating through complex areas [42], or even provide equitable access to facilities and services that would otherwise be logistically implausible [44], these applications have seemingly not been explored for TTGEs. This is an area that would benefit from additional studies, as TTGEs are a growing market and providing new technological accessibility solutions would allow more players to engage with this style of game, whilst also discovering accessibility methods that may be translatable to other forms of media.

3.3. *What Are the Ecological Considerations of Using AR over Physical Products?*

Whilst this was a research question entering this review, we have not discovered any indication that the existing literature has explored this topic in any capacity. There is a gap in the literature for research into this field and identifying if there are any ecological benefits, advantages, or even disadvantages to using AR for TTGEs rather than the physical manufacturing and distribution of pieces, boards, and books/manuals.

4. Discussion

The results of this study have revealed that there are gaps in the existing literature for both accessibility and for sustainability in TTGEs. With regard to accessibility, little research exists for how TTGEs could be expanded upon with AR to add accessibility options for a variety of users.

To refer back to the example we provided in the introduction, users with Aphantasia are unable to mentally visualise the described content in a TTGE, which may impact their ability to engage with stories/action, which can be aided with the use of miniatures, tokens or props, but could be fully visualised using AR. Tabletop strategy game players who need to paint miniatures (something which is usually a requirement to participate in official tournaments) may struggle to do so if impacted by any condition that causes difficulties with fine motor skills, such as Parkinsons disease, multiple sclerosis, arthritis, etc. This is not limited to just the painting, as models must be transported, deployed to a tabletop and then moved around during gameplay, which can also present accessibility challenges for some players. During the operation of gameplay, depending on the game system, there may be complex rules to follow and adhere to, players must keep track of the statistics of individual units and any changes made to them by gameplay elements, calculations may need to be performed, large volumes of dice rolls may need to be kept track of, among many other things that can all contribute to cognitive overload. The rules, cards, and sheets used for TTGEs are generally printed with similar font sizes, which can be small to minimise the number of pages/cards printed, particularly with games that are particularly dense with rules and procedures, which can present accessibility concerns for players with visual impairments. Alternatively, the paint schemes used by players for their miniatures may be visually striking when seen with typical colour vision; however, for players with colour blindness, these may be harder to see, particularly when placed over certain terrain, which can cause an unequal gameplay experience if players are required to make strategic decisions but are unable to identify a miniature from a terrain piece.

These are just some of the examples we identified as enthusiastic players of TTGEs, both from general observation and from lived experience of witnessing these problems during gameplay. We had anticipated to address how these concerns had already been explored in prior research and use that to inform future study; however, we have instead identified that further research is required to explore how AR can be used to address these accessibility concerns and help provide equitable solutions to make sure that broader ranges of players can participate in and enjoy recreational TTGEs.

In Section 2.5, we sought to also explore the ecological impacts of TTGEs to explore how AR could also be used to offset the environmental impact of manufacturing and distributing TTGEs. TTGEs using miniatures generally cast them from metal, plastic, or resin, all with environmental costs to their manufacture. This is increased for games themed around large army battles rather than smaller-scale skirmishes, where players are required to buy large volumes of miniatures to participate in gameplay. Even beyond the miniature themselves, there is also an environmental cost of producing terrain, cards, tokens, books, manuals, dice, and any other gameplay tools that may be required for a game. This is compounded further by the environmental cost of distributing them, whether this be by land, sea, or air. It would not be responsible to make the assertion that these costs would be eliminated by the use of AR, as devices capable of rendering AR have their own environmental costs in manufacturing, distribution, and general usage. However, given the proliferation of smart devices in modern society, it can be reasonable assumed that many players of TTGEs already own and regularly use a smart device, meaning that using them could potentially lessen the carbon costs of consuming TTGEs. This is unproven so far, and further research is required to identify if the use of AR could lead to more sustainable gameplay practices.

During the introduction, we introduced the WCAG guidelines to compare against when identifying the accessibility features of existing AR TTGE projects. This was conducted with the intention of using an existing set of guidelines/framework to evaluate against with accessibility requirements in mind. However, this proved to be ineffective, as the WCAG guidelines are primarily designed for traditional web-based content, with text and buttons displayed on a website using a standard desktop or mobile GUI. As such, many of the guidelines pertain to tradition web features, such as fonts, text sizes, content being resizable, whether aspects of content can be interacted with using a keyboard as well as a mouse, the order of pages, etc. Many of these requirements are either specifically addressing web pages/content, or address whether the content is deemed "programmatically determined", the concept of whether the content can be accessed via an API for assistive technologies to adjust the presentation of the content. Whilst we sought to identify a set of guidelines or framework to evaluate against, the WCAG guidelines generally proved to be unsuitable for most AR purposes.

Furthermore, the comparative alignment of WCAG 2.1 and XAUR presented in Table 3 shows that most AR applications for tabletops (and even the non-tabletop applications examined for accessibility) achieve partial compliance with the Perceivable criteria of WCAG 2.1, though mostly through use of colour contrast with local environments. When compared against XAUR, many studies were also only compliant with the guidelines in regard to use of colour and contrast, with few offering other accessibility options such as magnification, voice commands, or motion agnostic interactions. The studies demonstrate strong visual accessibility, but limited consideration for other accessibility factors and none showed engagement with existing accessibility devices, such as hearing aids or screen readers. Whilst the guidelines presented across WCAG 2.1 and XAUR were intended to be used to identify adherence with accessibility requirements, both are designed to assist in ensuring existing applications can be brought in line with accessibility requirements, rather than how development of an application can be informed to ensure it is accessible for specific groups of users. It has become clear that a full framework for evaluating the accessibility requirements of an AR application is needed, which could be explored in future research to provide a consistent way for AR researchers to compare projects.

It is also important to distinguish between gaps caused by a lack of existing research and those arising from limitations within the current accessibility frameworks (WCAG2.1 and XAUR). Several accessibility gaps identified in this review (such as the absence of multimodal interaction options, motion agnostic control schemes, or support for assistive technologies) reflect the limitations within the existing literature on AR TTGEs. The studies that have focused on accessibility were using the medium as a way to create bespoke learning experiences for children with autism, rather than exploring how to design or implement accessibility options within more conventional recreational gaming experiences to enable wider audiences to participate. Additionally, other gaps have become evident from limitations within the existing frameworks, such as WCAG 2.1. Many of the success criteria from WCAG 2.1 require concepts that are not applicable to AR systems. For example, the entire Section 2.1 (Operable—Keyboard Accessible) requires functionality to be operable through a keyboard interface, something which may not be applicable to a HMD-based application that instead uses other forms of inputs. Section 2.4 (Operable—Navigable) determines success criteria exclusively based on the content being a web page, as does Section 3.1.1 (Understandable—Language of Page), etc. Consequently, there is a gap in the literature from a lack of exploration of how accessibility can be implemented in AR TTGEs, along with no dedicated guidelines that are directly applicable to the creation of such projects.

To synthesise findings across the studies examined in Chapter 2, the systems designed within them have been grouped by implementation type, accessibility focus, and sustainability potential. Table 4 presents this meta-framework to address how AR can be used for accessibility, or estimated environmental impact within Tabletop Gaming contexts.

Table 4. Meta framework.

AR Implementation Type	Typical Use Cases	Accessibility Characteristics (WCAG 2.1/XAUR Alignment)	Sustainability Potential	Observed Challenges	Example Studies
Mobile/Tablet AR	Entertainment, Educational	Some Perceivable alignment with contrast. Limited XAUR potential for spatial audio, voice commands or interactions with assistive technology. Strong potential for motion agnostic interactions with screen controls.	Moderate—Generally re-uses existing hardware/devices, but new hardware may be required periodically as part of regular upgrade cycles	High accessibility via existing device tools (assuming applications use programmatically determined features). Limited potential for immersive experiences. Logistical challenges for TTGEs owing to viewing angles and device comfort.	Huynh et al. [12] Rizov et al. [15] Rocha & Lopes [42] Rashid et al. [44]
Projection-Based AR	Educational	Some perceivable alignment if the projection contrasts with scenery. Potential for alignment with XAUR depending on how each configuration is set up. Strong potential alignment with Safe Harbour Controls (4.11) as users can more easily leave the environment or disable projection.	Low—Projectors are not commonly owned hardware, meaning new hardware would likely be required	Previously used for children in the prior literature and well suited to Classroom environments. Interactions typically require physical manipulatives which may limit accessibility options for motion agnostic interactions. Has high potential for visual accessibility augmentation on game boards or terrain for TTGEs.	Dolce et al. [20] Wu et al. [34] Wu et al. [35]
Head-Mounted Display AR	Entertainment, Educational, Immersive Experiences	Some alignment with perceivable depending on contrast levels. Possible benefits for Understandable/Operable criteria if systems are designed to integrate with assistive technologies.	Low—Generally requires purchasing new hardware to implement	HMDs may create more immersive experiences with spatial AR and audio; however, these devices are seldom owned by consumers and so the additional carbon costs must be factored in to the setup costs.	Nilsen [17]

Table 4. *Cont.*

AR Implementation Type	Typical Use Cases	Accessibility Characteristics (WCAG 2.1/XAUR Alignment)	Sustainability Potential	Observed Challenges	Example Studies
Hybrid/Multi Device systems	Educational, Accessibility	Highly variable depending on devices used. Adherence with WCAG2.1 and XAUR guidelines are possible and should be considered as required for each setup.	Variable—Depending on hardware configuration	Contextual depending on devices used; however, there is significant potential to offset financial and carbon costs of implementation using more commonly owned devices. Each setup must be individually assessed and evaluated against accessibility guidelines.	Lee et al. [32] Puyuelo et al. [41]

4.1. Future Roadmap

After synthesising the findings in Table 4, we propose a future roadmap for the ongoing development of research within this field. The following proposals are for future research that could explore these points further. This would ensure that further study on accessibility and sustainability within TTGEs is fully supported by both a bespoke framework and quantitative data on the potential carbon costs of AR tabletop games.

1. Development of a full accessibility-first framework for AR design. The current guidelines demonstrate how to adapt or retrofit existing applications to ensure they are accessible, rather than how they can be designed specifically for users with accessibility requirements. Due to the nature of AR applications, they can be created as bespoke tools to foster inclusion for specific accessibility requirements (such as our example from the introduction, users with Aphantasia), and so a framework to evaluate how a design of a system meets these requirements is essential.
2. Quantitative assessment of sustainability in AR tabletop games. Future studies should explore how AR can contribute to more sustainable Tabletop Gaming Experiences. This includes calculations of carbon estimates, explorations of AR solutions that use varying implementation methods, and experimentation with eco-friendly alternatives. These can be benchmarked against the CO2E figures published by manufacturers/publishers to estimate scalability, along with potential impacts on carbon emissions or other such environmental concerns.

Furthermore, to complement the roadmap outlined above, we also identify a set of practical guidelines for developing future AR TTGEs. These guidelines are informed by the combined findings of Tables 3 and 4 which highlighted common accessibility features, recurring gaps, and implementation trends. These have been organised into the four principles of the WCAG2.1 guidelines (Perceivable, Operable, Understandable, and Robust) to provide a structured set of priorities for improving accessibility in future AR TTGE development, along with reference to the relevant WCAG 2.1 or XAUR guidelines where applicable.

Perceivable:

Future AR TTGEs should prioritise clarity for user perception to ensure that digital elements are distinguishable, usable, and customisable within variable tabletop environments.

- Use adaptive colour and contrast (WCAG 1.4.3) to ensure augmented content remains visible in different environments or lighting conditions. Avoid using any dull colours for AR content to ensure it does not blend in with the background (XAUR 4.6).

- Avoid conveying information through colour alone (WCAG 1.4.1); AR content should be distinguishable with additional visual information such as icons, patterns (XAUR 4.3), or even alternative forms of media if appropriate.
- Provide optional tools for accessibility, such as magnification tools (XAUR 4.7), adjustable sizes for any text/AR content, screen readers/audio alternatives, and high-contrast modes.
- Ensure spatial audio is used where appropriate to support users who either need assistance with navigation in augmented spaces, or to assist those who may miss audio used with mono/stereo configurations (XAUR 4.17 & 4.18).

Operable:

Tabletop games may include varying physical requirements depending on the game system, and so any AR TTGE should ensure interactions can be performed in multiple ways. This will allow users with accessibility requirements to be able to participate regardless of individual gameplay mechanics.

- Support alternative input methods, such as voice commands (XAUR 4.5), tap/swipe gestures (XAUR 4.9), pointer-based interactions (WCAG 2.5.1), or even simple gesture controls to reduce reliance on fine motor movements.
- Offer motion agnostic interaction options (XAUR 4.2), particularly for users who cannot perform large/complex gestures, or for those who experience fatigue. Furthermore, all interactions should be comfortably performable from a sitting position, with no expectation the user is required to stand or move during operation (XAUR 4.4).
- Ensure that core interactions do not depend on device tilting or continuous arm lifting if a mobile device is used (WCAG 2.5.4). The design should allow for users to keep their device stationary for the entirety of use if required.

Understandable:

To maintain clarity during gameplay, AR systems should minimize cognitive load and promote predictable behaviour.

- Maintain consistent placement and behaviour of AR content to reduce confusion when physical or virtual components are moved (WCAG 3.2.2).
- Use clear and predictable feedback cues (whether visual, audio, or even haptic, depending on system configuration) to indicate successful interactions/state changes (WCAG 3.2—multiple).
- Provide informative optional tooltips (WCAG 3.3.5) and appropriate button/label names on virtual input methods to ensure that users can clarify actions (WCAG 3.3.2). There should be no confusion on the purposes of buttons, menus, or any other virtual interaction methods.
- Avoid any sickness triggers (XAUR 4.16) such as flashing lights, rapid motion, or extremely loud audio, as these can be disorienting or triggering to some users. They may also contribute to cognitive overload, which should be avoided.
- Ensure there is a quickly accessible option to hide/dismiss AR content or exit out of the application. Users with cognitive impairments may become overwhelmed and so a Safe Harbour control (XAUR 4.11) is needed to allow a quick escape from the AR space if required by the user.

Robust:

AR applications made for TTGEs must be accessible across device types and remain compatible with assistive technologies.

- Design with device variability as a key consideration and ensure that core features function consistently across different smart devices (e.g., the functionality should work regardless of if the user is on an iPhone or an android device).
- Use standardized, programmatically determinable structures where possible to ensure compatibility with existing accessibility tools (XAUR 4.1). Users who need to use dedicated screen readers, screen magnification tools, or users who require a second screen device (XAUR 4.14), should be provided with the means to use their accessibility tools with any developed application.

This is by no means an exhaustive list; however, it includes the common findings identified from the existing frameworks and current literature.

4.2. Reporting Guidelines

Finally, we identified a set of reporting guidelines for future studies on AR TTGEs. Future empirical studies should adopt consistent reporting practices to support evaluation, comparison, and replication. Based on the gaps identified by this review, along with the limitations of existing accessibility frameworks, these following data points should be included in the future literature:

1. Device and Hardware Specifications: This includes device model, operating system, display type, and input methods. These directly influence accessibility, ergonomics, and the possible carbon calculations of the setup.
2. Accessibility Features included in the project/system: This can include magnification, motion agnostic controls, safe harbour mechanisms, spatial audio, alternative input modalities, or compatibility with assistive technologies, etc.
3. Environmental Conditions: This can include lighting, surface reflectivity, tabletop configuration, noise levels, or any other pertinent information. These factors may affect colour contrast, perceptibility, spatial audio clarity, or even be contributors toward cognitive overload.
4. User Characteristics Relevant to Accessibility: This includes any accessibility needs of participants (e.g., low vision, colour blindness, motor impairments, etc.), providing these are ethically and appropriately reported. This provides essential context for interpreting the efficacy of any accessibility considerations within the design of the system.
5. Interaction Design Details: This includes how users interact with any AR or digital content (such as voice controls, gestures, swipes, etc.).
6. Sustainability Indicators: This includes estimated energy usage, device power requirements, and whether the system re-uses existing consumer devices or requires purchasing new hardware.
7. Usability Challenges and Accessibility Barriers: Any observed challenges within the study for accessibility. These should be clearly documented to inform future research and prevent recurring issues in future studies.
8. Framework Evaluation: Future studies should report how their projects were evaluated for accessibility along with the frameworks used and any identified limitations, either of the study itself, or of the framework. This will help to further improve how AR TTGEs are evaluated for accessibility and ensure that a comprehensive set of guidelines may be maintained to ensure future projects can be developed with accessibility in mind.

5. Conclusions

Whilst some of the literature has explored the field of AR for TTGEs, this paper has identified a gap in understanding how this technology can address accessibility and sustainability in the modern gaming climate. Ensuring equitable participation in games requires addressing the accessibility barriers wherever possible, and AR can be a functional solution to this as it provides new and innovative ways to visualise content, communicate information, automate gameplay processes, and ensure that players can customise the game to fit their own individual requirements. Likewise, sustainability concerns must also be addressed, as climate change is a pressing concern that affects us all, and if there are environmentally friendly adjustments that can be made to the way in which we engage with hobbies, then they should be explored to allow consumers to make informed decisions when making purchases. Future studies may show that the carbon costs of AR-based TTGEs are lower than producing/distributing physical product. Alternatively, they may be comparable, or could even be worse; however, further study and exploration is required to identify if this is the case and if so, what measures can be taken to mitigate it, or what alternative solutions may be available to result in greener hobby consumption.

Future research should use the findings of this paper to inform research into the use of AR technologies for both accessibility and sustainability. This will identify methods of creating gameplay experiences that are accessible, and with an exploration into the CO2e costs of creating such an experience with AR compared to traditional/physical methods. This is to help ensure that the future of TTGEs can be built with a stronger foundation of how to develop games that are accessible to all and sustainable for the planet.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
D&D	Dungeons & Dragons
HCI	Human–Computer Interaction
HMD	Head-Mounted Device
LARP	Live-Action Role-Playing
RPG	Roleplaying Game
TTGE	Tabletop Gaming Experience
TTRPG	Tabletop Roleplaying Game
VTT	Virtual Tabletop
WCAG	Web Content Accessibility Guidelines (Version 2.1)
XR	Extended Reality

References

1. Critical Role Productions, LLC. Critical Role (TV Series 2015–)-IMDb. IMDB. Available online: https://www.imdb.com/title/tt4834232/ (accessed on 4 June 2025).
2. Bevan, R. Baldur's Gate 3 Has Sold 15 Million Copies. Available online: https://www.thegamer.com/baldurs-gate-3-sales-15-million-larian-losses/ (accessed on 4 June 2025).
3. Yin-Poole, W. Space Marine 2 Made Millions for Games Workshop, Now It's on the Hunt for the Next Big Warhammer Video Game-IGN. IGN. Available online: https://www.ign.com/articles/space-marine-2-made-millions-for-games-workshop-now-its-on-the-hunt-for-the-next-big-warhammer-video-game (accessed on 4 June 2025).
4. Owlcat Games. Pathfinder: Wrath of the Righteous. Available online: https://wrath.owlcat.games/news/72 (accessed on 4 June 2025).
5. Dollosa, S. How Much Money Did Baldur's Gate 3 Make?-gamer.org. TheGamer. Available online: https://www.gamer.org/how-much-money-did-baldurs-gate-3-make/ (accessed on 4 June 2025).
6. Valentine, R. Warhammer 40,000: Space Marine 2 Made Millions for Games Workshop, and Now it Wants More Hit Videogames: 'Clearly We Are Looking for the Next One' | PC Gamer. PC Gamer. Available online: https://www.pcgamer.com/games/third-person-shooter/warhammer-40-000-space-marine-2-made-millions-for-games-workshop-and-now-it-wants-more-hit-videogames-clearly-we-are-looking-for-the-next-one/ (accessed on 4 June 2025).
7. MacCallum-Stewart, E. 'You'Re Going To Be Amazing': The Mercer Effect and Performative Play in Dungeons & Dragons. In *Fifty Years of Dungeons & Dragons*; Sidhu, P., Carter, M., Zagal, J.P., Eds.; The MIT Press: Cambridge, MA, USA, 2024; pp. 121–140. [CrossRef]
8. Ardacious Pty Ltd. Ardent Roleplay Augmented Reality App-Ardent Roleplay. Available online: https://ardentroleplay.com/ (accessed on 3 September 2025).
9. Nathan. Tool or Gimmick? Augmented Reality and Tabletop-Arkenforge Tabletop. Arkenforge. Available online: https://arkenforge.com/tool-or-gimmick-augmented-reality/ (accessed on 3 August 2025).
10. The World Wide Web Consortium (W3C). Web Content Accessibility Guidelines (WCAG) 2.1. Available online: https://www.w3.org/TR/WCAG21/ (accessed on 18 September 2025).
11. The World Wide Web Consortium (W3C). XR Accessibility User Requirements. XR Accessibility User Requirements. Available online: https://www.w3.org/TR/xaur/#xr-user-needs-and-requirements (accessed on 29 October 2025).
12. Huynh, D.-N.T.; Raveendran, K.; Xu, Y.; Spreen, K.; MacIntyre, B. Art of defense. In *ACM SIGGRAPH Symposium on Video Games*; Association for Computing Machinery (ACM): New York, NY, USA, 2009; pp. 135–142. [CrossRef]
13. CATAN GmbH. Welcome to the World of CATAN | Home | CATAN. Available online: https://www.catan.com/ (accessed on 9 October 2025).
14. Molla, E.; Lepetit, V. Augmented reality for board games. In Proceedings of the 9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010-Proceedings, Seoul, Republic of Korea, 13–16 October 2010; pp. 253–254. [CrossRef]
15. Rizov, T.; Djokic, J.; Tasevski, M. Design of a Board Game With Augmented Reality. *FME Trans.* **2019**, *47*, 253–257. [CrossRef]
16. StayInFront Inc. 3D and Augmented Reality Product Visualization Platform | Augment. Available online: https://www.augment.com/ (accessed on 11 September 2025).
17. Nilsen, T. Tankwar-AR games at GenCon Indy 2005. In Proceedings of the ACM International Conference Proceeding Series, Singapore, 6–11 November 2005; Volume 157, pp. 243–244. [CrossRef]
18. ARToolKit. Available online: https://www.hitl.washington.edu/artoolkit/ (accessed on 10 September 2025).
19. Gen Con LLC. Gen Con Indy 2005 Information | FanCons.com. Available online: https://fancons.com/events/info/1246/gen-con-indy-2005 (accessed on 10 September 2025).
20. Dolce, A.; Nasman, J.; Cutler, B. ARmy: A study of multi-user interaction in spatially augmented games. In Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops, Providence, RI, USA, 16–21 June 2012; pp. 43–50. [CrossRef]
21. Chen, M.F. Game products: Innovative pathways for nursing education and clinical training. *J. Nurs.* **2024**, *71*, 4–5. [CrossRef]
22. Asai, K.; Takase, N. Learning molecular structures in a tangible augmented reality environment. *Int. J. Virtual Pers. Learn. Environ.* **2011**, *2*, 1–18. [CrossRef]
23. Ahayalimudin, N.A.; Ahmad Jais, S.I.I. The Use of Augmented Reality in Tabletop Exercise for Disaster Preparedness Training: A Descriptive Abstract. *Disaster Med. Public Health Prep.* **2024**, *18*, e255. [CrossRef]
24. Al Mahmud, A.; Mubin, O.; Octavia, J.R.; Shahid, S.; Yeo, L.; Markopoulos, P.; Martens, J.B. AMAZEd: Designing an affective social game for children. In Proceedings of the 6th international Conference on Interaction Design and Children, IDC 2007, Aalborg, Denmark, 6–8 June 2007; pp. 53–56. [CrossRef]
25. Mirrorscape Inc. Mirrorscape. Available online: https://www.mirrorscape.com/ (accessed on 27 October 2025).
26. Tilt Five Inc. Tilt Five | AR Made to Crowd Around. Available online: https://www.tiltfive.com/ (accessed on 27 October 2025).

27. PolyDemons. The RPG Engine | Polydemons. Available online: https://www.polydemons.com/the-rpg-engine (accessed on 28 October 2025).
28. Tabletopia. Tabletopia Website. Available online: https://tabletopia.com/ (accessed on 29 October 2025).
29. Lazerbrazier Studios. Realm's Crossing. Available online: https://store.steampowered.com/app/3148940/Realms_Crossing/ (accessed on 29 October 2025).
30. /r/TiltFive. Reddit. Available online: https://www.reddit.com/r/TiltFive/ (accessed on 29 October 2025).
31. Google LLC. Google Translate—Apps on Google Play. Available online: https://play.google.com/store/apps/details?id=com.google.android.apps.translate&hl=en_GB (accessed on 6 June 2025).
32. Lee, I.J.; Lin, L.Y.; Chen, C.H.; Chung, C.H. How to Create Suitable Augmented Reality Application to Teach Social Skills for Children with ASD. In *State of the Art Virtual Reality and Augmented Reality Knowhow*; IntechOpen: London, UK, 2018. [CrossRef]
33. LeGoff, D.B. Use of LEGO© as a therapeutic medium for improving social competence. *J. Autism Dev. Disord.* **2004**, *34*, 557–571. [CrossRef] [PubMed]
34. Wu, Q.; Wang, W.; Liu, Q.; Zhang, R.; Pai, Y.S. Augmented tabletop interaction as an assistive tool: Tidd's role in daily life skills training for autistic children. *Int. J. Hum. Comput. Stud.* **2025**, *202*, 103517. [CrossRef]
35. Wu, Q.; Xu, R.; Liu, Y.; Lottridge, D.; Nanayakkara, S. Players and Performance: Opportunities for Social Interaction with Augmented Tabletop Games at Centres for Children with Autism. *Proc. ACM Hum. Comput. Interact.* **2022**, *6*, 161–184. [CrossRef]
36. Vick, B. Designing for Accessibility at Roll20. Roll20 Blog. Available online: https://blog.roll20.net/posts/designing-for-accessibility-at-roll20/ (accessed on 26 September 2025).
37. Miss Avacyn. Roll20 Community Corner #3. Roll20 Blog. Available online: https://web.archive.org/web/20170418013359/https://blog.roll20.net/post/159579651315/roll20-community-corner-3 (accessed on 26 September 2025).
38. Roll20 Forum-Accessibility Search. Roll20 Forum. Available online: https://app.roll20.net/forum/search?q=Accessibility&c= (accessed on 26 September 2025).
39. Dave (Forum User). Community Forums: Accessibility Question: Macro to Whisper All the Items in a Sheet's Repeating Section? | Roll20: Online Virtual Tabletop. Roll 20 Forum. Available online: https://app.roll20.net/forum/post/11343897/accessibility-question-macro-to-whisper-all-the-items-in-a-sheets-repeating-section (accessed on 26 September 2025).
40. Cora. Accessibility Enhancements | Foundry Virtual Tabletop. FoundryVTT Website. Available online: https://foundryvtt.com/packages/accessibility-enhancements (accessed on 26 September 2025).
41. Puyuelo, M.; Higón, J.L.; Merino, L.; Contero, M. Experiencing Augmented Reality as an Accessibility Resource in the UNESCO Heritage Site Called 'La Lonja', Valencia. *Procedia Comput. Sci.* **2013**, *25*, 171–178. [CrossRef]
42. Rocha, S.; Lopes, A. Navigation based application with augmented reality and accessibility. In Proceedings of the Conference on Human Factors in Computing Systems-Proceedings, Honolulu, HI, USA, 25–30 April 2020. [CrossRef]
43. Google LLC. Use Live View on Google Maps-Android-Google Maps Help. Available online: https://support.google.com/maps/answer/9332056?hl=en&co=GENIE.Platform=Android (accessed on 11 June 2025).
44. Rashid, Z.; Melià-Seguí, J.; Pous, R.; Peig, E. Using Augmented Reality and Internet of Things to improve accessibility of people with motor disabilities in the context of Smart Cities. *Future Gener. Comput. Syst.* **2017**, *76*, 248–261. [CrossRef]
45. Wulandari, D.; Rochim, R.A.; Cahyani, S. Validation Results of Augmented Reality Media on Climate Change and Analysis of Students' Prior Knowledge on Global Warming Material in the 'Kurikulum Merdeka'. *Stud. Learn. Teach.* **2024**, *5*, 638–652. [CrossRef]
46. Abad-Segura, E.; González-Zamar, M.D.; la Rosa, A.L.-D.; Cevallos, M.B.M. Sustainability of educational technologies: An approach to augmented reality research. *Sustainability* **2020**, *12*, 4091. [CrossRef]
47. Álvarez-Nieto, C.; Álvarez-García, C.; Parra-Anguita, L.; Sanz-Martos, S.; López-Medina, I.M. Effectiveness of scenario-based learning and augmented reality for nursing students' attitudes and awareness toward climate change and sustainability. *BMC Nurs.* **2022**, *21*, 245. [CrossRef] [PubMed]
48. Ferreira-Santos, J.; Pombo, L. The Art Nouveau Path: Promoting Sustainability Competences Through a Mobile Augmented Reality Game. *Multimodal Technol. Interact.* **2025**, *9*, 77. [CrossRef]
49. Negi, S.K. Exploring the impact of virtual reality and augmented reality technologies in sustainability education on green energy and sustainability behavioral change: A qualitative analysis. *Procedia Comput. Sci.* **2024**, *236*, 550–557. [CrossRef]
50. Strada, F.; Lopez, M.X.; Fabricatore, C.; dos Santos, A.D.; Gyaurov, D.; Battegazzorre, E.; Bottino, A. Leveraging a collaborative augmented reality serious game to promote sustainability awareness, commitment and adaptive problem-management. *Int. J. Hum. Comput. Stud.* **2023**, *172*, 102984. [CrossRef]
51. Wang, K.; Tekler, Z.D.; Cheah, L.; Herremans, D.; Blessing, L. Evaluating the effectiveness of an augmented reality game promoting environmental action. *Sustainability* **2021**, *13*, 13912. [CrossRef]
52. Verstraete, E.L.; Kuo, S.; Adams, N.; Zachwieja, A.J. Embodying the impact of climate change for decision makers using augmented reality (AR): A case study of climate-threatened cultural heritage sites in Western Alaska. *Environ. Sci. Policy* **2025**, *171*, 104178. [CrossRef]

53. Scope 1, 2, and 3 Emissions Explained | CarbonNeutral. Carbon Neutral. Available online: https://www.carbonneutral.com/news/scope-1-2-3-emissions-explained (accessed on 12 September 2025).
54. Hasbro, I. Impact Report. Hasbro Reports. 2024. Available online: https://csr.hasbro.com/en-us/reports (accessed on 15 September 2025).
55. Mattel Inc.; Citizenship | Mattel, Inc. Corporate Mattel-Citizenship. Available online: https://corporate.mattel.com/citizenship (accessed on 12 September 2025).
56. Games Workshop Limited. Environment | Games Workshop Group PLC | Investor Relations. Games Workshop-Environment. Available online: https://investor.games-workshop.com/environment?utm_source=chatgpt.com (accessed on 12 September 2025).
57. Spin Master Ltd. Spin Master Ltd.Corporate Social Responsibility—2023 CSR Report. Spinaster-Corporate Social Responsibility. Available online: https://csr.spinmaster.com/csr-news/2023-csr-report (accessed on 12 September 2025).
58. The Lego Group. Sustainability Statement. Reporting-Sustainability-Lego.com. 2024. Available online: https://www.lego.com/en-gb/sustainability/reporting?locale=en-gb (accessed on 12 September 2025).
59. Greenhouse Gas Protocol. Scope 2 Guidance | GHG Protocol. GHG Protocol Scope 2 Guidance. Available online: https://ghgprotocol.org/scope-2-guidance (accessed on 12 September 2025).
60. Zeff, M. Apple Vision Pro Sales Are so Weak that Apple Is Already Slashing Its Forecasts. Quartz-Tech & Innovation. Available online: https://qz.com/apple-vision-pro-sales-forecasts-analyst-1851431280 (accessed on 15 September 2025).
61. Singh, N.; Ogunseitan, O.A. Disentangling the worldwide web of e-waste and climate change co-benefits. *Circ. Econ.* **2022**, *1*, 100011. [CrossRef]
62. Leroux, F. How annual smartphone upgrades impact the environment. Android Police. Available online: https://www.androidpolice.com/environmental-impact-annual-smartphone-upgrades/ (accessed on 15 September 2025).
63. Knight, S. How Often Do People Upgrade Their Phone? (2023 Statistics)-SellCell.com Blog. Sellcell. Available online: https://www.sellcell.com/blog/how-often-do-people-upgrade-their-phone-2023-statistics/ (accessed on 15 September 2025).