Virtually Lost in Learning

Improving Navigational Efficiency in Virtual Reality Leads to Enhanced Learning

The research reported in this thesis was funded by the European Union's Horizon 2020 research and innovation program under grant agreement No 732599, the REVEAL project, and conducted at Utrecht University and, partially, Sheffield Hallam University.

Printed by Boekendeal.nl

Virtually Lost in Learning

Improving Navigational Efficiency in Virtual Reality Leads to Enhanced Learning

Vrijwel Verloren in Leren

Verbetering van de Navigatie-Efficiëntie in Virtual Reality Leidt tot Verbeterd Leren

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. Henk Kummeling, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op maandag 14 maart 2022 des ochtends te 10:15 uur.

door

Christopher Ferguson

geboren op 11 September 1992,
te Ashington, Verenigd Koningkrijk

Promotor:	Prof.dr. R.C. Veltkamp
Co-promotor:	Dr. E.L. van den Broek

This thesis was (partly) accomplished with financial support from the European Union's Horizon 2020 research and innovation program under grant agreement No 732599, the REVEAL project.

Dit proefschrift werd mede mogelijk gemaakt met financiële steun van het onderzoeks en innovatieprogramma Horizon 2020 van de Europese Unie onder subsidieovereenkomst nr. 732599, het REVEAL project.

To Maximus Powell Ferguson (AKA Max Power),
May you go through life as your name suggests.

"Playtime is precious. Play builds brain pathways for thinking, creativity, flexibility, empathy and many other lifelong skills" - Heather Shumaker

Contents

Acknowledgments

Firstly, I would like to express my sincere gratitude to my co-promotor dr. dr. Egon L. van den Broek for the continuous support of my research, patience, motivation, and vast technical knowledge. His guidance pushed me to keep going through the hard times, where there were long periods of writing and exhausting periods of practical work. I could not have asked for a better advisor and mentor. My sincere thanks also goes to dr. Herre van Oostendorp, whose psychological knowledge was of great help throughout this research, as well as my masters students, Sam de Redelijkheid and Ioannis Fermanis. I'd also like to thank Prof. dr. Remco Veltkamp for his support through this process and send a special thank you to Sjoerd Welcker for assisting me with Dutch translations.

Moving closer to home, I'd like to thank my parents, Marie and Trevor, for their support over the years, along with my brother, Andrew, his wife, Val, and my grandparents, Margery, Dave, Winnie, and Jack. I'm also grateful for all the headspace I got on long walks with our pets Denzil, Oscar, and Freddie.

My journey started in Sheffield, where I completed a five-year sandwich course: MComp Games Software Development. I'm immensely appreciative to the teaching staff, who helped me to succeed in a topic that I was extremely passionate about. This includes, but not limited to: Jake Habgood, Mark Featherstone, Pascale Vacher, Adrian 'Scranner' Oram, and Paul Parry. I'd also like to mention some of my classmates that made big contributions, especially in group work, namely: Nick Edwards, Luke Evans, and Lucy Child. In my fourth year of this programme, I was also honoured to live with incredible people such as: Nefyn Roberts, Andrew Weir, Thaer

Killiani, Jasmine Thomas, and Anna Nichols. Their presence made that year of university one to remember and I look forward to the next reunion.

During my course at Sheffield Hallam, I was given an incredible opportunity to live abroad in Germany for a year. That year was spent living in Reutlingen with many great friends, namely Matt Flexman, Calie Dickey, Joe Smallwood, Julia Österlund, and Alejandro Campos, who were always around for a cup of tea, a beer..and even a Döner! I was immensely privileged to spend half of this year working at the Max Planck Institute for Biological Cybernetics in Tübingen. I am indebted to my colleagues, namely: Florian Soyka, Better Mohler, Markus Lehrer, and Joachim Tesch, for enabling me to connect with my huge passion for VR and game research and starting me off on my journey towards this PhD, including my first published article.

On the subject of Germany, I feel it is appropriate to pay tribute to my late German teacher, Mr. Gary Frankland. Mr. Frankland was a caring teacher and always knew how to motivate his students, whilst showing respect and kindness. He is one of the reasons why I wanted to live in Germany and also why I planned to return. Ultimately, I ended up a few kilometres short and ended up in the Netherlands! Although my German language competency has faded, the skills he taught me helped me to learn Dutch instead and settle in the Netherlands.

In the Netherlands, I have been fortunate to meet many fantastic people, who were a welcome distraction outside of work. A lot of these people frequented O'Leary's Irish Pub in Utrecht. Incredible people such as owner Adrian Cuddy, Tom Lewis, Rob den Tuinder, Jamie Hulme, Matt Burke, Megan Tregoning, Alan Longmuir, Michael Fletcher, Orlagh Cuddy, Anna Hulme, and many more were a great source of laughs and helped to drain away the stress. Through O'Leary's I also ended up joining Rugby Club Nieuwegein and would like to thank all of my teammates for teaching me that Monday mornings are always better when you've put your body on the line the day before. Unfortunately, for much of 2020 and 2021, both the pub and rugby were unavailable to me. Fortunately, lockdown was made much more bearable with many trips into Verdansk with my teammates, such as Grant Marais, Alex Smith, Laura Cullen, Chris Watts, Adam Griffiths, Dave Ravenscroft, Jobie Warner, and Ben Krige.

One final person I would like to thank is Gabrielle Thomas. In the time that I've known Gabrielle, I have never met someone so supportive and caring. Not only did she keep me going through the difficult periods, which seemed to consist of non-stop writing and analysis, as well as keeping me company through the lockdowns, she also helped me improve my life significantly and blessed me with a wonderful home and family. Not only is she responsible for us having our beautiful Bernese Mountain Dog, Winnie, who helps break up my working day with long walks and playtime, she also gave me a handsome baby boy Max, whose smile is the first thing I see when I return home from a long day at work. I don't think I'd have got this far if it wasn't for you, Gabs. Thank you so much.

CHAPTER 1

Introduction

This chapter contains elements from the following publication:

Habgood, J., Moore, D., Alapont, S., Ferguson, C. & Oostendorp, H. van, “The reveal educational environmental narrative framework for playstation vr”, in: *Proceedings of the 12th European conference on games based learning*, ed. by Ciussi, M., Sophia Antipolis, France: Academic Conferences and Publishing International Limited, 2018, pp. 175–183

"A growing body of research has begun to reveal that video and computer games have tremendous educational value."
Kapp (2007)

"Captain's personal log. I'm entering the ship's holodeck, where images of reality can be created by our computer. Highly useful in crew training, highly enjoyable when used for games and recreation" says Captain Jean-Luc Picard (Tormé, 1988). It's the late 90s and Star Trek: The Next Generation is being shown on repeat on BBC 2 with Patrick Stewart playing Captain Picard. I am sitting with my Dad watching it on a CRT TV and thinking of the fun I would have with the so-called holodeck and if there was a chance of it existing in the future.

It's now 2020 and, in some aspects, it appears that nothing has changed. The now Sir Patrick Stewart is still playing the same character. Although, this is a new show, set further down the line. It's also not being shown on a television channel, which fewer and fewer people are viewing. The screen is also not the same bulky CRT screens that were once ubiquitous yet now rarely seen. Although society nowadays often tries to reboot old shows and rely on old ideas, technology moves forward. Captain Picard might still be here but this new Star Trek show is being shown on Amazon Prime, an online streaming service, viewed on flat-screen TVs and mobile phones, which are probably as large as the mobile phones that existed in the 90s but without buttons and consisting of a large screen. Technology has moved on but is the holodeck no longer fiction?

The use of video games for recreation is now a big part of many people's lives. In the USA alone more than 214 million people play video games for one hour or more per week (Association, 2020). This includes 64% of U.S. adults and 70% of those under 18. But, are these games 'highly useful in crew training', as the holodeck was described? Nowadays, the use of games outside of their traditional use is becoming more mainstream with video games being used for teaching and training. These serious games range from subject-related educational games used in classrooms and higher education to training and simulation games for industrial applications (Göbel et al., 2010). Not only is the development of these games increasing every year, so are the number of organizations adopting these for staff training (Torrente et al., 2009).

According to Westra et al., 2009, "serious games are applications developed with

Figure 1.1: A PlayStation VR head-mounted display.

game technology and game design principles for non-entertainment purposes, including games used for educational, persuasive, political, or health purposes". The quality of such games is measured in how they encourage the player to perform certain actions, how well they can motivate the player, and how the experience contributes towards a player's learning goals (Brusk et al., 2007). The advantage of using game technology for learning is that games can capture the concentration of players for long periods, providing realistic and compelling challenges (Bellotti et al., 2010). The use of games in education is not a new concept. Even as far back as 1938, Johan Huizinga put forward the view that the playing man, the homo ludens, develops abilities through play. Although, initially, the fixation that children had with these games alarmed both parents and educators alike, educational researchers soon focused on harnessing this technology to enhance knowledge, skills, and other personal attributes (Shute et al., 2017).

However, it takes more than games to recreate a holodeck, including providing an environment with full immersion, the physical feeling of being in a virtual space achieved by multi-sensory modalities (i.e. sound and vision) to surround the user, which is fully interactive, so the user can modify the environment and receive feedback according to their actions (Carrozzino & Bergamasco, 2010).

Due to the increasing level of computing power available to mainstream users and the substantial reductions in hardware prices, a Head-Mounted Display (HMD) for use with Virtual Reality (VR) (see Figure 1.1) has become a commercially off-the-shelf, general low-cost, electronic device (Arnaldi et al., 2018). This has led to VR-presented serious games becoming more prominent in educational settings Merchant et al., 2014. Moreover, VR is also used successfully across many different industries for information acquisition and skill improvement; for example, in surgery Thomsen et al., 2017, evacuation training Feng et al., 2018, the military van Doesburg et al., 2005, and education Newbutt et al., 2020.

VR allows a user, whilst wearing an HMD, to feel present within a computer-generated virtual environment, creating a parallel environment that is both immersive and interactive (Maples-Keller et al., 2017). There are three core aspects of visual perception for VR applications (Meijer, 2011):

- High-quality graphics: This increases a human's sense of realism. This is particularly important for novice users.
- Level of Detail (LoD): This improves a human's sense of depth.
- Stereoscopic displays (e.g., HMDs): These facilitate precise manual interactions with objects. This is especially useful when a VR represents a small-scale space.

The added immersion caused by VR has many advantages, namely a better experience in the form of greater presence (Schuemie et al., 2001), improved engagement (van den Broek, 2012), and higher cognitive interest (Parong & Mayer, 2018).

Presence (i.e., player's feeling being physically present in the game (Slater, 2002), is often mentioned as a key component of VR and is caused by immersion resulting in the perception of the presented virtual environment as real (Slater & Usoh, 1993). The terms presence and immersion are sometimes confused. Immersion refers to the level of sensory fidelity, whereas presence is a psychological response of a user (Berkman & Akan, 2019). Presence is shown to increase enjoyment (Tussyadiah et al., 2018)). It is also noted to be an indirect influence that aids learning outcomes in games (Lee et al., 2010). On the one hand, the added presence has been found to lead to increased learning (Alhalabi, 2016; Passig et al., 2016; Webster, 2016). On the other hand, this same feeling of presence in VR was observed with reduced learning performance (Makransky et al., 2019; Moreno & Mayer, 2002; Richards & Taylor, 2015).

Engagement (i.e., heightened concentration, interest, involvement, and enjoyment (Kim, 2018)) catalyzes learning (Abdul Jabbar & Felicia, 2015; Imlig-Iten & Petko,

2018) and has also been found to be positively affected using VR (Flavián et al., 2020). This is particularly true when compared to traditional learning or a video (Allcoat & Mühlenen, 2018; Parong & Mayer, 2018).

Finally, we can look to cognitive interest (i.e., understanding topics and becoming more interested (Harp & Mayer, 1997)), which serves as intrinsic motivation to explore and experience new and unfamiliar things (Van der Sluis et al., 2014). This is of particular importance to VR environments that a user must explore in order to learn. Again, VR leads to higher levels of cognitive interest (Chang et al., 2019; Parong & Mayer, 2018; Zhao et al., 2020).

As shown by the positive effect of VR on these three elements, the added immersion and interaction provided by VR has the potential to enable players to fully experience a new scenario. Nevertheless, compelling content, in the form of a strong storyline, is needed to provide this additional immersion (Biggin, 2017; Ryan, 2015) In fact, immersive educational linear narratives combined with immersive VR technology have been found to be successful for both learning and experience (Calvert & Abadia, 2020). As such, the increased immersion of VR makes it perfect for users to experience a strong and powerful story, making it the perfect candidate for environmental storytelling(Wiederhold, 2018).

Game designers Smith and Worch offer a working definition of environmental storytelling as a “staging player-space with environmental properties that can be interpreted as a meaningful whole, furthering the narrative of the game" (2010, p.15). A key genre of game that suits this definition is narrative-centered discovery games.

Narrative-centered discovery games, which have considerable learning potential (Kee, 2011; Mortara et al., 2014), combine the learning affordances of two distinct game genres: narrative-centered games and discovery games. Narrative-centered games provide a strong narrative through powerful, emotive storylines, often presented auditorily (Habgood et al., 2018a) and been found to provide a motivating, engaging, and organized learning experience (Dickey, 2006; Lee et al., 2006; Lester et al., 2014; Marsh, 2010). In discovery games, players freely explore the virtual environment within the game with minimal guidance whilst solving problems (i.e. completing in-game tasks and discovering useful items) (Kriz, 2010; Toh & Kirschner, 2020). This takes a constructivist approach, where players actively construct representations of reality by linking new information to prior knowledge (Toh & Kirschner, 2020). Combining both of these game genres results in a self-directed learning experience that, which promotes ‘cognitive curiosity’ Malone & Lepper, 1987, making use of intrinsic motivation (Toh & Kirschner, 2020), where a player performs an activity for its own sake or enjoyment without reward (Liao et al., 2019), and has been found to lead to higher learning outcomes (Habgood & Ainsworth, 2011). In narrative-centred discovery games, players are transported to another place and time period and must explore the environment to discover items and hear audio narratives that reveal the in-game story (Lester et al., 2014; Malone & Lepper, 1987) (see Figure 1.2). This stimulates players to construct appropriate mental models (Furlough & Gillan, 2018; Wasserman & Banks, 2017).

Figure 1.2: Examples of exploring a VR narrative-centered discovery game and finding items.

More recently, focus has shifted to the use of these types of games in cultural heritage, which includes historical monuments and locations that have exceptional historic, scientific, or social value (Corbeil, 2011; Vecco, 2010) for the accurate reconstruction of historical sites and events (Hanes & Stone, 2019). The use of VR is also encouraged due to its benefits of presenting lost or damaged artifacts and interacting with a previous time period (Bekele et al., 2018; Gonizzi Barsanti et al., 2015; Slater & Sanchez-Vives, 2016).

VR serious games have been consistently found to lead to increased retention of spatial knowledge (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010), knowledge constructed from observations gathered whilst traveling through an environment (Kuipers, 1978), however, the level of retention for story knowledge, knowledge constructed from a story a person has been told or experienced (Schank & Abelson, 1995), does not always point in this direction (An et al., 2018; Fowler, 2015; Huang et al., 2019; Makransky et al., 2019; Mikropoulos & Natsis, 2011). Perhaps such narrative-based discovery games, which involve exploration could be key to unlocking the full potential of VR.

Often, VR games make use of a variety of different locomotion systems compared to traditional free movement, such as (Habgood et al., 2018b). In an empirical study, node-based movement, where locations are defined by game designers for players to jump to (Habgood et al., 2018b). Moreover, this movement system has additional advantages. From a performance perspective, it removes the need for computationally expensive collision detection by limiting the position of a player. Moreover, this also enables the guiding and controlling of the players' attention through the game (Habgood et al., 2018b), which is of vital importance for knowledge transfer in games.

Node-based movement is very similar to the node-link used in hypertext systems. Because of the similarity in navigation between a game using a node-based movement system and a hypertext system, along with the fact that both systems feature rich information spaces and encourage exploration, it can be argued that, when carrying out information-searching tasks, actions across both systems are remarkably similar. As such, it can be argued that analytics and measures used for assessment in hypertext systems are also usable in these types of serious VR games. In fact, node-based movement is used in a variety of commercial VR games, such as Batman Arkham VR (Rocksteady Studios, 2016), Chronos (Gunfire Games, 2016), Dead Secret (Robot Invader, 2015), and the critically-acclaimed Half Life: Alyx (Valve, 2020), so such analytics may also have a commercial benefit.

Analytics are a vital part of serious games and a research area of high interest since such measures enable educators to measure learning performance, which can also be communicated to the developers, this can be used to real-time feedback or even assist a player, along with allowing an educator to adapt their teaching strategy (Hendrix et al., 2019; Shute et al., 2017; Zook & Riedl, 2015).

The problem with common approaches when developing analytics for serious games is that they often try and find patterns using log analysis and data mining, which are not appropriate for more-complex educational games (Minović et al., 2015). Moreover, some game analytics make use of existing tools for this data analysis (Liu et al., 2015; Minović et al., 2015; Serrano-Laguna et al., 2012), which are not tailored to educational games and do not allow for real-time analysis.

This mass collection of shallow interaction data (Perez-Colado et al., 2018), which is then mined is then not correctly aligned with the mental operations a player needs to carry out in building an adequate mental model to effectively complete a task (Furlough & Gillan, 2018). Instead, game analytics should be developed based on cognitive analysis of the in-game tasks. Nevertheless, in recent years, development in this area has improved, with the introduction of educational analytical dashboards for players to examine their performance post-play to find ways to improve (Seaton et al., 2019). However, these were limited and, again, did not offer the functionality to monitor players in real-time.

Recently, research has focused on real-time node-link visualizations, which may be relatable to games using a node-based movement system. For example, both Wallner & Kriglstein, 2014 Andersen et al., 2010 visualized game states as color-coded nodes. This is interesting as the concept of explicit encoding makes use of node trees. Although neither of these publications focused on serious games, they underline the benefit of using node-link visualizations to provide powerful data analysis yet allow for easy readability. Such analytics are also extremely versatile so they can be applied to many different games. As such, hypertext usability measures should indeed be examined to determine if they would be instrumental for providing appropriate serious game analytics.

One such area where appropriate analytics could focus on is navigational efficiency (i.e. how efficiently a user completes a goal (i.e. finding information), in terms of taking the shortest path by visiting the minimum number of locations without revisiting the same locations multiple times (Smith, 1996). This is because navigating through complex virtual environments challenging and lead to disorientation, where players lose their sense of location and direction (Conklin, 1987; Head et al., 2000). Disorientation occurs when navigation is too much of a cognitive burden and leads to cognitive overload (Gwizdka & Spence, 2007), i.e. an excessive amount of load placed on a person's working memory when carrying out a task (Chen, 2016). This is rooted in cognitive load theory, which states that there are a finite amount of working memory resources that are used for cognitive processing (Sweller et al., 2011). Exceeding these results in cognitive overload. In narrative-based discovery games, navigation is part of the learning process so navigation problems leading to disorientation have a negative effect on learning (Sweller et al., 2011).

Altogether, there are three types of cognitive load identified: intrinsic, which is associated with the complexity of the task, extraneous, which is related to the way that the task is presented, and germane, which is produced by processing and constructing schemas to handle new information for learning new skills (Sweller et al., 2011). Intrinsic and germane cognitive load are part of the learning process, and it can be assumed that navigational efficiency represents extraneous cognitive load, as it is related to the presentation of the task itself.

In this respect, navigation can be considered as extraneous cognitive load, which is recommended to be reduced (Sweller et al., 1998) So, one way of avoiding cognitive overload disrupting the learning process would be to make use of adaptivity. Adaptivity is defined as "adjustments which improve the individual player experience" (Lopes & Bidarra, 2011). So, an adaptive system within a narrative-based discovery game, measuring the navigational efficiency of a player, could be used to adapt the game difficulty to the proficiency of players to assist them before cognitive load is too high, players become overloaded, or become too heavily loaded, and their learning is negatively affected.

So, going back to the initial question, is the holodeck no longer fiction? Almost. As the visual quality of HMDs improve (Coburn et al., 2017) and omnidirectional treadmills and haptic feedback devices mature (Hooks et al., 2020), the holodeck is quickly becoming reality. In fact, a world representing another popular work of fiction, Ready Player One (Cline, 2011), looks to be on the horizon. Nevertheless, research has shown that many choices must be made when developing serious games for VR to realize optimal learning. Therefore, this thesis aims to investigate the effects that VR narrative-based discovery games have on learning and the type of experience that a player has and how they can be better designed to provide an optimal learning experience for players. This concerns:

i. Virtual Reality
ii. Narrative-Centred Discovery Games
iii. Story Knowledge
iv. Spatial Knowledge
v. Navigational Efficiency
vi. In-Game Experience Aspects:
    - Presence
    - Engagement
    - Cognitive Interest,

which will be discussed over four chapters with a conclusion.

Firstly, to be able to effectively investigate VR, and serious games in general, it must be ensured that these games are developed appropriately along with relevant analytics to improve the development of these games as well as assess how well players are performing. Chapter 2 details the importance of stories in video games, particularly serious games, with respect to educational goals. It presents a dashboard, the Story Scaffolding Dashboard (SSD), which provides real-time visual analytics to track and evaluate the presence of a story within the game. This dashboard is also used to provide further real-time visual analytics for assessing player performance in serious games. This includes an implicit measure, Lostness, which enables assessment of a player's navigational efficiency as they complete tasks in the game.

Building on this chapter, which used the SSD to ensure that an educational game featured a strong story, Chapter 3 investigates the effect that a game presented in VR has on learning, for both story and spatial elements. The in-game experience of a player (i.e. their engagement, presence, and cognitive interest) is also evaluated. This chapter also makes use of the Lostness measure, for measuring navigational efficiency, introduced in the previous chapter, to investigate the effect of VR on this variable. This is important as the effect of serious game presented in VR compared to the same game presented in non- VR is not well known and the literature sometimes provides conflicting results. In this regard, it was found that navigational efficiency and spatial knowledge were higher in VR, yet there was no difference for story knowledge or the in-game experience of players.

As the main result that only spatial knowledge showed improvement in VR compared to non- VR, the next step, taken in Chapter 4, is to investigate which elements of serious VR games lead to better learning to identify how to presenting content within a game for optimal learning. Due to the nature of narrative-centered discovery games, two elements are investigated: story structure, the main aspect of narrative-centered games, and freedom of navigation, the main aspect of discovery games. These elements are evaluated with respect to learning, for both story and spatial elements, and the in-game experience of a player (i.e. their engagement, presence, and cognitive interest). Interestingly, it is shown that an implicit story structure, compared to an explicit structure, has no effect on story knowledge but can also increase already highly-retained spatial knowledge. When it comes to navigation, replacing free navigation with a guided tour, despite having no effect on spatial knowledge, leads to an improvement in story knowledge. This is at the detriment to the in-game experience, however, in the form of lesser presence and cognitive interest. This result is explained by introducing the Zone of Proximal Development (ZPD), which puts forward that learners can carry out easier tasks independently, reach a point of optimal learning with guidance, and then struggle to complete more difficult tasks even with guidance (Vygotsky, 1978, p. 86). This is in line with cognitive load theory (Sweller et al., 2011). It can be proposed that freely navigating a VR narrative-centered discovery game without guidance can be too difficult for some players (i.e., cognitive overload, cognitive load that is too high) yet too easy when they are fully guided through the game (i.e., cognitive underload, cognitive load that is too low). In this regard, it is shown that removing the cognitive burden of navigation leads to increased retention of story knowledge with the disadvantage of a lesser in-game experience, which may indicate being in the lower area of the ZPD and experiencing cognitive underload. The results of this chapter show that it is necessary to investigate if providing appropriate guidance when necessary can lead to optimal learning without a lesser in-game experience.

The findings that full guidance whilst navigating in VR serious games has on both learning ans in-game experience, along with the other results obtained throughout previous chapters is used, in Chapter 5, to develop an adaptive system to ensure that all players receive a personalized experience in a VR serious game. This system ensures players are at the optimal level of challenge necessary for effective learning by using the Lostness measure to assess the navigational efficiency of players and provide appropriate guidance depending on their performance. Lostness data is used to determine the specificity of keywords used to describe in-game items that must be found to complete tasks and progress further throughout the game. This personalized experience leads to experience lower levels of cognitive load by ensuring that players are in the correct area of the ZPD and leads to enhanced retention of both story and spatial knowledge, without the drawback of a reduced in-game experience.

Chapter 6, the Conclusion, summarizes and discusses the findings of all chapters and, accordingly, forms the epilogue of this thesis. This will deliver a roadmap towards the future of VR serious games and how they can effectively be used to provide the best immersive learning experience for all.

With that, to once again quote Captain Picard, engage.

CHAPTER 2

The Storyline Scaffolding Dashboard: Serious Game Analytics through Connected Story and Gameplay Graphs

Abstract - Stories are considered essential in serious game development. However, often there is a sub-optimal match between the initial story and the final game and no tools/dashboards are available to relieve this. To solve this omission, we developed the open-source cross-platform Storyline Scaffolding Dashboard (SSD) for serious games. The SSD uses explicit encoding to relate story and gameplay tree graphs and as such serves two groups of stakeholders: i) game developers who can assess and, subsequently, improve their game's story completeness, and ii) educators who can assess players' performance in real-time and adapt their teaching strategy accordingly. Two initial formative user studies confirmed the SSD's potential to aid in the advancement of serious games' capabilities.

This chapter is based on the following publication:

Ferguson, C., van Oostendorp, H. & van den Broek, E. L., "The development and evaluation of the storyline scaffolding tool", in: *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, Sept. 2019, pp. 1–8, DOI: `10.1109/VS-Games.2019.8864538`

which is based on an extended, fully rewritten manuscript, which is currently under review.

"The only thing it takes to sell toys, vitamins, or magazines is the power of story"
Harris (2014)

2.1 Introduction

It has been proposed that narrative-centered games make use of environmental storytelling and provide rich storylines to increase immersion (Biggin, 2017; Ryan, 2015) top provide a successful learning experience (Calvert & Abadia, 2020). Consequently, some game studios employ a dedicated team of story writers and designers in the design phase. Traditionally, story design takes place well in advance of game development and is often not fully implemented by the development team (Bethke, 2002; Howitt, 2015). Major problems arise when parts of the story are missing from the game. A game-story mismatch can have grave implications for serious games, as educational goals can be absent, leading to costly and time-consuming re-teaching (Wallner & Kriglstein, 2015). To avoid problems and requiring 'narrative paramedics' (Pratchett, 2012), consistent connections between the story and gameplay are necessary.

Many tools exist that facilitate the design and development of in-game stories. These allow to i) create playable multiple-choice stories (Leinonen & Munroe, 2014; Twine, 2009), ii) act as programming languages (Nelson, 1993), and iii) support full story organization into separate chapters with images, plans, and a journal (Literature & Latte, 2007). Techniques from the motion picture industry are also adopted, such as speculative scripts and storyboards (Wood, 2015), which provide an overview of the in-game flow of events and interactions (Rankin et al., 2011). However, a support tool that secures the connections between story and gameplay is non-existent, which we remedy in this article. Using 'explicit encoding' and node tree graphs, we will connect story and gameplay explicitly (see Fig. 2.1). Explicit encoding provides a compact, high-level overview of the gameplay and story, displaying these as tree graphs, with links between nodes across both tree graphs explicitly visualized (Gleicher et al., 2011; Holten & Wijk, 2008). Throughout the development process, this allows a game designer to assess how the story is represented in the game by creating these links as development progresses.

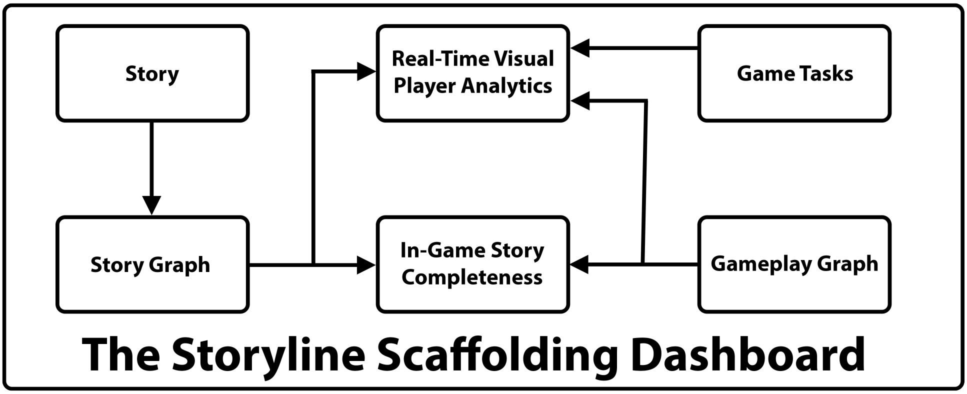


Figure 2.1: Framework of the Storyline Scaffolding Dashboard.

Additionally, this can be built upon, inspired by existing node-link visual analytics identified in the Introduction (Chapter 1) (Andersen et al., 2010; Wallner & Kriglstein, 2014) to provide learning analytics to assess players' progress, performance, and learning outcomes whilst the game is being played. Giving this support to educators is necessary to ensure the use of serious games in educational settings.

As detailed in the Introduction (Chapter 1), learning analytics represent data about learners with the aim of improving learning by allowing educators to track players through the game and assess their learning performance (Clow, 2013; Shute et al., 2017). They are often collected through game logs, which contain the activities a player has performed (Schwendimann et al., 2017). For this rich data to be both readable and meaningful, so that an educator to fully understand player behavior and provide an accurate assessment, learning analytics must be presented through visualizations (Sutherland et al., 2012).

Consequently, learning dashboards, defined as "a single display that aggregates different indicators about learner(s), learning process(es) and/or learning context(s) into one or multiple visualizations" (Schwendimann et al., 2017, p.37), have grown in popularity in recent years (Schwendimann et al., 2017) and have been found to lead to positive effects, such as increasing learning performance and assisting educators (Auvinen et al., 2015; Shoufan et al., 2015).

Most learning dashboards collect learning analytics through game logs, which contain the activities a player has performed (Schwendimann et al., 2017). For this rich data to be both readable and meaningful, so that an educator to fully understand player behavior and provide an accurate assessment, learning analytics must be presented through visualizations (Sutherland et al., 2012). This is a key feature of learning dashboards. However, visualizations present in many learning dashboards are identical to other dashboard applications, such as web analytics (i.e. simple charts and graphs), with a lack of visualizations tailored towards learning (Schwendimann et al., 2017). Moreover, in some implementations, visualizations are only available afterward with no functionality for real-time analysis (Alonso-Fernandez et al., 2017; Seaton et al., 2019).

Another problem with existing learning dashboards is that they often do not use a full learning model or fully assess in-game behavior, which is common with many game frameworks and analytics (Calvo et al., 2016; Knobbout & Van Der Stappen, 2020; Mangaroska & Giannakos, 2019; Matcha et al., 2020; Minović et al., 2015; Reese et al., 2015; Schwendimann et al., 2017). For accurate player assessment in games, learning dashboards should provide a full learning model along with analytics based on information-processing characteristics indicative of learning, namely focusing attention on the correct location and accessing the relevant information from memory (Furlough & Gillan, 2018).

To provide the necessary features for the appropriate development of serious games and accurate player assessment, we present a dashboard to provide analytics for assessing in-game story completeness and real-time assessment of a player whilst learning. This serves two groups of stakeholders:

1. Game Developers: The relationship between gameplay and story (in-game story completeness) is quantatively and visually expressed so can be monitored throughout development.

2. Educators: During gameplay, node-based performance metrics provide insight into player performance. This enables educators to assess learning performance, which can also be communicated to the developers, and also allows an educator to adapt their teaching strategy (Shute et al., 2017).

Our novel open-source cross-platform Storyline Scaffolding Dashboard (SSD) presented in Section 2 (see Fig. 2.1), is an improved iteration upon the Storyline Scaffolding Tool (SST) (Ferguson et al., 2019), designed to provide serious game analytics by tracking in-game story completeness and evaluating in-game player behavior. In Section 2.3, we discuss two formative user studies that assess both the SSD's main functionalities. We close in Section 2.4 with a concise discussion.

2.2 Storyline Scaffolding Dashboard (SSD)

In this section, we introduce our open-source cross-platform SSD, which is available, including source code, at `https://www.gamecomponents.eu/content/732/storyline-scaffolding-dashboard`. This section will provide its theoretical framework, implementation, and usage.

2.2.1 Theoretical Framework

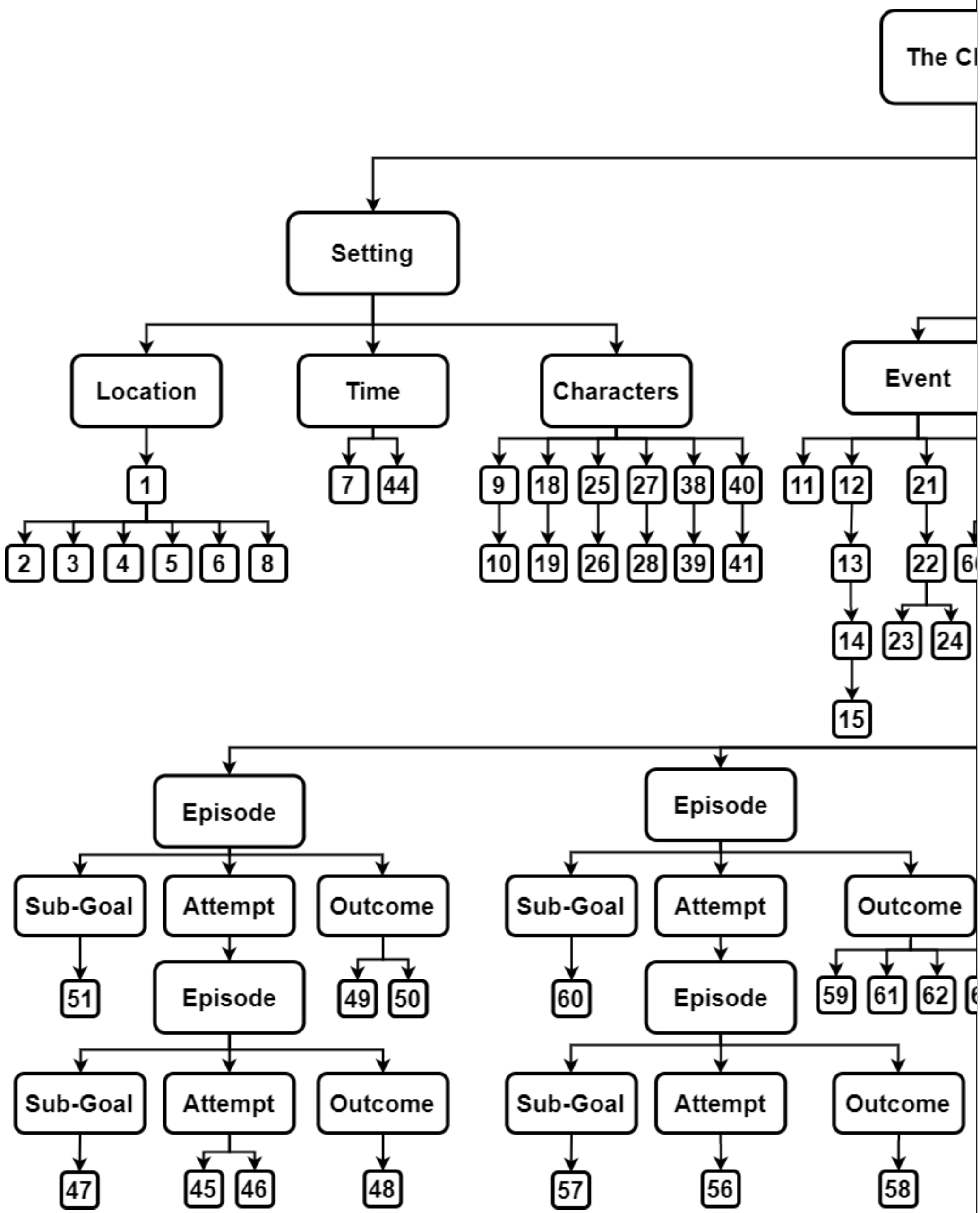
The main functionality of the SSD is centered around explicit encoding. This involves expressing the story and gameplay as node tree graphs and visualizing links between both graphs to assess in-game story completeness (see Fig. 2.1).

Story Grammar Theory (SGT) provides a hierarchical representation of how a story unfolds (Cunningham, 2019; Elman & McRae, 2019; Thorndyke, 1977). To our knowledge, this has not been used within game development before. SGT defines a story (such as the one defined in List 2.1) into four main parts: setting, theme, plot, and resolution, which are then split into more sections, using 10 available rules (Thorndyke, 1977). For example, setting consists of characters, location, and time and the plot consists of episodes that contain attempts, outcomes, and a subgoal (see Fig. 2.2). This leads to the story graph.

For the gameplay, a behavior tree graph (gameplay graph) is used. This is a hierarchical and directional structure, commonly used in major games and game engines, that represents the flow of game events (behavior) and the events that need to be carried out to unlock later events (Robertson & Watson, 2015). Therefore, the SSD can be used with a wide variety of different games without modification, and developers can create links between the gameplay and story, which the SSD will visualize, to track in-game story completeness.

1. The Chantry
2. is a country house,
3. in Berkeley
4. near to the River Severn in the county of Gloucestershire, England.
5. It stands between Berkeley Castle and the church
6. and was originally built as housing for priests.
7. In 1823,
8. it was the home to a physician and widower
9. called Edward Jenner.
10. Jenner also had a second home in Cheltenham.
11. Jenner's main work was on birds and cuckoos
12. yet him and his colleagues carried out many interesting experiments,
13. which scared a lot of people,
14. including improving grass growth using human blood
15. and launching balloons.
16. Jenner turned his attention to the study of smallpox
17. after observing that dairymaids appeared to be protected from smallpox after having suffered from cowpox.
18. He was told this by Sarah Nelmes
19. a milkmaid.
20. Cowpox resembles a mild form of smallpox.
21. Smallpox is a horrifying disease
22. which killed 1 in 5 people who caught it
23. and scarred and/or blinded many others.
24. It affected both rich and poor people.
25. Queen Mary II of England
26. was killed
27. and Beethoven and Mozart
28. were left scarred
29. Some people couldn't live with the terrible scarring and took their own lives.
30. Once someone had had smallpox they couldn't get it again.
31. Smallpox scars were an asset to servants seeking employment as it showed they couldn't bring the disease into a household.
32. Jenner was immune to smallpox
33. as he went through the process of inoculation when he was younger.
34. Inoculation involved deliberately infecting someone with smallpox by scratching pus from a smallpox scar into their bloodstream
35. This induced a milder form of smallpox which most people survived
36. and gave them future immunity to the disease.
37. Inoculation was used in Africa and Turkey before it came to Europe and America.
38. Lady Mary Wortley Montagu
39. brought the practice of variolation to England from Turkey
40. The Reverend Cotton Mather
41. brought inoculation to The Americas after being taught the practice by an African slave,
42. however, other preachers regarded the process as sinful.
43. Jenner took the practice one step further by using an inoculant which came from a related non-fatal disease (cowpox).
44. In 1796,
45. Jenner extracted the pus from cowpox lesions on a milkmaid's arm
46. and scratched this onto the arm of an 8-year old boy called James Phipps
47. to see if this made him immune to smallpox.
48. James developed mild fever, but quickly recovered.
49. Eight weeks later Jenner injected James with pus from a fresh smallpox lesion.
50. No disease developed
51. and Jenner concluded that Phipps was now protected against smallpox.
52. Jenner was working at the time of the Napoleonic Wars between Britain and France
53. but still helped the French people
54. and was held in high regard by Napoleon,
55. who spent thousands of francs promoting vaccination throughout his empire.
56. Jenner submitted a paper describing the experiment to the Royal Society
57. to share his work
58. but was rejected.
59. Jenner privately commissioned a booklet to publish his "Inquiry"
60. to show the public
61. but it received a mixed reaction from the medical community.
62. Jenner received widespread ridicule,
63. particularly from other members of the medical profession.
64. Despite this, the British Parliament eventually granted Edward Jenner a grant of £10,000 for his smallpox research
65. In later years, Jenner was known to entertain guests in the drawing room,
66. hosting musical parties,
67. reciting poetry,
68. and settling questions.
69. Jenner made no personal attempt to enrich himself through his discovery,
70. which saved many millions of lives worldwide
71. and would eventually lead to the eradication of one of mankind's most horrific diseases.
72. The smallpox virus was finally eradicated in 1980 following a global immunisation campaign led by the World Health Organisation.

List 2.1: The story of The Chantry game. The numbers correspond to the numbers on the story graph in Fig. 2.2.


The Cl
Setting
Location
Time
Characters
Event
1
7
44
9
18
25
27
38
40
11
12
21
2
3
4
5
6
8
10
19
26
28
39
41
13
22
14
23
24
15
Episode
Episode
Sub-Goal
Attempt
Outcome
Sub-Goal
Attempt
Outcome
51
Episode
49
50
60
Episode
59
61
62
Sub-Goal
Attempt
Outcome
Sub-Goal
Attempt
Outcome
47
45
46
48
57
56
58

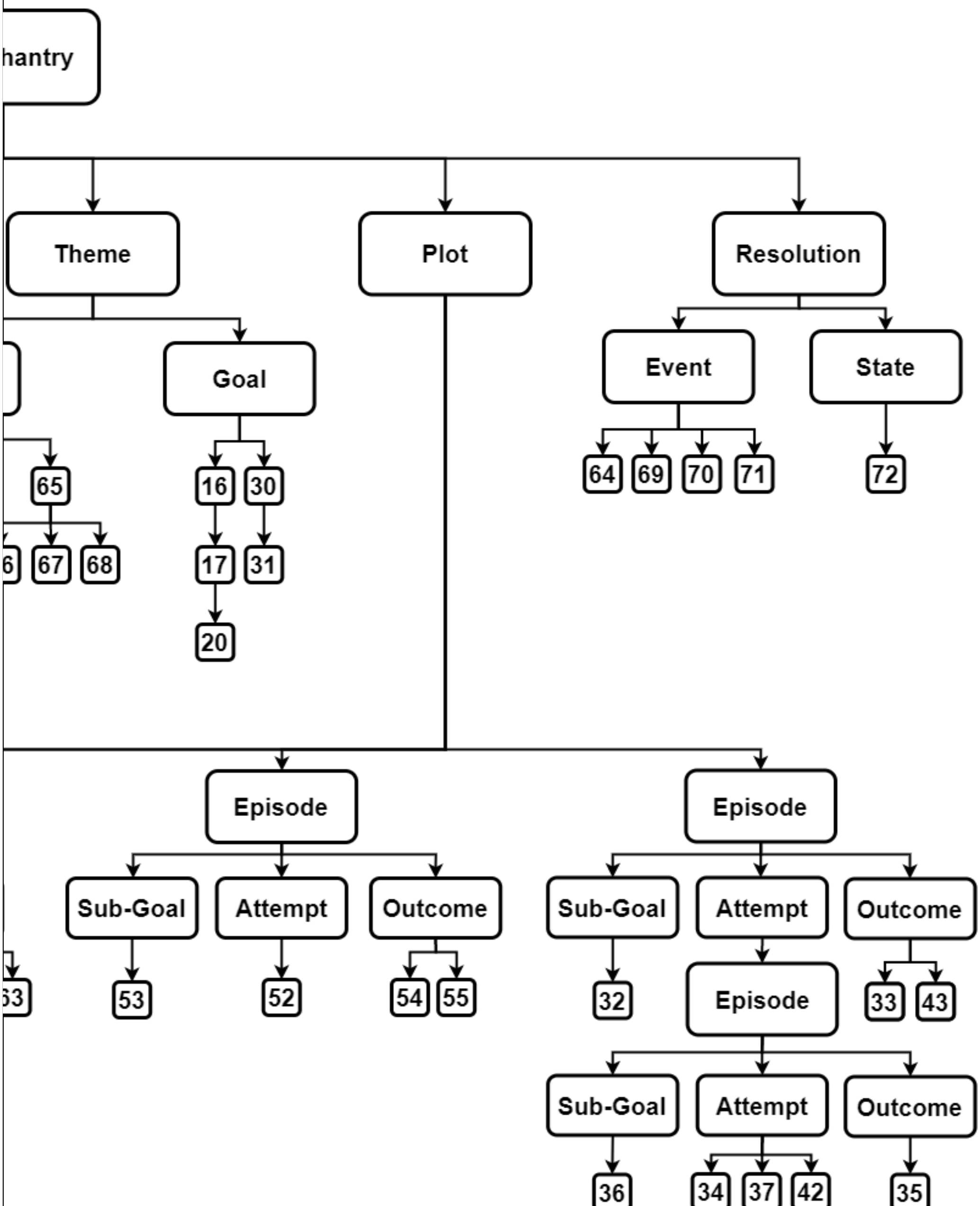


Figure 2.2: A game's story graph according to the Story Grammar Theory (SGT) (Elman & McRae, 2019; Thorndyke, 1977). The numbers represent a sentence from the story in List 2.1.

Moving on to player analytics, specifically appropriate performance metrics and visualizations for accurate player learning assessment (Shute et al., 2017). In the Introduction (Chapter 1), it was proposed that node-based movement in serious games is very similar to the node-link used in hypertext systems, which means that analytics and measures used for assessment in hypertext systems are also usable in these types of serious VR games. Moreover, it was also proposed that navigational efficiency (i.e. how efficiently a user completes a goal) could be an area to focus on, particularly in discovery games, where it it necessary to explore the in-game environment to find useful items and complete learning objectives. This is due to disorientation causing high levels of cognitive load, ultimately leading to cognitive overload, which can hinder learning. Therefore, for measures of in-game performance, we include progress and navigational efficiency. Progress simply considers the number of learning objectives that the player has completed (i.e. items that they have found). Navigational efficiency can be quantified using the lostness measure (Smith, 1996), which originates from hypertext. For a given task, the lostness (L) is defined as follows:

$$\sqrt{\left(\frac{N}{S}-1\right)^2+\left(\frac{R}{N}-1\right)^2}, \tag{2.1}$$

where R is the minimum number of steps needed to be made, S is the total number of steps a player has made, and N is the number of unique steps a player has made. A low lostness value indicates high navigational efficiency and a high value indicates low navigational efficiency (Smith, 1996). This is a highly versatile measure that can be used in any activity that can be defined in a minimum number of steps (R) and the path that a user/player/person taken can be measured to provide S and N.

For example, at the start of a game, a player goes towards a door to start a task and goes there directly, taking three steps, giving a lostness value of 0 ($R = 3, S = 3, N = 3 : L = 0$). To find the first item, which requires four steps to be taken, the player briefly goes the wrong direction, taking one extra step, then turns around and finds the item, which results in a lostness value of 0.2 ($R = 4, S = 5, N = 4 : L = 0.2$). The second and final item to be found to complete the task requires five steps to be taken. Unfortunately, the player gets lost before finding it, leading to a lostness value of 0.653 ($R = 5, S = 17, N = 12 : L = 0.653$).

Progress bars were chosen to visualize these performance metrics, as they allow quantitative data to be easily visualized and understood quickly (Myers, 1985). Moreover, a label was added to each progress bar to give additional quantitative information (Reese et al., 2015). These progress bars are shown for tasks, learning objectives (i.e. items to be found), and the overall game. Finally, an additional dialog is provided, which visualizes a player's navigational efficiency over time.

To ensure maximum compatibility with serious games, the SSD makes use of the recent the Realising an Applied Gaming Ecosystem (RAGE) project, which developed an open source infrastructure to deploy learning analytics for serious games (Serrano-Laguna et al., 2017). Part of this project is the Serious Games Interaction Model (SGIM). This is based on xAPI, which is a commonly-used online learning standard for expressing learner interactions through actor-verb-object-datetime statements (e.g. Player started task1 at 12-10-2020 15:07:21) (Serrano-Laguna et al., 2017). This makes it possible to collect data about a wide range of experiences a person has within a serious game. These statements are often stored in an online Learning Record Store (LRS) database, which can be queried later (Serrano-Laguna et al., 2017). This allows for learning data integration, which allows the comparison of learning data from a multitude of learning activities, and is not often considered by other learning dashboards (Schwendimann et al., 2017).

Within learning dashboards, the following types of six learning indicators have been identified, which give the following information (Schwendimann et al., 2017):

- Learner-related indicators - Information about learners.
- Action-related indicators - Actions performed by learners,
- Content-related indicators - Content learners interacted with
- Result-related indicators - The outcome of learners' activities.
- Context-related indicators - The context where the learning took place.
- Social-related indicators - How learners interacted with others.

The SSD provides four of these indicators. Although it does not give information about learners themselves and does not provide information on interactions with others, it does provide action-related indicators, in the form of the SGIM logs, content and context-related indicators through the lighting up of the story and gameplay graphs, and result-related indicators in the form of task information and lostness.

2.2.2 Technical Implementation

Publications on learning dashboards do not often make clear the technology used to build them (Schwendimann et al., 2017). In contrast, to allow for the SSD to be understood, as well as adaptable for specific needs, we will provide this information as well as making it freely-available and open-source. The SSD is built around ZodiacGraph (Sielaff, 2015), a node tree Graphical User Interface (GUI) module for Qt, a toolkit for developing cross-platform applications. It is written in C++11. The SSD can be deployed across Linux, macOS, and Windows. Code changes were tracked, using source control, and uploaded to GitHub.

Classes were provided to handle functionality for both graphs, including creating, editing, and specializing story and gameplay nodes, and, most importantly, handling the linking across both graphs (see Fig. 2.3, explained further in Box 2.1). To allow the user to create links, a dialog was developed where a gameplay node could be selected, along with the appropriate story node(s) to be linked. A sidebar was developed to show in-game story completeness measures, such as the number of story and gameplay nodes with and without connections (see Fig. 2.3, Box 2.1).

The SSD's player analytics module, making use of RAGE and SGIM, distinguishes three phases:

1. Interaction collection: The SSD receives time-stamped game interaction data over Transmission Control Protocol (TCP) in SGIM format from the RAGE analytics platform;

2. Real-time and batch analysis: The data from phase 1 is printed in raw form at the bottom of the SSD (see Fig. 2.3, Box 2.1) and saved to a log file as real-time and batch analysis takes place; and

3. Visualization (see Fig. 2.3, Box 2.1): The game and story progression of a player are indicated by gameplay and story node colors. Performance metrics are visualized through progress bars; lostness over time is further detailed in an additional dialog.

An interaction collector was developed to manage the TCP connection and receive data from the game. A class for real-time and batch analysis was implemented that interprets messages from the game, analyzes them, and triggers events within the SSD, including visualizations, according to the messages received.

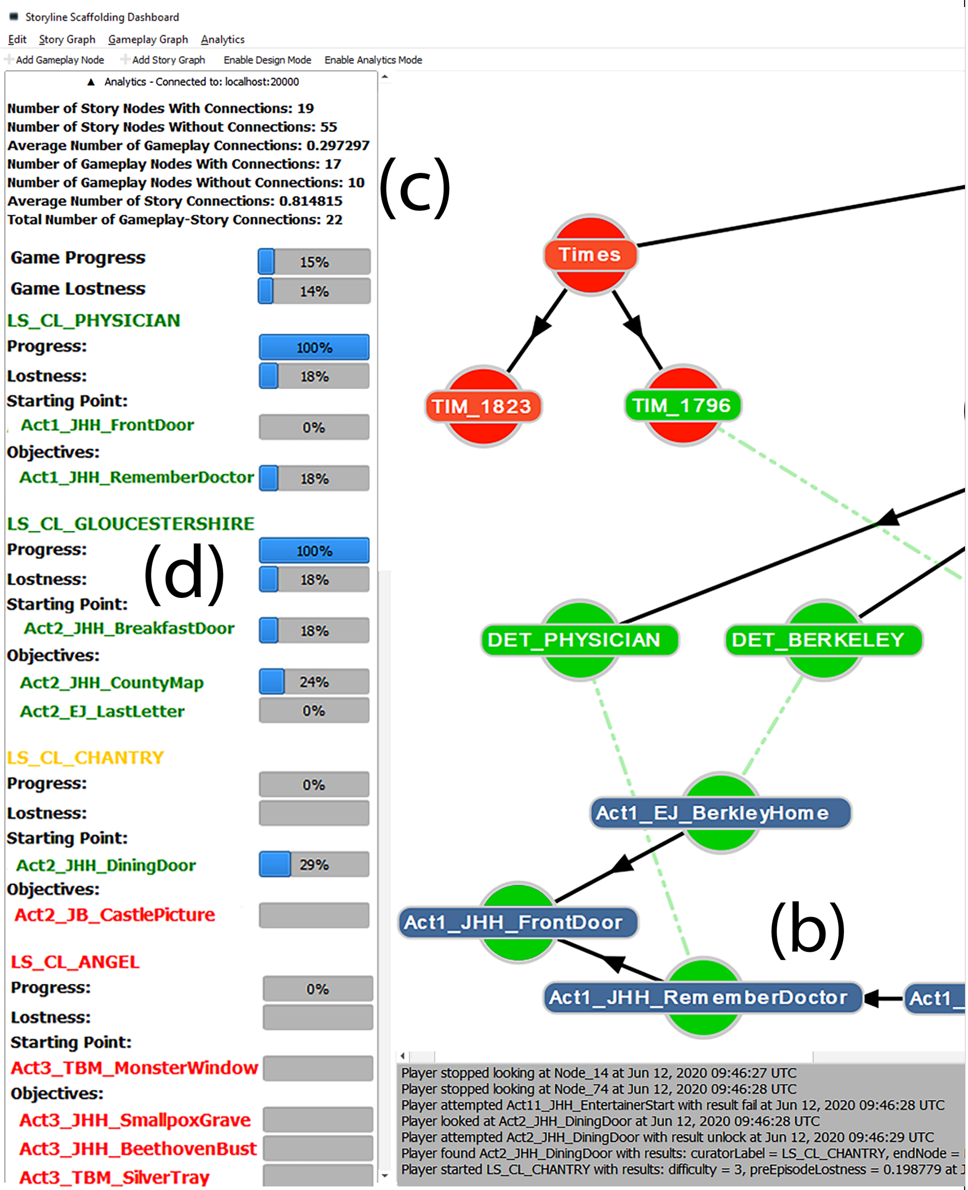
All files used in the SSD are saved in JavaScript Object Notation (JSON) format, a highly readable file format. This included the story and gameplay graphs, the task and objective information, and the log files consisting of player-game interactions. Functionality for exporting and importing these log files was added to the SSD to enable the review of play sessions at a later time.

2.2.3 Usage

As was indicated at the end of the Chapter 1 Introduction, the SSD's functionality serves two groups of stakeholders: game designers and educators. They can make use of the SSD as follows:

- Game Designers: The SSD allows a story or game designer to manually create, edit, and delete nodes for both the story and gameplay graphs to streamline game development throughout the development process. Options are shown to create and delete nodes, with the sidebar used to edit nodes. To create links between nodes to be visualized through explicit encoding, the user of the SSD right clicks on a node and selects the link option. This shows a dialog with a list of nodes. By selecting these nodes and clicking on save, the dialog closes and the links are created. The completeness measurements in the sidebar are also updated.

- Educators: The SSD enables real-time visual analytics to assess player performance and learning. This is realized by loading information on the in-game tasks and connecting to an SGIM server running on the game. When the interaction collector receives an interaction from the game, this interaction is collected and analyzed. A log file is written to and saved concurrently. The educator can choose to load this file into the SSD at any time to review the results.



Storyline Scaffolding Dashboard
Edit Story Graph Gameplay Graph Analytics
Add Gameplay Node
Add Story Graph
Enable Design Mode
Enable Analytics Mode
Analytics - Connected to: localhost:20000
Number of Story Nodes With Connections: 19
Number of Story Nodes Without Connections: 55
Average Number of Gameplay Connections: 0.297297
Number of Gameplay Nodes With Connections: 17
Number of Gameplay Nodes Without Connections: 10
Average Number of Story Connections: 0.814815
Total Number of Gameplay-Story Connections: 22
Game Progress
15%
Game Lostness
14%
LS_CL_PHYSICIAN
Progress:
100%
Lostness:
18%
Starting Point:
Act1_JHH_FrontDoor
0%
Objectives:
Act1_JHH_RememberDoctor
18%
LS_CL_GLOUCESTERSHIRE
Progress:
100%
Lostness:
18%
Starting Point:
Act2_JHH_BreakfastDoor
18%
Objectives:
Act2_JHH_CountyMap
24%
Act2_EJ_LastLetter
0%
LS_CL_CHANTRY
Progress:
0%
Lostness:
Starting Point:
Act2_JHH_DiningDoor
29%
Objectives:
Act2_JB_CastlePicture
LS_CL_ANGEL
Progress:
0%
Lostness:
Starting Point:
Act3_TBM_MonsterWindow
Objectives:
Act3_JHH_SmallpoxGrave
Act3_JHH_BeethovenBust
Act3_TBM_SilverTray
(c)
(d)
(b)
Times
TIM_1823
TIM_1796
DET_PHYSICIAN
DET_BERKELEY
Act1_EJ_BerkleyHome
Act1_JHH_FrontDoor
Act1_JHH_RememberDoctor
Player stopped looking at Node_14 at Jun 12, 2020 09:46:27 UTC
Player stopped looking at Node_74 at Jun 12, 2020 09:46:28 UTC
Player attempted Act11_JHH_EntertainerStart with result fail at Jun 12, 2020 09:46:28 UTC
Player looked at Act2_JHH_DiningDoor at Jun 12, 2020 09:46:28 UTC
Player attempted Act2_JHH_DiningDoor with result unlock at Jun 12, 2020 09:46:29 UTC
Player found Act2_JHH_DiningDoor with results: curatorLabel = LS_CL_CHANTRY, endNode =
Player started LS_CL_CHANTRY with results: difficulty = 3, preEpisodeLostness = 0.198779 at

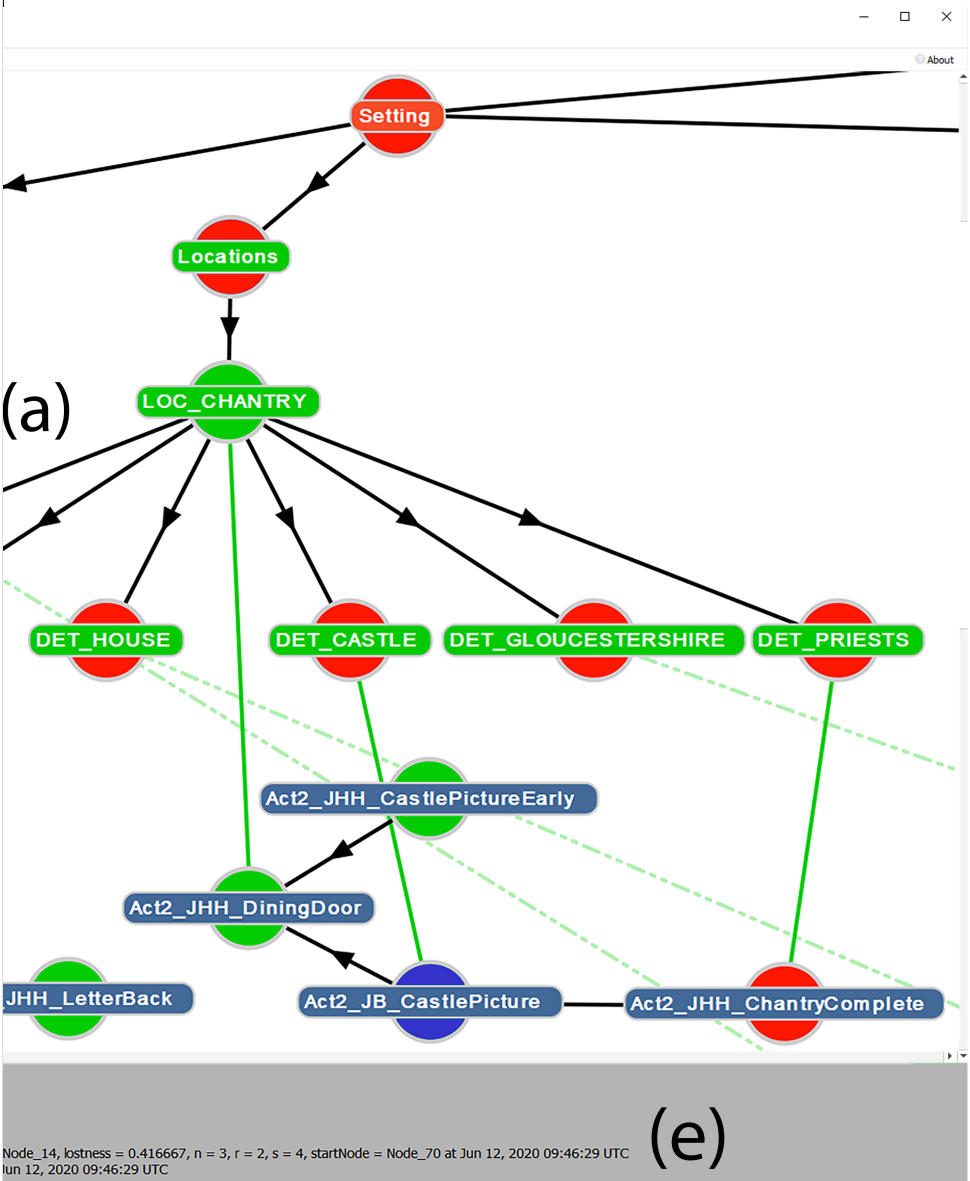


Figure 2.3: The Storyline Scaffolding Dashboard (SSD) interface in player analytics mode, including: (a) the story graph and (b) gameplay graph, including the connections between both graphs, as well as (c) quantitative measures of in-game story completeness and (d) player analytics in the sidebar, the (e) raw text log of in-game player interactions, and the (f) lostness graph.

Box 2.1 : Further Explanation of the SSD's Analytics as Shown in Fig. 2.2

(a)	– The story graph uses Story Grammar Theory to display each story element in a node tree graph format.
(b)	– The gameplay graph shows each event and the flow of the game in a node tree graph format.
(c)	– Quantitative measurements of in-game story completeness (e.g. number of linked nodes, number of connections, etc.) are displayed at the top of the sidebar
(d)	– Tasks and objectives (items), which are shown red when not started, yellow when in-progress, and green when completed. Progress bars show a player's progress and navigational efficiency (lostness).
(e)	– The text log prints raw in-game data as it is sent to the SSD.
(f)	– Graph showing real-time lostness of a player over time
	– Solid green lines represent gameplay-story links around the current player location in the gameplay graph.
	– Faded and dashed green lines represent gameplay-story links in all other areas of the game.
	– Black links represent story-story links and gameplay-gameplay links.
TIM_1796	– Green labels indicate that story content is included in the game.
TIM_1823	– Red labels indicate that story content is not included in the game.
Act2_JHH_ChantryComplete	– A red gameplay node indicates that it is locked.
Act2_JB_CastlePicture	– A blue gameplay node indicates it can be unlocked.
Act2_JHH_DiningDoor	– A green gameplay node indicates that it is unlocked.
TIM_1796	– A red story node indicates this story information has not been found.
LOC_CHANTRY	– A green story node indicates this story information has been found.

2.3 User studies

To assess the SSD's use for its two groups of stakeholders: game designers and educators, we have executed a formative user study for both groups. This is vital as a recent review of player-facing educational dashboards found that few articles on player-facing dashboards executed such a study, which can be detrimental as users may not use a system due to non-identified usability issues (Bodily & Verbert, 2017).

Study A evaluates the SSD's ability to assist a game designer in tracking in-game story completeness. As such, we assess the SSD's use to optimize game development and improve design and gameplay. Study B evaluates the SSD's ability to provide an educator with analytics to assess player performance and learning, whilst the game is being played.

In both studies, A and B, the Chantry (Steel Minions & the Jenner Trust, 2018), a serious game for the PlayStation VR platform was used. Both studies include 6 participants, which is likely to unveil most usability problems (Macefield, 2009; Nielsen, 1992); such a small sample is acceptable if the experimental evaluation is part of a more comprehensive validation strategy (al., 2020), as is the case here. Both studies made use of the SSD as described above.

2.3.1 Study A: Gameplay-Story Linking

4 experts participated: three programmers and a historian/story designer with prior knowledge of the game and story. Additionally, 2 novices participated: game technology students, without prior knowledge. Using two different groups allowed for evaluation from multiple perspectives, specifically the difference between participants familiar with the game, story, and development process and those that were not. Moreover, this group nicely represented one of the SSD's stakeholder groups: game designers.

SGT's rewrite rules were used to create the story graph from the initial story of the Chantry (see Fig. 2.2). This was presented to the participants with the story text and the unlinked story and gameplay graphs were loaded into the SSD. To determine what parts of the story were referenced in each gameplay node, videos of each node being unlocked were transferred to a tablet so game behavior could be viewed, whilst still being able to examine the SSD. They were then invited to go through each gameplay node and attempt to link each gameplay node to the appropriate story node(s). This would help assess how well users were able to create links between the story and gameplay graphs to visualize in-game story completeness and how usable the SSD was in this regard.

The following SSD calculations were made (also see Fig. 2.3):

1. Total number of connections – total number of connections between gameplay and story nodes overall;

2. The average number of connections per story node (story content referenced 0 or more times); and

3. Story graph completeness – the percentage of the story graph that is referenced in the game (nodes that have at least one connection to a gameplay node)

To get participants' specific opinions on usability-related aspects of the story graph, gameplay graph, linking, and the SSD, that could easily be processed, a custom usability questionnaire using 29 questions on a 5-point Likert scale (1: strongly disagree – 5: strongly agree) (Preston & Colman, 2000), 7 to 8 questions per topic. Examples of the questions asked are: "the story graph seems understandable", "the gameplay graph gives a good representation of the sequence of events in a game", "linking graphs make it easier to determine the presence of the storyline within the game", and "the GUI is inviting to use". The average of all questions related to each topic was used to get a reliable impression. The sessions ended with a short interview, allowing participants to formulate some afterthoughts and provide additional insights into the usability of the system (Wise et al., 2014).

Table 2.1: Mean Effectiveness (and Standard Deviations).

	All	Experts	Novices
Total number of connections (0-∞)	52.5 (20.9)	61.25 (19.94)	35.00 (8.49)
Connections per story node (0-∞)	0.89 (0.38)	1.05 (0.39)	0.59 (0.42)
Story graph completeness (0-1)	0.59 (0.35)	0.64 (0.34)	0.49 (0.14)

The results for the SSD's effectiveness are shown in Table 2.1. Interestingly, the mean total number of connections was 52.5, less than one connection per story node (i.e., 0.89), and the number of connections created by each participant varied considerably (standard deviation of 20.9). Moreover, there are large differences between novice participants and expert participants, particularly for the mean number of connections (35.0 vs 61.3) and completeness (49% vs 64%). Overall, on average, the completeness of the story within the game was only viewed as 59%.

Table 2.2: Usability Per Topic - Means (and Standard Deviations), with $\min - \max : 1 - 5$.

	All	Experts	Novices
Story Graph	3.84 (0.72)	3.93 (0.59)	3.64 (0.51)
Gameplay Graph	3.11 (0.70)	3.30 (0.55)	2.67 (0.71)
Linking	3.40 (1.12)	3.50 (1.18)	3.20 (0.40)
SSD's Design and Use	3.32 (0.93)	3.48 (1.00)	3.00 (0.57)

For the SSD's usability results, see Table 2.2. Overall, the participants appreciated the story graph, as shown by a mean score of 3.84. In all sections, experts gave slightly higher ratings than novices. For the novices, the gameplay graph was difficult to understand (2.67), likely because they lacked prior knowledge of the game. The linking topic received moderate scores, with all participants feeling the process could be improved and giving feedback. Finally, the SSD's GUI received unfavorable ratings from half of the participants, indicating that changes need to be made. All but one participant gave a favorable rating on the SSD's value for thoughtfully integrating educational content into a game.

In the interviews, participants expressed that the story graph clearly separated each part of the story and gave a clear idea of how all the information is linked together (e.g., information regarding protagonists or sequence of events to complete goals). One participant remarked that the SSD allows to easily check which story elements are included and this was backed up by another participant, who felt that some story nodes were missing, Importantly, one participant felt that the story graph seemed useful and logical but may hinder productivity as this will also need to be maintained, requiring time and effort. There were also remarks that the link process should be more intuitive, with a search bar as well as the option of seeing the descriptions of story nodes when linking. Finally, one participant felt that the SSD could be used by individuals who may not be technically inclined, a key aim.

2.3.2 Study B: Player Analytics

6 PhD-students on game research participated. Despite them not being educators, they were expected to give high-quality feedback due to their experience in working with and developing serious game analytics.

Using feedback from Study A, an updated, accurate, story text and graph, linked to the gameplay graph, were provided. Additionally, an annotated screenshot of the SSD was provided to explain the analytics.

To assess usability, an 8-item 5-point Likert questionnaire (Preston & Colman, 2000) was used. For further feedback, participants were asked additional questions, such as if they'd prefer the gameplay-story links be visible when in analytics mode, be removed, or only be visible in the area the player is currently exploring. The participants then examined the story text and graph along with the gameplay graph and links between both. Subsequently, for 15 minutes, they watched a live game playthrough and the SSD's representation of the received interaction data.

Finally, in a controlled order, participants were shown the final static data of 3 players and asked to rank the players' performance, taking into account the visualized nodes and performance metrics: progress and lostness. Once again, the session was ended with a short interview.

Table 2.3: Usability Per Question - Means (and Standard Deviations), with $\min - \max : 1 - 5$.

	All
The changing colors on the story graph were: (very unclear-very clear)	4.50 (0.54)
The changing colors on the gameplay graph were: (very unclear-very clear)	4.50 (0.54)
Following the player through the game was: (very difficult-very easy)	4.17 (0.75)
The story topics that the player was learning about were: (very difficult to understand-very easy to understand)	4.00 (0.63)
The game events that the player was interacting with were: (very difficult to understand-very easy to understand)	4.33 (0.82)
The lostness indicator bars made a player's navigational efficiency: (very difficult to understand-very easy to understand)	4.33 (0.82)
The progress indicator bars made a player's progress through different tasks: (very difficult to understand-very easy to understand)	4.17 (0.75)
The extra information provided by the text log was: (not useful at all-very useful)	3.17 (1.60)

The results on usability for player analytics in the SSD are presented in Table 2.3. All aspects were well-received, as shown by mean scores > 4, particularly when it came to the story and gameplay nodes changing color. These responses indicated how participants felt about tracking players through the game. For the additional performance metrics, the bars presenting lostness and progress were also perceived highly. The raw textual information shown in the log received mixed appreciation. Some participants found it helpful, whilst others did not even notice it.

For displaying gameplay-story links, no participant was in favor of removing them. 4 participants preferred making the story links clearer for the current area, by making these lines solid, compared to faded and dashed lines in other areas but 2 preferred having all links shown in the same way. This suggests an option should be added to the SSD to allow educators to choose where to show the links.

Despite the high usability scores, only half of the participants correctly ranked the players based on the output of the SSD. To gain insight into their choices, participants were asked to explain them in the interview. One participant admitted that they did not take into account the full game, leading to an incorrect ranking. Interestingly, two participants explained that they misunderstood a high lostness value as being efficient, rather than the opposite, so ranked the players in reverse order. Therefore, in future versions, the lostness bar will be inverted and labeled 'Navigational Efficiency', as well as having a different color to the progress bar, another interview suggestion, to avoid confusion. This should assist educators to better assess player learning and performance.

The interviews also revealed that participants appreciated the lostness and progress bars and that they enjoyed being able to see the player move through the gameplay graph. This confirms the SSD's potential.

2.4 Discussion

The open-source cross-platform Storyline Scaffolding Dashboard (SSD) was introduced to provide analytics for serious games to both game developers and educators. The SSD allows to both optimize game development and enables real-time assessment of player performance whilst learning, which allows educators to tailor their teaching strategy. So, the SSD is developed for the following two stakeholders:

- Game Developers: The SSD allows game designers, to create both a story graph, based on Story Grammar Theory (SGT) (Thorndyke, 1977), and a gameplay graph. Using the explicit encoding approach, both the story and gameplay are visualized as tree graphs with links shown between them (Gleicher et al., 2011; Holten & Wijk, 2008). This allows users to create links between the gameplay and story graph to enable the assessment of in-game story completeness: how much of the story is present in the game.

- Educators: The SSD can also be a valuable dashboard for educators as it provides real-time analytics to track players through the game. This can be applied for assessment, feedback, and player assistance (Shute et al., 2017).

A user study showed that the SSD is promising to assess story completeness and immediately showed its use. A large proportion of the initial in-game story was missing from a commercial game, the Chantry (Steel Minions & the Jenner Trust, 2018), indicated by participants only linking 59% of story nodes on average. This evaluation demonstrated that the SSD can unveil problems with in-game story completeness. Nevertheless, follow-up studies should be executed to apply the SSD during development

The Chantry's story was updated after the finding of low in-game story completeness and used, in the second user study, to assess the SSD's merit for educators. The participants indicated that the SSD provided good measures to assess player performance. Usability was judged very well (i.e., > 4, with max: 5) and 5 of the 6 participants ranked the players correctly once they fully understood the lostness measure. The usage of assets from RAGE, particularly SGIM, made it eligible for inclusion in RAGE's exemplary game components and tools inventory. This features game components to aid easier, faster, and more cost-effective creation of successful games.

It should be noted that the SSD is not limited to serious games, however, is limited to narrative-based games, as a story is required to build a story graph. On the other hand, the player analytics of lostness and progress, as well as the lighting up the gameplay nodes, can be used for all games where there are tasks, where items need to be found to complete learning objectives. So, the SSD can be valuable outside the educational domain as well. However, with regard to progress and lostness, care should be taken to ensure that the halting problem (Burkholder, 1987) does not occur. Likely, this will hardly be the case as most serious games have an optimal path and a reachable state, which allows unambiguous feedback and assessment. However, in regular games, this is not always the case.

The SSD can be extended in many ways. For example, we used a knowledge-based approach to assess in-game story completeness, however, formal graph matching algorithms can be included as well (Carletti et al., 2018). This would be complementary to the current approach and could enrich and perhaps automate the matching process. Moreover, player performance metrics can be extended easily as well. The two elements of the Lostness measure: uniqueness ($\frac{N}{S} - 1$) and directness ($\frac{R}{N} - 1$) are valuable by themselves (Smith, 1996).

As with all xAPI statements, SGIM-formatted interaction data can be stored in an online Learning Record Store (LRS) database (Serrano-Laguna et al., 2017), to be queried for later analysis. By including this functionality, further post-hoc analysis of saved player interaction data would be possible for multiple players, including on a group level, to unveil common strategies and issues. An LRS would also assist with monitoring multiple players simultaneously, which could lead to personalized lesson plans and tailored instruction based on game analytics (Gombolay et al., 2019). This could also allow for further learning data integration (Schwendimann et al., 2017). However, as with all learning data, ethics and data privacy are always a concern so care should be taken (Gursoy et al., 2017; Schwendimann et al., 2017)

Taken together, the open-source cross-platform SSD showed to have potential value for both game developers and educators. To the authors' knowledge, the SSD is unique with its foundation in SGT and knowledge-based graph matching. In both development and its usage, the SSD can significantly contribute to the advancement of the capabilities of serious games. Nevertheless, despite the number of participants being deemed sufficient for this kind of study (Macefield, 2009; Nielsen, 1992), care should be taken when generalizing the results of these studies due to the low sample size.

The SSD ensured that the story of a commercial game, the Chantry, was fully documented. This will assist with carrying out further evaluations on this game, particularly with regard to developing knowledge tests to assess learning. As such, using this game, the next chapter will use one of the measures developed as part of the SSD, lostness, to evaluate player performance in the Chantry in a VR experiences vs a non-VR experience.

CHAPTER 3

Virtual Reality Aids Game Navigation: Evidence from the Hypertext Lostness Measure

Abstract - Instead of traditional free movement, node-based movement can be used in Virtual Reality (VR) games. In node-based movement systems, players navigate by jumping to set locations. Node-based movement is similar to hypertext navigation. We show that the hypertext lostness measure can be used as a game analytic to evaluate navigational efficiency. In a randomized controlled trial with 25 adolescent participants, an immersive desktop game environment and a VR game environment were compared on the transmission of in-game educational content and navigational efficiency. Results show that the hypertext lostness measure is also valuable outside its original hypertext domain: in VR. Playing the game in VR did not improve players' retention of factual knowledge but did significantly improve players' spatial knowledge and navigation efficiency. We conclude: i) the hypertext lostness measure is also valuable for node-based VR games and ii) VR games add to spatial learning, even when compared with already immersive desktop games.

This chapter is based on the following publication:

Ferguson, C., Broek, E. L. van den, Oostendorp, H. van, Redelijkheid, S. de & Giezeman, G.-J., "Virtual reality aids game navigation: evidence from the hypertext lostness measure", *Cyberpsychology, Behavior, and Social Networking*, vol. 23, no. 9, 2020, pp. 635–641, DOI: 10.1089/cyber.2019.0435

"Why shouldn't people be able to teleport wherever they want?"

Luckey (2015)

3.1 Introduction

In the previous chapter, serious games were introduced, with emphasis on the importance of a well-designed and well-defined story as well as appropriate player analytics for assessing learning performance. Rapid increases in computing power and advances in technology have led to VR-presented serious games becoming more prominent in educational settings (Merchant et al., 2014) and as a means for storytelling (Wiederhold, 2018). Due to this growth, focus has shifted to the use of VR narrative-centered games due to their considerable learning potential (Kee, 2011; Mortara et al., 2014). These games provide a motivating, engaging, and organized learning experience (Adams et al., 2012; Dickey, 2006; Lee et al., 2006; Lester et al., 2014; Marsh, 2010) and is expected to lead to positive learning results, as focused attention and an increased affect during encoding have been found to enhance retention of information (Baddeley et al., 1984; Murdock, 1965; Parkin et al., 1982).

However, as previously mentioned, navigation in VR, which is a key part of narrative-centered games, can be overwhelming for its users (Darken & Sibert, 1993). This is due to the high cognitive load caused by navigation, which leads to cognitive overload, causing users to lose their sense of location and direction (i.e. disorientation) (Conklin, 1987; Head et al., 2000). Cognitive overload is common in VR, (Andersen et al., 2016a; Andersen et al., 2016b; Makransky et al., 2019) and leads to inhibited learning (Sweller et al., 2011), as a user simultaneously devotes limited cognitive resources to both navigation and comprehension (Bolter, 2000; Sharples, 1999).

As presented in the Introduction (Chapter 1), node-based movement is where players move between predefined positions (Habgood et al., 2018b). This makes navigation similar to navigating hypertext systems, responsive node-based systems with branches leading to text and other media (Barnet, 2019). Although disorientation and cognitive load are still an issue when it comes to navigating these systems (Conklin, 1987; Head et al., 2000), measures are available to identify this. Lostness (Smith, 1996), the hypertext measure introduced in Chapter 2 has shown to be successful in predicting success in information-seeking tasks in hypertext (Herder, 2003; McEneaney, 2001; Otter & Johnson, 2000) can also be used in VR games that use a node-link approach, due to the similarity in process and structure.

VR narrative-centered games involve two types of knowledge: story knowledge, which is constructed from a story a person has been told or experienced (Schank & Abelson, 1995), and spatial knowledge, which is constructed from observations gathered whilst traveling through an environment (Kuipers, 1978). There is general agreement on VR's contribution to visual (spatial) information processing (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010), yet there is disagreement on VR's contribution to learning (An et al., 2018; Fowler, 2015; Huang et al., 2019; Makransky et al., 2019; Mikropoulos & Natsis, 2011). This can at least partly be explained by two factors: i) most research compared VR with traditional educational methods rather than comparing the same game presented in VR and a non-VR/desktop environment (Pierce et al., 2017); ii) the majority of studies did not use fully immersive VR, by using either low-end headsets, primitive controls, or both (An et al., 2018; Huang et al., 2019; Makransky et al., 2019). This study deviates from the existing studies as it: i) gives a direct comparison between VR and a non-VR game and ii) uses full immersive VR and, hence, aids natural observation (Desai et al., 2014; Zhdanov et al., 2019) and natural control (Chen & Luo, 2019).

3.2 Research Questions

We will examine possible differences between a node-based non-VR and VR game on navigational efficiency and knowledge retention. We will control for possible differences in experienced presence, engagement, and cognitive interest (see the previous section). This brings us to the following research questions: Compared to a node-based non-VR game (control condition), will VR have a positive effect on:

a. navigational efficiency?
b. the retention of the educational story content? and
c. the retention of spatial knowledge?

We expect that each of these research questions will be answered in the affirmative.

3.3 Method

3.3.1 Participants

25 adolescents (i.e., 12 males and 13 females) aged 13-18 (mean: 15.00, SD: 1.32) participated. They represent the target audience for the game used. None of them

did have a medical reason disqualifying them from using VR. All were recruited from a University Technical College in the UK. This college is open to new, alternative, technical methods of teaching, which minimized the risk that eventual differences between VR and non-VR would be caused by a negative attitude. Both individual and parental informed consent was obtained. Participants were randomly assigned to either the VR (6 male and 7 female) or the non-VR (6 male and 6 female) condition.

3.3.2 VR Game Environment

Figure 3.1: Using node-based movement to complete the Gloucestershire task in The Chantry. The task screen lists two items that a player needs to find to hear story information relating to that particular item.

As with the previous chapter, "The Chantry" (Steel Minions & the Jenner Trust, 2018) will be used for this study. "The Chantry" is a narrative-centered discovery game for PlayStation VR, which tells the story of Dr. Edward Jenner, his invention of vaccination, and the smallpox virus it helped eradicate (`https://jennermuseum.com/`), in which players must explore the house of the late Dr. Jenner. When attempting to open a closed door, the player is presented with a task, which represents a particular story topic and list of items that must be found, each representing an information-searching activity (i.e. having to find a particular item) (see Fig. 3.1). To open the doors and progress further through the game, players must discover and interact with these items, which contain further information on the story topic, in the form of an audio narrative. Such tasks are common in traditional games, where players need to discover items, such as a sword, key, or potion, to defeat an enemy or progress to a new area. The game uses node-based movement, where locations and items are defined by game designers for players to jump to and pick up, respectively (see Fig. 3.1) As such, tasks can be completed in a predefined minimum number of steps; so, the lostness measure can be applied.

3.3.3 Apparatus

In both conditions, the game ran at 60Hz, reprojected to 120Hz, and was rendered identically. A DualShock 4 controller (model: CUH-ZCT1) was used to control the game. Standard over-ear headphones provided the audio.

In the VR condition, participants wore a Sony PlayStation VR headset (model: CUH-ZVR1) to play the game on a Base PlayStation 4 Development Kit (DUH-D1000AA). In the non-VR condition, participants were seated 50 cm away from a standard 22" HD screen (resolution: 1920x1080).

To specify the level of immersion in the non-VR setting, we calculated participants' horizontal Instantaneous Field of View (IFOV) as follows (Van der Sluis et al., 2018):

$$2 \times tan^{-1}\left(\frac{D_c + d_e}{2l}\right) \tag{3.1}$$

where D_c is the screen size, d_e is the standard eye separation parameter of 0.63cm, and l is the distance from the eyes to the screen, resulting in an IFOV of 55 degrees.

To control the VR condition, participants used natural observation to look at a node and used a button on the controller to move to that node or pick up an item. The item was moved and rotated naturally by tracking the controller, which moved with the participants' hands. In the non-VR condition, participants used the controller's left analog stick to move the game camera to look at nodes and the right analog stick to rotate an item after it was picked up. The key difference between conditions was that both the natural head and hands controls in the VR condition were replaced by traditional game controls in the non-VR condition. The navigation mode and node-based movement remained the same across conditions, enabling the use of the lostness measures.

3.3.4 Measurements

Lostness

The lostness formula, introduced in Chapter 2 (see 2.1), explained how the minimum number of steps needed to be made (R), the total number of steps a player has made (S), and the number of unique steps a player has made (N) are used to give a value of lostness (L) for an information-searching task. To apply lostness to the full game, all items were considered, no matter the task that they belonged to. Finding the start of a task was also considered finding an item and included in the measurement. Thus the full game lostness (G_L) can be defined as:

$$G_L = \sqrt{\left(\frac{\sum_{o=1}^{n} N_o}{\sum_{o=1}^{n} S_o} - 1\right)^2 + \left(\frac{\sum_{o=1}^{n} R_o}{\sum_{o=1}^{n} N_o} - 1\right)^2}, \tag{3.2}$$

with n being the number of consecutive item pairs in the player's path through the game and R_o, N_o, and S_o are respectively the required steps, total steps taken, and unique steps taken for the oth item pair.

Questionnaires

Knowledge retention was measured through a bespoke knowledge test, consisting of 24 randomized true/false statements (50% true and 50% false). 16 related to the story (e.g., "Vaccination was already popular in England by 1800.") and 8 spatial (e.g., "The library was very close to the dining room and located on the first floor.")

Three standard in-game questionnaires were used: the Game Engagement Questionnaire (Brockmyer et al., 2009) (example item – "I feel like I can't stop playing"), the igroup Presence Questionnaire (Schubert, 2003) (example item –"I felt present in the virtual space"), and the Perceived Interest Questionnaire (Schraw et al., 1995) (example item – "I thought the game's topic was fascinating"). Each of these questionnaires consists of 5-point Likert scales, with high Cronbach's coefficient alphas, being respectively .85, .85, and .91.

3.3.5 Procedure

Upon being seated, participants were given health and safety information, as well as instructions on how to play the game, both in oral and written form. Also, an informed consent form was given. They were asked whether or not everything was clear to them. If not, additional explanation was provided. After this, they signed the informed consent form.

The participants were given 30 minutes to play the game. Next, they completed the knowledge test and the three experience questionnaires. Finally, the participants were debriefed and informed about the nature of both the study and the game.

3.4 Results

Given the rather small sample size and the accompanying non-normal data distribution, the Wilcoxon signed-rank test was used to compare the VR and non-VR/desktop conditions on lostness and both story-based and spatial-based knowledge. Additionally, we controlled for effects on presence, engagement, and cognitive interest. The means and standard deviations of these measures in each condition are provided in Table 3.1.

Table 3.1: Mean and Standard Deviation of All Measures for Both Non-Virtual Reality and Virtual Reality Conditions.

	Non-VR	VR
Lostness	0.62 (0.13)	0.47 (0.11)
Spatial Correct (max 8)	3.67 (1.30)	4.92 (1.38)
Fact Correct (max 16)	7.75 (1.78)	9.23 (2.68)
Presence (1-5)	3.11 (0.43)	3.01 (0.35)
Cognitive Interest (1-5)	3.71 (0.54)	3.65 (0.52)
Engagement (1-5)	3.04 (0.53)	2.91 (0.52)

Participants in the VR condition showed a higher navigational efficiency (i.e., were less disorientated) when carrying out the in-game tasks than in the non-VR/desktop condition. This is shown by the lostness measure (*desktop median* = 0.627, *VR median* = $0.511, Z = 5, p = .008$) (see Fig. 3.2). Participants in the VR condition also performed better on spatial-based knowledge questions (*desktop median* = 0.5, *VR median* = $0.75, Z = 55.5, p = .041$). In contrast, no significant difference was found for story-based knowledge (see Fig. 3.3).

No significant differences were found with regards to presence, cognitive interest, and engagement.

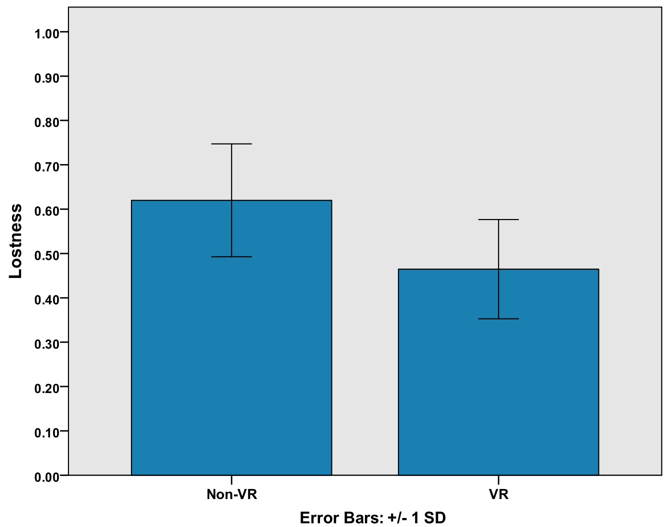


Figure 3.2: Comparison of the local (*left*) and global (*right*) lostness measures for the desktop and Virtual Reality (VR) environment.

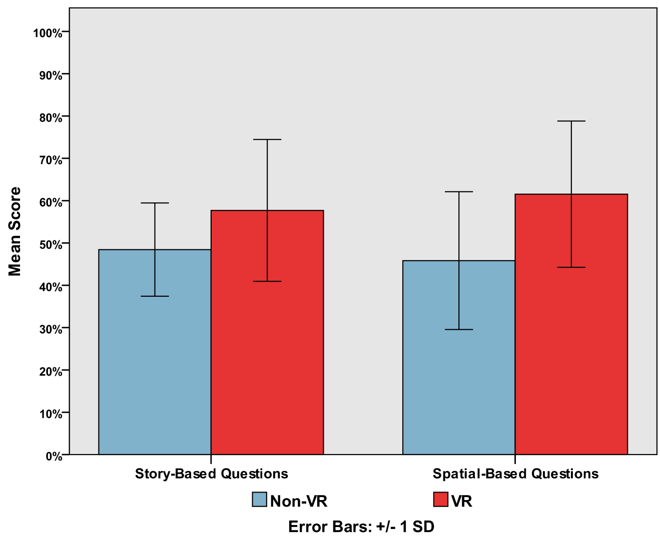


Figure 3.3: Comparison of the percentage of correct answers on the story (*left*) and spatial (*right*) knowledge questionnaire.

3.5 Discussion

Using a game employing a node-based movement system, fully immersive VR and non-VR/desktop were compared on both learning and navigational efficiency. Compared to the non-VR/desktop game, the VR game leads to both higher navigational efficiency (confirming research question a) and to higher retention of spatial information (confirming research question c). In contrast, no difference was found on the retention of story-based educational content (denying research question b). As expected, none of the control variables presence, engagement, and cognitive interest unveiled any difference between VR and non-VR/desktop.

Compared to the participants playing the game in a desktop/non-VR environment, participants in VR had lower lostness values, identifying that they were more efficient in navigation. Moreover, this finding confirmed the value of lostness as a measure for in-game navigation. Further research is required to investigate the full potential and validity of both measures, as both gave the same effect. For future research, we recommend using these measures as game analytics to enable real-time game adaptation, based on player performance (Caballero-Hernández et al., 2017; Shute et al., 2017; Van Oostendorp et al., 2014).

Retention was also higher for spatial knowledge in the VR condition than in the non-VR/desktop condition. This reaffirms the view that VR has a positive effect on spatial memory (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010) and vindicates its use in disciplines that rely heavily on spatial knowledge (Thomsen et al., 2017; van Doesburg et al., 2005). Moreover, the combination of higher spatial knowledge retention and higher navigational efficiency found in the VR compared to the non-VR/desktop condition mirrors hypertext findings that spatial ability is a predictor of navigational performance (Juvina & Oostendorp, 2008; Van Oostendorp & Karanam, 2013).

In contrast to spatial information, no significant difference was found for the retention of story-based information. A simple explanation is that no significant difference, across conditions, was found in two of the control variables: cognitive interest and engagement, which are thought to be related to learning (Fredricks et al., 2004; Garner & Gillingham, 1991). An additional explanation for the lack of difference in retention scores could be related to previous findings that visual information is retained better in VR than in non-VR, due to the increased visual information; but, at the expense of information presented in other ways (Huang et al., 2019). Previous research also suggested that multimodal synergy (i.e., the synergy of information originating from multiple modalities (Perakakis & Potamianos, 2008), could improve with increasing IFOV (Van der Sluis et al., 2018). In this study, multimodal synergy was likely already maximally exploited with the non-VR/desktop condition, which already had a large IFOV, and VR could not improve the synergy effect further.

When it comes to learning, cognitive overload is often mentioned as being a problem with VR, (Andersen et al., 2016a; Andersen et al., 2016b; Darken & Sibert, 1993; Makransky et al., 2019). Although we did not examine this directly, our data does not suggest this when a VR game is compared with a non-VR/desktop game. Nevertheless, as knowledge test scores were relatively low in both conditions, it could be argued that cognitive overload occurred in both conditions, as participants were not familiar with the game and the node-based movement system. With more experience in using these games and VR, cognitive load could reduce. Again, this encourages follow-up research on adaptivity to assist a disoriented and overloaded player using the lostness measure. This would be in line with our previous research using the same game and knowledge test, which found significantly higher retention of educational story content when players were guided through the environment, reducing the cognitive burden of navigation (Ferguson et al., 2020b).

Finally, this study's participants are from a University Technical College and study technical subjects, rather than the subject addressed by the game (history). These students follow education on a level less advanced than university students, which are often used as participants. This could explain their relatively low knowledge test scores. Moreover, a sample size of 25 can be considered quite small. A follow-up study is needed to reliably generalize the findings to a larger population.

In conclusion, we integrated the hypertext lostness measure in an educational game that uses a node-based movement system and features goal-directed information-seeking tasks. The lostness measure showed that VR improves in-game navigational efficiency compared to non-VR. Additionally, we found that VR also improves spatial knowledge acquisition. In contrast, in addition to a lack of effect on in-game experience: engagement, presence, and cognitive interest, VR did not aid story-based knowledge retention. This partially supported findings that only visually-presented information is better retained in VR (Huang et al., 2019), whilst differing from other research that found that VR hindered learning (Makransky et al., 2019). Finally, this study showed the value of hypertext lostness measures in node-based games and VR and showed that, even within a gaming context, VR's merit is significant.

Following these results, especially the fact that only spatial information was retained better in VR, the next chapter will investigate the dominant features of VR narrative-centered games to investigate their impact on knowledge retention. This will help determine the best way to present learning content in VR for better learning.

CHAPTER 4

On the role of interaction mode and story structure in virtual reality serious games

Abstract - Narrative-centered games in Virtual Reality (VR) provide rich, high-fidelity environments that provide a fully immersive and interactive storytelling experience for use in teaching. Yet, it is not fully known how learning experience is affected by freely exploring the environment (interaction mode) and having an explicit story structure. A randomized controlled 2x2 study with 42 adolescents was performed to correct this omission and find the effect that these two factors have on recalling important information and on how a player feels when playing a game. They explored a narrative-centered VR game with different interaction modes (active vs passive) and story structures (explicit vs implicit) and then completed a knowledge test and standardized questionnaires, regarding their sense of presence, cognitive interest and engagement during the game. Results show that allowing players to navigate freely through the game has positive effects on cognitive interest and a feeling of presence. An implicitly structured game leads to increased recall of spatial information. However, for optimal learning of factual knowledge, guidance is beneficial.

This chapter is almost identical to the following publication:

Ferguson, C., Van den Broek, E. L. & Van Oostendorp, H., "On the role of interaction mode and story structure in virtual reality serious games", *Computers & Education*, vol. 143, no. 103671, 2020, DOI: `10.1016/j.compedu.2019.103671`

"We are working hard to educate a new generation in old ways, using tools that have ceased to be effective."

Prensky (2007)

4.1 Introduction

In the previous chapter, we took the potential game analytics identified in the first chapter and used them to compare player performance across the same narrative-centered game in VR and non-VR. Although it was found that playing a narrative-centered game in VR led to higher knowledge retention in the spatial dimension, this did not apply to story-based knowledge. Moreover, no difference in the type of experience that player had was found between the two mediums. Subsequently, the effective components of Narrative-centered discovery games in VR should be examined to identify how knowledge retention, particularly in the story dimension, can be improved, as well as the in-game experience.

Narrative-centered discovery games consist of two main components: active interaction, from discovery games, where a player is free to choose the direction they take and the items that they interact with, and an explicit story structure, from narrative-centered games, a storytelling experience that is structured so that some parts of the story must be told before other parts become available. As such, in this chapter, we examine these two components in detail and investigate their effect on knowledge acquisition as well as players' feelings on their in-game experience. It is hoped that manipulating these two variables will enable us to examine what variables are important for learning and player experience.

4.1.1 The Role of Interaction Mode

Within education, it is debated whether or not learning improves when students are allowed to explore the educational content and given choices on what to learn freely or if students must be strictly guided in the topics to be learned. On the one hand, in classroom environments, teachers present students choices because they believe it increases effort and learning (Flowerday & Schraw, 2000) and educational literature even indicates that choice leads to increased cognitive engagement, positive affect, creativity, and achievement (Kohn, 1993). On the other hand, (Flowerday & Schraw, 2000) also found that choice has a negative effect on cognitive task performance but a positive effect on attitude. Also, (Flowerday et al., 2004) report that effects of choice on learning are small, with choice having more effect on personal engagement and attitude. Moreover, it has also been found that controlling environments reduce autonomy, decrease motivation, and result in lower attitudes and performance in the classroom (Flink et al., 1990; Grolnick & Ryan, 1987; Miserandino, 1996). This could imply that giving students a choice could lead to a better interest in the subject matter and higher levels of engagement, at the risk of hindering learning performance.

In the previous chapter, we were able to make use of the lostness measure (Smith, 1996) to quantify navigational efficiency, finding that players were more efficient at navigating in VR. This navigation, with full freedom of choice, in games increases the amount of cognitive load and can lead to cognitive overload, where a players gets disoriented and, thus, suffers from inhibited learning.

The choice between freedom of choice and strict guidance, as well as disorientation and cognitive load, can be traced back to the Zone of Proximal Development (ZPD): "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance or in collaboration with more capable peers" (Vygotsky, 1978, p. 86). This suggests that students can carry out easier tasks independently but require guidance to reach the next level and complete more difficult tasks. Focusing on full guidance could lead to players being assisted in tasks that they could already accomplish without assistance, which could account for the more positive attitude found in players that have freedom of choice.

When investigating video games in particular, this freedom of choice versus guided learning approach can also be applied in the context of the interaction mode that is present in a game: active navigation, where the player chooses which path to take, or passive navigation, where players are put on a set path similar to a guided tour in a museum. In this regard, research into games backs up the results found in classroom research. For instance, (Conniff et al., 2010) found that players were more motivated and attentive and felt more present in an active navigation condition, supporting further arguments that greater involvement and immersion occur as a result of increased interaction with an environment (IJsselsteijn et al., 2001; Witmer & Singer, 1998). On the other hand, (Topu & Goktas, 2019) instead found that there were higher levels of cognitive engagement as well as achievement when users were given guidance through a virtual environment.

The effect of these contrary interaction modes has also been investigated concerning spatial memory. It was found that memory for spatial layout was better with active navigation compared to passive (Brooks, 1999; Christou & Bülthoff, 1999) and that passive navigation was not sufficient for creating a sense of place (Conniff et al., 2010). However, some research found no difference (Gaunet et al., 2001).

Based on this brief review, it would be expected that the attitude of players, namely engagement, presence and cognitive interest, in a virtual environment would be better in active interaction and also lead to better spatial knowledge retention. However, the literature on the retention of factual knowledge is sparse and inconsistent, so it remains to be seen which type of navigation is beneficial for this. The literature points towards the fact that players will recall more factual knowledge due to being guided through the environment and being less overwhelmed but, conversely, the lack of choice affecting their attitude may result in lower recall.

4.1.2 The Role of Story Structure

Story structure is often cited as important in the context of education, particularly when it comes to retention and recall. This is of high importance as this is how assessments take place in the form of examinations. There is a wide array of consistent research into the positive effect of a strong story structure on learning. People use a story schema as a means for understanding as well as use it as a set of retrieval cues (Bartlett, 1932) and texts with a clear structure help in understanding and retention (Lorch et al., 1993; Rouet, 2006). Story-based texts are better comprehended than texts without storylines. They are read faster and better recalled (Graesser et al., 1980; Karen M. Zabrucky, 1999; Norris et al., 2005; Thorndyke, 1977).

Strong explicit story structures in educational games have been found to have a positive effect on declarative knowledge acquisition (Gustafsson et al., 2010; Smith & Baker, 2011), performance (Kelleher et al., 2007) and particularly a positive effect on procedural knowledge or skill acquisition (Serrano & Anderson, 2004). Research also found a positive effect on learning, (programming) skills and engagement (Dickey, 2006; Dickey, 2011; Jemmali et al., 2018; McQuiggan et al., 2008; Rowe et al., 2011). Moreover, in their recent quantitative meta-review, (Wouters & Oostendorp, 2017) report a positive effect of narrative elements in games, especially on motivation. This indicates that a strong story structure is necessary for optimal learning as well as keeping the player engaged and motivated, which are important indicators of learning. On the other hand, (Adams et al., 2012) found no positive effect on declarative knowledge and (Garneli et al., 2017) found no performance effect at all. Moreover, some research was only able to find an effect on motivation and enjoyment (Armstrong & Landers, 2017; Bopp, 2016; Cordova & Lepper, 1996; Hsu & Wang, 2010; Kopfman et al., 1998).

All in all, multiple claims have been made about the importance of structuring educational content, particularly when recalling stories (Mandler & Johnson, 1977); but, this has not (yet) been applied to narrative-centered VR games. This study will inform on whether an explicit structure is important for recalling information learned in these types of games as well as the effect this has on how a user feels whilst playing the game. In addition to this, because of the planned implementation of the implicit storyline condition (see methods section), it is expected that this condition may also have a positive effect on the recall of spatial information. Rather than players having to follow the explicit story structure to continue to different parts of the game, they will be able to explore the whole environment from the beginning and, thus, be able to build up a detailed spatial mental representation.

We assume that story structure and the specific interaction mode are important features of narrative-centered VR games. We want to know empirically the importance of each, and also of their eventual interaction effect on learning and feeling (presence, engagement, and cognitive interest) of participants. Therefore, the current paper explores the effect of both interaction mode and story structure via a randomized controlled trial (RCT). This involves playing a narrative serious game in a VR environment, identifying if an explicit story structure and interaction, in the form of freedom of choice, is necessary for retention and positive experience.

4.2 Research Questions

In a randomized controlled study with a 2x2 factorial design, we will examine the underlying factors (interaction mode and story structure) determining the effects of narrative-centered VR games on learning and player experience. The following research questions will be studied by examining two variables that might be involved:

a. What is the role of typical VR interactive navigation compared to merely a passive simulation (i.e. a guided tour without interaction)?

b. What is the role of structuring educational content through an explicit story structure compared to an implicit (i.e. unstructured) story structure?

Both of these variables (interaction mode - passive vs active - and story structure – implicit vs explicit) will be simultaneously examined in a 2x2 factorial design so their interaction can also be investigated. For example, we might find that retention is better in the active interaction mode than in the passive interaction mode when the structure is explicit, and no difference when the structure is implicit. Based on the above-mentioned related studies, we formulate the following hypotheses:

Compared to a passive simulation (guided tour), active interaction leads to:

a. Participant's improved understanding;
b. Lower retention of the materials after some delay;
c. Higher cognitive interest for the subject matter
d. More engagement and (sense) of presence; and
e. A more detailed mental representation with more accurate spatial information.

Compared to implicitly structured games, explicitly structured games lead to:

a. Participant's improved understanding;
b. Higher retention of the materials after some delay;
c. Higher cognitive interest for the subject matter; but
d. Less engagement and (sense) of presence; and
e. A less detailed mental representation with less accurate spatial information.

Regarding the interaction effects of structure with interaction mode, it is predicted that structure will have no significant effect within the guided tour conditions compared to the conditions featuring active interaction. This is because the guided tour provides the structure that is missing in the implicit-structured condition.

4.3 Method

4.3.1 Participants

A total of 42 adolescents, 38 males and 4 females, aged 13-17 (mean: 15.12, SD: 1.17), were recruited from a University Technical College. They had differing levels of VR experience and indicated this experience on a post-experiment questionnaire on a 5-point Likert scale (from 1 = "Used very little" to 5 = "Used all the time"; mean: 2.57, SD: 1.31). Informed consent, both individual and parental, was obtained before the experiment along with information that would disqualify a participant from taking part, such as being susceptible to migraines. The participants were randomly assigned to the four conditions, making groups of 12 (2 female), 10, 10 (2 female), and 10 participants.

4.3.2 Modified Game Versions

Once again, "the Chantry" (Steel Minions & the Jenner Trust, 2018), a narrative-centered game for the PlayStation VR platform, is used in this study.

Figure 4.1: A task screen, with a list of items that need to be found, which are used to provide the explicit story structure in the game. These are removed in the implicitly structured version.

In the explicit story structure condition, which is the same as the original game, players interact with closed doors and even window shutters. Upon trying to open these, the player is presented with a list of items that contain story information, in the form of an audio narrative, which must be found and interacted with to continue through the game and access further parts (see Figure 4.1). In the implicitly-structured version, these doors and shutters will be open from the start. Items can still be interacted with to access the game narrative but not interacting with these items will not hinder access to different parts of the game.

For the active interaction condition, this will be the same as the original game, where the player can choose where to go, in which order to pick items up and how long to stay in one place listening to the game narrative. On the other hand, those in the passive interaction condition (guided tour) will be forced to take the most optimal path through the game, picking up items in the most appropriate order and being forced to listen to the complete audio narrative before moving on (see Figure 4.2). Apart from the differences in structure and interaction, all of the participants played the same game with the same educational content.

(a) Passive Interaction (Guided Tour). (b) Active interaction.

Figure 4.2: The left picture shows the active interaction condition, where more than one option is available, and the right picture shows that the player is forced to choose the option on the right.

4.3.3 Apparatus

As with the previous study, each participant wore a Sony PlayStation VR headset (model: CUH-ZVR1) to play the game on a Base PlayStation 4 Development Kit and controlled the game using a PlayStation DualShock 4 controller (model: CUH-ZCT1). Standard over-ear headphones provided the audio. To control the game, participants used their head movements to look at a node and used a single button press on the controller to move to that node or pick up an item. In the active interaction condition, an item is moved and rotated by doing the same action holding on the controller, this is done automatically in the passive interaction condition.

4.3.4 Measurements

As with the previous chapter, evaluate learning in the game, participants were provided with a short knowledge test, consisting of 24 true/false statements (16 story, 8 spatial) to gauge how well the in-game content was remembered. Again, the same standardized questionnaires consisting of 5-point Likert scales were used to measure engagement (Brockmyer et al., 2009), presence (Schuemie et al., 2001) and cognitive interest (Schraw et al., 1995).

4.3.5 Procedure

Upon being seated, participants were given instructions in both oral and written form. This involved safety information, such as not to try and physically grab anything and what to do in the event of motion sickness. This was followed by instructions on what to do in the game and how to use the controls. After all of the participants were satisfied with the instructions, they were given 30 minutes to play through the game, including a simple controls tutorial and learning about the story.

Afterward, the participants were invited to complete the knowledge test and the three questionnaires. Once these were completed, all of the participants were debriefed and informed about the nature of the study, including how their condition differed from the full game, and the future plans for the game.

After the experiment, the average scores on the engagement, presence, and cognitive interest questionnaires, and the percentage of correct answers on both the factual and spatial questions of the knowledge test were collected and analyzed.

4.4 Results

A Multivariate analysis of variance (MANOVA) was performed to identify any significant difference between passive vs active interaction as well as between explicit vs implicit structure of the game. Presence, engagement, cognitive interest, and the spatial and factual knowledge test results were examined as dependent variables. Interaction mode and structure were independent between-subjects variables. Player age, gender, and VR experience served as covariates. This data all followed a normal distribution. In the MANOVA, interaction mode was found to have an overall significant effect in favor of the guided tour $(F(5,31) = 4.006, p = 0.006, \eta_p^2 = 0.393)$, whereas the variable structure showed neither a main effect nor was an interaction effect found. Means and standard deviations are shown in Table 4.1.

Next, we analyzed the univariate effects on the dependent variables. It was found that all but one of the dependent variables were affected by one or more of the conditions. The number of correct answers based on the story (factual knowledge) was significantly affected by interaction mode $(F(5,31) = 7.203, p = 0.011, \eta_p^2 = 0.171)$, in favor of the guided tour condition, with participants giving approximately 10% more correct factual answers (see Figure 4.3). Although the interaction mode affected factual knowledge, this was not true for spatial knowledge. Moreover, when we investigate the effect of structure on spatial knowledge, we find an effect in favour of implicit structure ($F(3,31) = 4.373, p = 0.044, \eta_p^2 = 0.111$), where approximately 7% more correct answers were given by participants (see Figure 4.4). No significant interaction effects were found.

Table 4.1: Mean and standard deviation (SD) of all measures of each condition.

	Explicit Structure	Implicit Structure	Explicit Structure	Implicit Structure
Factual Knowledge (0-1)	0.71 (0.12)	0.66 (0.15)	0.61 (0.11)	0.56 (0.16)
Spatial Knowledge (0-1)	0.45 (0.20)	0.54 (0.17)	0.50 (0.13)	0.56 (0.12)
Presence (1-5)	2.87 (0.37)	3.06 (0.36)	3.36 (0.47)	3.18 (0.53)
Cognitive Interest (1-5)	3.02 (0.82)	2.8 (0.77)	3.66 (0.85)	3.39 (0.63)
Engagement (1-5)	2.77 (0.72)	2.98 (0.59)	3.07 (0.61)	3.07 (0.46)

Interestingly, cognitive interest was significantly affected by the interaction mode ($F(5,31) = 4.65, p = 0.038, \eta_p^2 = 0.117$) in favor of active interaction (see Figure 4.5). There was also a significant difference in participants' experienced presence ($F(5,31) = 4.163, p = 0.049, \eta_p^2 = 0.106$) in favor of active interaction (see Figure 4.6). This shows that freedom of choice does lead to a better experience although no differences were unveiled on engagement across any of the conditions.

There was a significant overall effect of the covariate age ($F(5,31) = 2.941, p = 0.028, \eta_p^2 = 0.322$).. This can be contributed solely to spatial knowledge ($F(5,31) = 8.136, p = 0.007, \eta_p^2 = 0.189$), which increased with participants' age. For neither participants' gender nor VR experience differences were found.

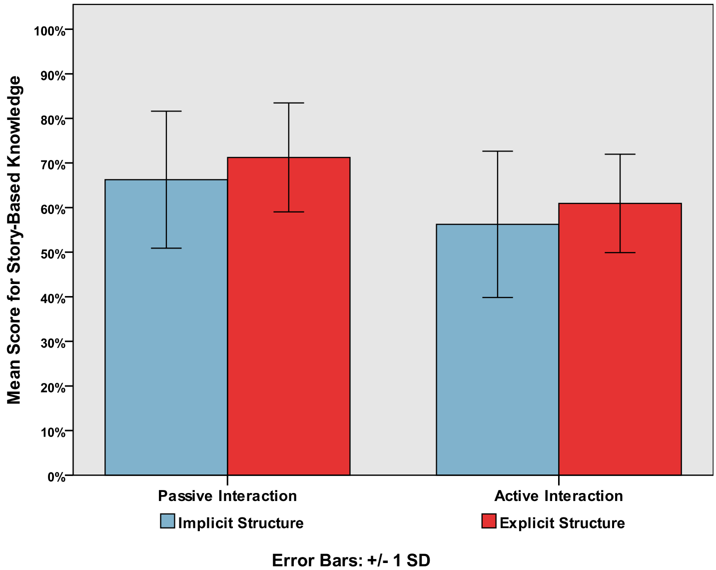


Figure 4.3: Means of correct answers on story-based questions in all conditions.

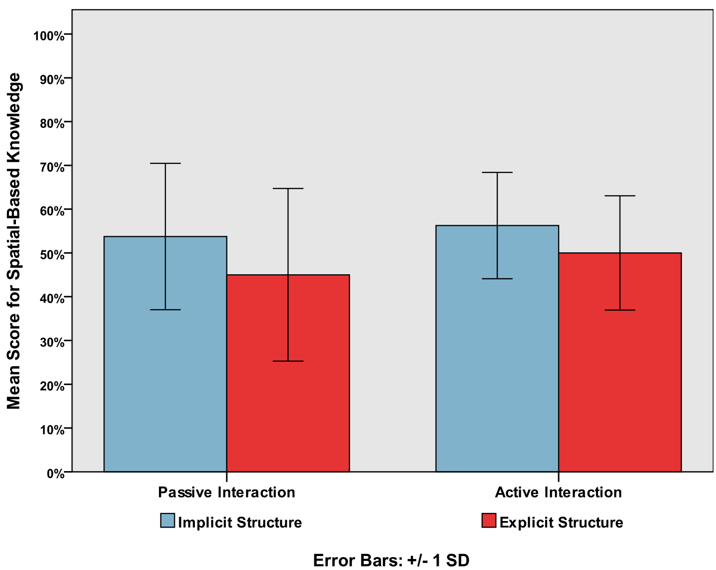


Figure 4.4: Means of correct answers on spatial-based questions in all conditions.

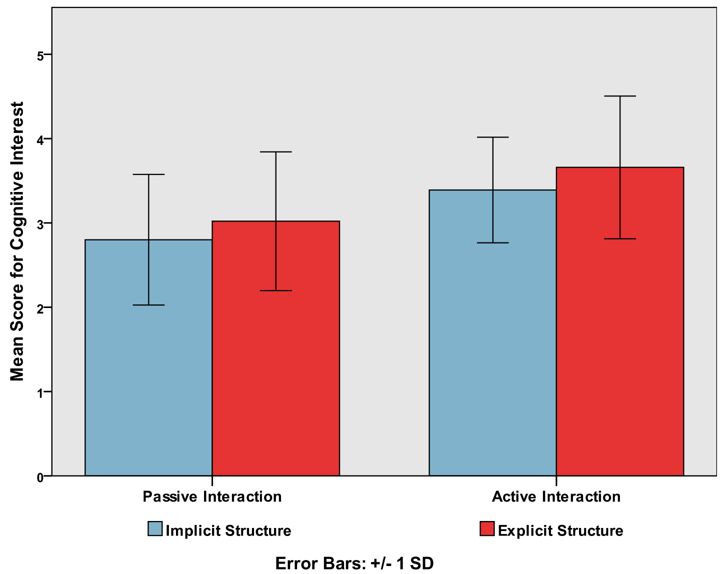


Figure 4.5: Means of cognitive interest in all conditions.

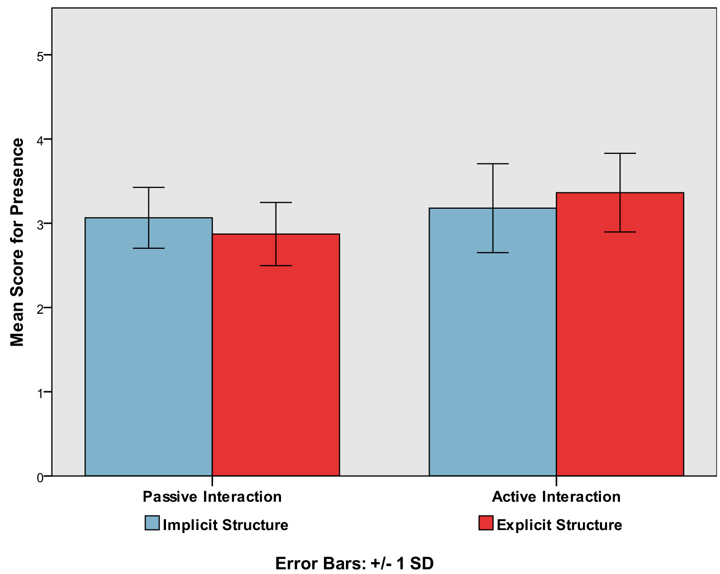


Figure 4.6: Means of presence in all conditions.

4.5 Discussion and Conclusion

VR narrative-centered games are used for environmental storytelling. In this study, we focused on active interaction and an explicit storyline within narrative-centered games. This allowed us to verify whether or not both characteristics are important when it comes to knowledge acquisition and a positive experience: the key goals of these types of games.

Firstly, we examined the role of active interaction compared to a passive, guided tour. Some significant differences were found related to interactive mode. As predicted in the hypotheses, in the passive interaction (guided tour) condition, it was found that participants had higher percentage of correct answers on the test focusing on factual knowledge showing that participants were able to retain and recall knowledge better although, contrary to the hypothesis, there was no significant difference for spatial knowledge between conditions. This does, however, back up (Vygotsky, 1978)'s theory of the Zone of Proximal Development (ZPD) as scaffolding through the guided tour (passive interaction condition) enabled participants to reach a higher level of learning. Nevertheless, it was shown that participants felt more present and showed more cognitive interest in the active interaction condition. This backs up the findings of (Flowerday & Schraw, 2000) who found that freedom of choice and interaction led to a negative effect on task performance (learning) but a positive effect on attitude. Unfortunately, one of these elements, less engagement, was unproven as no significant difference was found regarding engagement. On one hand, it is expected that cognitive interest would correlate positively with the higher retention of story-based knowledge measured in the guided tour condition but, on the other hand, this also fits with (Flowerday & Schraw, 2000)'s research showing that people find a subject more interesting when given freedom of choice. This leads to an interesting dilemma where educators and developers of such games must choose between either a more positive learning experience for a player resulting from active interaction or better factual knowledge retention via a guided tour. Alternatively, as mentioned earlier, participants were fully guided in the passive interaction condition so they might have been assisted with tasks that they were already able to complete without assistance. This could account for the better learning but the lack of positive feeling. Cognitive overload was mentioned as a possible consequence of navigation with freedom of choice, however, it could be that the lesser feelings of present and cognitive interest noted by participants in the passive interaction condition led to cognitive underload, excessively low cognitive load that can lead to similar cognitive fatigue (Paas et al., 2010; Young & Stanton, 2002). Therefore, if the game was able to detect and adapt when the player needs guidance, taking ZPD into account, this could lead to optimal learning and a better positive feeling in the game. This consideration points to a game environment in which adaptivity plays a role: only controlling and supporting a player when it is really necessary (Shute et al., 2017).

Compared to the active interaction mode that allowed players to skip, the guided tour version of the game forced participants to listen to the full game narrative that contained the story information. Consequently, these participants were exposed to more of this content, which explains some of the increased factual knowledge retention. Because of this finding, before release, the game was modified to queue important narrative audio so that important information is still played even when the player moves on. It is also plausible to propose that these results could be interpreted as showing that narrative-centered games influence learning better when a player is guided through the environment, perhaps by a schoolteacher. Future studies into the effect of an narrative-centered game within a classroom environment would be beneficial for this area of research as it would show one of the possible applications of this kind of technology.

Secondly, we also examined the effect of maintaining an explicit story structure, where all story elements are explicitly structured in an effective order, compared to having an implicit structure. Only one significant difference, in favor of the implicitly structured version, was found. Participants scored higher on the spatial part of the knowledge test in the implicit version, showing that they were able to retain and recall this type of knowledge better when the game was not following an explicit structure. This can be explained by the fact that this condition effectively changed the game into an 'open-world' scenario, meaning that the entire game environment (and therefore a large amount of spatial information) was available to the participants immediately from the beginning of the game, rather than players having to follow the explicit structure to access areas of the game only available in later parts of the story. Moreover, this open-world design may have encouraged exploration around the environment and take in more spatial information, leading to this result. This, in turn, shows that a game with an implicit story structure (open-world) is best for spatial knowledge transfer without necessarily hindering factual knowledge acquisition.

Finally, there was an effect of the covariate age found, which was unexpected.

However, this was only due to a highly significant relationship with spatial knowledge retention, which aligns with research from (Gathercole et al., 2004) which found a linear increase in memory from age four through adolescence. As such, this study emphasizes the significant development of adolescent's cognitive skills and the importance of considering this when designing educational games, with and without VR.

Taken together, narrative-centered discovery VR games have the potential to provide a fully immersive and interactive learning experience and this study showed how this experience is affected by removing the ability to freely explore the environment and the explicit story structure, both features that are key in these types of games.

This study showed that an implicitly structured (open-world) game leads to increased recall of spatial information. For optimal learning of factual knowledge, guidance remains beneficial, in line with ZPD (Vygotsky, 1978). However, guidance in the form of passive interaction, a guided tour with little player input, was detrimental to the game experience, with reduced levels of presence and cognitive interest being reported. It is possible that giving guidance only when a player needs it may avoid this lesser game experience, and may even lead to even higher levels of knowledge retention. Therefore, building on these findings, in Chapter 5, we will investigate a a game with a system that offers guidance, when it is detected that a player needs it, to evaluate the effect this has on learning and the in-game experience of a player.

CHAPTER 5

Adaptive Narrative-Centered Discovery Learning: Textual Specificity Increases Learning and Reduces Cognitive Load in Serious Games

Abstract - Narrative-centered discovery games provide a high-fidelity experience, via serious games that combine interactive tasks with a strong storyline. They hold the promise of higher outcomes; but, can also lead to cognitive fatigue, which hinders learning. To avoid this, the Zone of Proximal Development (ZPD) theory was exploited. Textual instructions were adapted real-time to ensure a personalized challenge for one group of learners, where the other group received static instructions. Compared to the control group, the learners with personalized instructions showed higher story and spatial learning, while having a decreased cognitive load and a similar experience. So, via a transparent theoretically well-grounded recipe, instructions given in narrative-centered learning environments can be personalized in real-time, which not only reduce learners' cognitive load but also increases their learning.

This chapter is almost identical to the following publication:

Ferguson, C., Van den Broek, E. L. & Van Oostendorp, H., "AI-Induced Guidance: Preserving the Optimal Zone of Proximal Development". [Under Review].

"The workers of the Games Generations will no longer accept, attend, or do training that is boring"

Prensky (2007)

5.1 Introduction

As mentioned in the Introduction, narrative-centered discovery games provide a self-directed learning experience that makes use of intrinsic motivation (Toh & Kirschner, 2020), where a player performs an activity for its own sake or enjoyment without reward (Liao et al., 2019), and has been found to lead to higher learning outcomes (Habgood & Ainsworth, 2011). Unfortunately, this self-directed learning approach means that learners may not discover important learning materials due to a lack of knowledge of what needs to be found in the game. This can lead to disorientation (i.e. poor navigational efficiency), where users lose their sense of location and direction (Conklin, 1987; Head et al., 2000) because navigation is too much of a cognitive burden, exceeding the capacity of a person's cognitive abilities (Chen & Fauzy, 2008; Darken & Sibert, 1996; Gwizdka & Spence, 2007). This is referred to as cognitive overload, inhibited learning due to a person's cognitive capacities being overloaded (Sweller et al., 2011).

In Chapter 4, it was shown that removing the cognitive burden of navigation, by offering full guidance through a guided tour, led to a higher retention of story-based knowledge, at the detriment of a lesser in-game experience. It could be, that removing the freedom of choice of a player through this full guidance could also have affected learning by inducing cognitive underload, excessively low cognitive load, which can also lead to similar cognitive fatigue to cognitive overload. (Paas et al., 2010; Young & Stanton, 2002). For effective learning, in games as well as other multimedia (Wang et al., 2020), there must be an appropriate level of cognitive load, the amount of working memory resources that are used for cognitive processing (Sweller et al., 2011). This can be better explained by the Zone of Proximal Development (ZPD) (Vygotsky, 1978), which was touched upon in the previous chapter.

ZPD puts forward that there are simple tasks that do little to challenge the learner (i.e., cognitive underload), which was provided by the passive interaction (i.e. full guidance or guided tour) in the previous chapter, leading to little learning. Conversely, there are more complex tasks that cannot be completed without assistance (i.e., cognitive overload), again compromising learning. The tasks in the middle of the ZPD, will provide an appropriate level of challenge without assistance being needed (i.e., an appropriate amount of cognitive load necessary for effective learning (Schnotz & Kürschner, 2007)). Although being in the correct area of ZPD is expected to lead to higher learning, again, it must be reiterated that VR games have been found to lead to higher learning in the spatial or visual dimension (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010) yet similar advantages have not been proven for story-based information (An et al., 2018; Fowler, 2015; Huang et al., 2019; Makransky et al., 2019; Mikropoulos & Natsis, 2011) so the effect that being in the correct area of ZPD has on these two dimensions should be investigated. On top of increased learning, being in the correct area of ZPD is also expected to lead to increased cognitive interest (Trif, 2015) (i.e., understanding topics and becoming more interested (Harp & Mayer, 1997), and higher engagement (Hamari et al., 2016) (i.e., heightened concentration, interest, involvement, and enjoyment (Kim, 2018)). This may also assist with maintaining a player's sense of presence (i.e., feeling being physically present in a virtual environment (Slater, 2002)), a key aspect related to the physically immersive nature of VR games, which can be broken when a player feels like they require assistance (Steiner & Voruganti, 2004). To ensure that players are within the correct area of ZPD for optimum learning, a personalized experience should be provided, which takes into account personal differences in players (i.e. variances in physical and gaming abilities) to provide an experience that meets their skill levels (Streicher & Smeddinck, 2016). This is also referred to as adaptivity: "adjustments which improve the individual player experience" (Lopes & Bidarra, 2011) and can ensure that players are in the ZPD by being provided with the appropriate level of challenge throughout the game. In other words, players should only be given guidance or additional challenge when necessary.

Adaptivity is provided through real-time feedback, a key feature of serious games. This feedback can direct learners, with the key goal of increasing performance, aiding learning outcomes, and improving knowledge construction (Moreno & Mayer, 2005; Shute, 2008). By providing feedback, in the form of guidance through increased information, players can be assisted with discovering important items to access key knowledge for learning (Kirschner et al., 2006; Mayer, 2004; Moreno, 2004) before they are overloaded. Conversely, this feedback can also provide a greater challenge by providing less information to players that are feeling underloaded.

There is a wide array of literature that presents many different types of adaptive systems in serious games to improve learning performance. Examples of these include Steiner & Voruganti (2004), who found that adding a trail of brightly colored stones was able to provide an obvious cue for players to discover a location quickly and effectively, and Peirce et al. (2008), who provided a companion, in the form of Galileo, to give players hints throughout the game. Both of these systems would be extremely effective for providing the navigational support necessary when a player is disoriented and overloaded (so in the upper area of ZPD) rather than underloaded players (lower area of ZPD) that require additional challenge. One such system meeting these requirements was developed by Clark et al. (2016), who modified the layout of challenges depending on a running average of a player score.

Based on the idea of modifying the layout of challenges depending on a player's score, it could be that task instructions given to a player within narrative-centered discovery games, could be modified depending on their performance to provide support or higher challenge. For example, for a player given a task to find several items, the descriptions of these items could be manipulated to modify the difficulty of these tasks to match how well the player has been performing to ensure that they are in the most appropriate area of the ZPD. For example, at the beginning of a task, a struggling player can be given additional information about items, in the form of more specific keywords, whereas, more proficient players will be challenged with less specific/more generic descriptions. Building a personalized adaptive system around ZPD is a key point of this research as learning theories are not often considered in game/VR development for improving learning outcomes Radianti et al. (2020) and Wu et al. (2012).

5.2 Adaptivity through Textual Specificity

The proposed adaptive system, textual specificity, is based on notions from cognitive psychology (encoding/recall specificity) and information retrieval (search specificity). In principle, this narrows the search space (more specific keywords) if a player is performing poorly, making it easier to find items, and, in contrast, widens it (less specific/generic keywords) if the player is performing well, making it more challenging to find items. Put simply, words rapidly guide early visual processing (Boutonnet & Lupyan, 2015). There is scant literature available that mentions the use of information searching in video games (Beheshti, 2012; Street et al., 1997), yet there is no literature available that makes use of textual specificity in this area.

Table 5.1: Examples of an item in a game using a textual specificity-based adaptive system according to five difficulty levels.

Level	Information Made Available	Example
Very Easy	Specific location information Specific description	A County Map on the Wall (Look Left)
Easy	Generic location information Specific description	A County Map on the Wall
Normal	No location information Specific description	A County Map
Hard	No location information Less Specific description	Representation of the County
Very Hard	No location information Generic description	The County

There are two different ways of increasing the chance of an item matching a request (i.e., an efficient search): adding more terms to the search string or making use of more specific phrases, such as choosing the word 'tea' over 'beverage' (Spärck Jones, 1988). 'Distractors', items of similar shape and color, play a key role when it comes to efficient search (Wolfe, 2007), and a large number of these distractors will increase the difficulty of a search task so a target needs to be unique (Duncan & Humphreys, 1989; Palmer, 1995; Wolfe et al., 1992). Accordingly, it can be argued that describing an item more specifically so that it becomes unique (i.e. *feature guidance* Wolfe, 2020) increases the efficiency of a visual search, decreasing the difficulty of an information-searching task, because it can be perceived distinctively to other similar items. In fact, it has been discovered that additional information (i.e specificity) in a target cue results in more accurate responses to rapid image presentation (Intraub, 1981; Schmidt & Zelinsky, 2009) and that a person perceives an item differently depending on the level of specificity in this cue (Carmichael et al., 1932; Jörg & Hörmann, 1978; Underwood, 1965). Therefore, at the beginning of a searching task, the specific features of an item are extracted from a target cue and is influenced by the specificity of this cue (Maxfield et al., 2014).

As well as the description of the item, the description of the location (i.e., *Scene guidance*) is also a key component of a successful search, as it is in information retrieval (Zhao et al., 2014). Guidance towards a location more likely to contain the target item is important in real-life search (Wolfe, 2020; Wright & Richard, 2000) with direct attention to a location enhancing responses in the visual cortex to stimuli presented there (Kastner et al., 1999).

On the one hand, using a more specific search term will reduce similarities between an item and distractors, as well as making the desired item more unique.

This will make the searching activity easier and will give less proficient players the support they need to find these items. On the other hand, using a less specific or more generic search term will increase the number of distractors, making the differences between an item and distractors less, as well as making the desired item less unique. This will make the searching activity more difficult and ensure that more proficient players are sufficiently challenged. To provide an appropriate challenge for a wide range of players, ensuring a personalized experience so that every player is in the optimal area of ZPD, five levels should be made available. These will be defined in the two dimensions identified as being important for a successful search: the description of the item (*feature guidance*) and the description of the location of the item (*scene guidance*). Examples of such a system are shown in Table 5.1.

We have proposed an ZPD-based adaptive system, which uses textual specificity to provide a personalized experience for players through real-time feedback. An empirical study will now be executed on an existing VR narrative-centered discovery game to investigate whether this system is effective in terms of reducing cognitive load (Schnotz & Kürschner, 2007), increasing learning (Kirschner et al., 2006; Mayer, 2004; Moreno, 2004; Moreno & Mayer, 2005; Shute, 2008) in both the story and spatial dimensions, and providing a positive in-game experience (i.e presence, engagement, and cognitive interest) (Hamari et al., 2016; Steiner & Voruganti, 2004; Trif, 2015). As such, the following research question will be examined:

Does an adaptive VR game result in less cognitive load and lead to better learning, as well as a better learning experience, compared to a non-adaptive game?

Based upon the above theoretical background, this initial question is decomposed into the following hypotheses:

Compared to a non-adaptive VR game, an adaptive VR game leads to:

a. A lower amount of cognitive load;

b. Higher retention of both story and spatial information;

c. Higher engagement and cognitive interest in the subject matter;

d. Without a lesser feeling of presence.

These hypotheses will be evaluated, in a randomized control study, once again, using, "the Chantry", a commercially-published VR serious game.

5.3 Methods

5.3.1 Participants

A total of 40 participants, 22 male and 18 female, aged 21-55 (mean: 31.80, standard deviation (SD): 7.27), that were residents of Utrecht, the Netherlands were recruited through email and online adverts. They had differing levels of VR experience and indicated this experience on a post-experiment questionnaire on a 5-point Likert scale (from 1 = “Used very little” to 5 = “Use all the time”, mean: 1.73, SD: 1.09). Informed consent was obtained along with information that would disqualify a participant from taking part, such as being susceptible to migraines or not having a professional comprehension of the English language. Eligible participants were randomly assigned to either the adaptive or the non-adaptive group, both consisting of 11 males and 9 females.

5.3.2 Apparatus

Game

As with the previous chapters, we will again use "the Chantry" (Steel Minions & the Jenner Trust, 2018), is a narrative-centered discovery game for PlayStation VR, which tells the story of Dr. Edward Jenner, his invention of vaccination, and the smallpox virus it helped eradicate (`https://jennermuseum.com/`). Once again, players must explore the house of the late Dr. Jenner, completing tasks by discovering items on a list to open a closed door/window shutter to progress further (see Fig. 5.1).

Hardware

Each participant wore a Sony PlayStation VR headset (model: CUH-ZVR1) to play the game on a PlayStation 4. They controlled the game using a standard PlayStation DualShock 4 controller (model: CUH-ZCT1) and wore noise-canceling over-ear headphones. To control the game, participants used their head movements to look at a movement/item node and used a single button press on the controller to jump to that node or pick up an item. An item that has been picked up is moved and rotated by doing the same action holding on to the controller as if the player is physically holding the item.

Figure 5.1: An example of a task being carried out using the node-based movement system in the Chantry, where two items need to be found to complete a task and progress to another area.

5.3.3 Measurements

Monitoring Variable

According to Jameson (2002), an adaptive system requires one or more monitoring variables to to infer characteristics of the user. This information is used to determine how to adapt the the game towards the user. As we identified navigation issues, specifically disorientation, as a key indicator of learning performance, the lostness measure (Smith, 1996), a measure of navigational efficiency, which was introduced in Chapter 2 and evaluated in Chapter 3 will be used as the monitoring variable.

Lostness considers, for an information-searching task (i.e., searching for and discovering an item), the minimum number of nodes needed to be visited, the number of unique nodes a player has visited, and the total number of nodes a player has visited, resulting in a value of between 0 and $\sqrt{2}$. 0 indicates that the task has been completed perfectly, illustrating high navigational efficiency (not disoriented) and $\sqrt{2}$ indicates that a user was completely disoriented, illustrating poor navigational efficiency. Therefore, lower lostness indicates higher navigational efficiency. To make use of the lostness measure, data must be available to determine when to adapt the game in terms of an upper threshold (i.e., poor navigational efficiency so in need of assistance) and a lower threshold (i.e., high navigational efficiency so in need of greater challenge).

As well as the data from the VR condition in Chapter 2 (n = 12), it was possible to use the control condition of Chapter 3 (n = 13) as the active interaction and explicit story structure was identical to the VR condition in Chapter 2. By analyzing the game logs of all of these participants to obtain their navigational efficiency through the lostness measure, we can use this data to determine an upper and a lower lostness threshold to determine when to induce adaptivity.

The Chantry consists of 11 tasks, with a mean number of 2.5 items (median: 3). Each task has a starting point, a door or window shutter, which can also be considered as an item to be found. Based on this, we use the navigational efficiency of a player for discovering the previous six items to determine the two thresholds as this represents around two full tasks, giving a reliable impression of the performance of the participant at that moment in the game. For the dataset, we investigated the lostness values for the previous six items (or less if six items had not been found yet) when a task was started. Altogether, this gave us 179 data points with a mean lostness of 0.427 and a standard deviation of 0.160, which followed a normal distribution. This rich dataset is extremely useful for informing an adaptive model, due to it consisting of many data points and being obtained from the target audience for the game (i.e., adolescents).

To obtain an upper and lower threshold, a K-Means Cluster analysis was performed to group all of the lostness data points into three clusters with center-points. Finding the center-point between the center-points of the lower and middle clusters will provide the lower threshold (i.e in the lower zone of ZPD, additional challenge necessary), whereas finding the center-point between the center-points of the middle and upper clusters will provide the upper threshold (i.e in the upper zone of ZPD, assistance necessary). A player between these two thresholds will be viewed as being in the correct area of ZPD for optimal learning. Although it could be argued that using five clusters would be more appropriate, one for each difficulty level, three clusters were used as the data was found to be more equally distributed with a minimal F difference and already highly significant ($F(2, 176) = 454.665, p < .001$). The center-point of the first cluster was 0.260 with 63 data points, the center-point of the second cluster was 0.454 with 81 data points, and the center-point of the third cluster was 0.665 with 35 data points. This resulted in a lower threshold of 0.357 and an upper threshold of 0.559.

Table 5.2: Means and standard deviations (SDs) of all measured variables for the 25 participants used for informing the adaptivity thresholds.

	Local Lostness	Presence	Cognitive Interest	Engagement	Story Correct Answers	Spatial Correct Answers
Mean	0.539	3.054	3.680	2.98	0.533	0.540
Std. Deviation	0.141	0.389	0.517	0.515	0.148	0.183

Overall, lostness levels were quite low across the game and, consequently, the distance between the clusters is small with more data points in the lower cluster than the upper cluster, which would indicate low game difficulty. Comparisons are not possible with other game-based research, as, despite the often-used term 'lostness' (Bidwell et al., 2007; Darken & Peterson, 2002; Power et al., 2017; Tüzün & Doğan, 2019; Wernbacher et al., 2012), game research does not make use of the measure. When comparing these values to the domain of hypertext, the origin of the lostness measure, the original author (Smith, 1996) found that a lostness value between 0.4 and 0.5 could indicate that a user is lost and certainly lost when their values were above 0.5. Moreover, our determined clusters and thresholds seem to be in line with other hypertext research (e.g., Larson & Czerwinski (1998) and Otter & Johnson (2000)). Finally, when investigating other variables measured alongside the selected lostness data points from the previous chapters (i.e. knowledge retention, engagement, presence, and cognitive interest, see Table 5.2), these values are above the middle of the scale. When combining this with low lostness values, we can determine that the game was not too easy nor too complex and was beneficial to the players. Furthermore, there is room for these values to either increase or decrease so if in-game adaptation is not successful, these values will probably drop, whereas, if this adaption is successful, these values can increase. As such, this game can be considered a good base to examine how adaptivity affects learning, navigational efficiency, and the type of experience that a player has within the game.

Post-Game Questionnaires

To evaluate in-game learning, participants were provided with a short knowledge test, consisting of 24 true/false statements about the game to gauge how well this was remembered. 16 of these questions concerned facts related to the story and 8 involved spatial aspects related to the location of items/rooms in the game.

Standardized questionnaires consisting of 5-point Likert scales were used to measure engagement (Brockmyer et al., 2009), presence (Schubert, 2003), and cognitive interest (Schraw et al., 1995).

To measure cognitive load, the NASA-TLX scale will be used. This is a highly valid cognitive load questionnaire, consisting of 6 questions, which has been used in many studies on cognitive load, including in VR research (Kamaraj et al., 2016; Lum et al., 2018; Stefanidis et al., 2007; Xu et al., 2020). To avoid the questions becoming too complicated and time-consuming, the unweighted version of the questionnaire will be used, which has been found to lead to no significant differences compared to the weighted version (Byers et al., 1989; Moroney et al., 1992).

5.3.4 Procedure

Upon being seated, participants were given instructions in both oral and written form. This involved safety information, such as not to attempt to physically grab anything and what to do in the event of motion sickness, along with their right to withdraw. This was followed by instructions on the game, including controls. Participants were then given 5 minutes to experience a simple controls tutorial before being instructed to play through the game for 30 minutes and learn about the story.

As each participant played the game, information on which tasks were started and completed, including found items and associated lostness values, were logged. In the adaptive version, when a participant started a new task, their lostness was compared to the thresholds and the difficulty changed if necessary. The task difficulty remained constant along with the labels for all items within the task.

Afterward, the participants were invited to complete the knowledge test and questionnaires. Once completed, game logs and questionnaire answers were exported and saved and all participants were debriefed and informed about the nature of the study, including how their condition differed from the full game, and the future plans for the game.

5.4 Results

To determine the differences across conditions, adaptive and non-adaptive, a Multivariate Analysis of Variance (MANOVA) was performed. For this, the presence of adaptivity was the only independent between-subjects variable. Presence, engagement, cognitive interest, and the results on the knowledge test, separated into the story and spatial aspects, were examined as dependent variables, which all followed a normal distribution. The presence of adaptivity was found to have an overall significant effect ($F(6,33) = 5.641, p < .020, \eta_p^2 = .506$). For univariate effects, it was found that cognitive load and knowledge retention, both story and spatial, were affected by the presence of adaptivity at a significant level ($p < .050$, see Fig. 5.2). There were no significant effects found for presence, engagement, and cognitive interest. The full results are shown in Table 5.3.

Table 5.3: Means, standard deviations (SDs), effect (F), significance (p) and ratio of variance (η_p^2) for the variables included in the MANOVA analysis.

	Non-Adaptive Mean (SD)	Adaptive Mean (SD)	$F(6, 33)$	p	η_p^2
Story Knowledge (0-1)	.625 (.111)	0.706 (.084)	6.817	.013	.152
Spatial Knowledge (0-1)	.525 (.165)	0.719 (.167)	13.636	.001	.264
Presence (1-5)	3.214 (.359)	3.136 (0.375)	.458	.503	.012
Cognitive Interest (1-5)	3.760 (.692)	3.580 (.652)	0.835	.367	.022
Engagement (1-5)	3.139 (.472)	2.934 (0.334)	2.395	.130	.059
Cognitive Load (0-100)	54.208 (13.111)	40.750 (13.456)	10.264	.003	.213

When comparing the results from Table 5.3 to Table 5.2, presence, engagement, and cognitive interest are similar. Moreover, for participants in the non-adaptive condition, spatial knowledge was also similar, whereas story-based knowledge was higher, which can be explained by the participants in this study being adults versus adolescents in the previous studies. This confirms that these results were representative of previous studies.

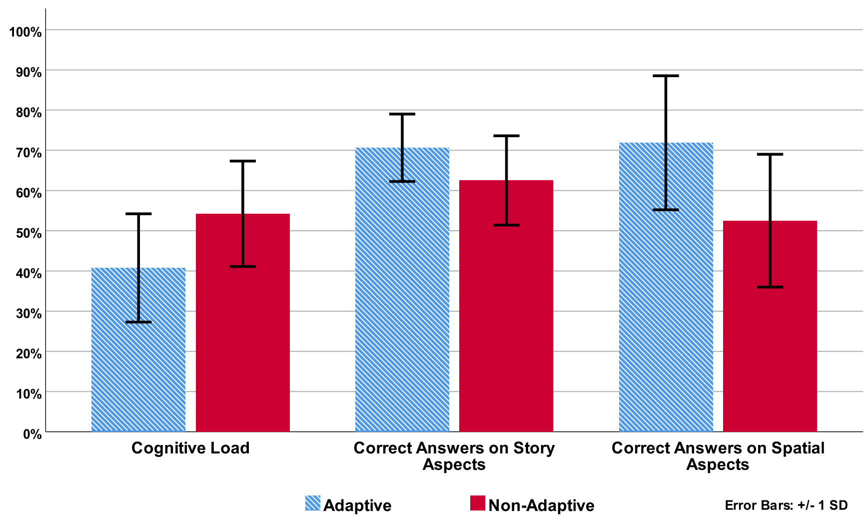


Figure 5.2: Chart showing the means of cognitive load and knowledge retention (story and spatial) for participants playing the adaptive version of the game compared to the non-adaptive version of the game. The lines indicate the mean and the shaded areas represent the standard deviation.

Overall, the mean lostness, used to inform the adaptive system, measured from the beginning of the game until the end of the play session, for players playing the adaptive version of the game was 0.473 (SD: 0.115) and 0.549 (SD: 0.135) for the non-adaptive condition. For the most part, in the adaptive version of the game, the adaptive system within the game was able to keep the average lostness of players within the optimum range to avoid cognitive overload, this is also shown by the smaller variance in the results compared to when the adaptive system was not present. As shown in Fig.5.3, lostness values followed a similar trend in both versions of the game, which follows events that occur at these points. For example, some of the higher peaks correspond to the events that lead to more of the game environment being unlocked, meaning that players need to explore more to discover these new areas and the items within them.

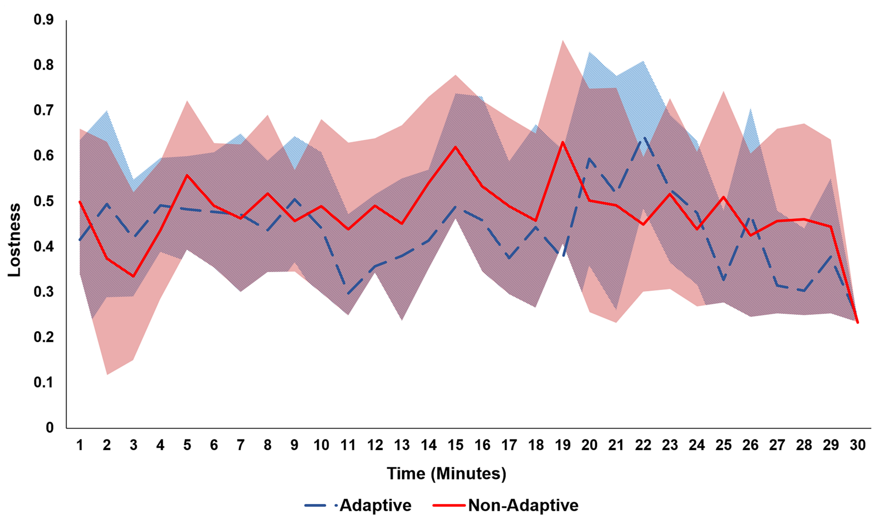


Figure 5.3: Chart showing the lostness values from the previous six items found throughout the play session for participants playing the adaptive version of the game compared to the non-adaptive version of the game.

Finally, in the adaptive condition, the average difficulty level for participants was 1.682 (SD: 1.030). However, these participants did not necessarily all experience an easier version of the game, with an average difficulty change of 0.087 (SD: 0.213) for each task, showing that participants varied in this aspect and each needed a different level of challenge. This shows the importance of personalization in games.

5.5 Discussion

In a serious Virtual Reality (VR) narrative-centered discovery game, an adaptive system was built using the principles of the Zone of Proximal Development (ZPD). This adaptive system provided a personalized experience, which provided players feedback in the form of modified labels for items part of a task in response to a player's navigational efficiency obtained from the lostness measure as players were exploring the game environment. Compared to the same game without this system, the adaptive game provided an appropriate level of challenge to player, leading to lower cognitive load (confirming hypothesis 1), higher retention of both story and spatial information (confirming hypothesis 2). Engagement, presence, and cognitive interest were not affected (rejecting hypothesis 3 and confirming hypothesis 4).

Cognitive load was also significantly lower in participants playing the adaptive game. Therefore, the support from the adaptive system in the game led to players being in the correct area of the ZPD, increased navigational efficiency, avoiding disorientation and cognitive overload, which inhibits learning (Conklin, 1987; Gwizdka & Spence, 2007; Head et al., 2000). This significantly lower average cognitive load occurred despite the additional challenge provided by the adaptive system for some players, which would have led to higher cognitive load. It appears that players being in the correct area of ZPD does indeed lead to higher learning with less effort, in the form of lower cognitive load.

For knowledge retention, the adaptive game led to significant increases in knowledge retention for both story and spatial aspects in the form of higher knowledge test scores. It appears that the lower cognitive load, reported by participants playing the adaptive version of the game, left cognitive capacity free for learning. Interestingly, this effect appeared to be stronger for spatial knowledge, compared to story knowledge. This could be due to the adaptive system giving additional location information to assist a player, which helped with remembering the location of different items with regard to their location. Moreover, there could also be limitations of the adaptive system which led to the story-based knowledge, provided by the strong audio narratives, not being recalled as well.

Finally, it was shown the experience aspects (i.e. presence, engagement, and cognitive interest) were not affected by the presence of the adaptive system. It appears as players had the same experience in each version of the game, although they were given more support in the adaptive version. It was expected that this appropriate level of challenge would lead to higher engagement and cognitive interest, in line with other findings (Hamari et al., 2016; Trif, 2015). When it comes to presence, it appears that the real-time feedback meant that players did not feel like they needed assistance so this feeling was not broken (Steiner & Voruganti, 2004).

Focusing on the adaptive system, it has been shown that the average difficulty varied for different participants, which can be interpreted as showing that a different level of challenge was needed for all participants. Therefore, for optimal learning in serious games, a personalized experience is necessary. Some participants still performed well even when the game was at the maximum difficulty, providing very generic labels. This was also observed by Tulving & Thomson (1973), who observed that "intelligent subjects in episodic memory experiments routinely encode to-be-remembered words semantically, and hence words meaningfully related to target items will serve as effective retrieval cues" (p. 359) so it can be hypothesized that these players were highly intelligent thus could still recall information despite these less-specific cues.

The adaptive system also led to some interesting effects. In some cases, the adaptive game appeared to make the start of the game easier, as players got lost whilst learning to play, resulting in them being presented with tasks at lower difficulty levels early on. Although some participants went on to complete tasks at higher difficulties, this additional support likely assisted them to grasp the game controls and gameplay itself. One participant even managed to complete the game at the second-lowest difficulty level. So, after struggling early in the game, the adaptive system provided this lower level of difficulty which resulted in more participants reaching tasks at later points of the game. The ZPD states that a learner can go further with assistance, which, if defined as how far they progressed in the game, holds true.

Although the adaptive system was successful, the higher lostness values, in certain areas, for participants playing the adaptive version of the game (see Fig. 5.3) indicates potential issues with the adaptive system. The difficulty of tasks was only set when they were started and remained constant. In some cases, a participant may have been given a difficulty level that was too high, putting them in the upper area of ZPD, and this remained the case until the task was completed or they ran out of time. It can be proposed that the timing of feedback is an important part of these systems. This is something that has been greatly investigated with a lack of agreement on when feedback should be presented. On the one hand, some researchers believe that immediate feedback prevents errors from being encoded in memory and helps the learning process (Bangert-Drowns et al., 1991; Corbett et al., 1997). On the other hand, some researchers put forward that learners may become too dependent on feedback and that delayed feedback may be more useful (Kulhavy & Anderson, 1972). In more recent game-based research, it was found that immediate feedback led to marginally better results and significantly less cognitive load (Johnson & Priest, 2014). It appears that giving struggling players additional information during a task may reduce cognitive load further, ensuring that these players are in the correct area of ZPD, and increase learning. However, such adaptivity would be one-sided as, although it is possible to give a player more information on a task if they are performing poorly, it is not possible to give them less information if they are performing well. A possible solution could be, in addition to setting task difficulty at the beginning of a task, would be to also provide additional helpful feedback for struggling players during the task if disorientation is still detected. Furthermore, as there is no map of the house, it could be that some participants still struggled with navigating at some points in the game as the additional specificity, in the form of increased location data, did not help them and resulted in further exploration and disorientation. This could also be the reason that story-based knowledge retention shows a smaller improvement than spatial-based knowledge, the discovery aspect of the game was affected more by adaptivity than the narrative-centered part of the game. Additionally, it should be noted that, as shown in Fig. 5.3, lostness values observed from both versions in the game appeared to follow the same trend, showing that some parts of the game were easier or harder than other parts. This means that the level of challenge is sometimes unable to be fully controlled by an adaptive system so some additional changes may need to be made when developing these games to ensure that this is the case.

As a final point, it must be noted that this novel adaptive system has only been tested on one game, of a specific genre, despite the general audience that participated in this study. To fully generalize these results, another empirical study should take place with a different serious game as well as making use of a larger sample should be used to investigate findings that spatial ability and gender have a significant role in multimedia learning (Heo & Toomey, 2020). Moreover, to fully evaluate the advantages and disadvantages of a textual specificity-based adaptive system, alternate forms of adaptivity should also be investigated, such as guiding a player towards an item (Steiner & Voruganti, 2004). In this regard, a new version of the lostness measure could be developed, which considers the closest item to a player to predict the next item they will discover to give a more real-time adaptive system.

In conclusion, based on ZPD (Vygotsky, 1978), we developed an adaptive system that provided a personalized experience through real-time feedback, which adapted the level of challenge in a narrative-centered discovery game based on a player's navigation efficiency. This system modified the specificity of keywords for task items to either increase or decrease the difficulty of a task so that each player faced an appropriate level of challenge to their performance. Our results showed that such a system can lead to lower levels of cognitive load, indicating that a player is in the correct area of ZPD, resulting in higher learning performance for both story and spatial aspects. This increased learning was achieved with the same feelings of engagement, presence, and cognitive interest. Follow-up research should investigate this type of adaptivity on other serious games as well as other types of adaptive systems using the lostness measure of navigational efficiency as part of a user model.

CHAPTER 6

Conclusion

"That's what games are, in the end. Teachers.
Fun is just another word for learning."
Koster (2014)

"Serious games are applications developed with game technology and game design principles for non-entertainment purposes, including games used for educational, persuasive, political, or health purposes". Westra et al., 2009. This technology is now being harnessed to enhance knowledge, skills, and other personal attributes (Shute et al., 2017) due to the realistic and compelling challenges made available (Bellotti et al., 2010). Enhancing such games with Virtual Reality (VR), can lead to higher levels of learning, at least in the spatial or visual dimension (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010). Learning using both serious games and VR have been linked with a more pleasant learning experience, in terms of greater presence (Schuemie et al., 2001), improved engagement (van den Broek, 2012), and higher cognitive interest (Parong & Mayer, 2018). As such, the use of serious games and VR in classrooms is slowly becoming more prominent. For example, over two million school children have tried Google Expeditions, an immersive VR experience launched in 2015, which promotes 'field trips to anywhere' (Charara, 2017). However, for a better VR experience, interaction with the virtual environment is more effective (Hudson et al., 2019). Recently, police in Birmingham teamed up with Virtual_Decisions to teach schoolchildren about the impact of peer pressure and gang culture(Parkes, 2020). The Virtual_Decisions VR experience places the participants in realistic scenarios where they face dilemmas and make choices, which result in various outcomes (Round Midnight, 2020). Moreover, VR is currently being used in some classrooms in the US to aid with teaching social sciences (Sobel & Jhee, 2020).

For VR serious games to be effective, a framework needs to be developed so that optimal learning can occur. A key game genre that can make use of VR to provide an immersive and interactive learning experience is narrative-centered discovery games. In these games, players are transported to another place and time period and must explore the environment to discover items and hear audio narratives that reveal the in-game story (Lester et al., 2014; Malone & Lepper, 1987). They are known for their strong storylines, often presented auditorily (Habgood et al., 2018a) and involve players freely exploring whilst solving problems (Kriz, 2010; Toh & Kirschner, 2020).

When it comes to integrating VR narrative-centered games in the curriculum, we discovered three main problems:

a. A lack of appropriate educational analytics to assess how well a player is learning

b. The differences in learning and in-game experience in VR compared to non- VR

c. Non-optimal learning within narrative-centered discovery games

The research began with the development of an educational dashboard. The goal of this dashboard works to ensure the presence of a well-defined story within a game and to measure the behavior and performance of a player within a serious game, with a node-based movement locomotion system, in real-time. These analytics, particularly the lostness measure (Smith, 1996), were then used to show that VR's advantage in the spatial dimension applies to both navigational efficiency and the retention of spatial information. Investigation then focused on the best way to display educational content in VR, with the most important finding being that fully guiding a player through a VR narrative-centered game can increase story knowledge retention, at the detriment to the in-game experience, specifically presence and cognitive interest. Finally, by developing an adaptive system based on the Zone of Proximal Development (ZPD), we were able to secure this high retention of story knowledge without the drawback of a lesser in-game experience.

The final results showed that a simple, transparent measure can be used to accurately assess how a player is performing in a VR serious game. Lostness (Smith, 1996) compares the minimum number of steps necessary to complete a task with the unique and total steps made by the player, quantifying their navigational efficiency. Moreover, by using this data, a ZPD-based novel adaptive system, making use of textual specificity to provide a personalized experience through real-time feedback was developed to ensure optimal learning.

Increased knowledge retention is, of course, the goal when it comes to serious games. However, it is also essential to preserve a positive in-game experience, in the case of engagement, presence and cognitive interest, where possible. Not only have these aspects been found to aid learning (Abdul Jabbar & Felicia, 2015; Lee et al., 2010; Van der Sluis et al., 2014), they have a large impact how involved the player becomes (Conniff et al., 2010; IJsselsteijn et al., 2001; Tussyadiah et al., 2018; Witmer & Singer, 1998) and lead to greater gratification throughout the learning process.

This research vindicated the use of VR for learning, initially showing that it was beneficial for the retention of spatial knowledge and also led to increased navigational efficiency. Although story-based knowledge did not show any improvement, this was not recalled any less compared to a non- VR condition. Moreover, with the usage of the lostness measure to inform the textual specificity-based adaptive system, the retention of story knowledge, along with the already highly-retained spatial knowledge, can be significantly increased.

Future work in this area can focus on different implementations of the lostness measure. For example, exploratory studies were executed, which investigated if lostness can be used as a predictive measure whilst the player is still trying to find an item. This research resulted in two versions of this predictive lostness measure: nearest lostness and minimal lostness. The nearest lostness measure, as the name suggests, gives the lostness to the nearest target. However, this may not always be the lowest lostness value, hence the need for the minimal lostness measure. This research found that both versions of the predictive lostness measure had a medium effect on being able to predict when a player needs assistance. Moreover, task time was also found to have a small effect. Both of these measures and task time can be valuable in serious games and should, therefore, be investigated further. This work also made use of a different system for adaptivity, using of glowing light orbs, which would guide the player to the next item that they needed to find. This adaptive system was able to increase the retention of story knowledge yet led to a lesser retention of spatial information. So, it appears that lostness can be used to inform different adaptive systems, which can have different effects on the retention of knowledge. Such lostness-based adaptive systems should be investigated for a variety of different games in order to determine the best system for different use cases. The findings of this research are available in Appendix A.

Overall, there of two major focuses for future research. The first is to investigate additional implicit, transparent, and easy-to-use analytics to measure player behavior in serious games. This can ensure that players, and how well they learn, can be effectively assessed and evaluated. Secondly, different types of adaptive systems, offering different kinds of real-time feedback to provide a personalized experience must be investigated and evaluated to examine their effect on learning. It could be that different adaptive systems can have a variety of different effects on both learning and in-game experience. Moreover, these effects could vary across different games and game genres.

The use of the findings in this thesis are not limited to simply playing games at home, where video games are often played. In fact, narrative-centered VR games can be used in the classroom or in museums. Digital exhibits, particularly ones involving games or VR are becoming quite common (Chang et al., 2018; Efstratios et al., 2018; Hepperle et al., 2020). Moreover, a VR headset is made available at Dr. Jenner's House, Museum, and Gardens so that the Chantry can be played within the museum. The only obvious problem to using the same adaptive system, as described in Chapter 5, would be if different players tried to play the game during the same play session. This would result in an incorrect player model as the lostness values would be obtained from different players. Augmented reality, which works to seamlessly integrate both real-world and virtual objects (He et al., 2018), is also becoming more popular in museum exhibits (He et al., 2018). As long as such exhibits feature the same information-searching tasks as in the Chantry, there is no reason why the lostness measure can't be used. However, further research will need to be carried out to confirm this.

To fully generalize the results proposed in this thesis to a wider range of games, further research must be carried out. For example, the Chantry, featured a node-based locomotion system, which made the lostness measure applicable. Teleportation, which node-based movement can be categorized under, is one of the most common methods of VR locomotion (Clifton & Palmisano, 2020; Paris et al., 2019). One major advantages of this system is directing the attention of the player (Habgood et al., 2018b), which is beneficial in serious games. Other advantages include a reduced risk of motion sickness, hence its ubiquity in VR, and avoiding the need for computationally-expensive collision detection, which is useful for projects with a low development budget (Habgood et al., 2018b).

As the node-based locomotion system is so common in VR, there are many games that the lostness measure can be applied to. Such games include Batman Arkham VR (Rocksteady Studios, 2016), Chronos (Gunfire Games, 2016), Dead Secret (Robot Invader, 2015), and the critically acclaimed 2020 VR game, Half life: Alyx (Valve, 2020). When it comes to games that do not use a node-based movement or a teleportation locomotion system, the use of the lostness measure for analytics may be more difficult. Nevertheless, using trigger zones to represent the nodes necessary to use the lostness measure could be a way of implementing the lostness measure in games using a traditional free movement locomotion system, expanding this research further. Applying this research to a variety of games and different movement systems could cement the findings of this research and lead to VR serious games complementing traditional education to enhance learning outcomes.

This research can also be generalized outside of serious games. Going back to what we discussed in Chapter 2, the analytics introduced, including lostness can be used for all games where there are searching tasks. The requirements for the use of the lostness measure is as follows:

It was pointed out in Chapter 2 that care should be taken to avoid the halting problem (Burkholder, 1987), which is unlikely in serious games as an optimal path and a reachable state in necessary for unambiguous feedback and assessment. However, in regular games, this is not always the case. The halting problem, of course, can be avoided by emphasizing the following requirements for using the lostness measure:

- A task must be able to be defined as a minimum number of steps to be taken
- A task must have a distinct start and end point that can be reached
- A player's actions must be able to be defined in terms of total steps and unique steps

By using these requirements, the lostness measure can be applied to traditional games. In particular, the information-searching tasks present in serious games are actually common in traditional games. To use one such example from my Childhood, Harry Potter and the Philosophers Stone was released for the PlayStation console in 2001 by Argonaut Games (Argonaut Games, 2001). The game is a third-person action adventure game where the player controls Harry Potter. One of the tasks is to find a missing sloth brain. Firstly, the task starts when the player is informed that the sloth brain is missing. By following a map, the player finds a locked door, casts a spell to unlock it, and, after defeating a troll, finds the sloth brain. The task ends when it is returned to the dungeon. This task has a starting point (i.e. when the player is informed the sloth brain is missing) and an end point (i.e. when the sloth brain is returned. Provided that this task can be defined in a certain number of steps and player actions can be defined in terms of total steps and unique steps, the lostness measure can be used. Such measures could be used to provide a personalized experience to a player through an adaptive system.

Adaptive systems have been used in a variety of mainstream games where they are often referred to as 'dynamic difficulty adjustment'. The 2008 game Left 4 Dead presented the "The AI Director" (Valve, 2008), which was used to generate a personalized and unique experience for a player every time. On 25 March 2021, a patent by Electronic Arts (EA) was published, titled 'dynamic difficulty adjustment' (Aghdaie et al., 2019). As EA is responsible for many mainstream titles, particularly the FIFA franchise (Games, 2020), such functionality should become more common and lead to a better gaming experience.

Despite the advantages of an adaptive system, care must be taken so that this functionality is not abused. EA have been accused of abusing this technology to push players into purchasing more loot boxes. Loot boxes are virtual items in video games that contain randomized contents that can improve player performance, which are often paid for using real-world money (Zendle & Cairns, 2018). Such items are found to be highly related to problem gambling (Zendle & Cairns, 2018; Zendle & Cairns, 2019), which is a major issue as these items are marketed towards children. The release of Star Wars: Battlefront 2 by EA led to huge criticism due to the implementation of these loot boxes, leading to accusations that the game was 'pay-to-win' (Dingman, 2017). After this controversy, loot boxes were ruled as games of chance in some countries, particularly Belgium and the Netherlands (België, 2018; Nederland, 2018), making them subject to further legislation and effectively outlawing them. Recently a class action lawsuit in California has accused EA of using an adaptive system to push players into buying these loot boxes, which can help improve their performance (Hustia, 2020). Despite a rebuttal from EA, expressing that the claims are "baseless and misrepresent our games" (Valentine, 2020), it is a warning that such systems can just as easily be abused as well as be used for social good.

In conclusion, we have provided effective real-time analytics for assessing player learning in VR narrative-centered games. This led to the development of an adaptive system, which showed it was possible to provide an optimal, personalized learning experience, with little cost or development. Moreover, such a personalized experience can be delivered using only a small dataset to inform the thresholds. One the way to developing this solution, advantages that VR presentation of a game had over a non-VR presentation were identified, along with the effect that an explicit story structure had on players compared to an implicit story structure and the effect of a full interactive game vs a guided tour.

The findings produced in this thesis provide information that can advance VR narrative-centered serious games for teaching in the classroom, museums, and in the home. Such findings are timely as, in the wake of the COVID-19 pandemic, workplaces, schools and museums are closed so both adults and children have to spend extended periods at home, which has resulted in a huge increase in digital media consumption (Samaroudi et al., 2020). On the one hand, many museums and cultural heritage institutions were able to adapt to this situation and accelerated digital transformation of the content that is usually provided onsite (Agostino et al., 2021; Samaroudi et al., 2020). On the other hand, a lack of institutions made use of VR for virtual visits, which was due to a lack of investment in this area (Samaroudi et al., 2020). VR is something that enhances overall tour experiences and increase the likelihood of a physical visit. (El-Said & Aziz, 2021; Lee et al., 2020; Sarkady et al., 2021) and there is a growing demand for such experiences as people appear to be more likely to take part in such experiences during the pandemic (Itani & Hollebeek, 2021). Nonetheless, as highlighted by the controversy over EA's planned use of adaptive systems, care must be taken to avoid the abuse of this functionality to exploit it players for financial gain.

In the Introduction, I asked if the holodeck is no longer fiction. I pointed out that, before we end up with such a system, or in a world like *Ready Player One* (Cline, 2011), where VR and other interactive technologies are used ubiquitously for education many choices must be made when developing serious games for VR to realize optimal learning. This thesis has provided guidance for the development of such games. In this regard, if game developers continue to provide appropriate in-game analytics for learning and systems that provide a personalized experience for optimal learning, the mass adoption of games technology and VR for educational purposes can become widespread. To end with another two quotes from Jean-Luc Picard, "Every choice we make allows us to manipulate the future" (Berman, 1991) and "Things are only impossible until they're not" (Berman, 1991).

Bibliography

[1] Abdul Jabbar, A. I. & Felicia, P., "Gameplay engagement and learning in game-based learning: a systematic review", *Review of Educational Research*, vol. 85, no. 4, 2015, pp. 740–779, DOI: 10.3102/0034654315577210.

[2] Adams, D. M., Mayer, R. E., MacNamara, A., Koenig, A. & Wainess, R., "Narrative games for learning: testing the discovery and narrative hypotheses.", *Journal of Educational Psychology*, vol. 104, no. 1, 2012, pp. 235–249, DOI: 10.1037/a0025595.

[3] Aghdaie, N., Kolen, J., Mattar, M. M., Sardari, M., Xue, S., Zaman, K. A.-u. & Moss, K. A., *Dynamic difficulty adjustment*, US Patent 10,286,323, May 2019.

[4] Agostino, D., Arnaboldi, M. & Lema, M. D., "New development: covid-19 as an accelerator of digital transformation in public service delivery", *Public Money & Management*, vol. 41, no. 1, 2021, pp. 69–72, DOI: 10.1080/09540962.2020.1764206.

[5] al., P. R. et, *ACM SIGSOFT Empirical Standards*, Oct. 2020, URL: https://github.com/acmsigsoft/EmpiricalStandards.

[6] Alhalabi, W., "Virtual reality systems enhance students' achievements in engineering education", *Behaviour & Information Technology*, vol. 35, no. 11, 2016, pp. 919–925, DOI: 10.1080/0144929X.2016.1212931.

[7] Allcoat, D. & Mühlenen, A. von, "Learning in virtual reality: effects on performance, emotion and engagement", *Research in Learning Technology*, vol. 26, Nov. 2018, DOI: 10.25304/rlt.v26.2140.

[8] Alonso-Fernandez, C., Rotaru, D. C., Freire, M., Martinez-Ortiz, I. & Fernandez-Manjon, B., "Full lifecycle architecture for serious games: integrating game learning analytics and a game authoring tool", in: *Serious Games*, ed. by Alcañiz, M., Göbel, S., Ma, M., Fradinho Oliveira, M., Baalsrud Hauge, J. & Marsh,

T., Cham: Springer, Nov. 2017, pp. 73–84, ISBN: 978-3-319-70111-0, DOI: 10.1007/978-3-319-70111-0_7.

[9] An, B., Matteo, F., Epstein, M. & Brown, D., "Comparing the performance of an immersive virtual reality and traditional desktop cultural game", in: *Proceedings of the 2nd International Conference on Computer-Human Interaction Research and Applications (CHIRA2018)*, Funchal, Madeira, Portugal: Insticc, Jan. 2018, pp. 54–61, DOI: 10.5220/0006922800540061.

[10] Andersen, E., Liu, Y.-E., Apter, E., Boucher-Genesse, F. & Popović, Z., "Gameplay analysis through state projection", in: *Proceedings of the Fifth International Conference on the Foundations of Digital Games*, FDG '10, New York, NY, USA: Association for Computing Machinery, 2010, 1–8, ISBN: 9781605589374, DOI: 10.1145/1822348.1822349.

[11] Andersen, S. A. W., Mikkelsen, P. T., Konge, L., Cayé-Thomasen, P. & Sørensen, M. S., "Cognitive load in distributed and massed practice in virtual reality mastoidectomy simulation", *The Laryngoscope*, vol. 126, no. 2, 2016, E74–E79, DOI: 10.1002/lary.25449.

[12] Andersen, S. A. W., Mikkelsen, P. T., Konge, L., Cayé-Thomasen, P. & Sørensen, M. S., "The effect of implementing cognitive load theory-based design principles in virtual reality simulation training of surgical skills: a randomized controlled trial", *Advances in Simulation*, vol. 1, no. 1, 2016, p. 20, DOI: 10.1186/s41077-016-0022-1.

[13] Argonaut Games, *Harry Potter and the Philosopher's Stone*, 2001.

[14] Armstrong, M. B. & Landers, R. N., "An evaluation of gamified training: using narrative to improve reactions and learning", *Simulation & Gaming*, vol. 48, no. 4, 2017, pp. 513–538, DOI: 10.1177/1046878117703749.

[15] Arnaldi, B., Guitton, P. & Moreau, G., *Virtual reality and augmented reality : myths and realities*, London, UK: ISTE Ltd. John Wiley & Sons, Inc, 2018, ISBN: 9781786301055.

[16] Association, E. S., *2020 Essential Facts About the Video Game Industry*, Oct. 2020, URL: https://www.theesa.com/esa-research/2020-essential-facts-about-the-video-game-industry/.

[17] Auvinen, T., Hakulinen, L. & Malmi, L., "Increasing students' awareness of their behavior in online learning environments with visualizations and achievement badges", *IEEE Transactions on Learning Technologies*, vol. 8, no. 3, Sept. 2015, pp. 261–273.

[18] Baddeley, A., Lewis, V., Eldridge, M. & Thomson, N., "Attention and retrieval from long-term memory.", *Journal of Experimental Psychology: General*, vol. 113, no. 4, 1984, pp. 518–540, DOI: 10.1037/0096-3445.113.4.518.

[19] Bangert-Drowns, R. L., Kulik, C.-L. C., Kulik, J. A. & Morgan, M., "The instructional effect of feedback in test-like events", *Review of Educational Research*, vol. 61, no. 2, 1991, pp. 213–238, DOI: 10.3102/00346543061002213.

[20] Barnet, B., *The SAGE Handbook of Web History*, 55 City Road: SAGE Publications Ltd, 2019, DOI: 10.4135/9781526470546.

[21] Bartlett, F. C., *Remembering: A Study in Experimental and Social Psychology.* Remembering: A study in experimental and social psychology. New York, NY, US: Cambridge University Press, 1932, pp. xix, 317–xix, 317, ISBN: 0-521-48278-X (Hardcover); 0-521-48356-5 (Paperback).

[22] Beheshti, J., "Teens, virtual environments and information literacy", *Bulletin of the American Society for Information Science and Technology*, vol. 38, no. 3, 2012, pp. 54–57, DOI: 10.1002/bult.2012.1720380313.

[23] Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S. & Gain, J., "A survey of augmented, virtual, and mixed reality for cultural heritage", *J. Comput. Cult. Herit.*, vol. 11, no. 2, Mar. 2018, DOI: 10.1145/3145534.

[24] België, K., *Belgische Kansspelcommissie oordeelt na analyse: "Betalende loot boxen zijn kansspelen"*, (Accessed on 04/14/2021), Apr. 2018, URL: https://www.gamingcommission.be/opencms/opencms/jhksweb_nl/gamingcommission/news/news_0061.html.

[25] Bellotti, F., Berta, R. & Gloria, A. D., "Designing effective serious games: opportunities and challenges for research", *International Journal of Emerging Technologies in Learning (iJET)*, vol. 5, no. SI3, 2010, pp. 22–35.

[26] Berkman, M. I. & Akan, E., "Presence and immersion in virtual reality", in: *Encyclopedia of Computer Graphics and Games*, ed. by Lee, N., Cham: Springer International Publishing, 2019, pp. 1–10, ISBN: 978-3-319-08234-9, DOI: 10.1007/978-3-319-08234-9_162-1.

[27] Berman, R., *A Matter of Time*, Jan. 1991.

[28] Bethke, E., *Game Development and Production*, Plano, Tex: Wordware Pub, Jan. 2002, ISBN: 978-1556229510.

[29] Bidwell, N. J., Lemmon, C., Roturu, M. & Lueg, C., "Exploring terra incognita: wayfinding devices for games", in: *Proceedings of the 4th Australasian Conference on Interactive Entertainment*, IE '07, Melbourne, Australia: RMIT University, 2007, pp. 1–8, ISBN: 9781921166877.

[30] Biggin, R., “Follow the story: narrative and immersion”, in: *Immersive Theatre and Audience Experience: Space, Game and Story in the Work of Punchdrunk*, Cham: Springer International Publishing, 2017, pp. 113–133, ISBN: 978-3-319-62039-8, DOI: 10.1007/978-3-319-62039-8_5.

[31] Bodily, R. & Verbert, K., “Review of research on student-facing learning analytics dashboards and educational recommender systems”, *IEEE Transactions on Learning Technologies*, vol. 10, no. 4, Dec. 2017, pp. 405–418.

[32] Bolter, J, *Writing space: computers, hypertext, and the remediation of print*, Mahwah, N.J: Lawrence Erlbaum Associates, 2000, ISBN: 978-0805829198.

[33] Bopp, M, “Storytelling as a motivational tool in digital learning games”, in: *Didactics of Microlearning*, ed. by Hug, T, Münster, Germany: Waxmann Verlag GmbH., 2016, pp. 250–266, ISBN: 3830918690.

[34] Boutonnet, B. & Lupyan, G., “Words jump-start vision: a label advantage in object recognition”, *Journal of Neuroscience*, vol. 35, no. 25, 2015, pp. 9329–9335, DOI: 10.1523/JNEUROSCI.5111-14.2015.

[35] Brockmyer, J. H., Fox, C. M., Curtiss, K. A., McBroom, E., Burkhart, K. M. & Pidruzny, J. N., “The development of the game engagement questionnaire: a measure of engagement in video game-playing”, *Journal of Experimental Social Psychology*, vol. 45, no. 4, 2009, pp. 624–634, DOI: 10.1016/j.jesp.2009.02.016.

[36] Brooks, B. M., “The specificity of memory enhancement during interaction with a virtual environment”, *Memory*, vol. 7, no. 1, 1999, pp. 65–78, DOI: 10.1080/741943713.

[37] Brusk, J., Lager, T., Hjalmarsson, A. & Wik, P., “Deal: dialogue management in scxml for believable game characters”, in: *Proceedings of the 2007 Conference on Future Play*, Future Play ’07, New York, NY, USA: Association for Computing Machinery, 2007, 137–144, ISBN: 9781595939432, DOI: 10.1145/1328202.1328227.

[38] Burkholder, L, “The halting problem”, *SIGACT News*, vol. 18, no. 3, Apr. 1987, 48–60, DOI: 10.1145/24658.24665.

[39] Byers, J. C., Bittner, A. C. & Hill, S. G., “Traditional and raw task load index (tlx) correlations: are paired comparisons necessary?”, in: *Advances in industrial ergonomics & safety*, ed. by Mital, A, London: Taylor & Francis, 1989, pp. 481–485.

[40] Caballero-Hernández, J. A., Palomo-Duarte, M. & Dodero, J. M., “Skill assessment in learning experiences based on serious games: a systematic map-

ping study", *Computers & Education*, vol. 113, 2017, pp. 42–60, DOI: 10.1016/j.compedu.2017.05.008.

[41] Calvert, J. & Abadia, R., "Impact of immersing university and high school students in educational linear narratives using virtual reality technology", *Computers & Education*, vol. 159, 2020, p. 104005, DOI: 10.1016/j.compedu.2020.104005.

[42] Calvo, A., Rotaru, D. C., Freire, M. & Fernandez-Manjon, B., "Tools and approaches for simplifying serious games development in educational settings", in: *2016 IEEE Global Engineering Education Conference (EDUCON)*, Apr. 2016, pp. 1188–1197.

[43] Carletti, V., Foggia, P., Saggese, A. & Vento, M., "Challenging the time complexity of exact subgraph isomorphism for huge and dense graphs with vf3", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 40, no. 4, Apr. 2018, pp. 804–818, DOI: 10.1109/TPAMI.2017.2696940.

[44] Carmichael, L., Hogan, H. P. & Walter, A. A., "An experimental study of the effect of language on the reproduction of visually perceived form.", *Journal of Experimental Psychology*, vol. 15, no. 1, 1932, pp. 73–86, DOI: 10.1037/h0072671.

[45] Carrozzino, M. & Bergamasco, M., "Beyond virtual museums: experiencing immersive virtual reality in real museums", *Journal of Cultural Heritage*, vol. 11, no. 4, 2010, pp. 452–458, DOI: 10.1016/j.culher.2010.04.001.

[46] Chang, H.-L., Shih, Y.-C., Wang, K., Tsaih, R.-H. & Lin, Z., "Using virtual reality for museum exhibitions: the effects of attention and engagement for national palace museum.", in: *PACIS 2018 Proceedings*, 2018, p. 145.

[47] Chang, Y.-S., Chen, Y.-S. & Chiang, C.-W., "The differences in pleasing value and learning performance among different groups using mobile augmented reality system for cultural environment learning", *Multimedia Tools and Applications*, vol. 78, no. 4, Feb. 2019, pp. 4965–4986, DOI: 10.1007/s11042-018-6928-y.

[48] Charara, S., *Over two million school kids have gone on Google Expeditions*, (Accessed on 03/29/2021), May 2017, URL: https://www.wareable.com/vr/expeditions-two-million-cardboard-6665.

[49] Checa, D. & Bustillo, A., "A review of immersive virtual reality serious games to enhance learning and training", *Multimedia Tools and Applications*, vol. 79, no. 9, 2020, pp. 5501–5527, DOI: 10.1007/s11042-019-08348-9.

[50] Chen, C. J. & Fauzy, W., “Guiding exploration through three-dimensional virtual environments: a cognitive load reduction approach”, *Journal of Interactive Learning Research*, vol. 19, Jan. 2008.

[51] Chen, F., *Robust multimodal cognitive load measurement*, Cham, Switzerland: Springer, 2016, ISBN: 978-3-319-31698-7.

[52] Chen, Q. & Luo, D., “The comparison and analysis of several common vr panoramic display methods”, in: *3rd International Conference on Mechatronics Engineering and Information Technology (ICMEIT 2019)*, Atlantis Press, 2019, pp. 357–363, ISBN: 978-94-6252-708-9, DOI: 10.2991/icmeit-19.2019.59.

[53] Christou, C. G. & Bülthoff, H. H., “View dependence in scene recognition after active learning”, *Memory & Cognition*, vol. 27, no. 6, 1999, pp. 996–1007, DOI: 10.3758/bf03201230.

[54] Clark, D. B., Virk, S. S., Barnes, J. & Adams, D. M., “Self-explanation and digital games: adaptively increasing abstraction”, *Computers & Education*, vol. 103, 2016, pp. 28–43, DOI: 10.1016/j.compedu.2016.09.010.

[55] Clifton, J. & Palmisano, S., “Effects of steering locomotion and teleporting on cybersickness and presence in hmd-based virtual reality”, *Virtual Reality*, vol. 24, no. 3, Sept. 2020, pp. 453–468, DOI: 10.1007/s10055-019-00407-8.

[56] Cline, E., *Ready player one*, New York: Crown Publishers, 2011, ISBN: 978-1524763282.

[57] Clow, D., “An overview of learning analytics”, *Teaching in Higher Education*, vol. 18, no. 6, 2013, pp. 683–695.

[58] Coburn, J. Q., Freeman, I. & Salmon, J. L., “A Review of the Capabilities of Current Low-Cost Virtual Reality Technology and Its Potential to Enhance the Design Process”, *Journal of Computing and Information Science in Engineering*, vol. 17, no. 3, July 2017, DOI: 10.1115/1.4036921.

[59] Conklin, J., “Hypertext: an introduction and survey”, *Computer*, vol. 20, no. 09, Sept. 1987, pp. 17–41, DOI: 10.1109/mc.1987.1663693.

[60] Conniff, A., Craig, T., Laing, R. & Galán-Díaz, C., “A comparison of active navigation and passive observation of desktop models of future built environments”, *Design Studies*, vol. 31, no. 5, 2010, pp. 419–438, DOI: 10.1016/j.destud.2010.04.003.

[61] Corbeil, P., “History and simulation/gaming: living with two solitudes”, *Simulation & Gaming*, vol. 42, no. 4, 2011, pp. 418–422, DOI: 10.1177/1046878108325440.

[62] Corbett, A. T., Koedinger, K. R. & Anderson, J. R., "Chapter 37 - intelligent tutoring systems", in: *Handbook of Human-Computer Interaction (Second Edition)*, ed. by Helander, M. G., Landauer, T. K. & Prabhu, P. V., Second Edition, Amsterdam: North-Holland, 1997, pp. 849–874, ISBN: 978-0-444-81862-1, DOI: 10.1016/B978-044481862-1.50103-5.

[63] Cordova, D. I. & Lepper, M. R., "Intrinsic motivation and the process of learning: beneficial effects of contextualization, personalization, and choice.", *Journal of Educational Psychology*, vol. 88, no. 4, 1996, pp. 715–730, DOI: 10.1037/0022-0663.88.4.715.

[64] Cunningham, L., "An adaptive model for digital game based learning", PhD thesis, University College Cork, 2019.

[65] Darken, R. P. & Peterson, B., "Spatial orientation, wayfinding, and representation.", in: *Human factors and ergonomics. Handbook of virtual environments: Design, implementation, and application*, ed. by Stanney, K. M., Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers, 2002, pp. 493–518, ISBN: 0-8058-3270-X (Hardcover).

[66] Darken, R. P. & Sibert, J. L., "Navigating large virtual spaces", *International Journal of Human–Computer Interaction*, vol. 8, no. 1, 1996, pp. 49–71, DOI: 10.1080/10447319609526140.

[67] Darken, R. P. & Sibert, J. L., "A toolset for navigation in virtual environments", in: *Proceedings of the 6th Annual ACM Symposium on User Interface Software and Technology*, Uist '93, New York, NY, USA: Association for Computing Machinery, 1993, 157–165, ISBN: 089791628x, DOI: 10.1145/168642.168658.

[68] Desai, P. R., Desai, P. N., Ajmera, K. D. & Mehta, K., "A review paper on oculus rift-a virtual reality headset", *International Journal of Engineering Trends and Technology*, vol. 13, no. 4, 2014, pp. 175–179.

[69] Dickey, M. D., "Game design narrative for learning: appropriating adventure game design narrative devices and techniques for the design of interactive learning environments", *Educational Technology Research and Development*, vol. 54, no. 3, June 2006, pp. 245–263, DOI: 10.1007/s11423-006-8806-y.

[70] Dickey, M. D., "Murder on grimm isle: the impact of game narrative design in an educational game-based learning environment", *British Journal of Educational Technology*, vol. 42, no. 3, 2011, pp. 456–469.

[71] Dingman, H., *How loot boxes are ruining games and making them unfair*, (Accessed on 04/14/2021), Oct. 2017, URL: https://www.pcworld.com/article/3231668/loot-boxes-ruining-gaming.html.

[72] Duncan, J. & Humphreys, G. W., "Visual search and stimulus similarity.", *Psychological Review*, vol. 96, no. 3, 1989, pp. 433–458, DOI: 10.1037/0033-295X.96.3.433.

[73] Efstratios, G., Michael, T., Stephanie, B., Athanasios, L., Paul, Z. & George, P., "New cross/augmented reality experiences for the virtual museums of the future", in: *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*, ed. by Ioannides, M., Fink, E., Brumana, R., Patias, P., Doulamis, A., Martins, J. & Wallace, M., Cham: Springer International Publishing, 2018, pp. 518–527, ISBN: 978-3-030-01762-0.

[74] El-Said, O. & Aziz, H., "Virtual tours a means to an end: an analysis of virtual tours' role in tourism recovery post covid-19", *Journal of Travel Research*, 2021, DOI: 10.1177/0047287521997567.

[75] Elman, J. L. & McRae, K., "A model of event knowledge.", *Psychological Review*, vol. 126, no. 2, Jan. 2019, pp. 252–291, DOI: 10.1037/rev0000133.

[76] Feng, Z., González, V. A., Amor, R., Lovreglio, R. & Cabrera-Guerrero, G., "Immersive virtual reality serious games for evacuation training and research: a systematic literature review", *Computers & Education*, vol. 127, 2018, pp. 252–266, DOI: 10.1016/j.compedu.2018.09.002.

[77] Ferguson, C., Broek, E. L. van den, Oostendorp, H. van, Redelijkheid, S. de & Giezeman, G.-J., "Virtual reality aids game navigation: evidence from the hypertext lostness measure", *Cyberpsychology, Behavior, and Social Networking*, vol. 23, no. 9, 2020, pp. 635–641, DOI: 10.1089/cyber.2019.0435.

[78] Ferguson, C., Van den Broek, E. L. & Van Oostendorp, H., "On the role of interaction mode and story structure in virtual reality serious games", *Computers & Education*, vol. 143, no. 103671, 2020, DOI: 10.1016/j.compedu.2019.103671.

[79] Ferguson, C., van Oostendorp, H. & van den Broek, E. L., "The development and evaluation of the storyline scaffolding tool", in: *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, Sept. 2019, pp. 1–8, DOI: 10.1109/VS-Games.2019.8864538.

[80] Flavián, C., Ibáñez-Sánchez, S. & Orús, C., "Impacts of technological embodiment through virtual reality on potential guests' emotions and engage-

ment", *Journal of Hospitality Marketing & Management*, vol. 0, no. 0, 2020, pp. 1–20, DOI: 10.1080/19368623.2020.1770146.

[81] Flink, C., Boggiano, A. K. & Barrett, M., "Controlling teaching strategies: undermining children's self-determination and performance.", *Journal of Personality and Social Psychology*, vol. 59, no. 5, 1990, pp. 916–924, DOI: 10.1037/0022-3514.59.5.916.

[82] Flowerday, T. & Schraw, G., "Teacher beliefs about instructional choice: a phenomenological study.", *Journal of Educational Psychology*, vol. 92, no. 4, 2000, pp. 634–645, DOI: 10.1037/0022-0663.92.4.634.

[83] Flowerday, T., Schraw, G. & Stevens, J., "The role of choice and interest in reader engagement", *The Journal of Experimental Education*, vol. 72, no. 2, 2004, pp. 93–114, DOI: 10.3200/jexe.72.2.93-114.

[84] Fowler, C., "Virtual reality and learning: where is the pedagogy?", *British Journal of Educational Technology*, vol. 46, no. 2, 2015, pp. 412–422, DOI: 10.1111/bjet.12135.

[85] Fredricks, J. A., Blumenfeld, P. C. & Paris, A. H., "School engagement: potential of the concept, state of the evidence", *Review of Educational Research*, vol. 74, no. 1, 2004, pp. 59–109, DOI: 10.3102/00346543074001059.

[86] Furlough, C. S. & Gillan, D. J., "Mental models: structural differences and the role of experience", *Journal of Cognitive Engineering and Decision Making*, vol. 12, no. 4, 2018, pp. 269–287, DOI: 10.1177/1555343418773236.

[87] Gadelha, R., "Revolutionizing education: the promise of virtual reality", *Childhood Education*, vol. 94, no. 1, 2018, pp. 40–43, DOI: 10.1080/00094056.2018.1420362.

[88] Games, E., *FIFA 21 - Football Video Game from EA SPORTS*, (Accessed on 04/14/2021), 2020, URL: https://www.ea.com/games/fifa/fifa-21.

[89] Garneli, V., Giannakos, M. & Chorianopoulos, K., "Serious games as a malleable learning medium: the effects of narrative, gameplay, and making on students' performance and attitudes", *British Journal of Educational Technology*, vol. 48, no. 3, 2017, pp. 842–859, DOI: 10.1111/bjet.12455.

[90] Garner, R. & Gillingham, M. G., "Topic knowledge, cognitive interest, and text recall", *The Journal of Experimental Education*, vol. 59, no. 4, 1991, pp. 310–319, DOI: 10.1080/00220973.1991.10806569.

[91] Gathercole, S. E., Pickering, S. J., Ambridge, B. & Wearing, H., "The structure of working memory from 4 to 15 years of age.", *Developmental Psychology*, vol. 40, no. 2, 2004, pp. 177–190, DOI: 10.1037/0012-1649.40.2.177.

[92] Gaunet, F., Vidal, M., Kemeny, A. & Berthoz, A., "Active, passive and snapshot exploration in a virtual environment: influence on scene memory, reorientation and path memory", *Cognitive Brain Research*, vol. 11, no. 3, 2001, pp. 409–420, DOI: 10.1016/S0926-6410(01)00013-1.

[93] Gleicher, M., Albers, D., Walker, R., Jusufi, I., Hansen, C. D. & Roberts, J. C., "Visual comparison for information visualization", *Information Visualization*, vol. 10, no. 4, Oct. 2011, 289–309, DOI: 10.1177/1473871611416549.

[94] Göbel, S., Wendel, V., Ritter, C. & Steinmetz, R., "Personalized, adaptive digital educational games using narrative game-based learning objects", in: *Entertainment for Education. Digital Techniques and Systems*, ed. by Zhang, X., Zhong, S., Pan, Z., Wong, K. & Yun, R., Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 438–445, ISBN: 978-3-642-14533-9.

[95] Gombolay, M. C., Jensen, R. E. & Son, S., "Machine learning techniques for analyzing training behavior in serious gaming", *IEEE Transactions on Games*, vol. 11, no. 2, June 2019, pp. 109–120, DOI: 10.1109/TCIAIG.2017.2754375.

[96] Gonizzi Barsanti, S., Caruso, G., Micoli, L., Covarrubias Rodriguez, M, Guidi, G., et al., "3d visualization of cultural heritage artefacts with virtual reality devices", in: *25th International CIPA Symposium 2015*, vol. 40, 5W7, Copernicus Gesellschaft mbH, 2015, pp. 165–172.

[97] Graesser, A. C., Hauft-Smith, K., Cohen, A. D. & Pyles, L. D., "Advanced outlines, familiarity, and text genre on retention of prose", *The Journal of Experimental Education*, vol. 48, no. 4, 1980, pp. 281–290, DOI: 10.1080/00220973.1980.11011745.

[98] Grolnick, W. S. & Ryan, R. M., "Autonomy in children's learning: an experimental and individual difference investigation.", *Journal of Personality and Social Psychology*, vol. 52, no. 5, 1987, pp. 890–898, DOI: 10.1037/0022-3514.52.5.890.

[99] Gunfire Games, *Chronos*, 2016, URL: https://www.oculus.com/experiences/rift/929508627125435/.

[100] Gursoy, M. E., Inan, A., Nergiz, M. E. & Saygin, Y., "Privacy-preserving learning analytics: challenges and techniques", *IEEE Transactions on Learning Technologies*, vol. 10, no. 1, Mar. 2017, pp. 68–81.

[101] Gustafsson, A., Katzeff, C. & Bang, M., "Evaluation of a pervasive game for domestic energy engagement among teenagers", *Comput. Entertain.*, vol. 7, no. 4, 2010, DOI: 10.1145/1658866.1658873.

[102] Gwizdka, J. & Spence, I., “Implicit measures of lostness and success in web navigation”, *Interacting with Computers*, vol. 19, no. 3, May 2007, 357–369, DOI: 10.1016/j.intcom.2007.01.001.

[103] Habgood, J., Moore, D., Alapont, S., Ferguson, C. & Oostendorp, H. van, “The reveal educational environmental narrative framework for playstation vr”, in: *Proceedings of the 12th European conference on games based learning*, ed. by Ciussi, M., Sophia Antipolis, France: Academic Conferences and Publishing International Limited, 2018, pp. 175–183.

[104] Habgood, M. P. J. & Ainsworth, S. E., “Motivating children to learn effectively: exploring the value of intrinsic integration in educational games”, *Journal of the Learning Sciences*, vol. 20, no. 2, Apr. 2011, pp. 169–206, DOI: 10.1080/10508406.2010.508029.

[105] Habgood, M. P. J., Moore, D., Wilson, D. & Alapont, S., “Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique”, in: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2018, pp. 371–378, DOI: 10.1109/VR.2018.8446130.

[106] Hamari, J., Shernoff, D. J., Rowe, E., Coller, B., Asbell-Clarke, J. & Edwards, T., “Challenging games help students learn: an empirical study on engagement, flow and immersion in game-based learning”, *Computers in Human Behavior*, vol. 54, 2016, pp. 170–179, DOI: 10.1016/j.chb.2015.07.045.

[107] Hanes, L. & Stone, R., “A model of heritage content to support the design and analysis of video games for history education”, *Journal of Computers in Education*, vol. 6, no. 4, Dec. 2019, pp. 587–612, DOI: 10.1007/s40692-018-0120-2.

[108] Harp, S. F. & Mayer, R. E., “The role of interest in learning from scientific text and illustrations: on the distinction between emotional interest and cognitive interest.”, *Journal of Educational Psychology*, vol. 89, no. 1, 1997, pp. 92–102, DOI: 10.1037/0022-0663.89.1.92.

[109] Harris, B., *Console wars : Sega, Nintendo, and the battle that defined a generation*, New York, NY: It Books, An imprint of HarperCollins Publishers, 2014, ISBN: 978-0062276704.

[110] He, Z., Wu, L. & Li, X. R., “When art meets tech: the role of augmented reality in enhancing museum experiences and purchase intentions”, *Tourism Management*, vol. 68, 2018, pp. 127–139, DOI: 10.1016/j.tourman.2018.03.003.

[111] Head, M., Archer, N. & Yuan, Y., "World wide web navigation aid", *International Journal of Human-Computer Studies*, vol. 53, no. 2, Aug. 2000, pp. 301–330.

[112] Hendrix, M., Bellamy-Wood, T., McKay, S., Bloom, V. & Dunwell, I., "Implementing adaptive game difficulty balancing in serious games", *IEEE Transactions on Games*, vol. 11, no. 4, Dec. 2019, pp. 320–327, DOI: 10.1109/TG.2018.2791019.

[113] Heo, M. & Toomey, N., "Learning with multimedia: the effects of gender, type of multimedia learning resources, and spatial ability", *Computers & Education*, vol. 146, 2020, p. 103747, DOI: 10.1016/j.compedu.2019.103747.

[114] Hepperle, D., Siess, A. & Wölfel, M., "Staging virtual reality exhibits for bystander involvement in semi-public spaces", in: *Interactivity, Game Creation, Design, Learning, and Innovation*, ed. by Brooks, A. & Brooks, E. I., Cham: Springer International Publishing, 2020, pp. 261–272, ISBN: 978-3-030-53294-9.

[115] Herder, E., "Revisitation patterns and disorientation", English, in: *Proceedings ABIS 2003*, 2003, pp. 291–294.

[116] Holten, D. & Wijk, J. van, "Visual comparison of hierarchically organized data", *Computer Graphics Forum*, vol. 27, no. 3, Sept. 2008, pp. 759–766, DOI: 10.1111/j.1467-8659.2008.01205.x.

[117] Hooks, K., Ferguson, W., Morillo, P. & Cruz-Neira, C., "Evaluating the user experience of omnidirectional vr walking simulators", *Entertainment Computing*, vol. 34, 2020, p. 100352, DOI: 10.1016/j.entcom.2020.100352.

[118] Howitt, G., *Writing video games: can narrative be as important as gameplay?*, 2015, URL: https://www.theguardian.com/culture/australia-culture-blog/2014/feb/21/writing-video-games-can-narrative-be-as-important-as-gameplay..

[119] Hsu, H.-Y. & Wang, S.-K., "Using gaming literacies to cultivate new literacies", *Simulation & Gaming*, vol. 41, no. 3, 2010, pp. 400–417, DOI: 10.1177/1046878109355361.

[120] Huang, K.-T., Ball, C., Francis, J., Ratan, R., Boumis, J. & Fordham, J., "Augmented versus virtual reality in education: an exploratory study examining science knowledge retention when using augmented reality/virtual reality mobile applications", *Cyberpsychology, Behavior, and Social Networking*, vol. 22, no. 2, 2019, pp. 105–110, DOI: 10.1089/cyber.2018.0150.

[121] Hudson, S., Matson-Barkat, S., Pallamin, N. & Jegou, G., "With or without you? interaction and immersion in a virtual reality experience", *Journal of Business Research*, vol. 100, 2019, pp. 459–468, DOI: 10.1016/j.jbusres.2018.10.062.

[122] Huizinga, J., *Homo ludens: Proeve eener bepaling van het spel-element der cultuur [Homo ludens: A study of the play-element in culture*, Haarlem, the Netherlands: Tjeenk Willink., 1938.

[123] Hustia, *Zajonc et al v. Electronic Arts Inc. | US District Court for the Northern District of California*, (Accessed on 04/14/2021), Nov. 2020, URL: https://dockets.justia.com/docket/california/candce/3:2020cv07871/368570.

[124] IJsselsteijn, W., Freeman, J. & Ridder, de, H., "Presence: where are we?", *Cyberpsychology, Behavior, and Social Networking*, vol. 4, 2001, pp. 179–182, DOI: 10.1089/109493101300117875.

[125] Imlig-Iten, N. & Petko, D., "Comparing serious games and educational simulations: effects on enjoyment, deep thinking, interest and cognitive learning gains", *Simulation & Gaming*, vol. 49, no. 4, 2018, pp. 401–422, DOI: 10.1177/1046878118779088.

[126] Intraub, H., "Rapid conceptual identification of sequentially presented pictures.", *Journal of Experimental Psychology: Human Perception and Performance*, vol. 7, no. 3, 1981, pp. 604–610, DOI: 10.1037/0096-1523.7.3.604.

[127] Itani, O. S. & Hollebeek, L. D., "Light at the end of the tunnel: visitors' virtual reality (versus in-person) attraction site tour-related behavioral intentions during and post-covid-19", *Tourism Management*, vol. 84, 2021, p. 104290, DOI: 10.1016/j.tourman.2021.104290.

[128] Jameson, A., "Adaptive interfaces and agents", in: *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications*, ed. by Jacko Julie, A, USA: L. Erlbaum Associates Inc., 2002, 305–330, ISBN: 0805838384.

[129] Jemmali, C., Bunian, S., Mambretti, A. & El-Nasr, M. S., "Educational game design: an empirical study of the effects of narrative", in: *Proceedings of the 13th International Conference on the Foundations of Digital Games*, Fdg '18, New York, NY, USA: Association for Computing Machinery, 2018, ISBN: 9781450365710, DOI: 10.1145/3235765.3235783.

[130] Johnson, C. I. & Priest, H. A., "The feedback principle in multimedia learning", in: *The Cambridge Handbook of Multimedia Learning*, ed. by Mayer, R. E., 2nd ed., Cambridge Handbooks in Psychology, Cambridge University Press, 2014, 449–463, DOI: 10.1017/CBO9781139547369.023.

[131] Jörg, S. & Hörmann, H., "The influence of general and specific verbal labels on the recognition of labeled and unlabeled parts of pictures", *Journal of Verbal Learning and Verbal Behavior*, vol. 17, no. 4, 1978, pp. 445–454, DOI: 10.1016/S0022-5371(78)90265-7.

[132] Juvina, I. & Oostendorp, H. van, "Modeling semantic and structural knowledge in web navigation", *Discourse Processes*, vol. 45, no. 4-5, 2008, pp. 346–364, DOI: 10.1080/01638530802145205.

[133] Kamaraj, D. C., Dicianno, B. E., Mahajan, H. P., Buhari, A. M. & Cooper, R. A., "Stability and workload of the virtual reality–based simulator-2", *Archives of Physical Medicine and Rehabilitation*, vol. 97, no. 7, 2016, 1085–1092.e1, DOI: 10.1016/j.apmr.2016.01.032.

[134] Kapp, K., *Gadgets, games, and gizmos for learning : tools and techniques for transferring know-how from boomers to gamers*, San Francisco, CA: Pfeiffer, an imprint of John Wiley, 2007, ISBN: 978-0787986544.

[135] Karen M. Zabrucky, D. M., "Influence of text genre on adults' monitoring of understanding and recall", *Educational Gerontology*, vol. 25, no. 8, 1999, pp. 691–710, DOI: 10.1080/036012799267440.

[136] Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R. & Ungerleider, L. G., "Increased activity in human visual cortex during directed attention in the absence of visual stimulation", *Neuron*, vol. 22, no. 4, Apr. 1999, pp. 751–761, DOI: 10.1016/S0896-6273(00)80734-5.

[137] Kee, K., "Computerized history games: narrative options", *Simulation & Gaming*, vol. 42, no. 4, 2011, pp. 423–440, DOI: 10.1177/1046878108325441.

[138] Kelleher, C., Pausch, R. & Kiesler, S., "Storytelling alice motivates middle school girls to learn computer programming", in: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Chi '07, New York, NY, USA: Association for Computing Machinery, 2007, 1455–1464, ISBN: 9781595935939, DOI: 10.1145/1240624.1240844.

[139] Kim, S., *Gamification in learning and education : enjoy learning like gaming*, Cham, Switzerland: Springer, 2018, ISBN: 978-3-319-47282-9.

[140] Kirschner, P. A., Sweller, J. & Clark, R. E., "Why minimal guidance during instruction does not work: an analysis of the failure of constructivist, discov-

ery, problem-based, experiential, and inquiry-based teaching", *Educational Psychologist*, vol. 41, no. 2, 2006, pp. 75–86, DOI: 10.1207/s15326985ep4102_1.

[141] Knobbout, J. & Van Der Stappen, E., "Where is the learning in learning analytics? a systematic literature review on the operationalization of learning-related constructs in the evaluation of learning analytics interventions", *IEEE Transactions on Learning Technologies*, vol. 13, no. 3, Sept. 2020, pp. 631–645.

[142] Kohn, A., "Choices for children: why and how to let students decide.", *Phi Delta Kappan*, vol. 75, no. 1, 1993, pp. 18–21.

[143] Kopfman, J. E., Smith, S. W., Ah Yun, J. K. & Hodges, A., "Affective and cognitive reactions to narrative versus statistical evidence organ donation messages.", *Journal of Applied Communication Research*, vol. 26, no. 3, 1998, pp. 279–300, DOI: 10.1080/00909889809365508.

[144] Koster, R., *A theory of fun for game design*, Sebastopol, CA: O'Reilly Media Inc, 2014, ISBN: 978-1449363215.

[145] Kriz, W. C., "A systemic-constructivist approach to the facilitation and debriefing of simulations and games", *Simulation & Gaming*, vol. 41, no. 5, 2010, pp. 663–680, DOI: 10.1177/1046878108319867.

[146] Kuipers, B., "Modeling spatial knowledge", *Cognitive Science*, vol. 2, no. 2, 1978, pp. 129–153, DOI: 10.1016/S0364-0213(78)80003-2.

[147] Kulhavy, R. W. & Anderson, R. C., "Delay-retention effect with multiple-choice tests.", *Journal of Educational Psychology*, vol. 63, no. 5, 1972, pp. 505–512, DOI: 10.1037/h0033243.

[148] Larson, K. & Czerwinski, M., "Web page design: implications of memory, structure and scent for information retrieval", in: *CHI '98 Human Factors in Computing Systems*, ACM, Inc, Apr. 1998, pp. 25–32.

[149] Lee, E. A.-L., Wong, K. W. & Fung, C. C., "How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach", *Computers & Education*, vol. 55, no. 4, 2010, pp. 1424–1442, DOI: 10.1016/j.compedu.2010.06.006.

[150] Lee, H., Jung, T. H., tom Dieck, M. & Chung, N., "Experiencing immersive virtual reality in museums", *Information & Management*, vol. 57, no. 5, 2020, p. 103229, DOI: doi.org/10.1016/j.im.2019.103229.

[151] Lee, K. M., Park, N. & Jin, S.-A., "Narrative and interactivity in computer games.", English, in: *Playing Video Games*, ed. by Vorderer, P. & Bryant, J.,

Playing video games: Motives, responses, and consequences. Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers, Mar. 2006, pp. 259–274, ISBN: 0-8058-5322-7 (Paperback); 0-8058-5321-9 (Hardcover); 9780805853223 (Hardcover), DOI: 10.4324/9780203873700.

[152] Leinonen, J & Munroe, J, *Texture*, 2014, URL: https://www.texturewriter.com..

[153] Lester, J. C., Spires, H. A., Nietfeld, J. L., Minogue, J., Mott, B. W. & Lobene, E. V., "Designing game-based learning environments for elementary science education: a narrative-centered learning perspective", *Information Sciences*, vol. 264, 2014, pp. 4–18, DOI: 10.1016/j.ins.2013.09.005.

[154] Liao, C.-W., Chen, C.-H. & Shih, S.-J., "The interactivity of video and collaboration for learning achievement, intrinsic motivation, cognitive load, and behavior patterns in a digital game-based learning environment", *Computers & Education*, vol. 133, 2019, pp. 43–55, DOI: 10.1016/j.compedu.2019.01.013.

[155] Literature & Latte, *Scrivener*, 2007.

[156] Liu, M., Kang, J., Lee, J., Winzeler, E. & Liu, S., "Examining through visualization what tools learners access as they play a serious game for middle school science", in: *Serious Games Analytics: Methodologies for Performance Measurement, Assessment, and Improvement*, ed. by Loh, C. S., Sheng, Y. & Ifenthaler, D., Cham: Springer, July 2015, pp. 181–208, ISBN: 978-3-319-05834-4, DOI: 10.1007/978-3-319-05834-4_8.

[157] Lopes, R & Bidarra, A., "Adaptivity challenges in games and simulations: a survey", *IEEE Transactions on Computational Intelligence and AI in Games*, vol. 3, no. 2, 2011, pp. 85–99, DOI: 10.1109/TCIAIG.2011.2152841.

[158] Lorch, R. F., Lorch, E. P. & Inman, W. E., "Effects of signaling topic structure on text recall.", *Journal of Educational Psychology*, vol. 85, no. 2, 1993, pp. 281–290, DOI: 10.1037/0022-0663.85.2.281.

[159] Luckey, P., *Palmer Luckey: Making Virtual Reality a Reality*, Aug. 2015, URL: https://www.wsj.com/articles/palmer-luckey-making-virtual-reality-a-reality-1438959172.

[160] Lum, H. C., Greatbatch, R., Waldfogle, G. & Benedict, J., "How immersion, presence, emotion, & workload differ in virtual reality and traditional game mediums", *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 62, no. 1, 2018, pp. 1474–1478, DOI: 10.1177/1541931218621334.

[161] Macefield, R., "How to specify the participant group size for usability studies: a practitioner's guide", *Journal of Usability Studies*, vol. 5, no. 1, Nov. 2009, 34–45, DOI: 10.5555/2835425.2835429.

[162] Makransky, G., Terkildsen, T. S. & Mayer, R. E., "Adding immersive virtual reality to a science lab simulation causes more presence but less learning", *Learning and Instruction*, vol. 60, no. 4, 2019, pp. 225–236.

[163] Malone, T. W. & Lepper, M. R., "Making learning fun: a taxonomy of intrinsic motivations for learning", in: *Aptitude, Learning and Instruction III: Conative and Affective Process Analyses*, ed. by Snow, R. & Farr, M., Hillsdale, NJ, USA: Lawrence Erlbaum Associates Publishers, 1987, pp. 223–253, ISBN: 0898597218.

[164] Mandler, J. M. & Johnson, N. S., "Remembrance of things parsed: story structure and recall", *Cognitive Psychology*, vol. 9, no. 1, 1977, pp. 111–151.

[165] Mangaroska, K. & Giannakos, M., "Learning analytics for learning design: a systematic literature review of analytics-driven design to enhance learning", *IEEE Transactions on Learning Technologies*, vol. 12, no. 4, Dec. 2019, pp. 516–534.

[166] Maples-Keller, J. L., Bunnell, B. E., Kim, S. J. & Rothbaum, B. O., "The use of virtual reality technology in the treatment of anxiety and other psychiatric disorders", *Harv Rev Psychiatry*, vol. 25, no. 3, 2017, pp. 103–113.

[167] Marsh, T., "Activity-based scenario design, development and assessment in serious games", *Gaming and Cognition*, 2010, 213–226, DOI: 10.4018/978-1-61520-717-6.ch010.

[168] Matcha, W., Uzir, N. A., Gašević, D. & Pardo, A., "A systematic review of empirical studies on learning analytics dashboards: a self-regulated learning perspective", *IEEE Transactions on Learning Technologies*, vol. 13, no. 2, June 2020, pp. 226–245.

[169] Maxfield, J. T., Stalder, W. D. & Zelinsky, G. J., "Effects of target typicality on categorical search", *J Vis*, vol. 14, no. 12, Oct. 2014.

[170] Mayer, R. E., "Should there be a three-strikes rule against pure discovery learning?", *American Psychologist*, vol. 59, no. 1, 2004, pp. 14–19, DOI: 10.1037/0003-066X.59.1.14.

[171] McEneaney, J. E., "Graphic and numerical methods to assess navigation in hypertext", *International Journal of Human-Computer Studies*, vol. 55, no. 5, 2001, pp. 761–786, DOI: 10.1006/ijhc.2001.0505.

[172] McQuiggan, S. W., Rowe, J. P., Lee, S. & Lester, J. C., “Story-based learning: the impact of narrative on learning experiences and outcomes”, in: *Intelligent Tutoring Systems*, ed. by Woolf, B. P., Aïmeur, E., Nkambou, R. & Lajoie, S., Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 530–539, ISBN: 978-3-540-69132-7.

[173] Meade, M. E., Meade, J. G., Sauzeon, H. & Fernandes, M. A., “Active navigation in virtual environments benefits spatial memory in older adults”, *Brain sciences*, vol. 9, no. 3, Feb. 2019, p. 47, DOI: 10.3390/brainsci9030047.

[174] Meijer, F., “Spatial Cognition in Synthetic Environments.”, English, PhD thesis, Netherlands: University of Twente, May 2011, ISBN: 978-90-365-3178-8, DOI: 10.3990/1.9789036531788.

[175] Meijer, F. & Van den Broek, E. L., “Representing 3D virtual objects: interaction between visuo-spatial ability and type of exploration”, *Vision Res.*, vol. 50, no. 6, Mar. 2010, pp. 630–635, DOI: 10.1016/j.visres.2010.01.016.

[176] Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W. & Davis, T. J., “Effectiveness of virtual reality-based instruction on students’ learning outcomes in k-12 and higher education: a meta-analysis”, *Computers & Education*, vol. 70, 2014, pp. 29–40, DOI: 10.1016/j.compedu.2013.07.033.

[177] Mikropoulos, T. A. & Natsis, A., “Educational virtual environments: a ten-year review of empirical research (1999–2009)”, *Computers & Education*, vol. 56, no. 3, 2011, pp. 769–780, DOI: 10.1016/j.compedu.2010.10.020.

[178] Minović, M., Milovanović, M., Šošević, U. & Conde González, M. Ángel, “Visualisation of student learning model in serious games”, *Computers in Human Behavior*, vol. 47, June 2015, pp. 98–107, DOI: 10.1016/j.chb.2014.09.005.

[179] Miserandino, M., “Children who do well in school: individual differences in perceived competence and autonomy in above-average children.”, *Journal of Educational Psychology*, vol. 88, no. 2, 1996, pp. 203–214, DOI: 10.1037/0022-0663.88.2.203.

[180] Moreno, R. & Mayer, R., “Learning science in virtual reality multimedia environments: role of methods and media”, *Journal of Educational Psychology*, vol. 94, 2002, pp. 598–610.

[181] Moreno, R., “Decreasing cognitive load for novice students: effects of explanatory versus corrective feedback in discovery-based multimedia”, *In-*

structional Science, vol. 32, no. 1, Jan. 2004, pp. 99–113, DOI: 10.1023/B:TRUC.0000021811.66966.1d.

[182] Moreno, R. & Mayer, R. E., "Role of guidance, reflection, and interactivity in an agent-based multimedia game.", *Journal of Educational Psychology*, vol. 97, no. 1, 2005, pp. 117–128, DOI: 10.1037/0022-0663.97.1.117.

[183] Moroney, W. F., Biers, D. W., Eggemeier, F. T. & Mitchell, J. A., "A comparison of two scoring procedures with the nasa task load index in a simulated flight task", in: *Proceedings of the IEEE 1992 National Aerospace and Electronics Conferencem_NAECON 1992*, 1992, 734–740 vol.2.

[184] Mortara, M., Catalano, C. E., Bellotti, F., Fiucci, G., Houry-Panchetti, M. & Petridis, P., "Learning cultural heritage by serious games", *Journal of Cultural Heritage*, vol. 15, no. 3, 2014, pp. 318–325, DOI: 10.1016/j.culher.2013.04.004.

[185] Murdock, B. B., "Effects of a subsidiary task on short-term memory", *British Journal of Psychology*, vol. 56, no. 4, 1965, pp. 413–419, DOI: 10.1111/j.2044-8295.1965.tb00983.x.

[186] Myers, B. A., "The importance of percent-done progress indicators for computer-human interfaces", *SIGCHI Bulletin*, vol. 16, no. 4, Apr. 1985, 11–17, DOI: 10.1145/1165385.317459.

[187] Nederland, K., *Loot boxes*, (Accessed on 04/14/2021), Apr. 2018, URL: https://kansspelautoriteit.nl/onderwerpen/loot-boxes/.

[188] Nelson, G, *Inform 7*, 1993, URL: https://www.inform7.com..

[189] Newbutt, N., Bradley, R. & Conley, I., "Using virtual reality head-mounted displays in schools with autistic children: views, experiences, and future directions", *Cyberpsychology, Behavior, and Social Networking*, vol. 23, no. 1, 2020, pp. 23–33, DOI: 10.1089/cyber.2019.0206.

[190] Nielsen, J., "Finding usability problems through heuristic evaluation", in: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '92, New York, NY, USA: Association for Computing Machinery, June 1992, 373–380, ISBN: 0897915135, DOI: 10.1145/142750.142834.

[191] Norris, S. P., Guilbert, S. M., Smith, M. L., Hakimelahi, S. & Phillips, L. M., "A theoretical framework for narrative explanation in science", *Science Education*, vol. 89, no. 4, 2005, pp. 535–563, DOI: 10.1002/sce.20063.

[192] Otter, M & Johnson, H, "Lost in hyperspace: metrics and mental models", *Interacting With Computers*, vol. 13, no. 1, Sept. 2000, pp. 1–40, DOI: 10.1016/s0953-5438(00)00030-8.

[193] Paas, F., Gog, T. van & Sweller, J., "Cognitive load theory: new conceptualizations, specifications, and integrated research perspectives", *Educational Psychology Review*, vol. 22, no. 2, June 2010, pp. 115–121, DOI: 10.1007/s10648-010-9133-8.

[194] Palmer, J., "Attention in visual search: distinguishing four causes of a set-size effect", *Current Directions in Psychological Science*, vol. 4, no. 4, 1995, pp. 118–123, DOI: 10.1111/1467-8721.ep10772534.

[195] Paris, R., Klag, J., Rajan, P., Buck, L., McNamara, T. P. & Bodenheimer, B., "How video game locomotion methods affect navigation in virtual environments", in: *ACM Symposium on Applied Perception 2019*, SAP '19, New York, NY, USA: Association for Computing Machinery, 2019, ISBN: 9781450368902, DOI: 10.1145/3343036.3343131.

[196] Parkes, T., *Virtual reality project to help Birmingham students understand consequences of crime | Express & Star*, (Accessed on 04/15/2021), Sept. 2020, URL: https://www.expressandstar.com/news/crime/2020/09/19/virtual-reality-project-to-help-birmingham-students-understand-consequences-of-crime/.

[197] Parkin, A. J., Lewinsohn, J. & Folkard, S., "The influence of emotion on immediate and delayed retention: levinger & clark reconsidered", *British Journal of Psychology*, vol. 73, no. 3, 1982, pp. 389–393, DOI: 10.1111/j.2044-8295.1982.tb01821.x.

[198] Parong, J. & Mayer, R. E., "Learning science in immersive virtual reality.", *Journal of Educational Psychology*, vol. 110, no. 6, 2018, pp. 785–797, DOI: 10.1037/edu0000241.

[199] Passig, D., Tzuriel, D. & Eshel-Kedmi, G., "Improving children's cognitive modifiability by dynamic assessment in 3d immersive virtual reality environments", *Computers & Education*, vol. 95, 2016, pp. 296–308, DOI: 10.1016/j.compedu.2016.01.009.

[200] Peirce, N., Conlan, O. & Wade, V., "Adaptive educational games: providing non-invasive personalised learning experiences", in: *2008 Second IEEE International Conference on Digital Game and Intelligent Toy Enhanced Learning*, 2008, pp. 28–35.

[201] Perakakis, M. & Potamianos, A., "Multimodal system evaluation using modality efficiency and synergy metrics", in: *Proceedings of the 10th International Conference on Multimodal Interfaces*, Icmi '08, New York, NY, USA: Asso-

ciation for Computing Machinery, 2008, 9–16, ISBN: 9781605581989, DOI: 10.1145/1452392.1452397.

[202] Perez-Colado, I., Alonso-Fernandez, C., Freire, M., Martinez-Ortiz, I. & Fernandez-Manjon, B., "Game learning analytics is not informagic!", in: *2018 IEEE Global Engineering Education Conference (EDUCON)*, Tenerife: IEEE, 2018, pp. 1729–1737.

[203] Pierce, M. B., Young, P. A. & Doherty, S. M., "Engagement and competence in vr and non-vr environments", *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 61, no. 1, 2017, pp. 2082–2085, DOI: 10.1177/1541931213602003.

[204] Power, C., Denisova, A., Papaioannou, T. & Cairns, P., "Measuring uncertainty in games: design and preliminary validation", in: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '17, New York, NY, USA: Association for Computing Machinery, 2017, 2839–2845, ISBN: 9781450346566, DOI: 10.1145/3027063.3053215.

[205] Pratchett, R., *Rewriting Lara Croft.* 2012, URL: https://www.gamesindustry.biz/articles/2012-10-05-rhianna-pratchett-rewriting-lara-croft..

[206] Prensky, M., *Digital game-based learning*, St. Paul, Minn: Paragon House, 2007, ISBN: 978-1557788634.

[207] Preston, C. C. & Colman, A. M., "Optimal number of response categories in rating scales: reliability, validity, discriminating power, and respondent preferences", *Acta Psychologica*, vol. 104, no. 1, Mar. 2000, pp. 1–15, DOI: 10.1016/S0001-6918(99)00050-5.

[208] Radianti, J., Majchrzak, T. A., Fromm, J. & Wohlgenannt, I., "A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda", *Computers & Education*, vol. 147, 2020, p. 103778, DOI: 10.1016/j.compedu.2019.103778.

[209] Rankin, A., Field, J., Kovordányi, R., Morin, M., Jenvald, J. & Eriksson, H., "Training systems design: bridging the gap between users and developers using storyboards", in: *Proceedings of the 29th Annual European Conference on Cognitive Ergonomics (ECCE '11)*, New York: ACM, Aug. 2011, pp. 205–212, DOI: 10.1145/2074712.2074752.

[210] Reese, D. D., Tabachnick, B. G. & Kosko, R. E., "Video game learning dynamics: actionable measures of multidimensional learning trajectories", *British*

Journal of Educational Technology, vol. 46, no. 1, Jan. 2015, pp. 98–122, DOI: 10.1111/bjet.12128.

[211] Richards, D. & Taylor, M., "A comparison of learning gains when using a 2d simulation tool versus a 3d virtual world: an experiment to find the right representation involving the marginal value theorem", *Computers & Education*, vol. 86, 2015, pp. 157–171, DOI: 10.1016/j.compedu.2015.03.009.

[212] Robertson, G. & Watson, I., "Building behavior trees from observations in real-time strategy games", in: *2015 International Symposium on Innovations in Intelligent SysTems and Applications (INISTA)*, Sept. 2015, pp. 1–7, DOI: 10.1109/INISTA.2015.7276774.

[213] Robot Invader, *Dead Secret*, 2015, URL: https://store.steampowered.com/app/402260/Dead_Secret/.

[214] Rocksteady Studios, *Batman: Arkham VR*, 2016, URL: https://store.steampowered.com/app/502820/Batman_Arkham_VR/.

[215] Rouet, J.-F., *The Skills of Document Use: From Text Comprehension to Web-Based Learning.* The skills of document use: From text comprehension to web-based learning. Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers, 2006, pp. xxi, 227–xxi, 227, ISBN: 0-8058-4602-6 (Hardcover).

[216] Round Midnight, *Virtual_Decisions*, http://www.roundmidnight.org.uk/virtual_decisions/, (Accessed on 04/15/2021), 2020.

[217] Rowe, J. P., Shores, L. R., Mott, B. W. & Lester, J. C., "Integrating learning, problem solving, and engagement in narrative-centered learning environments", *International Journal of Artificial Intelligence in Education*, vol. 21, no. 1–2, 2011, 115–133.

[218] Ryan, M.-L., *Narrative as virtual reality 2 : revisiting immersion and interactivity in literature and electronic media*, Baltimore: Johns Hopkins University Press, 2015, ISBN: 978-1421417974.

[219] Samaroudi, M., Echavarria, K. R. & Perry, L., "Heritage in lockdown: digital provision of memory institutions in the uk and us of america during the covid-19 pandemic", *Museum Management and Curatorship*, vol. 35, no. 4, 2020, pp. 337–361, DOI: 10.1080/09647775.2020.1810483.

[220] Sarkady, D., Neuburger, L. & Egger, R., "Virtual reality as a travel substitution tool during covid-19", in: *Information and Communication Technologies in Tourism 2021*, ed. by Wörndl, W., Koo, C. & Stienmetz, J. L., Cham: Springer International Publishing, 2021, pp. 452–463, ISBN: 978-3-030-65785-7.

[221] Schank, R. C. & Abelson, R. P., "Knowledge and memory: the real story.", in: Advances in social cognition, Vol. 8. Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc, 1995, pp. 1–85, ISBN: 0-8058-1445-0 (Hardcover); 0-8058-1446-9 (Paperback).

[222] Schmidt, J. & Zelinsky, G. J., "Search guidance is proportional to the categorical specificity of a target cue.", *The Quarterly Journal of Experimental Psychology*, vol. 62, no. 10, 2009, pp. 1904–1914, DOI: 10.1080/17470210902853530.

[223] Schnotz, W. & Kürschner, C., "A reconsideration of cognitive load theory", *Educational Psychology Review*, vol. 19, no. 4, Dec. 2007, pp. 469–508, DOI: 10.1007/s10648-007-9053-4.

[224] Schraw, G., Bruning, R. & Svoboda, C., "Sources of situational interest", *Journal of Reading Behavior*, vol. 27, no. 1, 1995, pp. 1–17, DOI: 10.1080/10862969509547866.

[225] Schubert, T. W., "The sense of presence in virtual environments:" *Zeitschrift für Medienpsychologie*, vol. 15, no. 2, 2003, pp. 69–71, DOI: 10.1026//1617-6383.15.2.69.

[226] Schuemie, M. J., Straaten, P. van der, Krijn, M. & Mast, C. A. van der, "Research on presence in virtual reality: a survey", *CyberPsychology & Behavior*, vol. 4, no. 2, 2001, pp. 183–201, DOI: 10.1089/109493101300117884.

[227] Schwendimann, B. A., Rodríguez-Triana, M. J., Vozniuk, A., Prieto, L. P., Boroujeni, M. S., Holzer, A., Gillet, D. & Dillenbourg, P., "Perceiving learning at a glance: a systematic literature review of learning dashboard research", *IEEE Transactions on Learning Technologies*, vol. 10, no. 1, Mar. 2017, pp. 30–41.

[228] Seaton, J. X., Chang, M. & Graf, S., "Integrating a learning analytics dashboard in an online educational game", in: *Data Analytics Approaches in Educational Games and Gamification Systems*, ed. by Tlili, A. & Chang, M., Singapore: Springer, Sept. 2019, pp. 127–138, ISBN: 978-981-32-9335-9, DOI: 10.1007/978-981-32-9335-9_71.

[229] Serrano, E. & Anderson, J., "Integrating learning, problem solving, and engagement in narrative-centered learning environments", *Journal of Family and Consumer Sciences Education*, vol. 22, no. 1, 2004, 1–16.

[230] Serrano-Laguna, Ángel, Martínez-Ortiz, I., Haag, J., Regan, D., Johnson, A. & Fernández-Manjón, B., "Applying standards to systematize learning analytics in serious games", *Computer Standards & Interfaces*, vol. 50, Feb. 2017, pp. 116–123, DOI: 10.1016/j.csi.2016.09.014.

[231] Serrano-Laguna, Ángel, Torrente, J., Moreno-Ger, P. & Fernández-Manjón, B., "Tracing a little for big improvements: application of learning analytics and videogames for student assessment", *Procedia Computer Science*, vol. 15, 2012, pp. 203–209, DOI: 10.1016/j.procs.2012.10.072.

[232] Sharples, M., *How we write : writing as creative design*, London: Routledge, 1999, ISBN: 9780415185875.

[233] Shoufan, A., Lu, Z. & Huss, S. A., "A web-based visualization and animation platform for digital logic design", *IEEE Transactions on Learning Technologies*, vol. 8, no. 2, June 2015, pp. 225–239.

[234] Shute, V., Ke, F. & Wang, L., "Assessment and adaptation in games", in: *Instructional Techniques to Facilitate Learning and Motivation of Serious Games*, ed. by Wouters, P. & Oostendorp, H. van, Cham: Springer International Publishing, 2017, pp. 59–78, ISBN: 978-3-319-39298-1, DOI: 10.1007/978-3-319-39298-1_4.

[235] Shute, V. J., "Focus on formative feedback", *Review of Educational Research*, vol. 78, no. 1, 2008, pp. 153–189, DOI: 10.3102/0034654307313795.

[236] Sielaff, C., *ZodiacGraph*, 2015, URL: https://github.com/clemenssielaff/ZodiacGraph.

[237] Slater, M., "Presence and the sixth sense", *Presence: Teleoperators and Virtual Environments*, vol. 11, no. 4, 2002, pp. 435–439, DOI: 10.1162/105474602760204327.

[238] Slater, M. & Sanchez-Vives, M. V., "Enhancing our lives with immersive virtual reality", *Frontiers in Robotics and AI*, vol. 3, 2016, p. 74, DOI: 10.3389/frobt.2016.00074.

[239] Slater, M. & Usoh, M., "Representations systems, perceptual position, and presence in immersive virtual environments", *Presence: Teleoperators and Virtual Environments*, vol. 2, no. 3, 1993, pp. 221–233, DOI: 10.1162/pres.1993.2.3.221.

[240] Smith, A.-L. & Baker, L., "Getting a clue: creating student detectives and dragon slayers in your library", *Reference Services Review*, vol. 39, no. 4, 2011, pp. 628–642, DOI: 10.1108/00907321111186659.

[241] Smith, H. & Worch, M., English, 2010, URL: https://www.gdcvault.com/play/1012647/What-Happened-Here-Environmental.

[242] Smith, P. A., "Towards a practical measure of hypertext usability", *Interacting with Computers*, vol. 8, no. 4, 1996, pp. 365–381, DOI: 10.1016/s0953-5438(97)83779-4.

[243] Sobel, K. & Jhee, C., *How K-8 Teachers Are Using Virtual and Augmented Reality in Classrooms Today*, (Accessed on 04/15/2021), 2020, URL: https://circlcenter.org/how-k-8-teachers-are-using-vr-and-ar-in-classrooms-today/.

[244] Spärck Jones, K., "A look back and a look forward", in: *Proceedings of the 11th Annual International ACM SIGIR Conference on Research and Development in Information Retrieval*, SIGIR '88, New York, NY, USA: Association for Computing Machinery, 1988, 13–29, ISBN: 2706103094, DOI: 10.1145/62437.62438.

[245] Steel Minions & the Jenner Trust, *The Chantry*, 2018, URL: https://store.playstation.com/en-gb/product/EP4325-CUSA12254\%5F00-DRJENNERSMALLPOX..

[246] Stefanidis, D., Haluck, R., Pham, T., Dunne, J. B., Reinke, T., Markley, S., Korndorffer, J. R., Arellano, P., Jones, D. B. & Scott, D. J., "Construct and face validity and task workload for laparoscopic camera navigation: virtual reality versus videotrainer systems at the sages learning center", *Surgical Endoscopy*, vol. 21, no. 7, July 2007, pp. 1158–1164, DOI: 10.1007/s00464-006-9112-9.

[247] Steiner, K. E. & Voruganti, L., "A comparison of guidance cues in desktop virtual environments", *Virtual Reality*, vol. 7, no. 3, June 2004, pp. 140–147, DOI: 10.1007/s10055-004-0125-1.

[248] Street, R. L., Gold, W. R. & Manning, T. R., *Health promotion and interactive technology : theoretical applications and future directions*, Mahwah, N.J: Lawrence Erlbaum Associates, 1997, ISBN: 9780805822052.

[249] Streicher, A. & Smeddinck, J. D., "Personalized and adaptive serious games", in: *Entertainment Computing and Serious Games: International GI-Dagstuhl Seminar 15283, Dagstuhl Castle, Germany, July 5-10, 2015, Revised Selected Papers*, ed. by Dörner, R., Göbel, S., Kickmeier-Rust, M., Masuch, M. & Zweig, K., Cham: Springer International Publishing, 2016, pp. 332–377, ISBN: 978-3-319-46152-6, DOI: 10.1007/978-3-319-46152-6_14.

[250] Sutherland, R., Joubert, M. & Eagle, S., *A Vision and Strategy for Technology Enhanced Learning: Report from the STELLAR Network of Excellence*, English, EFC, European Commission, May 2012.

[251] Sweller, J., Ayres, P. & Kalyuga, S., "Cognitive load theory", in: *Cognitive Load Theory*, New York, NY: Springer, 2011, pp. 237–242, ISBN: 978-1-4419-8126-4, DOI: 10.1007/978-1-4419-8126-4_18.

[252] Sweller, J., Van Merrienboer, J. J. G. & Paas, F. G. W. C., "Cognitive architecture and instructional design", *Educational Psychology Review*, vol. 10, no. 3, Sept. 1998, pp. 251–296, DOI: 10.1023/A:1022193728205.

[253] Thomsen, A. S. S., Bach-Holm, D., Kjærbo, H., Højgaard-Olsen, K., Subhi, Y., Saleh, G. M., Park, Y. S., Cour], M. [la & Konge, L., "Operating room performance improves after proficiency-based virtual reality cataract surgery training", *Ophthalmology*, vol. 124, no. 4, 2017, pp. 524–531, DOI: 10.1016/j.ophtha.2016.11.015.

[254] Thorndyke, P. W., "Cognitive structures in comprehension and memory of narrative discourse", *Cognitive Psychology*, vol. 9, no. 1, 1977, pp. 77–110.

[255] Toh, W. & Kirschner, D., "Self-directed learning in video games, affordances and pedagogical implications for teaching and learning", *Computers & Education*, vol. 154, 2020, p. 103912, DOI: 10.1016/j.compedu.2020.103912.

[256] Topu, F. B. & Goktas, Y., "The effects of guided-unguided learning in 3d virtual environment on students' engagement and achievement", *Computers in Human Behavior*, vol. 92, 2019, pp. 1–10, DOI: 10.1016/j.chb.2018.10.022.

[257] Tormé, T., *The Big Goodbye*, Jan. 1988.

[258] Torrente, J., Moreno-Ger, P., Fernández-Manjón, B. & Blanco, Á. del, "Gamelike simulations for online adaptive learning: a case study", in: *Learning by Playing. Game-based Education System Design and Development*, ed. by Chang, M., Kuo, R., Kinshuk, Chen, G.-D. & Hirose, M., Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 162–173, ISBN: 978-3-642-03364-3.

[259] Trif, L., "Training models of social constructivism. teaching based on developing a scaffold", *Procedia - Social and Behavioral Sciences*, vol. 180, 2015, pp. 978–983, DOI: 10.1016/j.sbspro.2015.02.184.

[260] Tulving, E. & Thomson, D. M., "Encoding specificity and retrieval processes in episodic memory.", *Psychological Review*, vol. 80, no. 5, 1973, pp. 352–373, DOI: 10.1037/h0020071.

[261] Tussyadiah, I. P., Wang, D., Jung, T. H. & Dieck, M. C. tom, "Virtual reality, presence, and attitude change: empirical evidence from tourism", *Tourism Management*, vol. 66, 2018, pp. 140–154, DOI: 10.1016/j.tourman.2017.12.003.

[262] Tüzün, H. & Doğan, D., "The effects of using on-screen and paper maps on navigation efficiency in 3d multi-user virtual environments", *International*

Journal of Gaming and Computer-Mediated Simulations (IJGCMS), vol. 11, no. 4, 2019, pp. 21–41, DOI: 10.4018/IJGCMS.2019100102.

[263] Twine, *Twine: An open-source tool for telling interactive, nonlinear stories*, 2009, URL: http://twinery.org..

[264] Underwood, B. J., "False recognition produced by implicit verbal responses.", *Journal of Experimental Psychology*, vol. 70, no. 1, 1965, pp. 122–129, DOI: 10.1037/h0022014.

[265] Valentine, R., *EA faces yet another class-action lawsuit connected to loot boxes | GamesIndustry.biz*, (Accessed on 04/14/2021), Nov. 2020, URL: https://www.gamesindustry.biz/articles/2020-11-11-ea-faces-yet-another-class-action-lawsuit-over-alleged-use-of-dynamic-difficulty-adjustment.

[266] Valve, *Left 4 Dead*, 2008, URL: https://web.archive.org/web/20090327034239/http://www.l4d.com/info.html.

[267] Valve, *Half-Life: Alyx*, 2020, URL: https://www.half-life.com/.

[268] van den Broek, E. L., "On making engagement tangible", in: *Proceedings of Measuring Behavior 2012: 8th International Conference on Methods and Techniques in Behavioral Research*, ed. by Spink, A., Grieco, F, Krips, O., Loijens, L., Noldus, L. & Zimmerman, P., Noldus Information Technology, Aug. 2012, pp. 90–93, ISBN: 978-90-74821-87-2.

[269] Van der Sluis, F., Van den Broek, E. L., Drunen, A van & Beerends, J., "Enhancing the quality of service of mobile video technology by increasing multimodal synergy", *Behaviour & Information Technology*, vol. 37, no. 9, 2018, pp. 874–883, DOI: 10.1080/0144929x.2018.1505954.

[270] Van der Sluis, F., Van den Broek, E. L., Glassey, R. J., Van Dijk, E. M. A. G. & de Jong, F. M. G., "When complexity becomes interesting", *Journal of the Association for Information Science and Technology*, vol. 65, no. 7, 2014, pp. 1478–1500, DOI: 10.1002/asi.23095.

[271] van Doesburg, W., Heuvelink, A. & van den Broek, E., "Tacop: a cognitive agent for a naval training simulation environment", English, in: *Aamas*, ed. by Dignum, F., Dignum, V., Koenig, S., S.Kraus, Singh, M. & Wooldridge, M., Acm, 2005, pp. 1363–1364, ISBN: 1595930949.

[272] Van Oostendorp, H. & Karanam, S., "Navigating in a virtual environment with model-generated support", in: *Proceedings of the 31st European Conference on Cognitive Ergonomics*, ECCE '13, New York, NY, USA: Associa-

tion for Computing Machinery, 2013, pp. 1–8, ISBN: 9781450322515, DOI: 10.1145/2501907.2501948.

[273] Van Oostendorp, H., Van der Spek, E. D. & Linssen, J., "Adapting the complexity level of a serious game to the proficiency of players", *EAI Endorsed Transactions on Serious Games*, vol. 1, no. 2, May 2014, pp. 1–8, DOI: 10.4108/sg.1.2.e5.

[274] Vecco, M., "A definition of cultural heritage: from the tangible to the intangible", *Journal of Cultural Heritage*, vol. 11, no. 3, 2010, pp. 321–324, DOI: 10.1016/j.culher.2010.01.006.

[275] Vygotsky, L. S., *Mind in Society : The Development of Higher Psychological Processes*, Cambridge: Harvard University Press, 1978, ISBN: 978-0674576292.

[276] Wallner, G. & Kriglstein, S., "Plato: a visual analytics system for gameplay data", *Computers & Graphics*, vol. 38, 2014, pp. 341–356, DOI: 10.1016/j.cag.2013.11.010.

[277] Wallner, G. & Kriglstein, S., "Comparative visualization of player behavior for serious game analytics", in: *Serious Games Analytics: Methodologies for Performance Measurement, Assessment, and Improvement*, ed. by Loh, C. S., Sheng, Y. & Ifenthaler, D., Cham: Springer, Jan. 2015, pp. 159–179, ISBN: 978-3-319-05834-4, DOI: 10.1007/978-3-319-05834-4_7.

[278] Wang, C., Fang, T. & Gu, Y., "Learning performance and behavioral patterns of online collaborative learning: impact of cognitive load and affordances of different multimedia", *Computers & Education*, vol. 143, 2020, p. 103683, DOI: 10.1016/j.compedu.2019.103683.

[279] Wasserman, J. A. & Banks, J., "Details and dynamics: mental models of complex systems in game-based learning", *Simulation & Gaming*, vol. 48, no. 5, 2017, pp. 603–624, DOI: 10.1177/1046878117715056.

[280] Webster, R., "Declarative knowledge acquisition in immersive virtual learning environments", *Interactive Learning Environments*, vol. 24, no. 6, 2016, pp. 1319–1333, DOI: 10.1080/10494820.2014.994533.

[281] Wernbacher, T., Pfeiffer, A., Wagner, M. & Hofstätter, J., "Learning by playing: can serious games be fun", in: *Proceedings of 6th European Conference on Games Based Learning*, 2012, pp. 534–541.

[282] Westra, J., Hasselt, H. van, Dignum, F. & Dignum, V., "Adaptive serious games using agent organizations", in: *Agents for Games and Simulations: Trends in Techniques, Concepts and Design*, ed. by Dignum, F., Bradshaw, J., Silverman, B. & Doesburg, W. van, Berlin, Heidelberg: Springer Berlin Hei-

delberg, 2009, pp. 206–220, ISBN: 978-3-642-11198-3, DOI: 10.1007/978-3-642-11198-3_14.

[283] Wiederhold, B. K., “The next level of virtual reality isn’t technology–it’s storytelling”, *Cyberpsychology, Behavior, and Social Networking*, vol. 21, no. 11, 2018, pp. 671–671, DOI: 10.1089/cyber.2018.29129.bkw.

[284] Wise, A., Zhao, Y. & Hausknecht, S., “Learning analytics for online discussions: embedded and extracted approaches”, *Journal of Learning Analytics*, vol. 1, no. 2, Aug. 2014, pp. 48–71.

[285] Witmer, B. G. & Singer, M. J., “Measuring presence in virtual environments: a presence questionnaire”, *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, 1998, pp. 225–240, DOI: 10.1162/105474698565686.

[286] Wolfe, J. M., “Guided search 4.0: current progress with a model of visual search.”, in: *Series on cognitive models and architectures. Integrated models of cognitive systems*, ed. by Gray, W. D., New York, NY, US: Oxford University Press, 2007, pp. 99–119, ISBN: 978-0-19-518919-3 (Hardcover), DOI: 10.1093/acprof:oso/9780195189193.003.0008.

[287] Wolfe, J. M., “Visual search: how do we find what we are looking for?”, *Annual Review of Vision Science*, vol. 6, no. 1, 2020, pp. 539–562, DOI: 10.1146/annurev-vision-091718-015048.

[288] Wolfe, J. M., Friedman-Hill, S. R., Stewart, M. I. & O’Connell, K. M., “The role of categorization in visual search for orientation.”, *Journal of Experimental Psychology: Human Perception and Performance*, vol. 18, no. 1, 1992, pp. 34–49, DOI: 10.1037/0096-1523.18.1.34.

[289] Wood, H., *Could there be a speculative script industry for narrative games?*, 2015, URL: https://www.gamesindustry.biz/articles/2017-07-11-could-there-be-a-speculative-script-industry-for-narrative-games.

[290] Wouters, P. & Oostendorp, H. van, “Overview of instructional techniques to facilitate learning and motivation of serious games”, in: *Instructional Techniques to Facilitate Learning and Motivation of Serious Games*, ed. by Wouters, P. & Oostendorp, H. van, Cham: Springer International Publishing, 2017, pp. 1–16, ISBN: 978-3-319-39298-1, DOI: 10.1007/978-3-319-39298-1_1.

[291] Wright, R. D. & Richard, C. M., “Location cue validity affects inhibition of return of visual processing”, *Vision Research*, vol. 40, no. 17, 2000, pp. 2351–2358, DOI: 10.1016/S0042-6989(00)00085-7.

[292] Wu, W.-H., Hsiao, H.-C., Wu, P.-L., Lin, C.-H. & Huang, S.-H., "Investigating the learning-theory foundations of game-based learning: a meta-analysis", *Journal of Computer Assisted Learning*, vol. 28, no. 3, 2012, pp. 265–279, DOI: 10.1111/j.1365-2729.2011.00437.x.

[293] Xu, W., Liang, H.-N., Zhang, Z. & Baghaei, N., "Studying the effect of display type and viewing perspective on user experience in virtual reality exergames", *Games for Health Journal*, vol. 9, no. 6, 2020, pp. 405–414, DOI: 10.1089/g4h.2019.0102.

[294] Young, M. S. & Stanton, N. A., "Malleable attentional resources theory: a new explanation for the effects of mental underload on performance", *Human Factors*, vol. 44, no. 3, 2002, pp. 365–375, DOI: 10.1518/0018720024497709.

[295] Zendle, D. & Cairns, P., "Video game loot boxes are linked to problem gambling: results of a large-scale survey", *PLOS ONE*, vol. 13, Nov. 2018, pp. 1–12, DOI: 10.1371/journal.pone.0206767.

[296] Zendle, D. & Cairns, P., "Loot boxes are again linked to problem gambling: results of a replication study", *PLOS ONE*, vol. 14, no. 3, Mar. 2019, pp. 1–13, DOI: 10.1371/journal.pone.0213194.

[297] Zhao, J., LaFemina, P., Carr, J., Sajjadi, P., Wallgrün, J. O. & Klippel, A., "Learning in the field: comparison of desktop, immersive virtual reality, and actual field trips for place-based stem education", in: *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2020, pp. 893–902, DOI: 10.1109/VR46266.2020.00012.

[298] Zhao, J., Jin, P., Zhang, Q. & Wen, R., "Exploiting location information for web search", *Computers in Human Behavior*, vol. 30, 2014, pp. 378–388, DOI: 10.1016/j.chb.2013.04.023.

[299] Zhdanov, A. D., Zhdanov, D. D., Bogdanov, N. N., Potemin, I. S., Galaktionov, V. A. & Sorokin, M. I., "Discomfort of visual perception in virtual and mixed reality systems", *Programming and Computer Software*, vol. 45, no. 4, 2019, pp. 147–155, DOI: 10.1134/s036176881904011x.

[300] Zook, A. & Riedl, M. O., "Temporal game challenge tailoring", *IEEE Transactions on Computational Intelligence and AI in Games*, vol. 7, no. 4, Dec. 2015, pp. 336–346, DOI: 10.1109/TCIAIG.2014.2342934.

Summary

Virtual Reality (VR), presented in many sci-fi movies and series such as Ready Player One (Cline, 2011) and Star Trek (Tormé, 1988), is often hoped to revolutionize training and teaching as it offers more immersion in the experience than any other medium (Gadelha, 2018). The benefits of VR and serious games for teaching are increased presence (i.e., players feeling being physically present in the game) (Schuemie et al., 2001; Slater, 2002), engagement (i.e., heightened concentration, interest, involvement, and enjoyment) (Kim, 2018; van den Broek, 2012), and cognitive interest (i.e., understanding topics and becoming more interested) (Harp & Mayer, 1997; Van der Sluis et al., 2014), which have all been linked to increased learning (Abdul Jabbar & Felicia, 2015; Checa & Bustillo, 2020; Imlig-Iten & Petko, 2018; Lee et al., 2010).

A type of application that can often be presented in VR is serious games: video games that serve an educational purpose and provide a learning experience (Westra et al., 2009). In Chapter 1, the introduction, we detail the potential of both VR and serious games and how VR serious games can be a useful tool within education. The difference between serious games played using a traditional setup (i.e., a monitor or TV) and VR is that VR gives a higher field-of-view, where players can look around naturally and feel more immersed in the virtual environment (Meijer, 2011). However, the expected benefits of VR have not been fully proven, only showing that there are advantages when it comes to spatial information (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010) and a better in-game experience in the form of greater presence (Schuemie et al., 2001), improved engagement (van den Broek, 2012), and higher cognitive interest (Parong & Mayer, 2018).

When it comes to story-based information, there are conflicting results, with some

research finding better learning performance, no difference, or even worse learning performance (An et al., 2018; Fowler, 2015; Huang et al., 2019; Makransky et al., 2019; Mikropoulos & Natsis, 2011). As such, it could be argued that, currently, the benefit of using this technology is not worth the additional cost. To enable optimal learning from VR serious games, it must be investigated how to effectively develop these games to catalyze learning. Often, in these games, there is a mismatch between the story (i.e., the educational content) and the gameplay (Bethke, 2002; Howitt, 2015). Moreover, some of these games simply use the gameplay as a reward for carrying out a learning activity (i.e. 'chocolate-covered broccoli') (Habgood & Ainsworth, 2011). A method that has been shown to result in higher learning outcomes is integrating the gameplay and learning content to motivate players through intrinsic motivation, where they perform activities for their own enjoyment (Liao et al., 2019; Toh & Kirschner, 2020).

A game genre that holds good promise when it comes to education, is the genre of narrative-centered discovery games (Kee, 2011; Mortara et al., 2014), where players are transported to another place and time period and must explore the environment to discover items and hear audio narratives that reveal the in-game story (Habgood et al., 2018a). These games combine the learning affordances of two distinct game genres: narrative-centered games and discovery games. Narrative-centered discovery games provide powerful, emotive storylines and, in discovery games, players freely explore whilst completing in-game tasks (Kriz, 2010; Toh & Kirschner, 2020). In-game tasks are referred to as information-searching tasks because players need to find educational content. These games provide an organized experience (Dickey, 2006; Lee et al., 2006; Lester et al., 2014; Marsh, 2010) and utilize a self-directed constructivist learning approach, where players actively construct representations of reality by linking new information to prior knowledge (Toh & Kirschner, 2020). This is a good example of using intrinsic motivation to enhance the learning experience and is expected to lead to higher learning goals. As part of this thesis, to test the development process and efficacy of such games, a game of this genre was developed, called the Chantry.

In the Chantry, players explore a reconstructed 18th-century Georgian house and learn the story of Dr. Edward Jenner, his invention of vaccination, and the smallpox virus it helped eradicate through the words of real historical characters (Steel Minions & the Jenner Trust, 2018). To open locked doors and progress further through the game, players must find items referenced in a list shown to them, which contain information in the form of an audio narrative. VR is encouraged for these types of games, as it is beneficial for presenting historical artifacts from the past (Bekele et al., 2018; Slater & Sanchez-Vives, 2016).

Despite narrative-centered discovery games being exploited to make use of intrinsic motivation, the risk of a game-story mismatch remains. Therefore, in Chapter 2, to show the current problem with the development of serious games, we identified a game-story mismatch in the Chantry and provided the Storyline Scaffolding Dashboard (SSD) to provide the ability to both quantify and visualize the game-story relationship to avoid this problem occurring. Moreover, additional functionality was built into the SSD to allow for real-time visual analytics for analyzing players, including learning performance, whilst in-game. One of the measures provided for this analysis was the lostness measure. Originally from the domain of hypertext, this measure is used to measure navigational efficiency in an information-searching task. Due to the node-based movement present in many VR games and the information-searching tasks present in narrative-centered discovery games, this could be a new useful game analytic.

Chapter 3 investigated differences between the same game presented in VR compared to a traditional non-VR setup. This investigated knowledge retention, for both the story and spatial dimensions, navigational efficiency, as measured by the lostness measure, and in-game experience of a player (i.e. presence, engagement, and cognitive interest). We discovered that there was no difference in either the in-game experience nor story knowledge retention of a players. However, it was shown that navigational efficiency and spatial knowledge is improved in VR.

Chapter 4 evaluated the effective components of a narrative-centered discovery game in VR: an explicit storyline, a major component of narrative-centered games and active navigation, a key component of discovery games. Research has shown that active navigation leads to a higher degree of presence and involvement, but also that passive navigation results in a higher degree of knowledge retention regarding both the storyline and spatial dimensions. Removing the cognitive burden of navigation can therefore improve learning, but can also result in a less positive gaming experience. This is endorsed by the cognitive load theory, the amount of available memory available for cognitive data processing (Sweller et al., 2011). Cognitive overload and underload can both hinder learning. For optimal learning performance, players should remain within the Zone of Proximal Development (ZPD) (Vygotsky, 1978).

Based on the theory of ZPD, adaptivity should be used in VR serious games to ensure that optimal learning occurs. In Chapter 5, such an adaptive system is presented that makes use of textual-specificity. This system works by presenting more specific instructions to narrow the search space, making it easier to find educational content, and, conversely, presenting less specific/generic instructions, making it more challenging to find educational content. This forces players into the center of the ZPD and gives them an appropriate level of challenge. It was found that, without having any impact on the in-game experience of a player, the adaptive system was able to reduce cognitive load and increase knowledge retention in both the story and spatial dimensions.

In Chapter 6, the conclusion, we discussed the findings and what this means for the future. We identify how VR serious games can best be designed for more effective learning. Moreover, we encourage further research in this area to investigate different options for adaptive systems and the presentation of these systems. We even detail how this work can be generalized to different areas, to be advantageous to other areas, including outside of games and VR, and even used in traditional games for leisure. Finally, we summarize our findings and how they can be useful for education during a lockdown and the possibilities in a post-pandemic world.

Samenvatting

In sciencefiction films, zoals Ready Player One (Cline, 2011) en Star Trek (Tormé, 1988) heeft Virtual Reality (VR) reeds een prominente rol gespeeld. Daarnaast kan VR ook een belangrijke rol spelen in de ontwikkeling van onderwijsmethoden, aangezien het de leerervaring kan verrijken, meer dan enig ander medium (Gadelha, 2018). De voordelen van het gebruik van VR in educatieve spellen zijn een verhoogde ervaring (o.a. door 3D beeld en geluid) (Schuemie et al., 2001; Slater, 2002), betrokkenheid (o.a. een hoger concentratieniveau, meer interesse en plezier) (Kim, 2018; van den Broek, 2012) en interesse (Harp & Mayer, 1997; Van der Sluis et al., 2014). Deze voordelen hebben bewezen bij te dragen aan het verbeteren van het leerproces (Abdul Jabbar & Felicia, 2015; Checa & Bustillo, 2020; Imlig-Iten & Petko, 2018; Lee et al., 2010).

Een toepassing waarbij VR goed geïntegreerd kan worden zijn zogenaamde serious games. Dit zijn games die een educatief doel en een leercurve bieden (Westra et al., 2009). In het eerste hoofdstuk, de Introductie, bespreken we het potentieel van zowel VR als serious games voor het onderwijs kan zijn. Het verschil tussen serious games, die gebruik maken van een traditionele opstelling (monitor or TV) en VR is dat VR een breder gezichtsveld geeft, waarbij spelers op een natuurlijke manier haar omgevingen kunnen verkennen en zich meer ondergedompeld voelen in de virtuele wereld (Meijer, 2011). VR heeft een positief effect op ruimtelijke informatievoorziening (Huang et al., 2019; Meade et al., 2019; Meijer & Van den Broek, 2010). Door spelers wordt daarnaast een grotere aanwezigheid gevoeld en hierdoor wordt de in-game ervaring verbeterd (Schuemie et al., 2001). Ook zorgt VR voor een hogere betrokkenheid (van den Broek, 2012) en een verhoogde cognitieve interesse (Parong & Mayer, 2018). Als het gaat om de verhaallijn van serious games, spreken onderzoeksresultaten elkaar tegen (An et al., 2018; Fowler, 2015; Huang et al., 2019; Makransky et al., 2019; Mikropoulos & Natsis, 2011). Dit zou een reden kunnen zijn om te beargumenteren dat de additionele kosten van VR niet opwegen tegen de voordelen. Om studenten in staat te stellen optimaal te leren door middel van de inzet van VR serious games, moet er onderzocht worden hoe deze games zo effectief mogelijk ontwikkeld kunnen worden. Een veelvoorkomend probleem in deze spellen is dat de relatie tussen de verhaallijn (oftewel de educatieve content) en de gameplay ontbreekt (Bethke, 2002; Howitt, 2015). Bovendien gebruiken sommige spellen de gameplay als beloning voor het uitvoeren van een leeractiviteit (Habgood & Ainsworth, 2011). Een methode die heeft laten zien te kunnen resulteren in betere educatieve resultaten is om de gameplay met de educatieve content te integreren en zo spelers intrinsiek te motiveren, terwijl ze activiteiten uitvoeren voor eigen plezier (Liao et al., 2019; Toh & Kirschner, 2020).

In het onderwijs laat het genre narrative-centered discovery games, games die draaien om hun verhaallijn, veelbelovende resultaten zien (Kee, 2011; Mortara et al., 2014). Dit genre draait om het meenemen van spelers naar een bepaalde plaats en tijdsperiode waarbij ze een omgeving moeten onderzoeken met als doel bepaalde items te ontdekken. Terwijl spelers dit doen, worden ze begeleidt door een verteller die een bepaalde verhaallijn onthuld (Habgood et al., 2018a). Dit speltype combineert leermogelijkheden uit twee specifieke speltypen: narrative-centered games en discovery of adventure games. Narrative-centered games geven krachtige, emotionele verhaallijnen, waar in discovery games spelers zich vrij bewegen in een wereld terwijl ze bepaalde taken moeten volbrengen (Kriz, 2010; Toh & Kirschner, 2020). Deze taken worden ook wel exploratief-informatieve taken genoemd, aangezien spelers op zoek moeten naar educatieve content. Deze games bieden een gestructureerde ervaring (Dickey, 2006; Lee et al., 2006; Lester et al., 2014; Marsh, 2010) en gebruikt een zelfsturende, constructieve leeraanpak. Deze leeraanpak houdt in dat spelers een nieuwe realiteit construeren door nieuwe informatie met bestaande kennis te verbinden (Toh & Kirschner, 2020). Dit is dan ook een goed voorbeeld waarbij intrinsieke motivatie gebruikt wordt om de leerervaring te verbeteren en er wordt verwacht dat dit resulteert in hogere leerdoelen. Een belangrijk onderdeel van dit proefschrift was om het ontwikkelproces en de werkbaarheid van dergelijke spellen te testen. Daarom is ook de Chantry ontwikkeld, een game met dit type. In de 'Chantry' ontdekken spelers een gereconstrueerd, 18e-eeuws Georgiaans huis en leren spelers het verhaal van Dr. Edward Jenner en zijn vaccinatie-uitvinding kennen. Ook ontdekken de spelers op welke manier Dr. Jenner heeft bijgedragen aan het uitroeien van het 'pokken' virus. Het verhaal wordt verteld door de woorden van echte, historische karakters (Steel Minions & the Jenner Trust, 2018). Om dichte deuren te openen en verder te komen in het spel moeten spelers items vinden, welke worden weergegeven op een referentielijst in de vorm van geluid of tekst. Het gebruik van VR in dit type spellen wordt aangeraden, aangezien VR zich uitstekend leent voor het op een unieke manier weergeven van historische artefacten (Bekele et al., 2018; Slater & Sanchez-Vives, 2016).

Al worden narrative-centered discovery games ingezet om de intrinsieke motivatie te stimuleren, het risico op een onjuiste interpretatie van de verhaallijn blijft bestaan. Zo wordt in Hoofdstuk 2 een foutieve interpretatie van de verhaallijn uit de Chantry geïdentificeerd en voorzien van de Storyline Scaffolding Dashboard (SSD). Het SSD verschaft de mogelijkheid om de relatie tussen gameplay en verhaallijn te kwantificeren en te visualiseren. Het doel hiervan is om te voorkomen dat een onjuiste interpretatie van de verhaallijn zich voordoet. Daarnaast is er ook een extra functionaliteit aan het SSD toegevoegd om real-time spelers en haar leerprestaties te kunnen analyseren, terwijl ze het spel spelen. Een van de variabelen die deze analyse mogelijk maakt, was de Lostness variabele, de mate van het verloren voelen. Vanuit het originele domein van hypertekst wordt deze variabele gebruikt om de efficiency van het navigeren naar exploratieve taken te meten. Binnen narrative-centered discovery games dienen spelers ook te navigeren. Zo kan de Lostness variabele ook in deze context gebruikt worden om gedrag te analyseren.

In Hoofdstuk 3 zijn twee versies van dezelfde game vergeleken: een VR en niet-VR versie. Hierdoor kon er onderzoek gedaan worden naar de mate van kennisbehoud, van zowel het verhaal en de ruimtelijke omgeving, efficiëntie van het navigeren en de beleving van een speler. Wij ontdekten dat er geen verschil in spelervaring en kennisbehoud was tussen beide versies. Wel was de spelnavigatie en ruimtelijke kennis beter in de VR versie.

In Hoofdstuk 4 zijn de effectieve componenten van een narrative-centered discovery games geëvalueerd. Onderzoek heeft uitgewezen dat actieve navigatie leidt tot een hogere mate van aanwezigheid en betrokkenheid maar ook dat een passieve navigatie resulteert in een hogere mate van kennisbehoud betreffende zowel de verhaallijn als ruimtelijke dimensies. Het weghalen van de cognitieve last van het navigeren kan het leren dus verbeteren maar kan ook resulteren in een minder positieve spelervaring. Dit wordt onderschreven door de cognitive load theory, de hoeveelheid beschikbaar geheugen die beschikbaar is voor cognitieve dataverwerking (Sweller et al., 2011). Cognitieve overbelasting en onderbelasting kunnen allebei de leercurve verhinderen. Voor een optimale leerprestatie dienen spelers binnen de Zone of Proximal Development (ZPD) te blijven (Vygotsky, 1978).

Gebaseerd op de ZPD-theorie zou adaptief vermogen gebruikt moeten worden om er voor te zorgen dat een optimale leercurve ontstaat. In Hoofdstuk 5 wordt zo'n adaptief systeem gepresenteerd dat specifieke instructies weergeeft om de te doorzoeken educatieve ruimte kleiner of juist groter te maken. Het bleek dat het adaptieve systeem in staat bleek om de cognitieve last te verlagen en tegelijkertijd de mate van kennisbehoud te verhogen, zowel qua verhaal als ruimtelijke voorstelling.

In Hoofdstuk 6, de Conclusie, hebben we de onderzoeksresultaten en de mogelijke effecten hiervan in de toekomst besproken. We hebben geïdentificeerd op welke manier serious games het beste ontwikkeld kunnen worden, zodat ze bijdragen aan een effectief leerproces. We beschrijven ook op welke manier dit gegeneraliseerd kan worden naar andere werkvelden en hoe dit voordelen kan opleveren, zelfs buiten serious games en VR om. Het kan zelfs veel voordelen opleveren voor reguliere games. We eindigen met een samenvatting van onze onderzoeksresultaten en hoe deze bruikbaar kunnen zijn voor onderwijs tijdens de COVID-19 lockdown en de mogelijkheden die het bied in een wereld ná de pandemie.

Curriculum Vitae

Chris Ferguson

11-09-1992	Born in Ashington, United Kingdom

Education

2006 – 2011	The Blyth School, Community College Blyth, Northumberland, United Kingdom
2011 – 2016	Sheffield Hallam University Sheffield, South Yorkshire, United Kingdom
2013 – 2014	Hochschule Reutlingen Reutlingen, Baden-Württemberg, Germany

Work Experience

Jun 2013 – Aug 2013	Junior Technical Designer Sumo Digital Sheffield, South Yorkshire, United Kingdom
Mar 2014 – Aug 2014	Research Assistant Max Planck Institute for Biological Cybernetics Tübingen, Baden-Württemberg, Germany
Sep 2016 – Jan 2017	Developer Support Engineer Sony Interactive Entertainment Europe London, United Kingdom
Feb 2017 – Apr 2021	PhD Candidate Department of Information and Computing Sciences Utrecht University Utrecht, Netherlands
Sep 2021 – Present	Simulated Reality Developer Dimenco Veldhoven, North Brabant, Netherlands