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

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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. VR did not improve players' retention of factual knowledge, but did significantly improve players' spatial knowledge and navigational efficiency. We conclude (a) the hypertext lostness measure is also valuable for node-based VR games and (b) VR games add to spatial learning, even when compared with already immersive desktop games.

Keywords: virtual reality (VR), knowledge, serious games, learning, lostness, navigation

Introduction

Nowadays, virtual reality (VR) is used successfully across many different industries for information acquisition and skill improvement; for example, in surgery,[1] the military,[2] and education.[3] The next step is to explore one of VR's next levels: storytelling.[4] However, navigation in VR can be overwhelming for its users.[5] A possible remedy was recently found: node-based movement, where players move between predefined positions.[6]

A key aim of many educational games is information acquisition, without explicit teaching, where items must be discovered to proceed further in the game. In particular, narrative-centered discovery games have considerable learning potential. 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.[7,8] This stimulates players to construct appropriate mental models.[9,10] Narrative-centered discovery games combine the learning affordances of two distinct game genres: (a) discovery games, where learning occurs by solving problems through exploration rather than being directly presented with learning content[11]; and (b) narrative-centered games, which use strong and emotive storylines, often presented auditorily. These games involve two types of knowledge: story knowledge, knowledge constructed from a story a person has been told or experienced[12]; and spatial knowledge, knowledge constructed from observations gathered while traveling through an environment.[13] This leads to higher and deeper learning than expository learning[14,15] as well as enhanced retention of information[16–18] as these games provide a motivating, engaging, and organized learning experience.[8,11,19–21] This is expected to lead to positive learning results as focused attention and an increased effect during encoding have been found to enhance retention of information.[16–18]

As in VR, navigation in hypertext systems, responsive node-based systems with branches leading to text and other media,[22] can be challenging and is frequently characterized by disorientation, where users lose their sense of location and direction.[23,24] This happens when navigation is too much of a cognitive burden and leads to cognitive overload[25] (i.e., an excessive amount of load placed on a person's working memory when carrying out a task[26]). Similar effects are known from VR.[5,27–29] Cognitive overload leads to inhibited learning[30] as a user simultaneously devotes limited cognitive resources to both navigation and comprehension.[31,32]

We pose that *lostness*,[33] a measure that is used to identify disorientation and has been shown to be successful in

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predicting success in information-seeking tasks in hypertext,[34–36] can also be used in VR games that use a node–link approach due to the similarity in process and structure. For a given task, lostness (L) is defined as follows:

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

where R is the minimum number of nodes needed to be visited, N is the number of unique nodes a player has visited, and S is the total number of nodes a player has visited. L results in a value of between 0 and $\sqrt{2}$; 0 indicates that the task has been completed perfectly (not disoriented) and $\sqrt{2}$ indicates that a user was completely disoriented, illustrating poor navigational efficiency.

VR might have the disadvantage of disorientation. In parallel, it also has many benefits[37] in addition to its key feature: natural observation through its head tracking enabled stereoscopic three-dimensional rendering[38]; most noteworthy benefits are as follows: (a) greater presence[39] (i.e., a player feeling being physically present in VR[40]), which aids learning outcomes in VR[41]; (b) improved engagement[42] (i.e., heightened concentration, interest, involvement, and enjoyment[43]), which catalyzes learning[44,45]; and (c) cognitive interest[46] (i.e., understanding topics and becoming more interested[47]), which serves as intrinsic motivation to explore and experience new and unfamiliar things,[48] a key part of narrative-based discovery games. Although these three aspects are known to positively influence learning,[49] there is no consensus on the differences in in-game experience between VR and non-VR games.[39]

There is general agreement on VR's contribution to visual (spatial) information processing.[50–52] However, there is disagreement on VR's contribution to learning.[27,51,53–55] This can at least partly be explained by two factors: (a) most research compared VR with traditional educational methods rather than comparing the same game presented in VR with a non-VR/desktop environment[56] and (b) the vast majority of studies did not make use of fully immersive VR by using either low-end headsets or primitive controls or both.[27,51,53] This study deviates from existing studies as it (a) gives a direct comparison between VR and a non-VR/desktop game and (b) uses fully immersive VR and hence aids natural observation[38,57] and natural control.[58]

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 with a node-based non-VR game (control condition), will VR have a positive effect on

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

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

Methods

Participants

Twenty-five adolescents (i.e., 12 males and 13 females) aged 13–18 years (mean: 15.00, *SD*: 1.32) participated. They represent the target audience for the game used. Participants were randomly assigned to either the VR (six males and seven females) or non-VR (six males and six females) condition. Given the design of the study and our previous experiences with a similar setup,[59] this number of participants is expected to be adequate to both verify the results and unveil sufficient power to generalize the results.

None of the participants had a medical reason disqualifying them from using VR. All were recruited from a University Technical College in the United Kingdom. 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.

VR game environment

A Sony PlayStation VR game, The Chantry,[60] a narrative-centered discovery game using a node-based movement system, was used. This game takes place in the house of Dr. Edward Jenner and tells the story of the invention of the smallpox vaccine. Players are required to find items related to descriptions on a list (Fig. 1), which reveal the story information through audio narratives. The tasks can be completed in a predefined minimum number of steps, so the lostness measure can be applied.

Apparatus

In both conditions, the game ran at 60 Hz, reprojected to 120 Hz, 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: 1920×1080).

To specify the level of the immersion in the non-VR/desktop setting, we calculated participants' horizontal instantaneous field of view (IFOV) as follows[56]:

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

where D_c is the screen size, d_e is the standard eye separation parameter of 0.63 cm, and l is the distance from the eyes to the screen. This resulted 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

FIG. 1. Using node-based movement to complete the Gloucestershire task in The Chantry. The two objectives shown on the list are completed when the player picks up the relevant items and hears the information attached to it. Color images are available online.

between conditions was that both the natural head and hand 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.

Measurements: calculating lostness

To assess different aspects of navigation behavior, two versions of the lostness measure, global and local, were developed. These reflect global and local path analysis, respectively,[61] also see the Introduction section.

Global lostness compares the path followed throughout to complete a task with the optimal path multiplied by the number of subtasks that the task included (e.g., see Gloucestershire in Fig. 1). This is done throughout the complete game. Subsequently, all global lostness values are summed and divided by the sum of the number of subtasks per task. This way, the tasks are normalized within the full game.

Local gathering compares the path followed throughout to complete a subtask with the optimal path (e.g., see County Map in Fig. 1). Throughout the complete game, the R, S, and N values are calculated for each subtask and summed. After the full game is finished, the summed R, S, and N values are used in the original lostness equation to determine the local lostness. No normalization is needed.

Measurements: questionnaires

Knowledge retention was measured through a bespoke knowledge test consisting of 24 randomized true/false statements (50 percent true and 50 percent false). Sixteen were related to the story (e.g., ''Vaccination was already popular in England by 1800.'') and eight to spatial aspects (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[62] (example item—''I feel like I can't stop playing''), the igroup Presence Questionnaire[63] (example item—''I felt present in the virtual space''), and the Perceived Interest Questionnaire[64] (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, 0.85, 0.85, and 0.91.

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. In addition, 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, participants were debriefed and informed about the nature of both the study and the game.

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 (both local and global) and both story-based and spatial-based knowledge. Additionally, we controlled for effects on presence, engagement, and cognitive interest. The

Table 1. Mean and Standard Deviation of All Measures for Both Non-Virtual Reality and Virtual Reality Conditions

	Non-VR		*VR*	
	Mean	SD	*Mean*	SD
Local lostness	0.62	0.13	0.47	0.11
Global lostness	0.71	0.13	0.57	0.15
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

SD, standard deviation; VR, virtual reality.

means and standard deviations of these measures in each condition are provided in Table 1.

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 both the global lostness (desktop median = 0.758, VR median = 0.617, $Z = 10$, $p = 0.023$) and local lostness (desktop median = 0.627, VR median = 0.511, $Z = 5$, $p = 0.008$) measures (Fig. 2).

Participants in the VR condition performed better on spatial-based knowledge questions (desktop median = 0.5, VR median = 0.75, $Z = 55.5$, $p = 0.041$). In contrast, no significant difference was found for story-based knowledge (Fig. 3).

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

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 parameters. Compared with 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 with the participants playing the game in a desktop/non-VR environment, participants in VR had both lower local and global lostness values, identifying that they were more efficient in navigation. This implies that VR aids spatial information processing on both a local level (i.e., fact finding) and a global level (i.e., information gathering). 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.[65–67]

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[50–52] and vindicates its use in disciplines that rely heavily on spatial knowledge.[1,2] Moreover, the combination of higher spatial knowledge retention and higher navigational efficiency found in VR compared with the non-VR/desktop condition mirrors hypertext findings that spatial ability is a predictor of navigational performance.[68,69]

In contrast to spatial information, no significant difference was found for 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.[70,71] 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

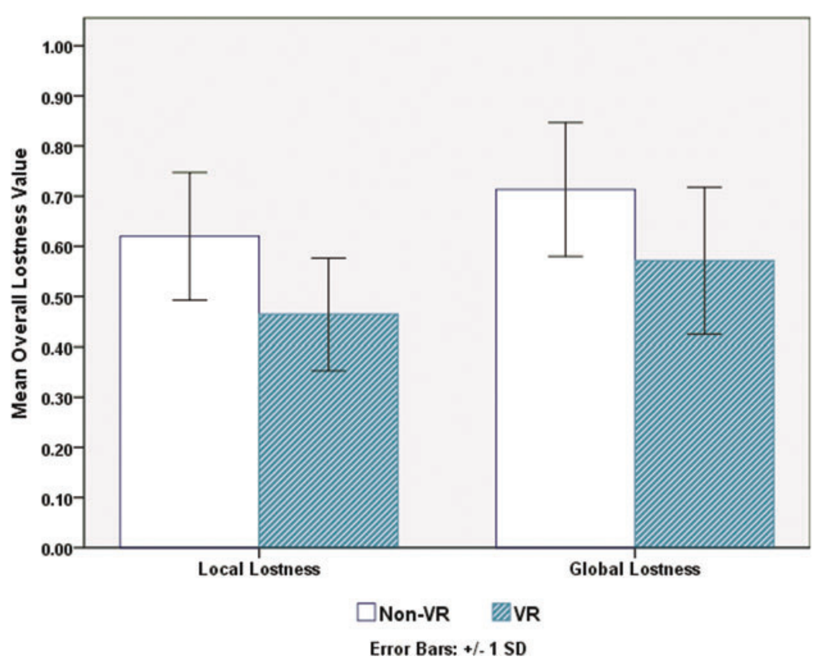

FIG. 2. Comparison of the local (*left*) and global (*right*) lostness measures for the desktop and VR environment. Error bars indicate standard error. VR, virtual reality. Color images are available online.

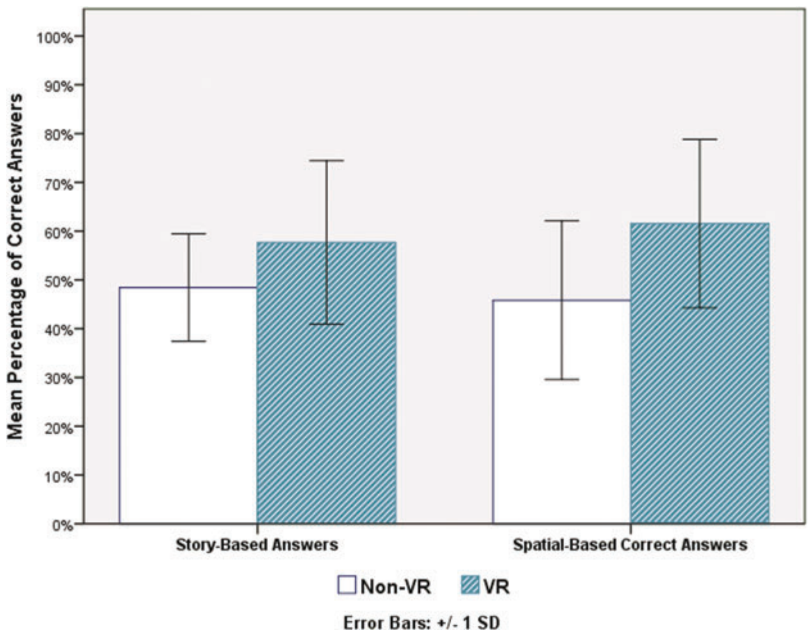

FIG. 3. Comparison of the percentage of correct answers on the story (*left*) and spatial (*right*) knowledge questionnaire. Error bars represent standard errors. Color images are available online.

in non-VR due to the increased visual information, but at the expense of information presented in other ways.[51] Previous research also suggested that multimodal synergy (i.e., the synergy of information originating from multiple modalities[72]) could improve with increasing IFOV.[51] 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.[5,27–29] Although we did not examine this directly, our data do 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, the cognitive load could reduce. Again, this encourages followup research on adaptivity to assist a disoriented and overloaded player using the lostness measure. This would be in line with previous research, which found significantly higher retention of educational story content when players were guided through the environment, reducing the cognitive burden of navigation.[59]

Finally, it should be noted that 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. A followup 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 with 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 in story-based knowledge retention. This partially supported findings that only visually presented information is better retained in VR,[51] while differing from other research that found that VR hindered learning.[27] Followup research should examine the best way to present learning content in VR for better learning. 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.

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References

1. Thomsen ASS, Bach-Holm D, Kjærbo H, et al. Operating room performance improves after proficiency-based virtual reality cataract surgery training. Ophthalmology 2017; 124: 524–531.
2. van Doesburg W, Heuvelink A, van den Broek EL. (2005) TACOP: A cognitive agent for a naval training simulation environment. In Dignum F, Dignum V, Koenig S, Kraus S, Singh MP, Wooldridge M, eds. *ACM Proceedings of the Industry Track of the Fourth International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS–05).* New York: ACM, pp. 35–42.

3. 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 2020; 23:23–33.
4. Wiederhold BK. The next level of virtual reality isn't technology—it's storytelling. Cyberpsychology, Behavior, and Social Networking 2018; 21:671.
5. Darken RP, Sibert JL. (1993) A toolset for navigation in virtual environments. In Hudson S, Pausch R, van der Zanden B, Foley J, eds. *Proceedings of the 6th Annual ACM Symposium on User Interface Software and Technology (UIST'93)*. New York: ACM, pp. 157–165.
6. Habgood J, Moore D, Wilson D, et al. (2018) Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* Reutlingen, Germany: IEEE, pp. 371–378.
7. Malone TW, Lepper MR. (1987) Making learning fun: A taxonomy of intrinsic motivations for learning. In Snow R, Farr MJ, eds. *Aptitude, learning, and instruction volume 3: conative and affective process analyses*. Hillsdale, NJ: Lawrence Erlbaum Associates Publishers, pp. 223–253.
8. Lester JC, Spires HA, Nietfeld JL, et al. Designing game-based learning environments for elementary science education: a narrative-centered learning perspective. Information Sciences 2014; 264:4–18.
9. Wasserman JA, Banks J. Details and dynamics: mental models of complex systems in game-based learning. Simulation & Gaming 2017; 48:603–624.
10. Furlough CS, Gillan DJ. Mental models: structural differences and the role of experience. Journal of Cognitive Engineering and Decision Making 2018; 12:269–287.
11. Adams DM, Mayer RE, MacNamara A, et al. Narrative games for learning: testing the discovery and narrative hypotheses. Journal of Educational Psychology 2012; 104:235–249.
12. Schank RC, Ableson RP. Knowledge and memory: The real story. In Wyer RS, ed. *Knowledge and memory: the real story.* Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 1–85.
13. Kuipers B. Modeling spatial knowledge. Cognitive Science 1978; 2:129–153.
14. Bruner JS. (1960) *The process of education.* Oxford: Harvard University Press.
15. Papert S. (1980) *Mindstorms: children, computers, and powerful ideas*. New York: Basic Books.
16. Baddeley A, Lewis V, Eldridge M, et al. Attention and retrieval from long-term memory. Journal of Experimental Psychology 1984; 113:518–540.
17. Murdock B, Bennet B. Effects of a subsidiary task on short-term memory. British Journal of Psychology 1965; 56:413–419.
18. Parkin AJ, Lewinsohn J, Folkard S. The influence of emotion on immediate and delayed retention: Levinger & Clark reconsidered. British Journal of Psychology 1982; 73:389–393.
19. Lee KM, Park N, Jin S. (2006) Narrative and interactivity in computer games. In Vorderer P, Bryant J, eds. *Playing video games: motives, responses, and consequences.* Hillsdale, NJ: Lawrence Erlbaum Associates Publishers, pp. 259–274.
20. Dickey M. 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 2006; 54:245–263.
21. Marsh T. (2010) Activity-based scenario design, development, and assessment in serious games. In van Eck R, ed. *Gaming and cognition: theories and practice from the learning sciences.* Hershey, PA: IGI Global, pp. 214–227.
22. Barnet B. (2020) Hypertext before the web—or, what the web could have been. In Brügger N, Milligan I, eds. *Sage handbook of web history*. London: Sage, pp. 215–226.
23. Conklin J. Hypertext: an introduction and survey. Computer 1987; 20:17–41.
24. Head M, Archer N, Yuan Y. World wide web navigation aid. International Journal of Human-Computer Studies 2000; 53:301–330.
25. Gwizdka J, Spence I. (2005) Indirect assessment of web navigation success. In van der Veer G, Gale C, eds. *CHI'05 Extended Abstracts on Human Factors in Computing Systems (CHI EA'05).* New York: ACM, pp. 1427–1430.
26. Chen F, Zhou J, Wang Y, et al. (2016) *Robust multimodal cognitive load measurement.* Cham: Springer International Publishing.
27. Makransky G, Mayer RE, Veitch N, et al. Equivalence of using a desktop virtual reality science simulation at home and in class. PLoS One 2019; 14:e0214944.
28. Andersen SA, Mikkelsen PT, Konge L, et al. 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 2016; 1:20.
29. Andersen SA, Mikkelsen PT, Konge L, et al. Cognitive load in distributed and massed practice in virtual reality mastoidectomy simulation. The Laryngoscope 2016; 126: E74–E79.
30. Sweller J, Ayres P, Kalyuga S. (2011) *Cognitive load theory.* New York: Springer.
31. Bolter JD. (2001) *Writing space.* Mahwah, NJ: Lawrence Erlbaum Associates.
32. Sharples M. (1999) *How we write: writing as creative design.* London, United Kingdom: Routledge.
33. Smith PA. Towards a practical measure of hypertext usability. Interacting with Computers 1996; 8:365–381.
34. Herder E. (2003) Revisitation Patterns and Disorientation. In *Proceedings of the German Workshop on Adaptivity and User Modeling in Interactive Systems ABIS 2003*. Karlsruhe: University of Karlsruhe, pp. 291–294.
35. McEneaney JE. Graphic and numerical methods to assess navigation in hypertext. International Journal of Human-Computer Studies 2001; 55:761–786.
36. Otter M, Johnson H. Lost in hyperspace: metrics and mental models. Interacting with Computers 2000; 13:1–40.
37. van den Broek EL, Meijer F, Landman RB. Augmenting mental models. Journal of Cybertherapy and Rehabilitation 2010; 3:19–21.
38. Desai P, Desai P, Ajmera K, et al. A review paper on oculus rift-a virtual reality headset. International Journal of Engineering Trends and Technology 2014; 13:175–179.
39. Schuemie MJ, van der Straaten P, Krijn M, et al. Research on presence in virtual reality: a survey. Cyberpsychology & Behavior 2001; 4:183–201.
40. Slater M. Presence and the sixth sense. Presence: Teleoperators and Virtual Environments 2002; 11:435–439.
41. Ai-Lim Lee E, Wong KW, Fung CC. How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach. Computers & Education 2010; 55:1424–1442.
42. van den Broek EL. (2012) On making engagement tangible. In Spink AJ, Grieco F, Krips OE, Loijens LWS, Noldus LPJJ, Zimmerman PH, eds. *Proceedings of Measuring Behavior 2012: 8th International Conference on Methods*

and Techniques in Behavioral Research. Wageningen, Netherlands: Noldus Information Technology, pp. 90–93.
43. Kim S, Song K, Lockee B, et al. (2018) *Gamification in learning and education: enjoy learning like gaming*. Cham: Springer International Publishing.
44. Abdul Jabbar AI, Felicia P. Gameplay engagement and learning in game-based learning: a systematic review. Review of Educational Research 2015; 85:740–779.
45. Imlig-Iten N, Petko D. Comparing serious games and educational simulations: effects on enjoyment, deep thinking, interest and cognitive learning gains. Simulation & Gaming 2018; 49:401–422.
46. Parong J, Mayer RE. Learning science in immersive virtual reality. Journal of Educational Psychology 2018; 110:785–797.
47. Harp SF, Mayer RE. The role of interest in learning from scientific text and illustrations: on the distinction between emotional interest and cognitive interest. Journal of Educational Psychology 1997; 89:92–102.
48. van der Sluis F, van den Broek EL, Glassey RJ, et al. When complexity becomes interesting. Journal of the Association for Information Science and Technology 2014; 65:1478–1500.
49. Checa D, Bustillo A. A review of immersive virtual reality serious games to enhance learning and training. Multimedia Tools and Applications 2020; 79:5501–27.
50. Meijer F, van den Broek EL. Representing 3D virtual objects: evidence for an interaction between visuo-spatial ability and the nature of exploration. Vision Research 2010; 50:600–635.
51. Huang K, Ball C, Francis J, et al. 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 2019; 22:105–110.
52. Meade ME, Meade JG, Sauzeon H, et al. Active navigation in virtual environments benefits spatial memory in older adults. Brain Sciences 2019; 9:47.
53. An B, Matteo F, Epstein M, et al. (2018) Comparing the performance of an immersive virtual reality and traditional desktop cultural game. In Silva HP, Constantine L, Escalona MJ, Ramirez AJ, Helfert M, eds. *Proceedings of the 2nd International Conference on Computer-Human Interaction Research and Applications (CHIRA2018)*. Funchal, Madeira, Portugal: INSTICC, pp. 54–61.
54. Mikropoulos TA, Natsis A. Educational virtual environments: a ten-year review of empirical research (1999–2009). Computers & Education 2011; 56:769–780.
55. Fowler C. Virtual reality and learning: where is the pedagogy? British Journal of Educational Technology 2015; 46:412–422.
56. Pierce MB, Young PA, Doherty SM. Engagement and competence in VR and non-VR environments. Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2017; 61:2082–2085.
57. Zhdanov AD, Zhdanov DD, Bogdanov NN, et al. Discomfort of visual perception in virtual and mixed reality systems. Programming and Computer Software 2019; 45:147–155.
58. Chen Q, Luo D. (2019) The comparison and analysis of several common VR panoramic display methods. In *3rd International Conference on Mechatronics Engineering and Information Technology (ICMEIT 2019)*. Dalian, China: Atlantis Press, pp. 357–363.
59. Ferguson C, van den Broek EL, van Oostendorp H. On the role of interaction mode and story structure in virtual reality serious games. Computers & Education 2020; 143:103671.
60. Steel Minions. (2018) The Chantry. https://store.playstation.com/en-gb/product/EP4325-CUSA12254_00-DRJENNERSMALLPOX (accessed Apr. 12, 2020).
61. Puerta Melguizo MC, Vidya U, van Oostendorp H. Seeking information online: the influence of menu type, navigation path complexity and spatial ability on information gathering tasks. Behaviour & Information Technology 2012; 31:59–70.
62. Brockmyer JH, Fox CM, Curtiss KA, et al. The development of the game engagement questionnaire: a measure of engagement in video game-playing. Journal of Experimental Social Psychology 2009; 45:624–634.
63. Schubert T, Friedmann F, Regenbrecht H. The Experience of Presence: factor analytic insights. Presence Teleoperators & Virtual Environments 2001; 10:266–281.
64. Schraw G, Bruning R, Svoboda C. Sources of situational interest. Journal of Reading Behavior 1995; 27:1–17.
65. van Oostendorp H, van der Spek ED, Linssen JM. Adapting the complexity level of a serious game to the proficiency of players. EAI Endorsed Transactions on Serious Games 2014; 14:e5:1–e5:8.
66. Caballero-Hernández JA, Palomo-Duarte M, Dodero JM. Skill assessment in learning experiences based on serious games: a systematic mapping study. Computers & Education 2017; 113:42–60.
67. Shute V, Ke F, Wang L. (2017) Assessment and adaptation in games. In Wouters P, van Oostendorp H, eds. *Instructional techniques to facilitate learning and motivation of serious games.* Cham, Switzerland: Springer International Publishing, pp. 59–78.
68. van Oostendorp H, Karanam S. (2013) Navigating in a virtual environment with model-generated support. In Palanque P, Détienne F, Tricot A, eds. *Proceedings of the 31st European Conference on Cognitive Ergonomics (ECCE'13)*. New York: ACM, pp. 1–8.
69. Juvina I, van Oostendorp H. Modeling semantic and structural knowledge in web navigation. Discourse Processes 2008; 45:346–364.
70. Garner R, Gillingham MG. Topic Knowledge, Cognitive Interest, and Text Recall: a Microanalysis. The Journal of Experimental Education 1991; 59:310–319.
71. Fredricks JA, Blumenfeld PC, Paris AH. School engagement: potential of the concept, state of the evidence. Review of Educational Research 2004; 74:59–109.
72. Perakakis M, Potamianos A. (2008) Multimodal system evaluation using modality efficiency and synergy metrics. In Digalakis V, Potamianos A, Turk MA, eds. *Proceedings of the 10th international Conference on Multimodal Interfaces (ICMI'08)*. New York: ACM, pp. 9–16.

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