EXPERIENCING FLOW IN VIRTUAL REALITY: AN INVESTIGATION OF COMPLEX INTERACTION STRUCTURES OF LEARNING-RELATED VARIABLES

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ABSTRACT

Theoretical background: Learning in virtual realities (VR) has become increasingly important. In this context, VR appears to be particularly conducive to affective learning objectives, such as perspective-taking in VR actors. Previous research has often focused on investigating cause-effect relationships that focus on the direct effects of different VR visualization technologies on learning outcomes. Little research has been conducted on more complex constellations of learning-related variables. Therefore, the present study aims at elaborating a research design that can be used to investigate both the direct effects of VR visualization technologies as well as the mediating effects of learning process variables latent in VR. For this purpose, the research design will be experimentally tested by comparing head-mounted display (HMD)-based VR with laptop-based VR with respect to the intended learning objectives, and controlling for influences by underlying learning processes (here: the experience of flow within VR).
Methods: 132 students of grades eight and nine were recruited. The subjects were assigned to experimental conditions (HMD vs. laptop). The VR content dealt with the exploration of the hiding place of Anne Frank at the time of World War II in Amsterdam. Questionnaires were used to collect several data including sociodemographic characteristics, knowledge gain, perspective-taking, subjective evaluation, and the learning process variable flow.
Results: A significant main effect for the variable VR visualization technology was uncovered averaged across all learning indicators. However, a superiority of HMD-based VR was found for the two evaluative indicators and also for the affective learning indicator. For the cognitive learning indicator, the effect was reverse. More relevant than unidirectional relationships are the mediating effects. Mediating effects through the experience of flow were discovered several times. Thus, the experience of flow within VR can significantly explain the cause-effect relationships between VR visualization technology and learning outcomes, even if, for the most part, only effects for evaluative indicators could be determined.
Conclusion: The present study was able to exemplify that the investigation of complex interaction structures of VR visualization technologies and learning process variables can make a large contribution to the understanding of learning in VR environments. Advantages of HMD-based VR over laptop-based VR with respect to some learning indicators were uncovered. The significant findings of the mediation analyses point to the fact that the direct effects of VR visualization technologies on parameters of learning can be significantly explained by learning process variables such as flow experience and are systematically overestimated if such learning processes are not taken into account.

KEYWORDS

Virtual Reality, Mediation Analysis, Learning Processes, Flow Experience, Anne Frank VR House

1. INTRODUCTION

Virtual reality (VR) is becoming increasingly popular. VR applications used for teaching and learning purposes are also gaining importance (e.g., Fowler, 2015). VR is said to promote in particular the acquisition of procedural skills, for example in skilled trades (e.g., Radianti et al., 2020), but also affective skills such as perspective-taking or prosocial behavior (e.g., Martingano et al., 2021). Here, the term VR is often used as a collective term for heterogeneous visualization technologies and is not used distinctively. This may mean 360° pictures viewed on tablets, or 360° movies viewed through cardboard goggles. In addition, the term encompasses environments in which so-called head-mounted displays (HMDs), which enclose ears and eyes, paired with data suits and controllers enable interaction in entirely computer-generated spaces. What they all have in common is the understanding of a computer-generated and realistic real-time representation that individuals virtually enter, experience multisensory, and in which they interact via artificial and natural user interfaces (Radianti et al., 2020; Zinn, 2019). A distinctive subdivision of VR visualization technologies is often challenging. Many studies, therefore, focus on the comparison of such visualization technologies with regard to the intended learning outcomes. Their goal is usually to find out with which technology learning is better or worse. The implication is that the technology could directly influence learning. However, in such media comparison studies, which are often viewed critically (e.g., Clark & Mayer, 2016), the instructional design behind the educational technology is neglected. It is not the technology that leads to better or worse learning, rather it is the interaction of many factors, of which the visualization technology is one.

In many previous studies on learning in VR environments, learning outcomes are the subject of research. Latent processes taking place within the VR experience have rarely been considered. These include the experience of presence (e.g., Mikropoulos, 2006), cognitive load (e.g., Parong & Mayer, 2021), or flow (e.g., Rutrecht et al., 2021). It can be assumed that such learning process variables can significantly explain the effects of VR visualization technologies on learning outcomes. In order to investigate the complex causal relationships, an experimental study was conducted. In this study, both, the direct effects on learning outcomes through VR visualization technologies as well as the indirect effects mediated by the learning process variable flow can be investigated. Therefore, we used a VR environment, which is accessible via two different visualization technologies (HMD vs. laptop) and which is a virtual replication of the Anne Frank House in Amsterdam.

The article is divided into the parts theoretical background, methodology, results, and discussion. In the first part, VR as a technology and the learning process variable flow are described. In the second part, the methodological approach including a description of the sample, procedure, measurement instruments, and data analysis is explained. In the third part, results are presented. Part four serves to interpret the results. Finally, implications and limitations of the work are discussed.

2. THEORETICAL BACKGROUND

2.1 Virtual Reality

VR has often been defined in terms of its technological features. Greenbaum (1992) wrote "*Virtual Reality is an alternate world filled with computer-generated images that respond to human movements. These simulated environments are usually visited with the aid of an expensive data suit which features stereophonic video goggles and fiber-optic data gloves."* (p. 58). While even today, depending on the discipline, educational technologies are often characterized and judged on the basis of their hardware conditions (i.e., on the basis of input and output devices), research in educational psychology attempts to define the technology more on the basis of its underlying cognitive processes (e.g., Bente, Krämer & Petersen, 2002). A definition by Biocca and Delaney (1995) addresses both. "*VR is the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment*." (p. 63). Nevertheless, the characterization of VR based on its technological characteristics is common and also relevant to the present study. Currently, three-dimensional environments exist that are presented via two-dimensional screens and are based on devices such as monitors, mice, joysticks, keyboards, microphones, and speakers (Burdea & Coiffet, 2003). Such VR environments are often classified as non-immersive (Cummings & Bailenson, 2016; Schroeder, 2010). Stereoscopic displays visually convey depth information, creating a spatial impression. However, many stimuli from the real environment are still perceived. Auditory content is presented via headphones or speakers. Navigation and interaction with virtual artifacts are done via mouse, joystick, or keyboard (Lee, Wong & Fung, 2010). When referring to laptop visualization technology in the following part of this article, the latter description is always meant. Immersive VR environments, on the other hand, are often associated with the use of HMDs. In the following text, this visualization technology will be linked with the abbreviation HMD. HMDs enclose eyes and ears. They fill the entire field of vision and largely block out environmental stimuli from the reality. Auditory VR content is conveyed via integrated headphones. The displays present an image to each eye from a slightly different viewing angle. This mimics natural human visual perception, creating the stereoscopic impression of a computer-generated virtual world. The sensors of the HMDs consider head movements and enable perspective changes and movements in space. This is often combined with data gloves, body suits, and controllers, whose functionalities are used to navigate, select and interact (Allmendinger, 2010; Andreas et al., 2010). Of course, a division in HMD and laptop VR is limited, but sufficient in the context of the present study. Nevertheless, other VR visualization technologies such as CAVEs (e.g., Buttussi & Chittaro, 2017) exist and VR technologies undergo on-going development activities.

As described above, HMD and laptop VR differ in terms of their technological features. Besides the visible differences, there are latent factors happening during a VR experience that differ depending on the kind of technology. These factors are considered to be correlates of human information processing and thus modify the experiences in VR. Hence, investigating such processes enables us to describe the experiential quality of VR learning in more detail. Among others, the experience of flow (e.g., Rutrecht et al., 2021) has been shown to be promising for learning in VR.

2.2 Flow Experience

Experiencing flow is understood to mean that a person experiences an activity as gratifying. The person perceives no or hardly any separation between himself and the activity (Csikszentmihalyi, 1997). Furthermore, the course of the action becomes automated and the action is usually performed faster and more effectively. Another characteristic of flow is the loss of the sense of time (Rutrecht et al., 2021). In educational psychology, the experience of flow is also classified as a performance-relevant component of learning motivation and described as increasing motivation (Engeser et al., 2005). Accordingly, flow is a positive emotion in the form of intrinsic reward (Sherry, 2004; Voiskounsky, Mitina & Avetisova, 2004). The experience of flow is also dependent on the fit between the individuum and the task. According to this, flow can only occur if the acting person is neither under- nor over-challenged (Csikszentmihalyi, 1997).

Rheinberg, Vollmeyer, and Engeser (2003) consider flow as a multidimensional construct consisting mainly of the facets smooth automated flow and absorbedness. Meant are the flow of action chains and the complete absorption in an activity. Based on these facets, Rheinberg et al. (2003) developed a questionnaire.

The experience of flow has been associated with the success of a VR learning activity. In a study by Bodzin et al. (2021), students explored their city's river watershed in VR. They reported significantly experiencing more flow and learning more. A comparison group was not implemented. In another study by Tai et al. (2022), again no control group was used. 143 engineering students were trained in VR regarding the care of car body parts. Procedural skills recorded in a post hoc test could be significantly explained by experiencing flow in the VR environment. Another study by Rutrecht et al. (2021) examined 100 subjects playing a performance-based rhythm game under an HMD or on a desktop. The game outcome could be significantly explained by the experience of flow. However, the groups did not differ with respect to flow. Overall, there is still little empirical research on the relationship between experiencing flow in VR and learning outcomes.

The present study intends to investigate to what extent VR visualization technologies are suitable to significantly support students' learning. Using a VR environment, which is a recreation of the hiding place of Anne Frank in Amsterdam, cognitive and affective indicators of learning as well as the subjective evaluation of the VR application will be examined in more detail. A special focus of the study will be on the learning process flow. The research design visualized in Figure 1 aims at a more appropriate representation of the complex interaction structures of learning-relevant variables and thus mediating relationships. Both, direct effects and indirect effects become measurable. By controlling for the additional variable flow, confounding can be avoided. If influencing variables that correlate with the independent variables, in this case VR visualization technology, and dependent variables, in this case learning indicators, are not controlled, so-called spurious effects can arise. The estimation of the correlations between the independent and dependent variables is biased if relevant factors are not controlled. Thus, correlations are systematically over- or underestimated. The interpretation of causality between independent variables and dependent variables is compromised. Studies that have been exclusively devoted to the comparison of two forms of media presentation have often failed to control for person-specific variables (e.g., experience of flow and presence) and thus for differences within the sample with respect to these variables. This is particularly problematic when the study is not a randomized experiment, in which person-specific variables are assumed to be balanced out due to random assignment to experimental conditions (Eid, Gollwitzer & Schmitz, 2010). If, as the research design underlying this paper suggests, additional variables are integrated that appear to be related to the independent and dependent variables, on the one hand confounding and thus biased results can be avoided and, at the same time, additional variance in the dependent variables can be systematically elucidated.

We hypothesize the following:

1. Main effect: Learning outcomes differ depending on visualization technology.
   (a) with respect to affective learning indicators: HMD > laptop
   (b) with regard to cognitive learning indicators: HMD = laptop
2. Mediating effect: More flow is experienced in the HMD conditions than in the laptop conditions. The more flow is experienced, the more beneficial for the learning outcomes.

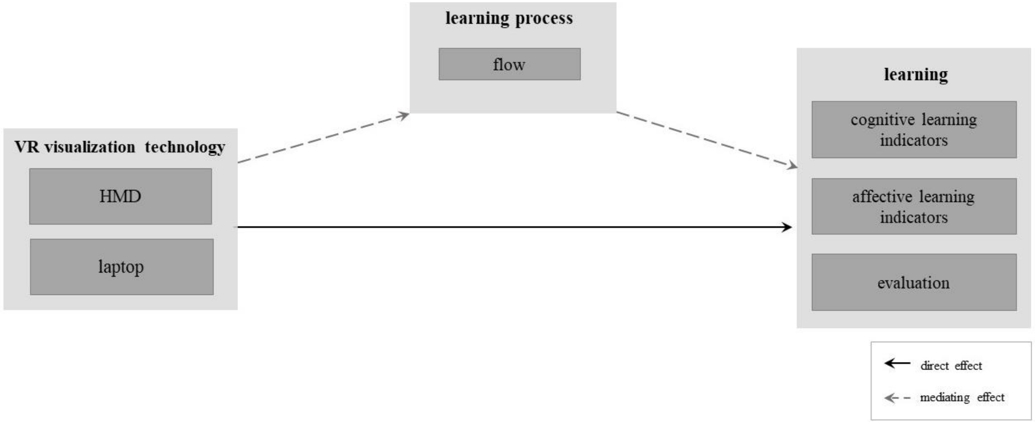

Figure 1. Research design

3. METHODS

3.1 Anne Frank VR House

The VR environment is the freely available *Anne Frank VR House*, jointly developed by the *Anne Frank Foundation* and *Force Field VR*. The application allows insights into the hiding place of 13-year-old Anne Frank, her sister, her parents and four other people. The hiding place was located in the back of a company building on Prinsengracht 263 in Amsterdam. The VR environment shows the living conditions of the eight people of Jewish origin in the period from 1942 to 1944. All eight rooms are reproduced in detail. No persons are depicted. Additional information about life in hiding and the history of those in hiding is included. An insight is provided by Figure 2.

Figure 2. The room of Anne Frank and Fritz Pfeffer
(http://edu.annefrank.org/dashinterhaus/; retrieved at 14.06.2022)

The application can be explored via two VR visualization technologies. On the one hand, HMDs and two associated controllers can be used. Teleportation, as well as body and head movements, can be used to explore room by room. On the other hand, it is possible to explore the virtual hiding place via various end devices with two-dimensional screens (e.g., tablets, laptops) by accessing the 360° web application with equivalent content. Here, the field of view is changed either by the touch function or by the mouse cursor.

3.2 Procedure

The single-scenario study included a pre-questionnaire, a VR experience, and a post-questionnaire. The VR experience itself took an average of 30 minutes. The experience differed between students in terms of the visualization technology used (HMD, here *Oculus Quest 2* vs. laptop, here *Dell Latitude 3510*). The online-questionnaire batteries included instruments on sociodemographic variables, evaluation, cognitive and affective learning outcomes, and the learning process variable flow.

3.3 Measurement Instruments

In addition to sociodemographic variables (gender, age, grade level), learning outcomes were collected at various levels. To measure cognitive learning, the subjects were asked to answer ten short knowledge questions (e.g., "*What did Anne's diary look like*?"). A maximum of two points per question was reachable, resulting in a maximum point value of 20. The internal consistency of the knowledge test is α = .71. In addition to cognitive learning objectives, affective learning was also considered. As an affective goal, perspective-taking in Anne Frank was set. Perspective-taking is understood as the ability to empathize with another person's feelings, which is considered as an essential prerequisite for the emergence of empathy or compassion (Dimitrova & Lüdmann, 2014). To test the extent of perspective-taking, students were asked to indicate how well they could empathize with Anne's life situation in the hiding place. A ten-point scale from 1 ("*not at all*") to 10 ("*very well*") was used as the response format. Students had to answer this question before and after the VR experience. In addition, the students were asked to evaluate the VR experience. To do so, they should indicate their level of satisfaction ("*I am satisfied with the virtual learning experience*.") as well as their tendency to recommend it ("*I would recommend the virtual backhouse to other students*.") on a scale of 1 ("*strongly disagree*") to 5 ("*strongly agree*"). In order to measure the experience of flow, the Flow Short Scale (FKS; Rheinberg et al., 2003) was used. The instrument consists of the two dimensions of smooth automated flow (example: "*I was completely absorbed in what I was doing*.") and absorbedness (example: "*I had no trouble concentrating*.") and a total of ten items. The questionnaire has a seven-point scale as a response format from 1 ("*strongly disagree*") to 4 ("*partly agree*") to 7 ("*strongly agree*"). Rheinberg et al. (2003) listed values from comparative studies. A mean of M = 5.16 (SD = .93) was found for graffiti spraying and a mean of M = 4.57 (SD = 1.13) for solving a statistics task. Rheinberg et al. (2003) reported a Cronbach's alpha of α = .90, and the internal consistency in the present study was α = 81.

3.4 Data Analysis

In addition to simple descriptive statistical analyses, a multivariate analysis of variance (MANOVA) and post hoc ANOVAs was conducted with visualization technology as the independent variable and the various learning indicators as the dependent variables. To explore the mediating effects of the learning process variable flow, mediation analyses were conducted. Therefore, the SPSS macro PROCESS (Hayes, 2013) was installed.

4. RESULTS

132 subjects (65 female, 63 male, 4 diverse) were surveyed. The sample of this study consists of students aged 12 to 17 years (M = 13.84, SD = .92). Students had to attend the eighth or ninth grade of a secondary school in Germany to participate. 74 students participated in the study via an HMD and 58 via a laptop.

Table 1 shows the mean and standard deviation for each variable. To assess the increase in perspective-taking from the first to the second measurement, a new variable was calculated that allows a pre-post comparison. The variable calculation involved subtracting the pre from the post value. Across the experimental conditions, there is an increase in perspective-taking in Anne Frank from the first to the second measurement, although the variation among students is quite large. In the knowledge test, the subjects received on average slightly more than half of the maximum twenty points that could be achieved. However, the high variation indicates very different performances among the students. Regarding the evaluation of the VR application, high means and low variation were found averaged across the experimental conditions. Only a few outliers were not satisfied and would not recommend the VR application to others. Compared to the values reported by Rheinberg et al. (2003) for activities such as graffiti spraying, the experience of flow in the present study can be classified as very high. Absorbedness in particular reached very high values.

Table 1. Means and standard deviations

	M	*SD*
knowledge test	10.89	4.36
perspective-taking	1.90	2.37
satisfaction	4.31	.91
recommendation	4.33	.93
flow: smooth automated flow	5.18	1.36
flow: absorbedness	5.37	1.38

To address hypothesis 1, a MANOVA was conducted with visualization technology as the independent variable and knowledge test, perspective-taking (pre-post), and evaluation as dependent variables. The MANOVA showed statistically significant differences between HMD-based and laptop-based VR ($F(4,119) = 14.96$, $p < .001$, $\eta^2 = .34$, Wilk's $\Lambda = .67$) for the combined dependent variables. Multi-factorial ANOVAs were then calculated for each of the four dependent variables. All were significant (see Table 2). Follow-up analyses showed that students in the HMD conditions are significantly more satisfied, more likely to recommend the VR application to others, and better able to empathize with Anne. In the knowledge test, however, the results of the laptop group are significantly better than those of the HMD group. Thus, subhypotheses a and b have been confirmed.

Table 2. Results of ANOVAs

	F	*df*	*p*	η^2
knowledge test	32.36	1,122	.00	.21
perspective-taking	3.80	1,122	.05	.03
satisfaction	13.36	1,122	.00	.10
recommendation	15.17	1,122	.00	.11

To address hypothesis 2, mediation analyses were performed. It was hypothesized that experiencing flow can systematically explain the direct effects of VR visualization technology on the learning outcomes we found in the MANOVA (see Figure 1). In a significant mediation, according to Baron and Kenny (1986), the independent variable (here: visualization technology) must correlate with the mediator (here: flow) and the mediator must correlate with the dependent variable (here: various learning indicators, evaluation). In a total mediation, the direct effect between independent and dependent variable disappears when the mediator is included. In a partial mediation, additional variance can be explained by adding the mediator. Eight mediation analyses were calculated. In four of these, we found statistically significant indirect effects mediated by flow, but mainly for the evaluative indicators. A significant mediation could be found, among others, for the mediator flow (subscale: automated process) and the dependent variable satisfaction. Within the analysis, a total effect of visualization technology on satisfaction was found (c = -.58**). The total effect means that students in the laptop group (group number 2) were significantly more dissatisfied than those in the HMD group (group number 1). After the mediator was included in the model, visualization technology significantly predicted the mediator flow (a = -.1.19***). Students in the laptop condition experienced significantly less flow than students in the HMD condition. Flow, in turn, predicted satisfaction (b = .29***). When students experienced more flow, they were also more satisfied. Path c`, the direct effect of visualization technology on satisfaction, did not become significant ($c$` = -.23). Thus, a total mediation could be detected. After the mediator flow (subscale: automated process) was integrated into the analysis, the correlation between visualization technology and satisfaction loses its statistical significance. Consequently, there is no direct correlation between visualization technology and satisfaction, but there is an indirect correlation, which can be completely explained by flow (indirect effect $ab_{flow\_auto\_process}$= -.28, 95% CI [-.525, -.070]). The confidence interval does not enclose the value zero. The indirect effect is estimated to be significant. For an illustration of the causal relationships, see Figure 3. The correlations are identical in the other significant mediation analyses and are therefore not listed separately again.

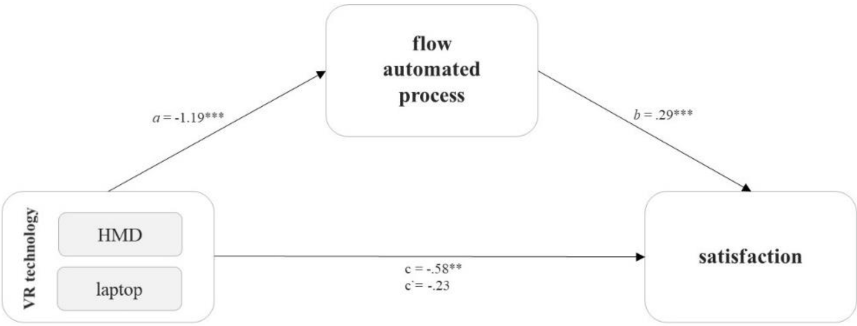

Figure 3. Example of a total mediation

5. CONCLUSION

In this study, the *Anne Frank VR House* was empirically investigated. Across the experimental conditions, it was found that the VR application can generally address cognitive and affective learning objectives and is rated extremely positively by students. In this respect, the application seems to be suitable for purposes of teaching and learning. Nevertheless, this study is not able to decide which VR visualization technology, here HMD or laptop, seems superior for presenting VR content. Unsurprisingly, significantly better student ratings were found for HMD compared to laptop. However, the use of HMDs also proved to be beneficial for affective learning objectives (i.e., perspective-taking). For cognitive learning objectives, it was even the other way around: Students on laptops answered significantly more knowledge questions correctly. Therefore, a decision for or against a VR visualization technology should always be a case-by-case decision made by a teacher based on the intended learning objectives.

Equally important as main effects were mediation effects. Indirect effects mediated by the experience of flow can significantly explain the effects of VR visualization technologies on learning outcomes. In some cases, the direct effect disappeared with the addition of the mediator and only the indirect effect mediated by flow proved to be statistically significant. At this point, it becomes obvious why latent process variables should be controlled in empirical studies. Otherwise, statistically significant direct effects are seemingly interpreted as significant or are overestimated systematically, although an underlying learning process is actually responsible for the correlation. Accordingly, complex interaction structures are more suitable for representing and investigating learning in VR. Unfortunately, only one mediation effect could be uncovered for the affective learning indicator as dependent variable. The majority of the significant mediation effects concern the evaluation of the VR application.

Hence, it seems of importance that follow-up studies also consider latent learning processes in VR. This is not limited to VR. Latent learning processes also play a crucial role in learning scenarios that make use of augmented reality or interactive videos, for example. Consequently, other educational technologies could be explored in qualitative and quantitative studies using the proposed research design. This approach goes beyond traditional approaches of media comparison studies, which are considered critical in the literature (Clark & Mayer, 2016). In addition, the research design makes it possible to uncover causal and correlational relationships through mediating learning process variables and thus help to avoid confounding.

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