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How do autonomy and learner characteristics combine to influence learners' learning outcomes and cognitive load in virtual reality learning environments? A fuzzy-set qualitative comparative analysis approach

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Abstract

Virtual reality learning environment (VRLE), which allow students to transcend time and space and provide them with a sense of immersion, is becoming more common in education. Although many studies have explored the effects of VRLE on learners' learning outcomes as well as learning experiences, the results of these studies indicate that the effects of VRLE on learning outcomes and cognitive load are mixed. This is influenced by multiple factors that can be broadly grouped into two categories: learner characteristics and VRLE features. This study aimed to investigate how the autonomy of VRLE and learner characteristics affect learning in the VRLE. 94 volunteered students (aged 18 to 26) were randomly assigned to a high-autonomy VRLE ($N=47$) or a low-autonomy VRLE ($N=47$). We did a fuzzy-set qualitative comparative analysis (fsQCA) and discovered that VRLE is not good for all students but only for those with particular features. According to the findings, teachers should personalize their use of instructional technology depending on the profiles of their students.

Keywords Virtual reality · Immersive virtual learning environment · fsQCA · Autonomy · Cognitive load

1 Introduction

The 2020 EDUCAUSE Horizon Report claims that virtual reality (VR) use is gradually increasing because of its greater immersion, accessibility, progressively lower costs, better device performance and wireless networks (Brown et al., 2020). VR is a technology that provides virtual immersion in a digital environment, offering users an interactive three-dimensional world in which to encounter multi-sensory

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and emotional experiences (Villena-Taranilla et al., 2022). Recently, VR has become popular in education because it allows students to be placed in different VRLE with a realism that cannot be achieved with traditional learning materials. At the same time, it breaks the temporal and spatial barriers of educational situations, thus enabling experiential learning (Blascovich et al., 2002; Cuesta Cambra & Mañas Viniegra, 2016). Additionally, VRLE has been widely investigated in education areas such as musical instruments (Yu et al., 2023), physics experiments (Crosier et al., 2000), mathematics (Demitriadou et al., 2020), architectural history (Chan et al., 2022), and traditional culture (Chen et al., 2018). While some studies have demonstrated the potential benefits of VR in education to stimulate learners' interest, increase interactivity, enhance personal self-efficacy, and promote understanding of abstract knowledge, findings on the effects of VR on learning outcomes (LO) and cognitive load (CL) are mixed (Demitriadou et al., 2020; Hamilton et al., 2021; Makransky et al., 2019; Smith et al., 2018; Villena-Taranilla et al., 2022; Zhao et al., 2020; Zheng et al., 2021). This inconsistent finding may be caused by learner characteristics (Hauptman & Cohen, 2011; Marraffino et al., 2022) and the VRLE feature (Johnson-Glenberg et al., 2021; Petersen et al., 2022). Previous studies have shown that prior knowledge (Chang et al., 2020), attitude towards VR (Larmuseau et al., 2018), VR experience (Sagnier et al., 2020), learning interest (Romine et al., 2020), and VRLE autonomy (Johnson-Glenberg et al., 2021) could affect students' learning performance. However, few of them invested their combined effect on students' LO and CL.

The majority of studies in VRLE employ variance-based approaches (e.g., analysis of variances or regression analysis), which provide a single solution for interpreting results. However, there is more than one pathway for high learning outcomes or low cognitive load, and there may be asymmetric relationships, i.e., attributes that are causally correlated in one configuration may be uncorrelated or even inversely correlated in the other configuration. The limitation of the variance-based approach is the challenging interpretation of interactions consisting of more than two variables (Olufadi, 2015). Therefore, fsQCA was conducted to remedy this deficiency. FsQCA is a qualitative analysis method that allows the identification of different configurations of sufficient or necessary conditions that constitute the result (Pappas & Woodside, 2021). Additionally, fsQCA maintains the integrity of individual cases in the dataset when analyzing the data and provides deeper empirical and theoretical exploration of the optimal combination of factors for a particular outcome (Hughes et al., 2019; Woodside et al., 2012).

Consequently, this study contributes by developing a fsQCA to explore how learner characteristics (prior knowledge, attitude towards VR, VR experience, learning interest) and VRLE features (autonomy) synergistically impact learners' LO and CL in VRLE. The VRLE is a Chinese Tujia instrumental virtual museum built with Unity 3D that presents the traditional culture and music culture of the Chinese Tujia. The findings of this study could offer suggestions on the future design of VRLE, how teachers use VR-assisted instruction, and VRLE is suitable for which type of students to learn independently in it.

In the remainder of the paper, we provide a literature review of the current state of VR applications in education and the current state of research on the respective variables in Chap. 2. In Chap. 3, the VR environment and data analysis methodology for this study are presented. In Chap. 4 we give the results of the data analysis and discuss them in Chap. 5. Finally, Chap. 6 summarizes the plans and conclusions for future work.

2 Literature review

2.1 Virtual reality learning environment

VRLE is a VR environment for the specific purpose of achieving teaching and learning (Duncan et al., 2012). VRLE provides educational content, allows for interaction, promotes skill development, and comes in many different forms (e.g., single or multiplayer, gamified or non-gamified, immersive or non-immersive) (Nowlan et al., 2023).

VRLE has been extensively developed and researched in recent years. However, research findings on the effects of VRLE on learners' LO and CL are inconsistent. For instance, several research studies indicated that VRLE seemed to positively impact student academic achievement and reduce CL (Demitriadou et al., 2020; Haryana et al., 2022; Martín-Gutiérrez et al., 2017; Villena-Taranilla et al., 2022). Similarly, Villena Taranilla et al. (2022) found that learners achieved better LO in VRLE than in traditional learning environments and suggested that this is because VRLE provides learners with exciting, immersive, and interactive experiences that promote motivation, which improves LO. Furthermore, VRLE provides an environment that is closer to the real environment and allows students to obtain more accurate information, so learners will have a higher germane cognitive load (Lin et al., 2021). Whereas some studies declare that VRLE has no significant effect on learners' learning outcomes compared to traditional learning environments (Harrington et al., 2018; Smith et al., 2018; Stepan et al., 2017). Nevertheless, these studies affirmed that VRLE motivates learning and provides learners with a better learning experience. In contrast, some studies have found that learners perform worse in the VRLE and that the VRLE increases additional cognitive load (Moreno & Mayer, 2002; Parong & Mayer, 2018; Richards & Taylor, 2015). Similarly, Makransky et al. (2019) explored learners' LO and CL in VRLE and found that the VRLE distracted learners and overloaded them cognitively, resulting in less opportunity to build LO. Although some studies have found mixed effects of VRLE on students' LO and CL, few studies have further analyzed the reasons. Existing studies have suggested two possible reasons: one being individual learner differences (Hauptman & Cohen, 2011; Marraffino et al., 2022), and the other being differences in VRLE (Johnson-Glenberg et al., 2021; Petersen et al., 2022).

2.2 Autonomy

According to the self-determination theory (a theory of motivation) proposed by Deci and Ryan (2004), autonomy (AUT) refers to the need for humans to actively participate in determining their behavior. When people perceive that their choices depend solely on their autonomous decisions, they feel psychologically free and contribute to intrinsic motivation (Deci & Ryan, 2013; Ryan & Patrick, 2009). Students' autonomy in the classroom primarily depends on teacher support, which contributes to students' autonomous self-regulation of learning, academic performance, and well-being (Niemiec & Ryan, 2009). When students learn independently in VRLE, their autonomy is provided by VRLE.

In general, related studies claimed that autonomy increases employees' willingness to work (Gajendran & Harrison, 2007), influences users' perceived competence and enjoyment of the game (Ryan et al., 2006), and stimulates learners' LI, especially benefiting students with low interest in the topic of study (Großmann & Wilde, 2020). In addition, autonomy has been proven to enhance learner satisfaction and promote learning in VRLE (Jung, 2011); for example, Johnson-Glenberg et al. (2021) declared that learners who autonomously used controller-operated content in VRLE learned more and performed better. However, different results were obtained by Shin et al. (1994), who found that high autonomy was not beneficial for all types of learners and that students with low prior knowledge performed better in the non-autonomous condition. This is probably because the provision of autonomy is accompanied by a reduction in learning support, thus hindering the learning of some students. Therefore, the impact of autonomy on learning outcomes is also mixed. Autonomy, as one of the features of VRLE, is a factor of interest to us.

2.3 Personal characteristics of learners

When immersing and learning in VRLE, students' LO may vary depending on their individual differences. Previous studies have indicated that factors like prior knowledge (Chang et al., 2020), attitude towards VR (Larmuseau et al., 2018), VR experience (Sagnier et al., 2020), and learning interest (Romine et al., 2020) greatly impacted students' mental experiences during the learning process, thereby influencing their performance. Therefore, we were also interested in how the factors synergistically influence students' learning.

Prior knowledge (PK) refers to the learners' knowledge of Chinese Tujia instrumental culture and music culture before the intervention. Prior knowledge is critical to successful learning experiences and influences the construction of new knowledge in the learning process. Related studies showed that a high level of prior knowledge had a positive impact on learners' LO, helping learners' reading comprehension, better remember new knowledge, and make connections between prior and new knowledge (DeSanctis & Poole, 1994; Huang, 2020; van Kesteren et al., 2012). In addition, an individual's level of prior knowledge was also a factor affecting intrinsic cognitive load, and learners with high prior knowledge usually have lower intrinsic cognitive load than learners with low prior knowledge (Huang, 2020; Seufert et al., 2007). In other words, learners with high prior knowledge might not be cognitively overloaded even when they learn in a learning environment with high extraneous cognitive load. Similarly, Han et al. (2023) suggested that the VRLE given to students with low prior knowledge should reduce the CL and provide additional support, but students with high prior knowledge did not need additional support.

Attitude towards VR (AVR) refers to a learner's acceptance of VR and is usually determined by a person's beliefs. The Technology Acceptance Model (TAM) stated that perceived usefulness, perceived ease of use, and self-efficacy reflect users' attitude towards VR (Davis et al., 1989). Previous research has shown that these factors, which reflect attitudes, have an impact on learners' experiences and learning performance in virtual environments. Larmuseau et al. (2018) found that perceived usefulness had a significant impact on the actual use of the VRLE, which had a positive impact on student performance. In addition, VR self-efficacy was also shown to be positively correlated with VR learning interest but negatively correlated with VR use anxiety (Tai et al., 2022). However, we couldn't exclude that learners' attitude towards VR was influenced by the novelty effect, which has been shown to affect self-efficacy and perceived usefulness (Thompson et al., 2020; Koch et al., 2018).

Virtual reality experience (VRE) refers to previous experience and knowledge of using VR devices and proficiency with VR technology. Proficiency in VR technology is necessary to participate in virtual worlds. Studies have shown that users with VR experience have a better experience and feel more connected to the virtual environment than those without VR experience (Sagnier et al., 2020). VR experience is a factor that cannot be ignored when students are learning in a VRLE. The study by Makransky et al. (2019) suggested that learners' unfamiliarity with technology can negatively affect learning because of the novelty of the technology and their unfamiliarity with operating the equipment.

Learning interest (LI), defined as a content-specific motivational characteristic that guides intrinsic motivation (Deci & Ryan, 1985), can be categorized into personal interest and situational interest. Personal interest is a person's preference for a certain behavior or activity; thus, it is difficult to change, while situational interest is the effect of the characteristics of the activity or learning task on the student's attraction (Chen et al., 1999). In this study, we only focused on situational interest on the one hand because situational interest tends to change with the learning situation or environment, and on the other hand because the research context of this study, VRLE, has been shown to stimulate learners' situational interest (Makransky & Petersen, 2021; Romine et al., 2020). The high presence and immersion of a VRLE could stimulate learners' situational interest (Parong & Mayer, 2018; Schutte, 2020). Situational interest promoted learning by increasing learner engagement and attention (Harackiewicz et al., 2016), and learners with high situational interest were willing to put more effort into their learning (Shen et al., 2007; Rotgans & Schmidt, 2014).

2.4 Cognitive load theory

Cognitive load theory (CLT) states that good instructional materials enhance learning by directing cognitive resources to learning-related activities, while inadequate instruction may occur when learners are expected to mentally integrate knowledge from numerous unrelated sources (Chandler & Sweller, 1991). The CL was divided into three categories: intrinsic cognitive load (ICL), extraneous cognitive load (ECL), and germane cognitive load (GCL); the ICL is determined by the degree of interaction of elements in the material and cannot be changed by instructional manipulation; ECL refers to the unnecessary load generated by the way information is presented and the learning activities in which the learner is engaged; and GCL, like ECL, is also influenced by the design of learning activities, while GCL enhances learning (Paas et al., 2003). Total CL is the sum of ICL, ECL, and GCL, and it cannot exceed the available working memory resources during the learning process.

Human cognitive resources are limited; cognitive overload occurs when the information exceeds the individual's cognitive processing capacity, which in turn hinders learning and negatively affects learner satisfaction (Hu et al., 2017). Additionally, Huang et al.'s (2020) study claimed that LO and CL are negatively correlated. Therefore, CL is often taken into account in the learner's learning process. However, studies exploring the effect of VRLE on CL have had inconsistent results, some findings indicated that learners have low cognitive load in VRLE, while others found that VRLE increases learners' cognitive load leading to cognitive overload (Haryana et al., 2022; Albus et al., 2021). For example, the study by Haryana et al. (2022) confirmed that individual CL was lowest when the learner was in the VRLE. Whereas several studies have proposed that the high presence and rich visual information of VRLE may distract learners and thus lead to cognitive overload (Albus et al., 2021; Whitelock et al., 2000). Furthermore, Seufert et al. (2007) study showed that ECL in multi-representational learning environments was rated as high, such as VRLE. In VRLE, learners have to deal with different types of multimedia resources that will generate different levels of element interaction and thus different CLs. Moreover, the irrelevant information essential in building VRLE could distract learners or cause cognitive overload (Howard & Lee, 2020). In addition to the learning environment, students have different personal characteristics that can make a difference in CL (Yu et al., 2023). For example, the study by Seufert et al. (2007) proposed that students with different levels of prior knowledge had different ICLs.

In a nutshell, in a VRLE, students' CL may influence by their individual characteristics (e.g., PK, AVR, VRE, and LI) (Endres et al., 2022; Marraffino et al., 2022; Zhang & Liu, 2023) and the features of the learning platform (e.g., autonomy) (Petersen et al., 2022; Yu et al., 2023). Therefore, we will explore what configurations produce the best results.

2.5 Present study

The primary purpose of this research is to use the fsQCA analysis of the data to investigate whether and how the autonomy afforded by a VRLE and student characteristics affects student learning. Two VRLEs that designed with different levels of autonomy were subsequently proposed. This study explored the following questions:

Q1. Are VRLE's autonomy, and learners' prior knowledge, attitude towards VR, VR experience, and learning interest necessary to cause high or low learning outcome and cognitive load?
Q2. What configurations of VRLE's autonomy, and learners' prior knowledge, attitude towards VR, VR experience, learning interest would cause high or low learning outcome?
Q3. What configurations of VRLE's autonomy, and learners' prior knowledge, attitude towards VR, VR experience, learning interest would cause high or low cognitive load?

3 Methodology

3.1 Learning context

In the current study, two VRLEs (i.e., VR-based museums) with different levels of autonomy were proposed. Specifically, in the high autonomy group, students can freely browse materials in the VRLE (Fig. 1A), while in the low autonomy group, the route with red arrows was marked on the floor of the VRLE, and the wall enclosed the navigation channel so that students could only follow a predetermined route to visit the virtual museum (Fig. 1B). This VRLE, which was upgraded from our previous work (Liu et al., 2022), presents traditional Chinese Tujia culture in the form of text, pictures, and videos, mainly for teaching students traditional Chinese Tujia instrumental and musical culture.

The VRLE was developed in Unity 3D and displayed on the HTC Vive HMD. Participants interacted in the VRLE through the controller (Fig. 2). The user presses the handle button to fire a ray, and when released, it is transmitted to the location where the ray is pointing. When the ray is pointed at the icon on the display picture and the trigger is pressed, a pop-up window for a text introduction or video display will appear (Fig. 3). This virtual museum focuses on the traditional Chinese

Fig. 1 Virtual museum with different degrees of autonomy. **A** The high autonomy of the virtual museum allows users to navigate freely through it, without route guidance, with pictures and text displayed on the walls, **B** the low autonomy of the virtual museum, in which users must follow the direction of the arrows to navigate, there are walls enclosing the navigation channel

Fig. 2 VR equipment

Fig. 3 Learning content presentation format. **A** Show pictures of the hand swinging dance, **B** a text introduction page that focuses on the origins, forms, application occasions, and characteristics of the hand swinging dance, **C** show pictures of the silk-stringed gongs and drums, **D** video of the silk-stringed gongs and drums performance

Tujia musical culture, including the basic structure of the instruments, how they are played, the occasions on which they are played, and the connection between music and traditional festivals.

3.2 Participants

In this study, a sample of 94 college students (14.89% male, 85.11% female) were recruited from a university in central China; among them, 94.68% were postgraduates and 5.32% were undergraduates. The participants were randomly divided into two experimental groups (i.e., high autonomy group and low autonomy group), with 47 students in each group. Students did not major in history, literature, or musicology and reported their voluntary participation in this study. After the experiment, subjects would receive a gift as a reward.

3.3 Instruments

Demographic Questionnaire (DQ) was used to collect participants' demographic information (gender, age, grade, etc.).

Tujia instrumental music knowledge test (TKT) was used to access participants' comprehension of Tujia music culture. Based on the information from exhibits in the VR-based museum and under the guidance of Tujia instrumental music experts, this study designed a TKT, aiming to evaluate the participants' knowledge of Tujia instrumental music before and after the study. It comprised 14 questions (10 multiple-choice questions and 4 true or false questions). The maximum test score is 70 points (5 points per question). We assigned pre-test scores as prior knowledge and post-test scores as LO.

Prior VRE Questionnaire (PVREQ) was used to measure the students' VR experience before the intervention; it was modified using Taylor et al.'s Game Experience Measure (GEM) to assess participants' background with video games (Taylor et al., 2009). The revised GEM was divided into two dimensions, which were game experience and game knowledge. We only adapted the game experience scale, the Cronbach's alpha of the game experience scale is 0.750. We slightly changed the computer games to VR (e.g., "I know a lot about VR games", etc.). The scale was a 5-point Likert rating.

Virtual Museum Experience Questionnaire (VMEQ) was used to measure the students' attitude towards VR, learning interest, and CL. Attitude towards VR can be reflected by TAM and self-efficacy; the attitude towards VR scale in this study was adapted from Davis (1989) and Pintrich (1991), who used the terms virtual museum and Tujia instrumental music knowledge to replace the terms in the original questionnaire. The scale for attitude towards VR includes three dimensions: perceived usefulness (2 items), perceived ease of use (2 items), and self-efficacy (3 items). Cronbach's alpha of the attitude towards VR scale was 0.839, indicating good reliability. The learning interest scale was adapted from the situational interest scale developed by Chen et al. (1999) and consisted of three items. The finalized items consisted of two dimensions: novelty, conceptualized as the gap between known information and the unknown, or information deficiency, and having the function of triggering students' exploratory behavior; and challenge, defined as the level of difficulty equivalent to one's own ability and the factor that may attract students to an activity. The Cronbach's alpha of the learning interest scale was 0.808. The CL survey was originally developed by Sweller et al. (1998). This study takes the survey used in Hsieh and Tsai's (2014) study, adapts it to a VRLE, and covers two items. The former, mental load, quantifies how much of one's brainpower is being used to digest the VRLE's contents, while the latter, mental effort, quantifies how much of one's brainpower is actually being used to do so (Cheng, 2017). The Cronbach's alpha of the CL scale was 0.897. The attitude towards VR scale and the learning interest scale were rated on a 5-point Likert scale : 1 = strongly disagree, 5 = strongly agree. The cognitive load scale was a 7-point Likert rating.

3.4 Procedure

This study used a quasi-experimental design; participants were randomly assigned to two experimental groups (i.e., high autonomy group, low autonomy group). Before the experiment, participants were asked to complete the DQ, TKT, and PVREQ to investigate their demographic information, the level of prior knowledge, and prior VR experience, which lasted for 15 min. Then, the experimenter introduced each participant to the basics of the VRLE and how to move and interact in the VRLE, and participants were free to familiarize themselves with the VRLE for 3 min. While students were learning in the VRLE, students in the low autonomy group were asked to follow a prescribed route to learn, and staff would remind them to return to the route when they deviated. However, students in the high autonomy group were free to study in the VRLE without any restrictions. After the experiment, students were required to complete the TKT again and the VMEQ to assess their LO, AVR, LI, and CL, which lasted for 15 min. Finally, some students were interviewed. The flow of this experiment is shown in Fig. 4.

3.5 Data analysis

Charles Ragin created a method called Fuzzy-set Qualitative comparative analysis (fsQCA) to obtain linguistic summaries from case-related data (Ragin, 2000). FsQCA is an analytical method for small sample sizes that suitable for application in contextual analysis (Kraus et al., 2018). While fsQCA has found most use in sociological and marketing research, it has recently been used to the subject of education in order to examine how different aspects of the classroom setting affect students' ability to learn.

The fsQCA process is divided into three steps: calibration, necessary condition testing, and truth table analysis. First, the calibration is mainly done by fuzzy set calculation, which converted the input values to a degree of membership between 0.0 and 1.0 (Ragin, 2008). The values inputted in this article includes autonomy, learner characteristic scores obtained through questionnaires and test scores, where autonomy is the independent variable set by us, so the high autonomy condition was assigned a value of 1 and the low autonomy condition was assigned a value of 0. Learner characteristic scores and test scores are calibrated according to the three qualitative breakpoints the threshold for full membership

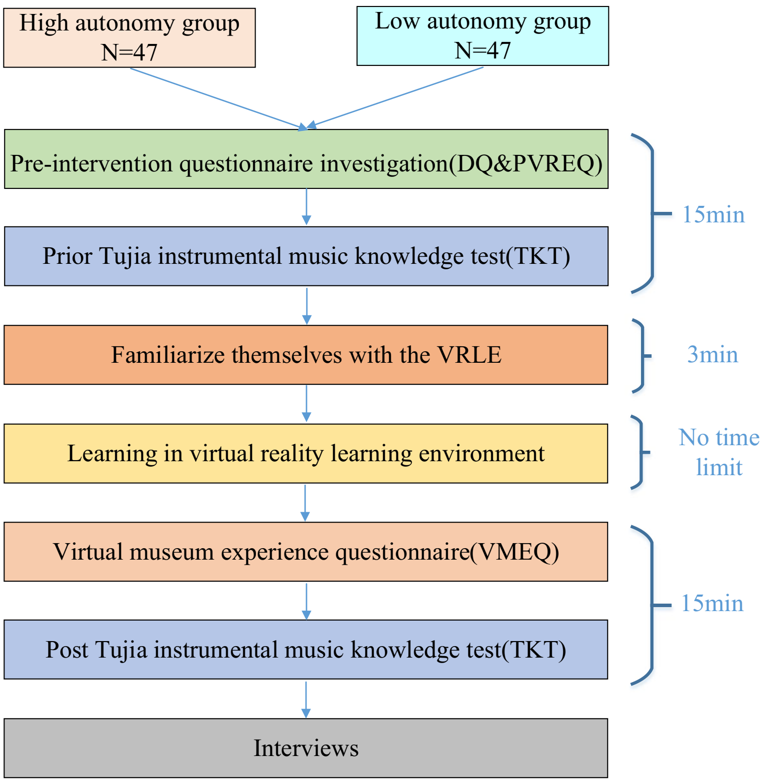

Fig. 4 Procedure of the experiment

(n1), cross-over point (n2), and full nonmembership (n3) (Ragin & Davey, 2016). Referring to the threshold delineation Ling et al. (2021), we calibrated the data using the calibrate (x, n1, n2, n3) function and set the values ranked 10%, 50%, and 90% as the threshold for n1, n2, and n3. For example, students who scored 65 or above (top 10%) in post-TKT (full marks 70) were full membership of the LO set, students who scored 55 (ranked 50%) were fuzziness, and students who scored 43 or below (bottom 10%) were full nonmembership of the LO set. In other words, the post-TKT scores of all subjects in the experimental group were ranked from highest to lowest, with scores in the top 10% being full membership, scores in the bottom 10% being full nonmembership, and scores right in the middle (50%) being fuzziness. The threshold values for conditions and results are shown in Table 1.

Second, the necessity of conditional variables needs to be analyzed before the analysis of fuzzy sets, and the necessity analysis refers to the degree to which a single conditional variable explains the outcome variable, which usually constitutes a necessary condition when the consistency is greater than 0.9. The last stage was to build the truth table, which would include all the causal combinations that could lead to the correspongding outcome. There were five possible

Table 1 Data calibration

Conditions and outcomes	M ± SD	Qualitative breakpoints		
		Full membership (n1)	Cross-over point (n2)	Full non-membership (n3)
AUT	/	1	/	0
PK	18.10 ± 13.88	35.00	15.00	0.00
AVR	29.67 ± 3.35	34.70	29.00	26.00
VRE	18.78 ± 3.87	24.00	19.00	14.00
LI	12.21 ± 1.95	15.00	12.00	10.00
LO	53.16 ± 9.67	65.00	55.00	43.00
CL	7.23 ± 2.69	11.00	7.00	4.00

AUT autonomy, PK prior knowledge, AVR attitude towards VR, VRE VR experience, LI learning interest, LO learning outcome, CL cognitive load

causes in this investigation (PK, AUT, AVR, VRE, and LI), hence there should be 32 ($32 = 2^5$) possible permutations in the truth table. However, it's likely that the sample doesn't cover all of the truth table's permutations. Setting frequency and consistency cut-offs in the truth table is necessary for isolating meaningful configuration (Ragin, 2008). This study considered combinations with at least one case and chose 0.8 as the consistency threshold. If more than 80% of students with the same mix of settings obtain satisfactory learning results, we consider this combination of conditions to be viable, and this is a common setting with realistic practical implications (Ling et al., 2021). In addition, the analysis results using QCA included complex solutions, parsimonious solutions, and intermediate solutions. Complex solutions give all possible combinations of conditions when applying traditional logical operations, and a very large number of combinations of conditions may be obtained, making interpretation quite difficult, and are therefore not considered in most cases. Parsimonious solutions are the simplified version of complex solutions, giving the most important conditions that cannot be excluded from any solution. Intermediate solutions are part of complex solutions that contain parsimonious solutions and are easier to interpret, so usually the results are analyzed applying intermediate solutions. (Ragin, 2008).

4 Results

4.1 Necessity of single condition

In general, the consistency of the condition is higher than 0.9, which indicates that the condition is necessary. The results of the analysis of the necessary conditions are shown in Table 2, and the consistency of all conditions is below 0.85, indicating that there is no single variable that can affect student LO and CL. This shows that students' LO and CL in the VRLE were affected by overlapping multiple factors and

Table 2 Necessary condition analysis results

Causal conditions	Consistency			
	LO	~LO	CL	~CL
AUT	0.536	0.474	0.499	0.501
~AUT	0.464	0.526	0.501	0.499
PK	0.721	0.558	0.589	0.668
~PK	0.530	0.626	0.634	0.544
AVR	0.598	0.602	0.595	0.638
~AVR	0.627	0.563	0.634	0.580
VRE	0.602	0.579	0.576	0.594
~VRE	0.640	0.598	0.627	0.600
LI	0.625	0.575	0.564	0.668
~LI	0.580	0.575	0.657	0.542

'~'means this condition/outcome does not exist. AUT autonomy, PK prior knowledge, AVR attitude towards VR, VRE VR experience, LI learning interest, LO learning outcome, CL cognitive load

Table 3 Configurations causing HLO and LLO

Causal conditions	HLO		LLO			
	A1	A2	B1	B2	B3	B4
AUT	●	●		●	⊗	⊗
PK	●	●	⊗	⊗	⊗	●
AVR	⊗	⊗	⊗	●	●	●
VRE	●	⊗	●	⊗	●	⊗
LI	⊗	●	⊗			⊗
Raw coverage	0.149	0.114	0.246	0.160	0.149	0.098
Unique coverage	0.060	0.025	0.101	0.088	0.076	0.042
Consistency	0.886	0.930	0.850	0.946	0.882	0.883
Overall Solution coverage	0.174		0.452			
Overall Solution consistency	0.893		0.873			

● indicate that this condition exists, ⊗ indicates this condition does not exist, the space means that it doesn't matter this condition exists or not, '~'means this condition/outcome does not exist. AUT autonomy, PK prior knowledge, AVR attitude towards VR, VRE VR experience, LI learning interest, LO learning outcome, CL cognitive load

variables rather than a single cause, and no antecedent condition is sufficient for the result.

4.2 Configurations of learning outcomes

The results of the analysis showed that students' high LO (HLO) and low LO (LLO) usually have the following combination of characteristics, as shown in Table 3. To clarify, the circles with slashes through them (⊗) and the solid black circles (●) represent the absence and existence of a condition, respectively, while the white spaces denote that it makes no difference either way. Two different configurations were found to produce HLO, with an overall coverage of 0.174 and an overall consistency of 0.893. And four different setups yielded LLO; overall coverage is 0.452 and overall consistency is 0.873. Overall coverage describes the extent to which the results can be interpreted by the configuration, while consistency (at least > 0.75) is used to define the strength of the relationship (Pappas & Woodside, 2021). And it is worth noting that the configurations of HLO and LLO were not exactly symmetric. Further interpretation of the results in this paper is as follows:

Configuration A1 showed that AUT*PK*~AVR*VRE*~LI ('*' means conditions exist at the same time, '~' indicates a negative set) could cause HLO (consistency = 0.886). And configuration A2 proved that HLO may be triggered under the conditions AUT*PK*~AVR*~VRE*LI (consistency = 0.930). The two configurations have about the same raw coverage, suggesting that they have a similar degree of correlation with student access to HLO. It's interesting that configuration AUT*PK*~AVR was the union of A1 and A2, which indicated that it was critical for HLO. It also illustrates that students with high PK and low AVR characteristics are more inclined to obtain HLOs in VRLEs with high AUT. A possible explanation is that low AVR will reduce student distraction, and students will pay less attention to the VRLE and more attention to the knowledge. In addition, the learner not only has to fulfill the configuration AUT*PK*~AVR, but also needs to have a high VRE or high LI in order to result in a HLO. By comparing the configuration A1 with the configuration A2 we also find that there is a substitution relationship between LI and VRE, since the presence of a high VRE replaces the need for a high LI.

Configuration B1 showed that ~PK*~AVR*VRE*~LI could cause LLO (consistency = 0.850). This configuration could be divided into two subsets: AUT*~PK*~AVR*VRE*~LI and ~AUT*~PK*~AVR*VRE*~LI. These two subsets showed that learners with this combination of characteristics acquired LLO in both high and low autonomy VRLE. In addition, among the four configurations of LLO, B1 has the largest raw coverage, indicating that it is empirically most relevant for LLO. Configuration B2 indicated that students with ~PK and ~VRE would cause LLO even with AVR and in high autonomy VRLE (consistency = 0.946). This was probably because learners with ~PK will be negatively influenced by learning with unfamiliar technology, especially in a high autonomy VRLE that requires the user to be skilled in operating the equipment.

Configuration B3 proved that LLO may be triggered under the conditions ~AUT*~PK*AVR*VRE (consistency = 0.882). There were six students in this category (raw coverage < 15%). This configuration could be divided into two subsets: ~AUT*~PK*AVR*VRE*LI (n = 1, student #26) and ~AUT*~PK*AVR*VRE *~LI (n = 5). The combination of characteristics in student #26 led to the opposite result from previous research, which showed that ~PK students benefited more in low autonomy settings (Shin et al., 1994). But student #26 is a case. Configuration B4 showed that students with ~VRE, ~LI, and in low autonomy VRLE would cause LLO even with PK and AVR (consistency = 0.883). Notably, in this condition, students with high PK achieve LLO. To provide a further explanation, we analyzed the students in this group. Two students were found in this configuration (raw coverage < 10%). One of the students said in the interview that she did not feel immersed and that she wanted to learn freely in the VRLE. This may be because the low-autonomy environment limits high PK students' learning and low LI reduces students' motivation to learn.

4.3 Configurations of cognitive load

The configurations causing high CL (HCL) and low CL (LCL) were subsequently analyzed. As shown in Table 4, the results indicated one configuration produced HCL, with an overall coverage of 0.110 and an overall consistency of 0.930. Moreover, three configurations producing LCL emerged; the overall coverage is 0.452, while the overall consistency is 0.859. Also, HCL and LCL configurations were not perfectly symmetrical. The explicit explanation of the results is as follows:

Configuration C1 showed that ~AUT*~PK*AVR*~VRE*~LI could cause HCL (consistency = 0.930). This type of student has two (raw coverage < 15%). Originally, low PK students had a high ICL, and the low AUT learning environment may add ECL (Seufert et al., 2007). In addition, this also shows that AUT, PK, VRE, LI, and CL are negatively correlated, while AVR and CL are positively correlated.

Configuration D1 showed that students with PK and high autonomy VRLE would cause LCL even with ~AVR and ~LI (consistency = 0,880). Meanwhile, configuration A1 was a subset of configuration D1, but the conditions for configuration A1 are more stringent than those for configuration D1. Configuration D2 proved that LCL may be triggered under the conditions PK*~AVR*~VRE*LI (consistency = 0.915).

Table 4 Configurations causing HCL and LCL

Causal conditions	HCL	LCL		
	C1	D1	D2	D3
AUT	⊗	●		⊗
PK	⊗	●	●	●
AVR	●	⊗	⊗	●
VRE	⊗		⊗	
LI	⊗	⊗	●	●
Raw coverage	0.110	0.187	0.214	0.231
Unique coverage	0.110	0.097	0.034	0.141
Consistency	0.930	0.880	0.915	0.829
Overall Solution coverage	0.110	0.452		
Overall Solution consistency	0.930	0.859		

● indicate that this condition exists, ⊗ indicates this condition does not exist, the space means that it doesn't matter this condition exists or not, '~'means this condition/outcome does not exist. AUT autonomy, PK prior knowledge, AVR attitude towards VR, VRE VR experience, LI learning interest, LO learning outcome, CL cognitive load

Meanwhile, configuration A2 was a subset of configuration D2, which indicated that D2 could cause HLO, but obtaining HLO was more restricted. According to the subordinated relation between D1, A1, and D2, A2, we found that LCL is a prerequisite for achieving HLO.

Configuration D3 proved that LCL may be triggered under the conditions ~ AUT*PK*AVR*LI (consistency = 0.829). We found that high PK is necessary to obtain LCL because configurations D1, D2, and D3 all included the condition of PK. This is tangent to the findings of Seufert et al. (2007), which found ICL is determined by learners' intrinsic characteristics. Specifically, students with high PK have lower ICL when learning new knowledge than students with low PK. Furthermore, among the three configurations of LCL, D3 has the largest raw coverage, indicating that it is empirically most relevant for LCL. A comparison of groupings D1 and D3 revealed that both students with high PK had more stringent grouping conditions for obtaining LCL results in the VRLE with low AUT than in the VRLE with high AUT.

5 Discussion

The study aimed to investigate whether and how the autonomy of the VRLE and learner characteristics synergistically affect the learning outcome and cognitive load of learners. With fsQCA, we obtained configurations leading to learning outcome and cognitive load and found that changes in a single factor do not necessarily change the results, and that to achieve a shift from low learning outcome or high cognitive load to high learning outcome or low cognitive load, it requires avoiding the occurrence of low learning outcome and high cognitive load configurations, which requires reconfiguring all factors simultaneously rather than changing individual factors individually.

5.1 Configurations of high learning outcome and low cognitive load

It shows that the configuration AUT*PK*~AVR is the critical condition that leads to high learning outcome, and prior knowledge is the critical condition for low cognitive load. This suggests that high prior knowledge has a positive effect on learners' acquisition of low cognitive load and high learning outcome. Consistent with previous research findings, high prior knowledge had a significant positive effect on learning outcome due to its ability to help learners remember new knowledge (Huang, 2020). And learners with high prior knowledge usually have lower intrinsic cognitive load (Seufert et al., 2007). Furthermore, comparing D1 and D3, we can find that high prior knowledge students have lower requirements to obtain low cognitive load in VRLE with high autonomy. Similarly, previous research has found that high prior knowledge affects the construction of individual knowledge, with high prior knowledge activating students' recollection of what they know and influencing their understanding of it (Liu et al., 2019). Moreover, high prior knowledge students tend to have better mental models, making them more capable of integrating and organizing new information than low prior knowledge students (Moreno & Mayer, 2005). As a result, high prior knowledge students usually achieve higher test scores and better academic performance. Therefore, high prior knowledge students in the VRLE are more likely to earn the low cognitive load. In contrast to prior research, which has shown that high prior knowledge students can perform well in both high and low autonomy settings (Shin et al., 1994). This study shows that high prior knowledge students are more suitable to learn in the high autonomy VRLE, which may be because the low autonomy format set up in this experiment restricts them, and one subject suggested in the interview that he would like to be free to learn in the VRLE. Similar to previous research findings, which found that high attitude towards VR may distract learners, such learners focus more on the VRLE than on the learning content (Liu et al., 2022). Thus, low attitude towards VR becomes a factor in the core configuration, leading to high learning outcome.

However, only configuration AUT*PK*~AVR by itself is not enough to obtain high learning outcome; they also require the presence of a VR experience or learning interest element as a peripheral condition for obtaining high learning outcome. Moreover, it shows a substituting relationship between VR experience and learning interest because the presence of high VR experience can compensate for the lack of learning interest, and vice versa.

Based on the above discussion, we present our view.

View 1. VRLE is not suitable for all types of learners; high prior knowledge and low attitude towards VR students are better suited to learning in a high autonomy VRLE. For this group of students, VR experience and learning interest can be substituted for each other.

Comparing the configurations of high learning outcome and low cognitive load, we find that A1 and A2 are subgroups of D1 and D2, respectively. It shows that low cognitive load can entail high learning outcome, and obtaining high learning outcome is more restricted. Many previous studies have found a negative correlation between cognitive load and learning outcome (Haryana et al., 2022; Refat et al., 2020). In line with this finding, the study by Huang et al. (2020) found that learning concepts that must be understood in a highly plausible VRLE may require too much attention from the learner, increase the load on the learner's working memory, and reduce learning performance. In addition, the acquisition of declarative knowledge relies on working memory (Maxwell et al., 2003). Therefore, when students' cognitive processing exceeds their ability, their speed and correctness of learning will be affected. Then, the results of this study found that low cognitive load is a prerequisite for the implementation of high learning outcome, and the configurations of high learning outcome are all formed on the basis of the configurations of low cognitive load.

Based on the above discussion, we present our view.

View 2. Low cognitive load does not just positively impact learning outcome; low cognitive load is a prerequisite for students to get high learning outcome.

5.2 Configurations of low learning outcome and high cognitive load

The findings suggest that instructional designers should avoid having learners learn entirely new knowledge in the VRLE. Although low prior knowledge is not a core condition that leads to low learning outcome, three of the four configurations that lead to low learning outcome satisfy low prior knowledge. Therefore, instructional designers should avoid having students enter VRLE learning in a state with low prior knowledge. This is the same result found in our previous study, which found that low prior knowledge students were not suitable for either high or low autonomy VRLEs (Liu et al., 2022). We recommend that instructional designers allow learners to learn new knowledge in a traditional teaching environment or other environments first, and then move on to VRLE for experiential learning when students have some knowledge base. Similarly, we find that while high attitude towards VR is not a critical condition that leads to low learning outcome, three of the four configurations that lead to low learning outcome satisfy high attitude towards VR. This may be because high attitude towards VR students allocate more attention to the VRLE experience than to the learning content. This indicates that the design of VRLE should pay more attention to the connection between teaching contents and the form of content presentation, reducing learners' reading difficulties in the VRLE and distractions.

Comparing the configurations of low learning outcome with those of high cognitive load, we do not find any connection between high cognitive load and low learning outcome. This is not symmetrical with the connection between high learning outcome and low cognitive load. This differs from previous studies, which found that high cognitive load negatively affects student performance and leads to students obtaining low learning outcome (Huang et al., 2020). This may be because the cognitive load of the students in the C1 grouping, although high, did not exceed their cognitive capacity; that is, it did not cause cognitive overload. Some of the subjects reported in the interview that the helmet made them feel tired and gave them headache after wearing it for a long time. It is possible that these factors contributed to the high cognitive load of the students.

Based on the above discussion, we present our view.

View 3. VRLE is not suitable for learners to learn new knowledge, and we recommend that learners learn the basics in an environment outside of VRLE before entering VRLE. The design of VRLE should focus more on the connection between learning contents and the presentation format.

6 Conclusion

Current research indicates that the effects of VRLE on students' learning outcome and cognitive load are mixed, with no consistent results yet. Students' learning performance in the VRLE is influenced by personal characteristics and the features of the VRLE. Traditional quantitative analysis method (e.g. ANOVA) is limited in their ability to analyze the impact of multi-factor combinations. Therefore, this study used fsQCA to analyze the effects of these factors (AUT, PK, AVR, VRE, and LI) on the combination of learning outcome and cognitive load of students. And we try to give some suggestions to instructional designers and VRLE designers through the discussion.

6.1 Implications

The main implications of this study are to reveal the combined effect of personal characteristics and VRLE features on student learning outcomes. This requires teachers to consider individual student differences when practicing and at which instructional stage to use VR technology. For example, when learners need to learn in the VRLE, the learners' prior knowledge level and VR experience need to be assessed in advance, and appropriate training should be carried out for learners with a low prior knowledge level or low VR experience before the learners are allowed to enter the VRLE. And it provides a highly autonomous learning environment for learners with a high level of prior knowledge. Another insight lies in the methodology. FsQCA has shown great potential in analyzing multifactor combination effects, especially in dealing with nonlinear relationships.

6.2 Limitations and future work

There are four main limitations to this article. Although these limit the results of the study, the number of findings does not diminish. First, we did not strictly control the amount of time that students spent in the virtual museum, and they were learning at their own pace. In this context, the results were unavoidably influenced by the length of learning time. Learning time cannot be ignored in future studies, as the length of study time could reflect the level of student effort. Second, because our research was contextualized in the Tujia virtual museum, the results need to be further verified in different VRLEs to affirm the generality of the findings. Third, this study did not control for the gender ratio and socioeconomic status of the subjects, which may have had an impact on the findings. For gamified learning and learning in VRLE, gender differences may affect students' ability to operate the devices (Antón-Sancho et al., 2022; Sagnier et al., 2020), and low-income families can lead to poor learning experiences and learning outcomes for learners (Su et al., 2023). This needs to be considered in future studies. Last but not least, we only explored what kinds of configurations led to the results but did not further explore how to change the configurations so as to reduce the appearance of negative results.

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Data availability The collected and analyzed data during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests There is no competing interest.

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