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How college students form flow experiences in a learning environment supported by VR-based virtual simulation

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ABSTRACT

Virtual reality (VR) can foster Flow Experiences (FE) and promote students' knowledge and understanding. Designing, developing, and applying VR-based courses represent key strategies for the digital transformation of higher education and improved talent cultivation. Using the person–artifact–task model, this study maps flow antecedents to interactions between person, artefact, and task, rather than treating them as independent variables, setting Technical Knowledge Preparation (TKP), Perceived Usefulness (PU), and Sense of Task Control (SoTC) as key antecedents of flow formation. A questionnaire survey was administered to 164 undergraduate students from China's local universities to explore these antecedents. The results revealed that the students' FE in VR-based learning environments were suboptimal, indicating the need for further improvement. PU was the most significant positive influencing factor affecting flow formation. Meanwhile, SoTC and TKP also had positive effects on the flow formation but did not reach statistical significance. Notably, for students with prior experience of using VR, TKP exerted a significant positive predictive effect on FE. Male students exhibited a significantly higher SoTC compared with female students, resulting in a weak negative correlation between SoTC and FE. These findings expand the understanding of pre-factors of flow formation in technology-supported environments. Learners are more concerned with PU than SoTC. In-depth integration of information technology and course content is more important for flow formation than balancing between task difficulty and learners' ability.

1. Introduction

With the advancement in digital education reform and increased emphasis on innovative, learner-centered teaching, the application of virtual reality (VR) in university teaching has attracted considerable scholarly attention across various countries. Here, VR refers to technical platforms (e.g., Unity3D) that present virtual simulation–based learning situations to improve students' learning outcomes. In 2013, the Chinese Ministry of Education launched the construction of a national-level VR experimental teaching center. In 2019, the Chinese government explicitly advocated the promotion of educational informatization through constructing and developing VR experimental teaching projects. In the same year, the Chinese Ministry of Education launched first-class undergraduate courses. Guided by a series of policies, VR teaching in China underwent three stages, namely, exploration and experimentation; development and construction; and application and innovation [1]. In a work report issued in 2024, the Chinese government emphasized the need to "vigorously develop digital education." Therefore, leveraging the advantages of VR to enhance the quality of digital education is an essential task in China's digital reform of education.

From the perspective of international research, flow theory (along with self-determination, social cognitive, expectancy–value, and goal-setting theories) has become an important theoretical foundation for analyzing learning behaviors and outcomes among college students [2]. Experiencing a flow state leads to optimal learning experiences and enhanced learning outcomes [3]. In China's higher education, many scholars have conducted innovative research based on flow theory. For instance, Cao [4] explored the influencing factors of the teaching effectiveness of ideological and political theory courses in universities. The results demonstrated that flow experience (FE) is a core factor influencing college students' sense of acquisition in these courses, and the intensity of their FE is directly related to the level of sense of acquisition. Yen et al. [5] found that in the context of integrating

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Glossary

VR	Virtual reality
FE	Flow experiences
TKP	Technical knowledge preparation
SoTC	Sense of task control
PU	Perceived usefulness

simulation-based learning systems into entrepreneurship education, FE in college students can promote improvements in learning performance and entrepreneurial self-efficacy.

Against the backdrop of China's vigorous advancement in the construction of high-quality VR courses, combined with national contextual realities and drawing on cutting-edge international research findings, this study adopts the PAT model to categorize the antecedents of flow formation as the interactions among person, artifact, and task, rather than treating them as independent variables. It further explores the triggering mechanism and formation rules of college students' flow experience in VR learning activities. The findings can not only effectively improve the quality of digital education in China, but also provide valuable references for the optimization and improvement of VR learning environments worldwide.

1.1. Literature review

1.1.1. Influence of FE on VR applications in higher education

As VR becomes increasingly integrated into higher education, optimizing learning experiences and enhancing teaching effectiveness have emerged as core issues. Flow, an optimal psychological state in which individuals become fully immersed in an activity and experience intense pleasure and satisfaction, offers a crucial theoretical perspective for understanding and designing efficient VR learning environments. The role of flow in VR teaching extends far beyond merely making learning engaging, through a set of complex psychological mechanisms, it profoundly shapes learners' motivation, cognitive processes, and ultimate learning outcomes.

Firstly, the FE can boost students' learning motivation and participation in academic activities. In a state of flow, learners are driven by the inherent fun and challenge of the task itself. They will voluntarily devote more time and energy to in-depth exploration [6]. Meanwhile, positive emotional experiences can strengthen students' self-efficacy, making them more willing to embrace new challenges and thus form a virtuous cycle of continuous learning. In addition, the deep concentration fostered by the flow state enables learners to move beyond passive watching or listening and engage in active cognitive processing. They take greater initiative to interact with the virtual environment and experiment with different solutions, thereby achieving a shift from superficial memorization to in-depth understanding [7].

Secondly, positive FE can effectively reduce cognitive load and improve learning efficiency. Highly immersive and complex VR environments may bring excessive sensory stimulation and complicated interactive operations, which increase extraneous cognitive load and interfere with learning [8]. However, when the VR environment is well-designed, the FE can serve as an effective regulator of cognitive load. High concentration allows learners to automatically filter out irrelevant distractions in the environment and focus their limited cognitive resources on core learning tasks, which objectively mitigates the impact of extraneous load. Meanwhile, the positive emotions and high motivational state brought by flow can enhance learners' willingness and ability to process complex information and construct knowledge, motivating them to invest more mental effort to cope with necessary intrinsic load and germane load [9]. Cristobal [10] found that flow fully mediated the inverse associations between VR usage and anxiety, stress, and depression, and partially mediated the positive correlation with well-being. Based on a study of art majors, Yang et al. [11]. discovered that the virtual reality group experienced a significantly more positive impact on their artistic attitude compared with the computer group.

Finally, the FE exerts both direct and indirect effects on college students' learning outcomes. Cristobal [12] found that the mediating effect of flow on college students' learning experience can be explained through motivation, curiosity, cognitive benefits, reflective thinking, and perceived value. Similarly, presence, learning motivation and flow experience jointly influence learners' emotions and academic performance [13]. The quality of creative products designed by learners in VR environments is significantly correlated with their FE, and the level of FE can be used to predict learning outcomes [14]. In desktop virtual reality environments, college students' self-efficacy exerts a significant influence on their FE. With flow experience serving as a mediating variable, self-efficacy further exerts an indirect effect on academic performance and learning satisfaction [15].

1.1.2. Influencing factors of flow formation

Defined as the holistic sensation of being fully immersed in an activity [16], flow was first introduced by Csikszentmihalyi [17]. It refers to a state of deep engagement in which individuals are entirely absorbed in tasks, potentially enhancing happiness and work efficiency. To experience flow, activities must be challenging and skill-demanding; they must merge action and awareness, provide immediate feedback, and require full concentration [18]. Csikszentmihalyi [19]. listed the factors that contribute to flow, however, he underscored them as the most exhibited factors, instead of exclusive ones.

Presently, a general consensus exists that flow can be classified into three stages: flow antecedents, FE, and flow consequences. Flow antecedents encompass clear goals, immediate feedback, potential control, and the merging of action and awareness. FE comprises concentration, loss of self-consciousness, time distortion, and telepresence. Flow consequences include positive emotions and autotelic experiences [20].

The antecedents of flow have become a key focus of international scholars, primarily because examining these factors is crucial for explaining elements that comprise optimal experiences and their incorporation into human-computer interaction design. Wan et al. [21] conducted an empirical study on the antecedents of flow among college students in game-based learning (GBL) contexts and found that learners highly value GBL with flow antecedents such as concentration and challenge, which are closely associated with learning motivations and metacognitive outcomes. The ability of GBL to enhance knowledge acquisition and provide immersive experiences is considered fundamental to students' performance expectations before adopting it as a learning tool. Jo and Park [22] confirmed that system updates, memorability, and the non-language barrier attributes of ChatGPT have significantly improved knowledge acquisition and application. Additionally, acquisition and application lead to significant increases in utilitarian value and satisfaction, thereby increasing word-of-mouth recommendations. Liang et al. [23] found that process experience, perceived risk, and personal innovation directly influenced users' acceptance of the metaverse in terms of application, while perceived cost exerted no impact. Meanwhile, interactivity, presence, and social presence indirectly influenced users' acceptance of the virtual world, whereas no impact was observed for information and enjoyment.

The integration of technology has increased the complexity of flow formation. In technology-mediated environments, activities must be viewed as a combination of tasks and tools (artifacts) required for task completion. The factors that influence FE depend on interactions among people, tasks, and artifacts. Given these changes, Finneran and Zhang [19] put forward the Person–Artifact–Task (PAT) model, which posits that three factors(person, artifact, and task) and the interactions among them primarily influence FE. It is a framework used in Human Factors and Ergonomics for analyzing interactions among people, including their tools (artifacts) and tasks. Simultaneously considering these elements helps designers and researchers in formulating effective, efficient, and satisfying user experiences.

Currently, the PAT model has become the main theoretical framework for exploring the causes of flow. In China, Jiang et al. [24] conducted a systematic review to organize and synthesize 78 international empirical studies that applied flow theory. The authors summarized the antecedents of flow by integrating the PAT model, thereby providing a clear and systematic pathway for the application of flow theory to the field of information behavior. In addition, numerous studies applied the PAT model to flow research across fields such as industrial design [25] and medical education [26]. The PAT model was used to analyze the factors of users' FE, with the objective of optimizing design methods and outcomes and enhancing user experience.

1.2. Theoretical framework

Based on the PAT model, the current study selected technical knowledge preparation (TKP, PU, and sense of task control (SoTC) as antecedents of flow. Compared with existing research, in terms of selecting flow antecedents, the current study focuses on the relationship among persons, artifacts, and tasks instead of their independent attributes. TKP, PU, and SoTC represent interactions between persons and artifacts, between tasks and artifacts, and between persons and tasks. Fig. 1 illustrates this change.

TKP refers to the extent to which a person masters the characteristics of an artifact and its application skills. In general, the more adequate the TKP, the easier the application of the artifact, especially during the stage of promoting and applying new artifacts. For example, in the early stage of mobile TV use, Zhou et al. [27] conducted a survey on users' acceptance behavior and found that perceived ease of use exerted a significant impact on FE. In addition, during the popularization stage of AR technology, Budi [28] underscored that the level of technology readiness of college students toward AR exerts a significant impact on FE and plays a crucial role in the process of the acceptance and popularization application of AR.

Therefore, based on these articles, the current study poses the following research question and hypothesis.

RQ1: What is the impact of college students' TKP on their FE in the VR-supported autonomous learning context?

H1: TKP exerts a significantly positive predictive effect on FE: the more comprehensive the TKP during college students' application of VR to learning, the more favorable the formation of FE.

According to Davis [29], PU refers to the degree to which users perceive that a certain tool or system can improve work performance. It places greater emphasis on the degree of matching or consistency between tasks and artifacts under human operation. In other words, when users believe that a specific artifact is the only one appropriate for completing a particular task or function, then experience flow becomes easy for them [19]. Currently, research results in the fields of online consumption and communication fully indicate that users' PU of artifact exerts a positive effect on flow formation. For instance, Chen et al. [30] considered PU as a content dimension of shopping websites and found that it exerted a positive impact on the FE of online consumers. Additionally, Xiong Wei et al. [31] revealed that users' PU of mobile social functions in WeChat plays a significant positive predictive role in their FE.

Therefore, given this stream of research, the study presents the following research question and hypothesis.

RQ2: What is the impact of college students' PU on their FE in the VR-based autonomous learning context?

H2: PU exerts a significantly positive predictive effect on FE: when college students apply VR to learning, the stronger the PU, the more conducive it is to the formation of FE.

SoTC denotes belief and level of confidence in one's ability to complete specific tasks. It is a manifestation of self-efficacy in specific situations and directly influences behavioral choices, levels of effort, and persistence when faced with challenges. According to FE theory, self-efficacy is an important precursor to flow. Individuals with high levels of self-efficacy are more likely to experience flow [32]. For instance, Fan Jia et al. [33] found that self-efficacy consistently and robustly predicts FE over time through a continuous tracking of undergraduates' English learning and using the cross-lagged panel model .

Therefore, the study highlights the following research question and hypothesis.

RQ3: What is the impact of college students' SoTC on their FE in the VR-based autonomous learning context?

H3: SoTC exerts a significantly positive predictive effect on FEs: when college students apply VR to learning, the stronger the SoTC, the more conducive it is to the formation of FE.

Therefore, to verify these hypotheses, this study constructed a conceptual model (Fig. 2).

2. Research design and participants

Existing studies demonstrated that significant differences exist in factors that influence college students' use of VR for learning across types of universities. In China, students from 985 Project universities placed more emphasis on the simulation, usefulness, and freedom of VR experimental teaching projects. In contrast, students from 211 Project universities paid more attention to the difficulty and complexity of project operations and the usability of the project [34]. To enhance the representativeness of the research sample, the current study conducted a

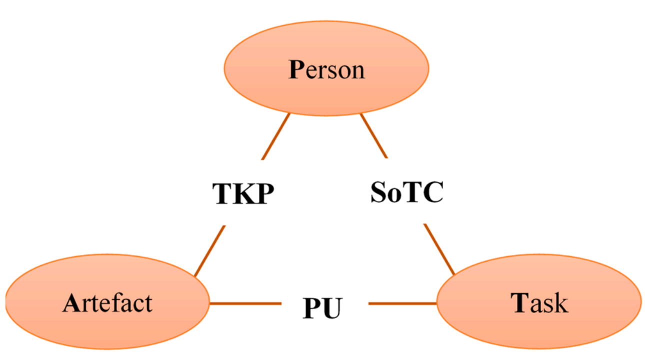

Fig. 1. Selection of flow antecedents.

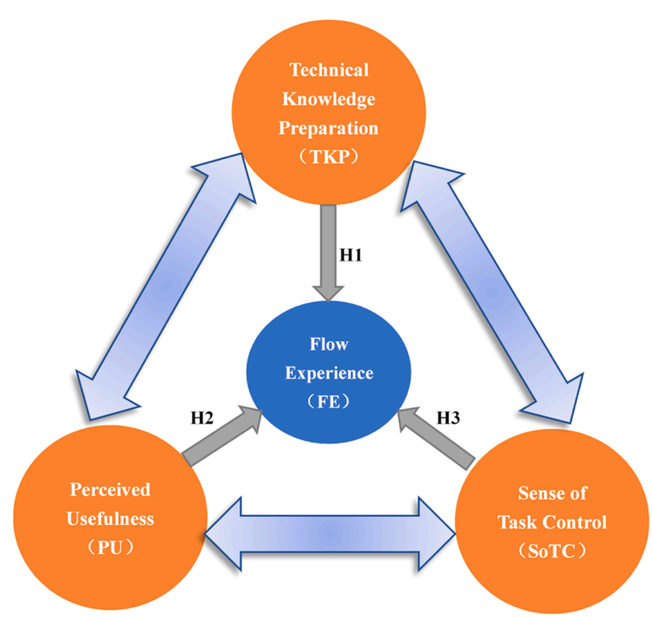

Fig. 2. Conceptual model.

questionnaire survey on an undergraduate university in Shaanxi Province that focuses on application. In this manner, this study distinguished itself from existing studies in China that focused on 211 Project or 985 Project universities. The participants were undergraduate students majoring in Digital Media and enrolled in the Animation Production course taught by members of the research team. The questionnaire was distributed by the instructor in the class. Before completing the questionnaire, the students were informed that the survey was anonymous, would not violate their privacy, and was unrelated to their course grades, and their informed consent was obtained. In conclusion, consent was obtained not only from the student participants but also from the school's teaching and administrative department. All data collection procedures complied with ethical standards. This course utilized desktop VR; during in-class exercises, students independently conducted task-oriented animation production using software for learning the principles of animation movement, which were developed using Unity3D. This course aims to cultivate students' animation production skills and strengthen their mastery of basic animation knowledge. It represents a tool-supported, task-based learning activity that aligns closely with the three core elements of the PAT model. Finally, a total of 164 valid responses were collected.

Table 1 exhibits the demographics of the participants. The sample was mainly composed of female students, with a relatively balanced distribution of sophomore, junior, and senior students. More than half reported prior experience in using VR software.

3. Research scales

3.1. The PAT scale

Based on the results of Yoshida et al. [35] and Meuter et al. [36], the current study developed the PAT scale for college students engaged in learning within a VR environment. During the scale development process, bilingual experts completed the forward translation. While ensuring the accuracy of professional terminology, the expressions were adjusted to conform to Chinese linguistic conventions. It includes three dimensions, TKP (6 items), PU (4 items), and SoTC (6 items), for a total of 16 items. Six items with factor loadings <0.5 were excluded after conducting exploratory factor analysis via SPSS 19.0. These items included three from the TKP dimension: (i.e., "I am fully confident in my ability to use VR software for learning," "Using VR software for learning is completely within my ability," and "My previous experience with 3D virtual spaces has enhanced my confidence in using VR software") and three from the SoTC dimension (i.e., "During the learning process, I always clearly know what I want to do or what I should do," "I can independently solve various problems encountered in VR experiment learning," and "I am clear about the progress of learning tasks when using VR software." Finally, 10 items were retained for analysis. Table 2 displays the results of the exploratory factor analysis and internal consistency test. Further calculations affirm that the AVE values of the PU, SoTC, and TKP dimensions are 0.614, 0.641, and 0.629, respectively, while their composite reliability(CR) values are 0.864, 0.843, and 0.836, respectively.

In essence, discriminant validity is a form of construct validity that emphasizes that measurement items intended to represent different constructs do not load under the same factor. Table 3 presents the results of the discriminant validity analysis of the PAT scale. The square roots of the AVE for PU, SoTC, and TKP were higher than the correlation coefficients among variables, which indicates that each dimension of the scale exhibits good discriminant validity.

In addition to exploratory factor analysis and discriminant validity analysis, this study conducted first-order confirmatory factor analysis on the PAT scale via AMOS 21.0, adopting the same sample data used for exploratory factor analysis. The values of the model fit index are as follows: CMIN/DF = 1.062, RMR = 0.026, GFI = 0.960, AGFI = 0.932, NFI = 0.945, RFI = 0.923, IFI = 0.997, TLI = 0.995, CFI = 0.997, and RMSEA = 0.019. These results indicate that the reliability and validity of the PAT scale fully meet the requirements.

Table 1
Demographic characteristics of the respondents.

Category	Groups	N	%
Gender	Male	57	34.8
	Female	107	65.2
Grade	Sophomore	52	31.7
	Junior	58	35.4
	Senior	54	32.9
Experience with VR software	No	71	43.3
	Yes	93	56.7

Table 2
Results of reliability and validity analyses of the PAT scale.

Items	Factor loading	Rotation sums of squared loadings (%)	Cronbach's alpha	
PU1—Using VR software has improved my learning efficiency.	0.790	26.25	0.813	0.839
PU2—The use of VR software has enhanced my understanding of the model knowledge.	0.796			
PU3—The use of VR software has facilitated my mastery of animation production techniques.	0.804			
PU4—The use of VR software has sparked my interest in creating animated characters.	0.743			
SoTC1—I think that I can handle anything that may happen in the environment supported by VR software.	0.812	47.67	0.789	
SoTC2—I am highly capable of completing learning tasks using VR software.	0.832			
SoTC3—I have a strong sense of control over every task I do using VR software.	0.756			
TKP1—I know how to use VR software to learn models or animations.	0.804	68.54	0.779	
TKP2—I know the advantages of using VR software for model and animation production learning.	0.780			
TKP3—I know the steps for using VR software.	0.795			

3.2. Flow experience scale

This study simplified the flow scale developed by Yoshida et al. [35] and formed a single-dimensional scale that comprises four items. After conducting exploratory factor analysis using SPSS 19.0, one factor with eigenvalue > 1 was ultimately extracted, including three questions. Table 4 presents the results. Further calculation and analysis demonstrate AVE and CR values of 0.764 and 0.907, respectively, for the FE Scale. Thus, the reliability and validity of the scale meet the research requirements.

Table 3
Results of the discrimination analysis of the PAT Scale.

Variable	TKP	PU	SoTC
TKP	0.914		
PU	0.369***	0.784	
SoTC	0.496***	0.371***	0.918

Table 4
Results of reliability and validity analyses of the FE scale.

Items	Factor loading	Rotation sums of squared loadings (%)	Cronbach's alpha
FE1—I feel very happy when using VR software to learn.	0.902		
FE2—I feel very comfortable when using VR software to learn.	0.847	76.40	0.845
FE3—I am engaged in learning within an environment supported by VR software.	0.872		

4. Results

4.1. Status description analysis

The items of both scales were rated using a five-point Likert-type scale; thus, the scores range from 1 to 5. The higher the score, the better the performance of the respondents in a variable. Tables 5, 6, and 7 display the results. Among the four variables (i.e., TKP, PU, SoTC, and FE), SoTC and PU obtained the lowest and highest scores, respectively. Based on variance score, the scores of each variable are relatively concentrated, while the degree of dispersion is small.

Table 6 and 7 illustrate the results of the t-test: men obtained significantly higher scores than did the women in TKP, SoTC, and FE, while the use of VR software exerted no effect on the performance of each variable.

Table 8 presents that the results of one-way analysis of variance, indicating no significant differences in the performance levels of each variable according to grades and highlighting that course learning experience does not exert significant impacts on TKP, PU, SoTC, and FE in course learning using VR.

4.2. Research hypothesis analysis

Prior to analysis of the research hypotheses, performing a normality test on the data of each dimension is necessary. Fig. 3 presents the test results for each dimension. The variables TKP, PU, SoTC, and FE approximately conform to normal distribution and are suitable for further analysis. In addition, the results of the Kolmogorov–Smirnov test show that the p-values of the normality tests for TKP, PU, SoTC and FE are 0.08, 0.12, 0.07 and 0.15 respectively, all of which are greater than 0.05, indicating that the data follow a normal distribution.

Data analysis was conducted on the preset model via AMOS 21.0. Fig. 4 and Tables 9 and 10 depict the results. The measured values of each indicator met the recommended values; thus, model fit was good (Table 8).

The results of the model fit test indicated that $CMIN/DF=1.066<3$, $RMR=0.029<0.1$, $GFI=0.948>0.90$, $AGFI=0.916>0.90$, $NFI=0.936>0.90$, $CFI=0.996>0.90$, $RMSEA=0.020<0.08$. The model exhibited satisfactory goodness-of-fit.

Table 10 indicates that only the effect of PU on FE reaches a significant level. Therefore, H2 is supported. Meanwhile, although SoTC and TKP exerted a positive predictive effect on FE, the effect did not reach a statistically significant level; hence, H1 and H3 are rejected.

Furthermore, the study conducted multiple-group analysis via AMOS 21.0 on the characteristics of the participants (i.e., gender, grade, and experience with using VR software).

Table 5
Results of descriptive statistics.

Variable	Mean	SE	SD	Variance
TKP	3.8618	0.05108	0.65418	0.428
PU	3.9680	0.04903	0.62793	0.394
SoTC	3.2825	0.06031	0.77239	0.597
FE	3.7114	0.05698	0.72967	0.532

Table 6
Results of independent-sample t-test (mean) between genders.

Variable	Males	Female	T	Cohen's d
TKP	4.0702	3.7508	3.347***	0.501
PU	4.0614	3.9182	1.395	0.229
SoTC	3.6608	3.0810	4.889***	0.802
FE	3.8713	3.6262	2.225*	0.339

Table 7
Results of independent-sample t-test (mean) between groups with different experiences with VR software.

Variable	E-Y	E-N	T	Cohen's d
TKP	3.9104	3.7981	1.090	0.172
PU	3.9919	3.9366	0.558	0.119
SoTC	3.2760	3.2911	−0.124	−0.026
FE	3.7312	3.6854	0.397	0.080

Table 8
Results of one-way analysis of variance (mean).

Variable	Sophomore	Junior	Senior	F	Partial η^2
TKP	3.8462	3.8391	3.9012	0.146	0.002
PU	3.9327	3.9655	4.0046	0.173	0.002
SoTC	3.1474	3.3333	3.3580	1.181	0.014
FE	3.6731	3.6034	3.8642	1.912	0.023

Conducting tests of measurement invariance is a crucial foundation for multi-group path difference analysis. Table 11 presents the results of measurement scale invariance across groups. Based on these criteria ($\Delta CFI < 0.001$, $\Delta RMSEA < 0.015$), the study confirmed that the tests of measurement invariance for all groups meet the research requirements, except for the ΔCFI and ΔRMSEA values derived from a small number of groups, which were slightly higher than the recommended thresholds (marked with * in Table 10). In summary, proceeding with the multi-group path difference analysis is appropriate.

Table 12 demonstrates that the absolute values of critical ratios are all <1.96, which indicates that no significant difference exists in the assumed influence weights between men and women. However, men's SoTC exerted a weak negative impact on FE and did not reach a statistically significant level, whereas women's SoTC exerted a significantly positive impact.

Table 13 affirms that the absolute values of the critical ratios are <1.96, which denotes that no significant difference exists in the estimated values of the three hypotheses across groups with different experiences of using VR software.

5. Conclusion

This study presented an empirical study that explores the development of FE among undergraduate students in learning environments that use VR-based desktop animation production in a single institution. The key intellectual contribution is reconceptualize PAT flow antecedents as relational interactions between person–artefact, artefact–task, and person–task rather than treating them as independent variables. Grounded in the PAT model, the study focuses on three antecedents of flow, namely, TKP, PU, and SoTC. Based on survey data, this study conducted a quantitative analysis of psychological constructs (flow and its antecedents). It also replicated and extended an established framework, the PAT model, and applied standard statistical procedures to identify significant predictors of flow. The major conclusions are summarized as follows.

First, when local college students learn in VR environments, their

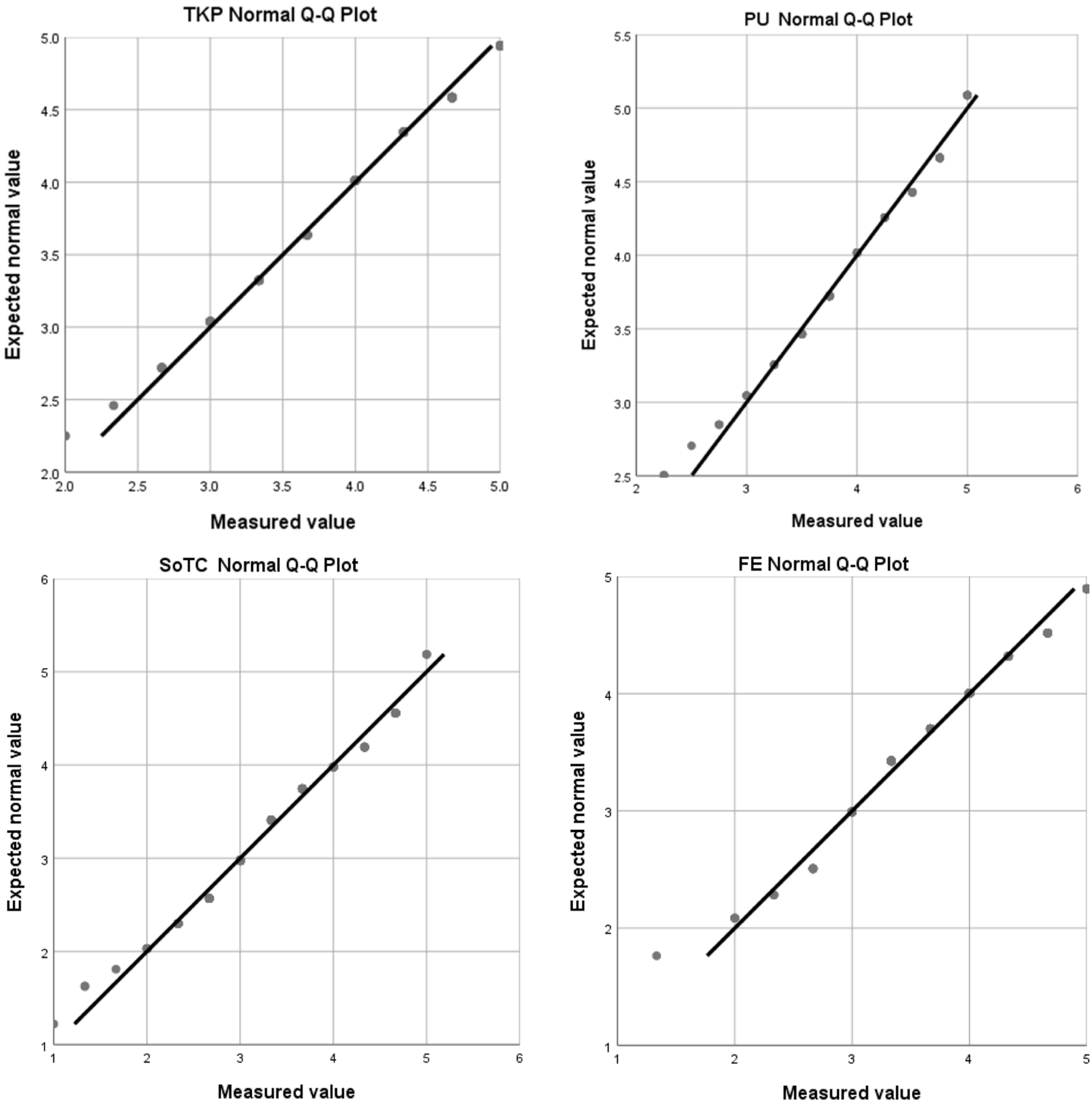

Fig. 3. Test results of normality analysis for study variables.

perception level of FE was suboptimal and required further improvement. Male students performed significantly better than did female students in TKP, SoTC, and FE. Moreover, the experience of using VR software did not exert a significant impact on the performance of college students in TKP, SoTC, PU, and FE.

Second, PU is the main antecedent influencing FE formation among local university students in VR-based scenarios. This finding aligns with those of Padilha et al. [37], who emphasized the significant impact of PU on students' behavioral intention to use VR technology. Compared with Vittersø [38], the current study expanded the antecedents of flow formation for learners in VR scenarios from the balance between persons and tasks to the integration between artifacts and tasks, thus enriching the antecedents of FE formation. This finding is consistent with the application research on VR in healthcare education conducted by Verkuyl et al. [39]: VR should be seamlessly integrated into course outcomes and curriculum planning.

Third, from the perspective of group categories, although analysis of the entire sample indicates that TKP exerted no significant impact on FE, it exerted a significant positive predictive effect on FE for the group with experience in using VR software. This is consistent with the findings of Zhao et al. [40], who pointed out that perceived effortlessness contributes to TikTok users' optimal flow experience. In addition, male students exhibited higher levels of SoTC, which exerted a certain negative impact on FE formation. This finding is consistent with Csikszentmihalyi's viewpoint [38]. When the level of difficulty of a task is high and an individual's skill level is low, then the individual will experience anxiety. When an individual's skill level is high but the level of difficulty of the task is low, then the individual will experience boredom.

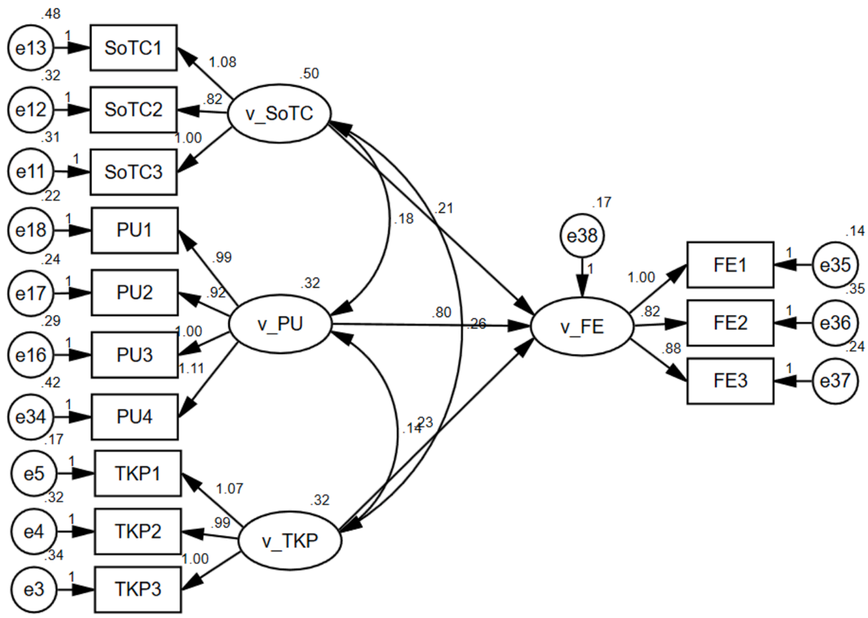

Fig. 4. Results of the preset model analysis.

Table 9
Results of model fit analysis.

Index	Recommend value	Measurement value	Results
CMIN/DF	1–3	1.066	Yes
RMR	<0.1	0.029	Yes
GFI	>0.9	0.946	Yes
AGFI	>0.9	0.916	Yes
NFI	>0.9	0.936	Yes
CFI	>0.9	0.996	Yes
RMSEA	<0.08	0.020	Yes

6. Recommendations

6.1. *Enhancing college students' PU of VR*

According to the TAM, perceived ease of use directly influences PU. For instance, in basic design education, the simplicity of operation of VR tools is positively correlated with the practicality perceived by students [41]. Therefore, decreasing the complexity of VR is key to enhancing PU. In the design of VR, emphasizing a clear interface design and intuitive interaction logic can decrease cognitive load, which enables students to focus more on learning content and less on the tool [42].

In addition, the detailed authenticity of virtual environments can enhance students' sense of immersion, which influences their perception that the technology is more closely aligned with practical applications and can significantly improve PU [43]. This concept underscores the importance of designing learning tasks that align with career development when integrating VR technology into learning tasks. The optimal design lies in "situational authenticity" instead of pure "graphical realism"—specifically, the environment, equipment, and operational processes must close replicate real-world work scenarios. Moreover, VR

Table 11
Results of measurement invariance tests.

	Groups	CFI	ΔCFI	RMSEA	ΔRMSEA	Result
Gender	Male	0.977	0.005	0.056	0.012	Yes
	Female	0.982		0.044		
Experience of using VR software	Yes	0.973	0.011*	0.051	0.013	Yes
	No	0.984		0.038		

Table 12
Analysis results of gender groups.

Index	H1: TKP → FE		H2: PU → FE		H3: SoTC → FE	
	Male	Female	Male	Female	Male	Female
Estimate	0.148	0.246	0.941**	0.679***	−0.070	0.273*
SE	0.336	0.132	0.312	0.120	0.372	0.116
CR	0.440	1.863	3.016	5.675	−0.189	2.359
Critical ratios	0.271		−0.785		0.882	

Table 13
Analysis results of various groups with experience in using software.

Index	H1: TKP → FE		H2: PU → FE		H3: SoTC → FE	
	Yes	No	Yes	No	Yes	No
Estimate	0.362*	0.048	0.871***	0.789***	0.186	0.288
SE	0.169	0.278	0.206	0.155	0.129	0.251
CR	2.137	0.172	4.220	5.085	1.442	1.148
Critical ratios	−0.966		−0.317		0.362	

Table 10
Results of structural equation model path analysis.

Hypothesis	Estimate	SE	CR	P	95% CI		R^2	Result
					Lower	Upper		
H1: TKP → FE	0.231	0.131	1.766	0.077	−0.156	0.514	0.693	No
H2: PU → FE	0.799	0.123	6.514	***	0.552	1.067		Yes
H3: SoTC → FE	0.210	0.106	1.972	0.049	−0.028	0.543		No

tasks should be closely integrated into student needs in terms of professional practice, internships, or employability skills. For example, learning motivation can be enhanced by simulating business competitions, industrial operations, or clinical scenarios, thus enabling students to envision how technology can support career development [44]. In future education reforms, the animation production-based tasks completed by the participants can be embedded into specific professional scenarios to enhance task authenticity.

Finally, full consideration should be given to individual differences when designing teaching activities. Scenarios should be designed on the basis of the diverse characteristics of students. Based on the findings of existing studies on VR teaching, there is a need to strengthen the cultivation of technical knowledge among female students, and implement personalized teaching. Meanwhile, in the construction of VR learning environments and the development of supporting resources, the Dynamic Difficulty Adjustment (DDA) algorithm can be integrated. Learning activities can be dynamically adjusted according to the characteristics of different student groups, so as to achieve genuine personalized learning and balance task challenge with learners' abilities and skills.

6.2. Promote the application of VR games in a rational manner

As an interdisciplinary technology that integrates computer science, engineering, and education, VR technology is a highly abstract and complex concept. Intuitively understanding its core principles, system architecture, and potential applications via traditional teaching methods is typically difficult for students. As a form of serious games that deeply integrate educational objectives into game mechanics and simulated environments, VR games provide an innovative solution to this education challenge. A synthesis of findings from meta-analyses [45,46] and systematic reviews [47] indicate that VR games significantly enhance students' procedural knowledge, principled cognition, and applied understanding of complex technical concepts. Learning occurs through multidimensional pathways such as experiential learning, cognitive construction, and emotional engagement.

However, success through VR games may not be automatically achieved, because a number of moderating variables influence their effectiveness. Thus, games must be closely integrated into curriculum objectives instead of considering them as isolated entertainment activities [48]. First, teachers need to design clear learning objectives and post-experience reflection sessions to guide students in elevating the gaming experience to achieve a rational understanding of technology. The second pertains to feedback mechanism. Immediate and clear feedback is key to learning [45]. Thus, games must provide effective feedback on the accuracy of students' operations, including explanations on technical principles. The last refers to fidelity. The level of fidelity in simulation influences the effectiveness of cognitive transfer [49]. Thus, an overly simplified simulation may fail to convey the core complexity of the technology.

7. Limitations

Although the study achieved its objectives, it has its limitations.

Firstly, the sample was drawn exclusively from a specific region and group, which inherently restricts the generalizability of the findings. The relatively small sample size may also have compromised the statistical power of the analysis, which led to difficulty in detecting subtle but potentially significant relationships between variables, especially in the context of multigroup path difference analysis. Moreover, Moreover, different forms of VR exert distinct effects on students' flow formation. Doğan [50] found that immersive VR significantly enhances the flow experience of law students compared to desktop VR. Participants in the immersive VR group demonstrated higher levels of focused attention, telepresence, time distortion, and interaction, indicating a more profound immersion. In this study, the sample is limited to desktop-based animation production in a single institution, whether the findings extend to immersive VR or other simulation contexts remains unclear and a topic for further research.

Secondly, reliance on self-reported questionnaires may have introduced response bias, because the participants might have provided socially desirable answers instead of accurate reflections of their true attitudes or behaviors. Moreover, all questionnaires were completed simultaneously. Harman's test results showed that there were three factors with eigenvalues greater than 1 in the PAT scale, namely TKP, PU, and SoTC, with a total cumulative variance contribution of 68.54%. Among them, the variance explained by the first extracted factor reached 41.36%, exceeding the commonly adopted empirical threshold of 40%, which indicates the presence of common method bias. And EFA and CFA used the same sample without cross-validation, inflating model fit. Furthermore, Flow is a highly complex concept. Oliveira et al. [51] analyzed the influence of FE on students' learning performance from multiple dimensions, including challenge–skill balance, merging of action and awareness, clear goals, feedback, concentration, control, loss of self-consciousness, and autotelic experience. In contrast, the FE scale adopted in this study was simplified to merely three items, and such a concise scale may fail to fully reflect the multidimensional nature of flow experience. The exploration of FE remains to be further deepened.

Finally, this study was primarily grounded in flow theory and the PAT model, which, although widely applied to college students' learning in VR scenarios, may partially account for the unique contextual factors of VR. This narrow theoretical scope may have overlooked other relevant theoretical perspectives that could offer alternative explanations for the results. Moreover, the R^2 of TKP, PU, and SoTC on FE is 0.693, which means that approximately 30.7% of flow variance remains unexplained. This may be affected by factors such as feedback quality, social presence, intrinsic motivation, and challenge–skill balance, which requires further investigation in future research. Additionally, in terms of data collection, this study adopts a cross-sectional research design. Due to the lack of chronological evidence and susceptibility to confounding factors, it cannot accurately infer causal relationships. The causal links between the influencing factors and the formation of flow revealed in the current findings require long-term follow-up and further verification in future research.

Building on the findings and limitations, the study proposes the following directions for future research to advance knowledge in this field. First, future studies should strive to expand the scope of the sample by including broader groups or regions from multiple provinces across China to enhance the generalizability of the findings. Second, combining qualitative interviews with quantitative surveys could offer a more comprehensive and in-depth understanding of learning supported by VR. Third, given the negative relationship between SoTC and FE among male students, future research should further strengthen the post-hoc analysis of nonlinear or interaction effects between variables. Finally, future research could integrate organizational behavior and self-determination theories to construct a comprehensive theoretical framework. This cross-theoretical integration could address the contextual limitations of a single theory and provide nuanced explanations for complex research phenomena.

Data availability statement

The data presented in this study are available upon reasonable request from the corresponding author due to the interviewees' request to maintain the privacy of conversation contents.

CRediT authorship contribution statement

Fei Wang: Writing – original draft, Methodology, Conceptualization. **Yunfu Li:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Junsheng Zhou:** Software, Data curation.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

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