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Interactivity and identity impact learners' sense of agency in virtual reality field trips

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Abstract

Agency, or the capacity to take intentional actions, is considered one of the primary affordances of virtual reality (VR) for learning. VR is expected to increase learners' agency because it allows for full-body interactivity from a first-person perspective, giving them novel ways of interacting with the digital environment. Yet, agency in immersive learning has not been well-studied relative to other affordances like presence, and more evidence is needed to understand how varied media and designs heighten or diminish agency. This mixed-method study addressed this need by developing and validating measures of sense of agency with 30 high school students who used VR field trips in their engineering class over four lessons. By comparing immersive videos to video game-like interactive graphical environments, the study illustrates some of the complexities of agency in VR. The findings indicate agency is not a unidimensional construct nor is it equivalent to full-body interactivity in VR as learners felt some types of agency when using immersive videos. Furthermore, learners' identities moderated associations between the type of VR media and their sense of agency, and agency did not change over time as the novelty of VR waned. These results suggest VR designers should consider varied ways of interacting in VR that are beneficial for learning. They also support the use of immersive videos when the educator's goal is to increase agency over learning or focus, and provide measures and direction for future research to assess the relationship between varied types of agency, features of VR experiences and learning outcomes.

KEYWORDS
agency, immersive learning, STEM education, virtual reality

Practitioner notes

What is already known about this topic

- Virtual reality (VR) can enhance learning by giving learners a strong sense of presence in the virtual environment and giving them agency over their learning through novel forms of interactivity.
- Many studies have looked at increasing the learner's presence in VR, but fewer have assessed learners' agency.
- Prior work found the impact of increased interactivity on learning was mixed: sometimes it increased learning outcomes and motivation, other times it did not.

What this paper adds

- This study develops and validates measures of learners' sense of agency within VR learning environments.
- This study finds that more interactivity in VR increases how much agency learners feel over their actions but not necessarily their agency over learning and attention.
- This study also finds variation in students' experiences of agency based on their culturally defined sense of self-construal.

Implications for practice and/or policy

- Practitioners interested in immersive learning technologies should consider the design of the media used rather than focusing only on the device's capability.
- Immersive videos may be effective tools for enhancing student agency, depending on the aims of the learning experience.
- Designers and educators should consider learners' identities such as self-construal, and understand student experiences may vary.

INTRODUCTION

Agency, or the capacity to take intentional actions based on one's goals and desires, is a key aspect of motivated and self-regulated learning (Reeve, 2013). For example, autonomy is considered a basic psychological need and facilitates intrinsically motivated learning (Patall et al., 2022; Ryan & Deci, 2000). Yet, traditional schooling tends to favour external methods of control, like rewards and punishment, and is organized to limit learners' agency over their learning process (Lepper & Henderlong, 2000; Reeve, 2009). New technologies present opportunities to increase learners' agency in classroom environments. In particular, virtual reality (VR) allows learners to interact with rich environments using their full bodies, making increased agency one of its primary affordances (Makransky & Petersen, 2021).

Despite the promise of VR to enhance learners' agency and therefore increase motivation and learning, agency has not been well studied in immersive learning technologies. Many studies focus on immersion and learners' sense of presence or 'being there' in the environment, comparing learning with a VR headset to a less immersive device. The results of VR on learning are mixed, including studies that find no benefit of VR for learning outcomes

(Carreon et al., 2023; Jensen & Konradsen, 2018; Radianti et al., 2020; Wu et al., 2020). However, the design of media used within VR, such as differences between videos and video game-like environments, is equally important to understand the impact of VR on learning and motivation beyond the device (Bower & Jong, 2020). Interactivity is an important design feature of 3D virtual environments (Dalgarno & Lee, 2010; Dede, 2009), and it is crucial to better understand interactivity and agency as VR's affordances.

This study addresses this need, focusing on learners' sense of agency and its association with varied types of interactivity. Furthermore, by studying a classroom implementation of commercially available VR applications, it addresses a need for more research on VR in authentic learning environments (Bower & Jong, 2020), or what has been termed 'state of the actual' research (Southgate, 2020). High school engineering students participated in four lessons with VR field trips, at times using immersive videos that allow for interactivity by controlling their field of view, and at others using video game-like interactive graphical environments that additionally allow interaction via their hands and bodies. The research investigated how to define and measure their sense of agency, how agency was impacted by the different types of VR, how their culturally defined identities were associated with variation in agency in VR, and whether agency shifted over time.

Related work

Sense of agency in VR

Agency has been identified as a primary affordance of VR for learning, along with providing a strong sense of presence in the environment (Johnson-Glenberg, 2018; Makransky & Petersen, 2021). Yet, relative to immersion and presence, agency is less well-studied to date and is not a well-defined construct in the context of learning with VR. On one hand, agency in VR is conceptualized as people's experience of consciousness and their embodied selves (Blanke & Metzinger, 2009). Measures focus on the user's motor control and feeling their virtual actions were self-generated (Kilteni et al., 2012; Polito et al., 2013). However, agency in learning is typically conceptualized more broadly such as supporting learners' autonomy, promoting intrinsic motivation and self-regulated learning (Code, 2020; Grotzer et al., 2021; Ryan & Deci, 2000; Zimmerman et al., 2015). Measures include asking learners how much they feel in control of their academic engagement and achievement (Patall et al., 2022; Queiroz et al., 2022).

These different definitions and measures of agency have implications for design and evaluation of educational VR. If the mechanism through which agency enhances learning is via embodied cognition by connecting the movement of one's body and mind, then agency should be defined and measured more narrowly as control over motor functions. Alternatively, if the mechanism through which agency improves learning is by supporting autonomy and encouraging self-regulated learning, then agency should be defined and measured more broadly as control over their learning experience.

Interactivity and agency in VR learning environments

While agency in VR learning environments is less well studied than immersion and presence in learning, studies have highlighted that a sense of agency is important for learning in both immersive videos and interactive graphical environments, considered less and more interactive respectively (McGivney, 2021; McGivney et al., 2022). Recent studies also experimented with varied levels of interactivity and measured learners' sense of agency. For

example, Queiroz et al. (2022) found that middle-school science students learned more from a 360-degree video when using a VR headset than a desktop computer, and the effect was mediated by heightened sense of agency over their learning. Petersen et al. (2022) and Johnson-Glenberg et al. (2021) each compared a higher-interactivity condition where learners navigated through a simulation or game, to a low-interactivity condition where learners watched a recording of someone else using it. Both studies found greater interactivity predicted greater sense of agency in terms of controlling their actions but mixed results on learning: Petersen et al. (2022) found agency predicted higher sense of embodied learning but lower learning outcomes and Johnson-Glenberg et al. (2021) found agency predicted in-game performance but not knowledge gains.

These results highlight a complex relationship between interactivity, agency and learning, echoing calls to look beyond interactivity as equivalent to agency (Harrell, 2013), and a need to better understand what defines agency for learning. More research is needed to understand the most effective modes of interactivity for varied learning goals.

Agency and cultural identity

Because VR situates a user in a first-person and embodied perspective, how people experience VR environments depends on their identities and individual characteristics. Personality traits are associated with sense of presence (Dewez et al., 2019; Sacau et al., 2008; Weibel et al., 2010), cultural norms embedded within an experience can be either marginalizing or empowering (Harrell, 2013; Nakamura, 2020) and VR experiences have powerful impacts on people's sense of self and associated behaviours (Bailenson, 2018; Blascovich & Bailenson, 2012; Slater & Sanchez-Vives, 2016). Therefore, how a person defines their sense of self and identity is a likely factor in their experience of VR. One way to measure this is self-construal, or whether one defines their identity fluidly in relation to others (interdependent) or fixed (independent), which are aligned with more collectivist and individualist cultures, respectively (Markus & Kitayama, 1991). This cultural variation in self-construal influences how sense of agency is valued individually or collectively (Hernandez & Iyengar, 2001), and is important for agency in VR because it explains how people connect their minds and bodies (Markus & Kitayama, 2010). The United States is not a uniformly individualistic culture, minority populations tend to have an interdependent self-construal (Fernández et al., 2005; Stephens et al., 2014), and classrooms of diverse learners will have varied ways of experiencing agency.

Hence, a learner's sense of agency in VR may depend on their self-construal. For example, a learner who has a more independent self-construal (individualistic ideals) may value agency in a VR environment by taking individual actions. A learner with an interdependent self-construal (collectivist ideals) may value the ability to interact with others to take actions or operate as collective agents (Hernandez & Iyengar, 2001). These culturally defined conceptions of agency have been shown to impact autonomy over learning generally (Ryan & Deci, 2000), but to date, studies have not accounted for learners' culture when measuring agency in VR.

Novelty effect in educational VR

Most research on learning with VR has been conducted in lab-based experiments measuring its impact in response to a brief experience, raising questions about whether its effects are due to technology's novelty (Hamilton et al., 2021; Wu et al., 2020). Some hypothesize that VR's novelty primarily drives engagement and motivation, increasing learning only when

the technology is unfamiliar. Yet, Huang et al. (2021) did not find that learners' engagement or learning decreased when using a solar system VR application three times in 2 weeks. Han et al. (2023) found learners' sense of presence, group cohesion and perception of realism in collaborative VR environments increased throughout an 8-week course. McGivney et al. (2022) found that students using VR experiences throughout a remote course described increased feelings of mastery over VR, suggesting the effectiveness may increase as novelty wanes. Studies of other immersive technologies also raise questions about the existence of a novelty effect in 3D learning environments, for example, learners' motivation shifts but does not wane over time (Metcalf et al., 2019). Evidence is thin on learning with VR over time in authentic education contexts (Bower & Jong, 2020; Southgate, 2020), and questions remain about how students' sense of agency changes with repeated VR use.

Research aims and questions

This study had two primary aims. First, to develop measures of sense of agency in VR learning environments that capture elements of agency over learning, drawing on definitions of autonomy support and agency as a sense of control over motor functions. Second, to explore questions about the predictors of agency in VR learning environments using those measures:

1. To what extent do different types of VR with varied interactivity predict students' sense of agency?
2. Does the relationship between VR type and sense of agency depend on students' self-construal identity?
3. Is there evidence of a novelty effect, in which sense of agency changes over time as the novelty of VR wanes?

MATERIALS AND METHODS

Participants

This study was conducted at an urban public charter high school in the Boston area, 67% of whose students are classified low income and 76% high needs. Participants were 30 students aged 16–18 (11th–12th grade) from two engineering classes. Five students identified as female and 25 as male. Twenty-eight students were second-generation Americans (parents born outside the United States) and one student was first-generation American (born outside the United States): 23 from Latin America and the Caribbean, 5 from Africa and 1 from Europe. All students (and their parent or guardian if under 18) consented to the study; they were informed that study participation was not required for VR field trip participation. This study was approved by the Harvard University Institutional Review Board.

Study design

This study employed design-based research to both develop lessons utilizing VR field trips and build an understanding of learning with them in an authentic classroom environment (Barab & Squire, 2004; Brown, 1992). The author worked with the engineering teacher for over 3 years, developing and implementing lessons that incorporated immersive technologies into instruction, beginning during COVID-19 remote schooling with cardboard VR

viewers and progressing to the in-person lessons with immersive VR described here. Each iteration led to refinement of research questions and lesson design. The full process is described in McGivney (2024). The study was designed to provide every student with a meaningful and equitable learning experience across four lessons while altering the order of using different types of VR experiences to answer research questions about their impact on students, depicted in Figure 1. Students were divided into two groups of 15: Group A used the interactive graphical environments in lessons 1 and 2 and immersive videos in lessons 3 and 4, and Group B in the reverse order.

Data collection

A concurrent mixed-method design was used (Creswell & Plano Clark, 2018) to collect survey and interview data longitudinally across the four lessons. Table 1 describes the instruments used for pre- and post-surveys. Agency measures, adapted from several existing scales, and their properties are described below.

A measure of relative independent self-construal was estimated by taking the difference between the independent self-construal and interdependent self-construal scales. The

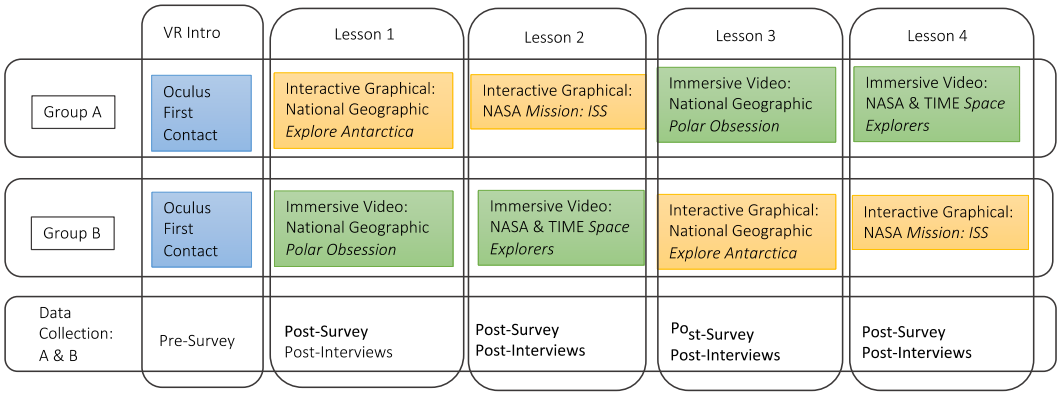

FIGURE 1 Study design.

TABLE 1 Survey instruments.

	Measures	Description/Sample items
Pre-survey	Demographics & Experience	Gender, Racial and Ethnic Identity, Age, Birthplace, Parents' Birthplace, Prior VR Use
	Self-Construal: 7-point Likert scale (Singelis, 1994) *Independent (15 items): alpha = 0.70* *Interdependent (12 items): alpha = 0.71*	Independent: 'My personal identity, independent of others, is very important to me' Interdependent: 'I feel my fate is intertwined with those around me'
Post-survey	Sense of Agency: 5-point Likert scale (14 items adapted from Queiroz et al. (2022), Tapal et al. (2017), Polito et al. (2013) and Johnson-Glenberg (2018))	'I felt I was in control of my actions' 'I could focus my attention where I wanted to' 'I could control what I was learning'

mean across all students was 0.10 and range from −1.55 (relatively interdependent) to 1.65 (relatively independent).

Interviews were conducted with eight students following each lesson, who were purposively sampled to represent a mix of genders, STEM interests, self-construal and membership in Groups A or B (see Table 2). Semi-structured interviews asked students to discuss what they learned, how they felt and whether they felt in control and like themselves in the VR experience.

Materials and implementation

The lessons' goal was to develop students' problem-finding and articulation skills and dispositions, the first step in engineering design and a challenge in engineering education (Lucas et al., 2014). The lessons use an experiential learning framework (Dede et al., 2017; Kolb et al., 2014). Students engaged in planning (a pre-work activity about the environment), acting (participating in a VR experience) and reflecting (written reflections and small group discussions). Students used applications about the International Space Station (ISS) and Antarctica and wrote about problems they saw that engineering could solve.

Four VR experiences were used that are available via the Oculus Store and YouTube, two interactive graphical environments and two 360-degree videos, depicted in Figure 2. All experiences were pre-loaded onto Oculus Quest 1 headsets to not rely on Wi-Fi. With the teacher, VR experiences were chosen for what would help students generate engineering problems and cover environments not accessible in real life. Furthermore, they were chosen as pairs of videos and interactive graphical environments covering similar environments and content. For Antarctica, *Nat Geo Explore* situates the learner in the shoes of a National Geographic photographer photographing wildlife while *Polar Obsession* follows a National Geographic explorer photographing wildlife, and both experiences focus on its landscape. *Mission:ISS* situates the learner in the shoes of an astronaut aboard the ISS to complete tasks in zero gravity while *Space Explorers* follows astronauts working and living aboard the ISS in zero gravity. In the interactive graphical environments, students could pick up objects and move their bodies to complete tasks like kayaking, photographing wildlife and setting up a base camp in Antarctica or working a robotic arm and conducting a spacewalk on the ISS. In immersive videos, they engaged with the scene by moving their heads to change their viewpoint and focus while observing a narrative. Students using interactive graphical environments could move around a 7-foot-square area and had a stationary boundary when using immersive videos (see Figure 3). Students in the latter condition could sit if they requested.

Development of agency measures

Sense of agency scales were constructed by first assessing dimensionality, then determining a factor structure based on definitions of agency and prior measures of distinct constructs. These constructs included agency defined and measured in a cognitive science tradition as control over one's body and actions, and actions feeling self-generated (Blanke & Metzinger, 2009; Kilteni et al., 2012; Polito et al., 2013), versus agency defined and measured from an education tradition as control and autonomy over what and how one learns (Code, 2020; Patall, 2021; Queiroz et al., 2022; Ryan & Deci, 2000). Items from a cognitive science theoretical background were adapted from the Sense of Agency Rating Scale (Polito et al., 2013) and studies that have used this scale in the context of VR interventions (Petersen et al., 2022). Items drawing on educational perspectives of agency were adapted

TABLE 2 Interview participants.

	Group	Gender identity	Ethnic/Racial identity	Grade	Age	Home language(s)	Parents born outside USA?	Independent self-construal
Brooklyn	A	Female	Hispanic/Black	12	18	Spanish	Yes	0.72
Mark	A	Male	Latino/White	12	17	English, Spanish	Yes	−0.85
Ivy	A	Female	Hispanic/Hispanic	11	16	English, Spanish	Yes	−0.67
Damian	A	Male	African American/Black	11	16	English	Yes	−1.55
Harry	B	Male	African American/Black	12	18	English	Yes	1.65
Jade	B	Female	Hispanic Afro-Latinx/Black	12	17	English, Spanish	Yes	0.73
William	B	Male	Hispanic/Hispanic	12	17	English, Spanish	Yes	0.38
Alex	B	Female	Guatemalan/Hispanic	12	17	English, Spanish	Yes	−0.5

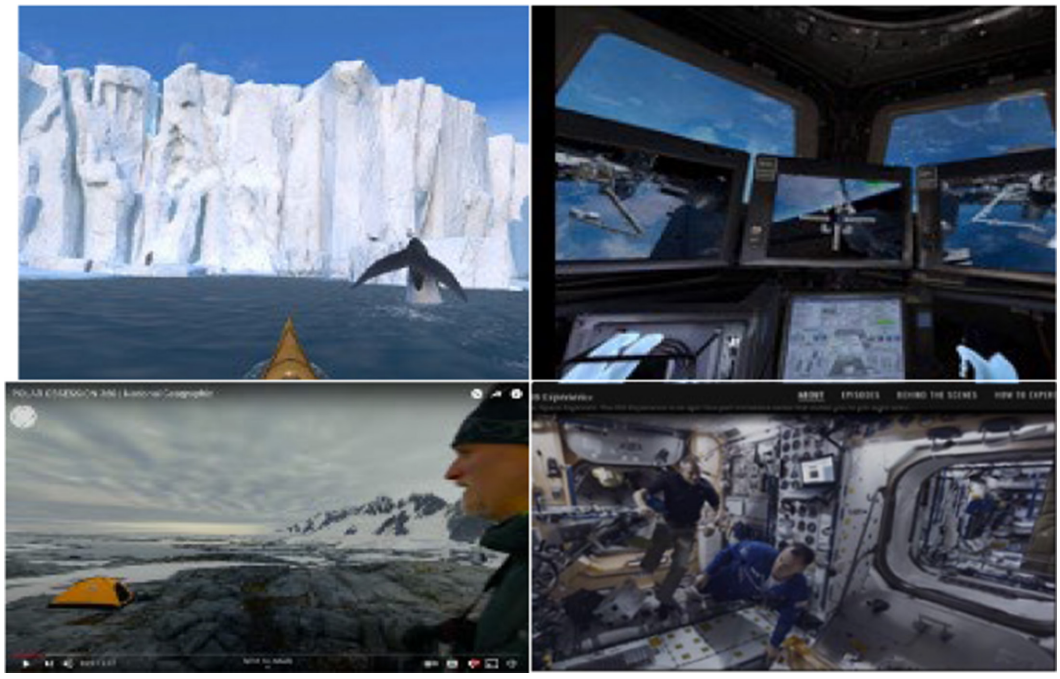

FIGURE 2 VR applications. Top: *National Geographic Explore* (2019) and *Mission:ISS* (2019) (interactive graphical environments). Bottom: *Polar Obsession* (2018) and *Space Explorers* (2021) (immersive videos).

FIGURE 3 Classroom implementation. Left: Interactive graphical environment. Right: Immersive video.

from autonomy measures from self-determination theory (Ryan & Deci, n.d.) and studies that have used similar scales in the context of VR interventions (Queiroz et al., 2022).

Because items were chosen from different theoretical orientations, confirmatory factor analysis (CFA) was used to assess the fit of the data to the hypothesized factor structure rather than exploratory factor analysis which assumes no *a priori* theory about the structure. To conduct this analysis with a sufficient sample size, data were pooled from all students' responses across the four lessons. Adequate fit is considered based on the following fit indices and their cut-offs: $CFI > 0.95$, $TLI > 0.90$, $RMSEA < 0.08$ and $SRMR < 0.08$ (Browne & Cudeck, 1993; Hu & Bentler, 1999). The coherence of the resulting measures was estimated for each lesson using Cronbach's alpha.

Figure 4 indicates a multidimensional structure of either two or three factors. Items were organized into a two- and three-factor structure based on theoretical perspectives. The three-factor structure separated items related to control over field of view/focus and those referring to actions in the VR. CFA was run on both models, and a likelihood-ratio test showed the three-factor structure had significantly better fit, $\chi^2(2, N = 99) = 129.16, p < 0.001$.

The three measures can be described as sense of agency over learning, sense of agency over attention and sense of agency over actions. The items and the standardized loadings for each factor are reported in Table 3, along with the fit statistics. A majority of the loadings qualify as adequate (>0.40) or good (>0.70). Reverse-coded items had the lowest correlation to factors, potentially indicating issues with student interpretation, but they are retained in analysis due to theoretical importance and coherence. Model fit may be considered adequate but should be confirmed in a larger sample as two of the fit statistics are slightly outside the recommended range ($CFI > 0.95$ and $SRMR < 0.08$).

Analysis of student interviews, described below, also revealed how students described their sense of agency in terms of learning, attention and actions, illustrated with quotes in Table 4. This supports the finding that agency is multidimensional.

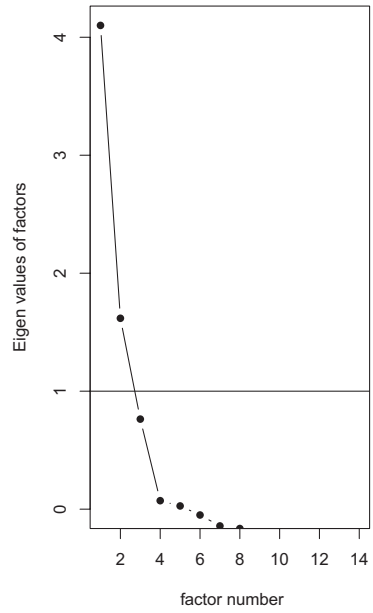

FIGURE 4 Agency measures scree plot.

TABLE 3 Confirmatory factor analysis.

Item	Standardized factor loadings		
	Learning	Attention	Actions
I could control what I was learning	0.63		
I preferred other people telling or showing me what to do rather than deciding on my own[a]	0.32		
Being able to choose where to focus my attention was important for learning	0.67		
I learned more when I controlled what to do	0.74		
My choices about what to do influenced my learning	0.72		
My viewpoint and head movements were under my control		0.66	
I felt I was in control of where to look		0.75	
I had freedom to focus where I wanted		0.83	
I could focus my attention where I wanted to		0.69	
I felt I was in control of my actions			0.81
I had freedom to explore			0.83
I felt that my experiences and actions were not caused by me[a]			0.48
My experiences and actions were under my control			0.89
The VR felt interactive			0.81
Fit statistics: *CFI = 0.93, TLI = 0.92, RMSEA = 0.071, SRMR = 0.086*			

[a]Reverse-coded items.

TABLE 4 Student discussion of dimensions of agency.

Sense of agency over learning	'I was able to control what I learned and what I do. So being able to do that—so that you learn more…when you're doing it yourself, you're learning. That's how I learn'. *William, Lesson 3, Nat Geo Explore*
Sense of agency over attention and focus	'I could see the things I wanted to…I decided to focus on the bones cause that's what interested me the most. I wouldn't say I had much power based on what I was looking for. But I definitely had a choice on what I could focus on'. *Damien, Lesson 3, Polar Obsession*
Sense of agency over actions and movement	'The fact that I could grab the [kayak] paddles and like go slow or like move from side to side. And also, with the ice picking, when ice picking up the iceberg it felt like I was in control. Cause I could move'. *Mark, Lesson 1, Nat Geo Explore*

Data analysis

To explore research questions about associations between agency and VR type, students' self-construal identities and change over time, survey data were analysed using random-effects regression models and interviews were analysed with a thematic analysis.

Quantitative analysis

A random-effects model was used to estimate the association between the type of VR (interactive graphical environment or immersive video) on students' sense of agency, controlling for their group, the environment (ISS or Antarctica) and individual characteristics gender, age and self-construal, allowing for a random intercept to control for individual student variation. Fixed-effects models were also run as a robustness check, controlling for all student-level variation and the associations between agency and VR type were similar in magnitude and significance.

$$Agency_{it} = \beta_{0i} + \beta_1 VRType_{it} + \beta_2 VREnvironment_{it} + \epsilon_{it}$$

$$\beta_{0i} = \gamma_0 + \gamma_1 Gender_i + \gamma_2 Age + \gamma_3 SelfConstrual_i + \gamma_4 Group_{it} + u_i$$

$$\epsilon_{it} \sim N\left(0, \sigma_y^2\right)$$

$$\beta_{0i} \sim N\left(\mu, \sigma^2\right)$$

Additionally, a random slopes model estimated whether the association between VR type and agency depended on students' level of independent self-construal:

$$Agency_{it} = \beta_{0i} + \beta_{1i} VRType_{it} + \beta_2 VREnvironment_{it} + \epsilon_{it}$$

$$\beta_{0i} = \gamma_{00} + \gamma_{01} Gender_i + \gamma_{02} Age + \gamma_{03} SelfConstrual_i + \gamma_4 Group_{it} + u_{0i}$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11} SelfConstrual_i + u_{1i}$$

$$\epsilon_{it} \sim N\left(0, \sigma_y^2\right)$$

$$\begin{matrix} u_{0i} \\ u_{1i} \end{matrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{matrix} \tau_{00} & \tau_{01} \\ \tau_{01} & \tau_{11} \end{matrix}\right]$$

Finally, a longitudinal growth curve estimated change over time in students' sense of agency across the four lessons:

$$Agency_{it} = \beta_{0i} + \beta_{1i} Lesson_{it} + \epsilon_{it}$$

$$\beta_{0i} = \gamma_{00} + \gamma_{01} Gender_i + \gamma_{02} Age + \gamma_{03} SelfConstrual_i + \gamma_4 Group_{it} + u_{0i}$$

$$\beta_{1i} = \gamma_{10} + u_{1i}$$

$$\epsilon_{it} \sim N\left(0, \sigma_y^2\right)$$

$$\begin{matrix} u_{0i} \\ u_{1i} \end{matrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{matrix} \tau_{00} & \tau_{01} \\ \tau_{01} & \tau_{11} \end{matrix}\right]$$

Qualitative analysis

Interview recordings were transcribed and coded using flexible thematic analysis (Bazeley, 2020; Braun & Clarke, 2006). The author and a graduate student research assistant who assisted with data collection reviewed each student's transcripts and wrote individual memos to generate an initial set of codes based on both emergent (*emic*) themes and those determined from prior literature (*etic*). After initial coding, themes were refined into analytical codes and applied to the full dataset. A second graduate student research assistant who had not been involved in data collection or codebook development coded a random 20% of transcripts to assess its reliability. See Table 5 for the codebook, frequency counts and inter-rater agreement percentages, and the appendix for a full description of codes. Codes with less than 97% agreement were investigated for disagreements, the codebook was revised to clarify definitions and transcripts re-coded for these codes. Final themes were generated by looking at each code across students and time and validated by triangulating findings with quantitative data and searching for discrepant evidence (Maxwell, 2010). Etic themes included different conceptions of agency from cognitive science versus education, and agency being hindered by lack of interactivity. Themes that emerged included how confusion and poor quality hindered their experience. The final themes described here are those that were either representative across students, being repeated in the majority of interviews and aligning with the quantitative data, such as the three conceptions of agency. Or they are themes that describe notable experiences even if not representative, including the discrepancy between students who found interactivity to lead to confusion versus those who found a lack of interactivity hindered their agency.

TABLE 5 Qualitative interview codebook.

Code	Occurrence in interviews (total = 27)	Number of students (total = 8)	Inter-rater agreement
Sense of agency heightened by controlling actions	16	7	98%
Sense of agency heightened by controlling attention and field of view	18	7	94%
Sense of agency related to learning	16	6	99%
Sense of agency hindered by lack of interactivity	18	8	93%
Confusion or boredom hinders experience of VR	14	6	98%
Poor quality or discomfort hinders experience of VR	14	8	100%
Feeling embodied	22	8	96%
Feeling disembodied	11	8	99%

RESULTS

1. To what extent do different types of VR with varied interactivity predict students' sense of agency?

Figure 5 visualizes mean sense of agency for each group across four lessons. While sense of learning and attentional agency remained similar for the two groups for each lesson, the pattern for actional agency suggests the type of VR affected it. Both groups reported a higher sense of actional agency when using interactive graphical environments (Group A: lessons 1 and 2, Group B: 3 and 4). Table 6 shows regression results estimating the association between the type of VR used and the three measures of sense of agency. Type of VR only predicts an increased sense of actional agency, with a student using this type of VR reporting a sense of agency over their actions one point higher than when using an immersive video, controlling for group, VR environment, gender, age and self-construal. Students in Group B reported higher learning and attentional agency than those in Group A, suggesting a potential impact on these types of agency of the order the VR is used. Additionally, older students (age range: 16–18) reported a higher sense of learning agency and students who identified as male a higher sense of agency over attention and focus. Students reported a lower sense of agency in the ISS experiences than in the Antarctica experiences.

Qualitative interviews illustrate complexity of the relationship between students' sense of agency and different types of VR (see Table 7). While some students described feeling more in control in the interactive graphical environments, and how that contributed to agency over their learning, others described how they felt they could learn more from the immersive videos, especially if they felt confused in the interactive graphical environments. In particular, three students in Group A expressed this after using the interactive graphical environments first and the immersive videos second.

FIGURE 5 Mean sense of agency by group across four lessons.

TABLE 6 Regression results: Predictors of sense of agency.

	Learning agency		Attentional agency		Actional agency	
Predictors	**Estimates**	**CI**	**Estimates**	**CI**	**Estimates**	**CI**
Intercept	−1.30	−4.99 to 2.40	4.70*	0.33 to 9.08	1.16	−3.81 to 6.14
Interactive graphical environment	0.12	−0.04 to 0.28	−0.05	−0.23 to 0.14	1.05***	0.83 to 1.28
Group B	0.38**	0.12 to 0.65	0.37*	0.06 to 0.68	0.24	−0.12 to 0.59
VR environment: ISS	−0.17*	−0.34 to −0.01	−0.31**	−0.50 to −0.13	−0.10	−0.32 to 0.13
Male	−0.07	−0.42 to 0.27	0.47*	0.06 to 0.88	0.38	−0.10 to 0.85
Age	0.30**	0.08 to 0.51	−0.06	−0.31 to 0.20	0.08	−0.21 to 0.38
Independent self-construal	−0.04	−0.26 to 0.17	−0.20	−0.45 to 0.06	0.28	−0.01 to 0.57
Random effects						
σ^2	0.17		0.23		0.31	
τ_{00}	0.07_{ID}		0.10_{ID}		0.12_{ID}	
ICC	0.30		0.31		0.29	
N	28_{ID}		28_{ID}		28_{ID}	
Observations	106		106		98	
Marginal R^2/Conditional R^2	0.250/0.472		0.228/0.470		0.477/0.627	

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 7 Student description of agency in interactive graphical environments and immersive videos.

Learning more from the interactive graphical environments through increased interactivity	'The 3D videos, it's like they are just doling out information and we just kind of have to sit there. We can turn our heads, but it's to a wall so… through those I felt like I was getting more information, but like maybe in a less interesting way. Versus like the interactive ones… is it giving me any clear cut answers? No. But it made me have to question what I was looking at more and then it left me with more questions when I was done'. *Jade, Lesson 4, Mission:ISS*
Learning more from immersive videos when interactive graphical environments presented confusion or too much exploration	'I like this one more, because it's just actually seeing what's going on, instead of like doing it yourself… [I like it better because] so many people could show me around. Just show me how it really felt, like instead of me doing it by myself and not really people helping me. Because the first one was a little bit challenging for me'. *Brooklyn, Lesson 3, Polar Obsession* 'I actually learned what they were doing and watched it on my own, because when I was doing the interactive one I didn't learn anything really. It was a free for all exploration game rather than trying to figure out what I was doing'. *Ivy, Lesson 4, Space Explorers*

TABLE 8 Interaction between VR type and self-construal on actional agency.

Intercept	2.02
	(2.19)
Interactive graphical environment	1.16***
	(0.15)
Independent self-construal	0.45*
	(0.19)
Group B	0.25
	(0.16)
VR environment = ISS	−0.13
	(0.09)
Male	0.41
	(0.21)
Age	0.03
	(0.13)
Interactive Independent self	−0.44*
	(0.22)
Observations	98
Log likelihood	−89.36
Akaike Inf. Crit.	202.72
Bayesian Inf. Crit.	233.74

*$p < 0.05$; ***$p < 0.001$.

2. Does the relationship between VR type and sense of agency depend on students' self-construal identity?

Because only actional agency was associated with VR type, only the interaction between actional agency and self-construal was modelled to estimate whether the association between actional agency and type of VR depends on a learner's sense of self-construal. As shown in Table 8, there is a significant interaction between VR type and self-construal in addition to their main effects. Figure 6 visualizes this association.

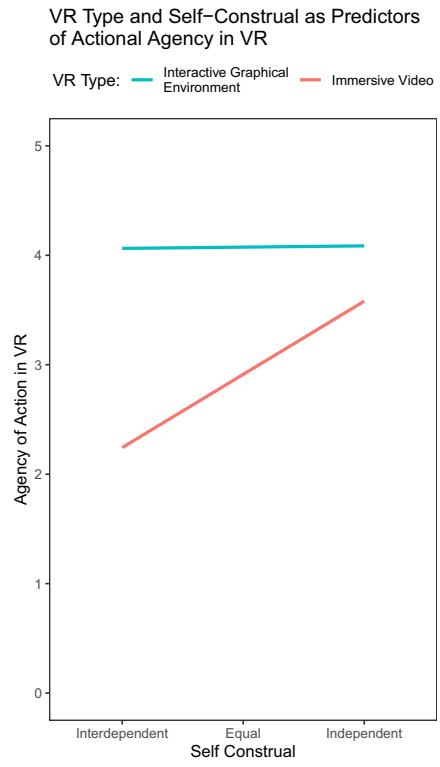

FIGURE 6 VR type and self-construal as predictors of actional agency.

TABLE 9 Interdependent self-construal and sense of agency.

Students with an interdependent self-construal express constrained agency in immersive videos	'I just felt like I had to listen pretty much. I didn't have, I couldn't do what they were doing. If that makes sense…I just feel like I had to watch'. *Ivy, Lesson 4, Space Explorers* 'I mean I couldn't interact with anyone. I couldn't move around and explore. I couldn't ask questions. So it just felt like I was this soul watching and staring… being able to float with them would have been interesting and then interact with them'. *Alex, Lesson 2, Space Explorers*

For learners with an independent self-construal, reported sense of actional agency is similar whether using an immersive video or an interactive graphical environment. But for learners with a more interdependent self-construal, who define themselves as more related to their social context, their reported sense of actional agency is lower when using an immersive video.

Qualitative interviews suggest an explanation for this greater difference for those who have a more interdependent self-construal (see Table 9). Alex, whose self-construal is more interdependent (*self-construal* = *−0.5*), described feeling constrained by not being able to interact with the people in the immersive videos. And Ivy (*self-construal* = *−0.67*) expressed she could not do what they were doing. It is possible that when experiences include social information, such as observing scientists working in complex environments, but do not allow for social interaction, learners who have a more interdependent sense of self feel constrained. On the other hand, independent self-construal learners may not seek as much social interaction, leading to similar levels of actional agency in the two types of VR. It is

TABLE 10 Change in student's sense of agency over time.

	Dependent variable		
	Learning agency	Attentional agency	Actional agency
	(1)	(2)	(3)
Intercept	−1.44	4.34*	2.12
	(1.90)	(2.19)	(2.34)
Lesson	0.04	−0.04	0.03
	(0.04)	(0.05)	(0.10)
Male	−0.06	0.52*	0.35
	(0.18)	(0.21)	(0.24)
Age	0.30**	−0.04	0.06
	(0.11)	(0.13)	(0.14)
Independent self-construal	−0.04	−0.21	0.27
	(0.11)	(0.13)	(0.14)
Group B	0.40**	0.39*	−0.19
	(0.14)	(0.16)	(0.17)
Observations	106	106	98
Log likelihood	−78.75	−95.48	−119.94
Akaike Inf. Crit.	177.51	210.95	259.89
Bayesian Inf. Crit.	204.14	237.59	285.74

*$p < 0.05$; **$p < 0.01$;

notable that not all learners with an interdependent self-construal expressed this sentiment, so this result should be interpreted tentatively and as a suggestive explanation, rather than a definitive one.

3. Is there evidence of a novelty effect, in which sense of agency changes over time as the novelty of VR wanes?

Table 10 shows results of the longitudinal growth models, conditional on individual characteristics and their intervention group. Time, indicated by the 'lesson' variable, is not a significant predictor of any type of agency variable. This indicates there is no evidence of an increase or decrease in students' agency across the four lessons.

DISCUSSION

This study developed new measures of agency in VR learning environments and explored interactivity's impact on agency within varied types of media, individual characteristics and change over time. The measures of agency indicate it is multidimensional, and students feel distinctions in control over their learning, attention and actions. Analysis of these measures found that heightened interactivity is associated with higher sense of agency over actions, but not over learning and attention. In terms of individual characteristics, this association between VR type and actional agency depended on a student's sense of self-construal, with those who have a more interdependent sense of self-feeling lower levels of agency in immersive video environments. Finally, the results do not indicate the presence of a novelty effect, as the agency measures did not change over time.

The study does have limitations. As part of a design-based research study using commercially available VR experiences, it was not highly controlled to isolate the effect of interactivity. The results presented here indicate associations and the study was exploratory in nature, therefore they should be interpreted with caution and replicated in controlled studies. While the longitudinal design and mixed methods provide a rich dataset, the number of participants is small and generalizability to other contexts may be limited. As an elective course, students were self-selected with high interest in STEM, and the teacher had a greater degree of flexibility in the curriculum than is likely to be observed elsewhere. Furthermore, there may be a gender bias as the sample is heavily weighted with male learners. Women are underrepresented in STEM fields and girls are less likely to be motivated and interested in fields like engineering, so the impact of these VR field trips on girls should be assessed in future studies, as this study primarily illustrates the impact on boys who are already highly motivated to study STEM.

On the other hand, the student demographic represents a population not typically included in research on VR, and the study was embedded in classroom practice, providing more ecological validity than a laboratory. This highlights how the findings may generalize better to classroom practice than a lab-based study, especially for schools serving primarily low-income and minority students. Furthermore, few studies of VR in education take place over multiple time points and collect in-depth data repeatedly with learners. This may make the findings more easily transferred to other classroom contexts.

The findings make important contributions to the understanding of learning with VR in classroom environments. While agency is typically regarded as a primary affordance of VR for learning (Johnson-Glenberg, 2018; Makransky & Petersen, 2021), this study indicates it is not a unidimensional construct, nor is it necessarily equivalent to full-body interactivity in VR. Students felt a similarly high sense of agency over their learning and attention when using an immersive video as an interactive graphical environment. This indicates immersive videos, which are more widely accessible and easier to implement in classrooms, may be effective to enhance learners' agency. On the other hand, interactive graphical environments were more effective at increasing students' agency over their actions. Therefore, for learning goals that rely on embodied cognition and agency as a sense of initiating one's actions (eg, Johnson-Glenberg et al., 2021), more interactivity via the learner's body and controllers is likely necessary.

The interaction between VR type and student self-construal suggests important differences in how identity can impact learning in VR environments. This finding aligns with research on the culturally defined nature of sense of agency that the type of autonomy valued will vary based on the cultural identity of the learner (Hernandez & Iyengar, 2001; Ryan & Deci, 2020). Learners in this classroom were diverse in their self-construal, with representation across more independent and interdependent identities, supporting prior research that minority populations in the United States do not necessarily identify with the dominant individualistic culture (Fernández et al., 2005; Stephens et al., 2014), nor do they share a uniform self-construal despite coming from primarily low-income immigrant families. The finding that interdependent students felt their agency was more constrained in immersive videos may indicate that such learners seek collective forms of agency in which they can act with others in VR, since in these videos social information was present but interaction was not. In general, this finding highlights the importance of media design to be inclusive and tailored to varied cultures and identities.

This study also contributes to an increasing interest in understanding the impact of emerging technologies as they become more commonplace in classrooms. Studies of learning with VR have been built on the premise that the novelty of the technology is what drives engagement and therefore learning, yet recent studies have not found learners' experiences or outcomes to decrease over time (Han et al., 2023; Huang et al., 2021). This study also finds that sense of agency does not decrease over time when used in classroom instruction, supporting the conclusion that learners' experiences can remain high or improve over time as they become more familiar with the technology (McGivney et al., 2022). Future

research should investigate how learners' engagement shifts over time to draw on different motivators, as has been shown with less-immersive technologies (Metcalf et al., 2019), and whether sense of agency drives motivation.

The focus of this paper is on learners' sense of agency as an outcome, and analysis of the learning outcomes is ongoing. However, early results indicate that immersive videos may have been more effective at delivering didactic knowledge but interactive graphical environments helped students connect more to scientific practices. Future research should investigate the role heightened agency over actions may play in this process and how to align types of agency needed to support certain learning outcomes.

CONCLUSION

The findings from this study contribute to a growing interest in utilizing VR in classroom instruction, focusing on its under-studied affordance to provide learners with enhanced agency. The findings illustrate the importance of VR media design beyond using VR headsets to increase immersion. The study shows that learners' sense of agency is multidimensional, and defining it as control over learning versus control over actions in the VR environment has design implications. Learners felt greater agency over their actions in interactive graphical environments but felt similar levels of agency over their learning in immersive videos as well. The association between VR type and agency over actions depended on their individual identities, but none of the agency constructs changed over time. Therefore, designers and researchers should attend to the nuance of the association between interactivity and agency. For example, provide learners opportunities for greater interaction when controlling actions is important, but use less-interactive environments to scaffold learning while maintaining agency over learning. Furthermore, VR experiences must attend to learners' identities and sense of self, considering how culturally defined identities will affect interaction design. Together, this research contributes to a growing interest in understanding the mechanisms through which VR supports intrinsically motivated learning beyond comparing devices (McGivney, 2023; Sobocinski et al., 2023).

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CONFLICT OF INTEREST STATEMENT

The author has no conflicts of interest.

DATA AVAILABILITY STATEMENT

To protect the privacy of the participants, data from this study are not publicly available. Upon request, the author can share de-identified quantitative survey data. Qualitative data cannot be shared due to confidentiality agreements with participants.

ETHICS APPROVAL

This study was approved by the Harvard University Institutional Review Board.

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APPENDIX

QUALITATIVE CODE DESCRIPTIONS

Code	Description
Sense of agency heightened by controlling actions	Students describe feeling in control or having agency based on being able to control their actions and movement within the VR, eg, being able to interact with objects, move where they want to and control their motions and actions

Code	Description
Sense of agency heightened by controlling attention and field of view	Students describe feeling in control or having agency based on being able to choose where to focus their attention and controlling their field of view, eg, controlling what they looked at, focused on and being able to look around at what they wanted to
Sense of agency related to learning	Students describe a sense of agency or feeling in control of their learning, eg, learning more when controlling what to do or being able to control what they were learning
Sense of agency hindered by lack of interactivity	Students describe a hindered sense of agency, or not being able to do or control what they wanted to because of a lack of interactivity, eg, when the experience is a video, or there were objects in the environment they could not touch
Confusion or boredom hinders experience of VR	Students describe how their experience of the VR application was impacted by their feeling confused or bored, eg, not knowing what to do, having difficulty understanding the experience or feeling bored
Poor quality or discomfort hinders experience of VR	Students describe their experience as being of poor quality or feeling uncomfortable using VR, including the quality impeding their ability to interact or understand, or feelings of being dizzy or nauseous that impacted their experience of the application
Feeling embodied	Students describe a sense of feeling embodied in the VR, eg, feeling like what they were doing with their virtual body was also what was happening to their real body. This includes when students describe ways their bodies reacted to the experience, such as their heart beating or the sensation of falling when near the edge of a cliff
Feeling disembodied	Students describe feeling disembodied in VR, eg, feeling they did not have a body, they were just eyes, or flattened

INTERVIEW PROTOCOL

	Required questions • *Potential probes*	Purpose
Initial impressions, general feelings and sense of agency ~4–5 minutes	**Tell me about the VR experience—what did you see or do?** • *I haven't done this one [in a while]—could you remind me what happens?* • *Can you describe that for me?* • *Did that surprise you?/Did anything you see surprise you?* • *Did you learn something?/Was that something you didn't know before?* **And how did it feel?** • *When did you feel that—can you describe to me what was happening?* • *Were there things you enjoyed? Things you didn't like?* • *Did you feel like you were in control?* • *Did you feel you could reach out and touch things?* • *Did you feel you could do the things you wanted to?* • *Was there anything you wanted to do that you couldn't?* • *[Responding to a detail]—was that something you wanted to do [or see]? Why/why not?*	Warm up, see what students take from the experience most immediately To see how students describe how they felt, including their sense of agency To understand over time what they focus on after doing VR changes To understand if what they focus on after doing VR is different when it is video or interactive

	Required questions • *Potential probes*	Purpose
Sense of self ~4–5 minutes	**Did you feel like yourself? Or, did you feel like someone else?** • *How did it feel to move around while you were using the VR?* • *Did you feel like you had your own body?* • *Did you feel comfortable?* • *Did anything make you feel uncomfortable?* • *Did you feel: Nervous? Scared? Excited?* • *Did it feel like a real place?* • *Did the people seem real?*	To understand how students felt about their virtual bodies To understand whether students felt like themselves To understand whether students' sense of self is different with interactive or video VR
Identity exploration ~5 minutes	**Tell me more about yourself and your interest in science and engineering** • *Why did you take this engineering class?* • *What do you want to do after high school?* • *Do you consider yourself a science person?* • *[if they want to be a scientist/engineer]—what is it that scientists /engineers do that you want to do?* **Did you see anything in this application that relates to your own interests?** • *Did anything surprise you about what the scientists (explorers/astronauts) do?* • *Are you interested in doing work like that?* • *Is there anything you learned that might be important for your community, or your life?*	To understand whether students engage in any identity exploration as a result of role playing as a scientist or by observing scientists
Wrap up ~1 minute	**Do you have any questions for me, or is there anything else you want to share?**	Give students opportunity to discuss/ask what they want