Complexity of Agency in VR Learning Environments: Exploring Associations with Interactivity, Learning Outcomes, and Affect

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Abstract. Agency, or the capacity for acting and exerting control, has been identified as a primary affordance of virtual reality (VR) for learning but has not yet been well-studied. In this study, we explore data derived from a larger study on collaborative learning in a VR environment to investigate how varied interactivity impacts sense of agency and subsequently whether agency is associated other affective dimensions of learning and learning outcomes. Factor analysis revealed two distinct constructs in assessing agency, over the VR and over their learning experience. Although the study conditions encouraged varied forms of interactivity, treatment conditions did not predict either agency construct. Results showed that both agency constructs were correlated with positive experiences in the VR. Moreover, we found that learning agency is linearly, negatively associated with learning outcomes. We find VR agency has a non-linear association. We discuss the implications of these findings in better understanding the complex relationships between VR design, learners' experiences of them, and how they affect learning. While more control over the environment may distract learners from retaining content, sense of agency may be important for engaging affective dimensions of learning.

Keywords: Virtual Reality · Agency · STEM Education

1 Introduction

Agency, or the capacity for acting and exerting control, has been identified as a primary affordance of virtual reality (VR) for learning [1, 2]. Because VR allows learners to interact with a digital environment with their full bodies, they have novel opportunities to take actions that heighten their control over the environment and their learning. Having agency is important for users to feel embodied in immersive environments [3]. Agency is

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also important for learning and fostering intrinsic motivation for learning, for example by supporting learners' autonomy to pursue their interests and control their learning experience [4].

Despite the promise of VR to enhance agency in learning environments, it has been relatively less well-studied than features like immersion and presence. Recent studies have compared more- and less- interactive versions of immersive VR learning experiences, finding that increased interactivity heightens agency [5] and increases learning outcomes [6]. Other studies have found that greater movement in a narration-rich VR experience targeting conceptual knowledge hindered learning but enhanced self-efficacy, an important motivational construct for learning [7]. Higher reported sense of agency has been shown to mediate the association between immersion and self-efficacy, even when it does not predict greater learning outcomes [8]. Full-bodied interactivity has been shown to increase some aspects of subjective sense of agency, while less-interactive media like VR videos are equally effective at giving learners a sense of agency over their learning and attention [9].

Together, these studies suggest a complex relationship between the design of interactivity within VR learning environments, the way learners experience a sense of agency, and the impact that has on their learning. As frameworks of immersive learning theorize, agency is a facilitator of affective dimensions of learning which can ultimately impact learning [1]. These effects may be challenging to observe, and it is not yet well understood how the design of VR environments and learning activities within them influence learning.

This paper contributes to the growing interest in better understanding learners' sense of agency in varied designs of educational VR and its relationship with affective dimensions of learning and learning outcomes. Utilizing data collected as part of a larger study on collaborative learning in VR, this study explored three research questions:

1. Do different levels of interactivity encouraged in the environment predict variation in learners' sense of agency?
2. Is sense of agency correlated with other subjective experiences VR learning environments, namely presence and emotions?
3. How is sense of agency associated with learning outcomes? Is agency associated linearly or non-linearly with learning outcomes?

2 Materials and Methods

Data for this exploratory analysis comes from a study of collaboration in VR learning environments [10]. The design-based research [11] experiment aimed to design an intervention leveraging VR's affordances for collaborative learning that is feasible to use in authentic education environments through rapid cycles of iteration over three days.

2.1 VR Dive Guide Experience

We developed a VR experience of a guided ocean dive and designed a collaborative experience for learners to work together and with 3D models. The Dive Guide VR experience was created in Engage [12], a collaborative VR platform. A virtual underwater environment was created using several 360-degree stereoscopic still photographs (also called "photospheres") of underwater scenes collected by the 501(c)3 nonprofit The Hydrous on Palauan coral reefs. We recorded a marine expert avatar (using the motion capture system embedded within the Engage platform) interacting with the photospheres while explaining about coral reefs and human activities' impacts on marine life. This recording lasted approximately ten minutes. In all conditions, participants watched the Dive Guide experience, joining the platform as an avatar, and the real-time movements of other learners rendered on avatars visible in the underwater environment. They all could move, talk, and see each other. Through the design cycles some aspects of the experience were changed over the three days to respond to needs of learners and technical issues. See Fig. 1 for screenshots of the Dive Guide and participants. See [10] for a full description of the design process.

Table 1. Treatment Condition Descriptions.

Conditions	Description	n
Viewing/ Discussion/Graphics ("Graphic")	Participants watched the Dive Guide VR experience. The facilitator paused the recording two times to share 3D models with participants and asked them to collaborate to apply what they were learning with models of coral, marine animals, and building blocks for building	45
Viewing/ Discussion ("Talk")	Participants watched the Dive Guide VR experience. The facilitator paused at the same times as the Viewing/Discussion/Graphics condition and asked participants to discuss what they were learning with each other. Only used on Day 1	11
Viewing ("Control")	Participants watched the Dive Guide VR experience without pausing	23

Three conditions were tested, described in Table 1. The control condition is termed "Viewing," where participants watched the Dive Guide VR without pausing. In this condition, participants could walk around the virtual environment, but did not manipulate any 3D objects. The most collaborative condition was "Viewing/Discussion/Graphics" with two opportunities for interacting with 3D models for a collaborative activity. Participants could duplicate, move and rescale 3D objects using the hand controllers. This is referred to as the "Graphic" condition for short. Figure 1 depicts the Viewing and the Graphics condition. Additionally, on the first day a set of participants were asked to have a discussion without 3D models, the "Talk" condition. In this condition participants could walk around the virtual environment but did not manipulate any 3D objects. A prior study showed the different conditions significantly predicted learning outcomes, and participants in the "graphic" condition learned more than those in the control condition [10].

Participants completed an orientation to the Meta Quest 2 headset, how to use the controllers to move and interact with objects and created an avatar in the Engage platform. Participants received individual instruction until they were comfortable, addressing varied experience and comfort levels in VR. They were then randomly assigned to a small group and condition.

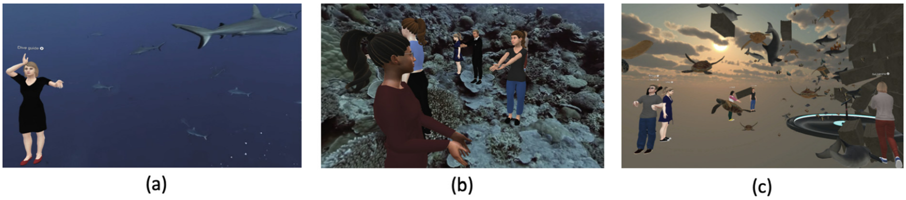

Fig. 1. The Dive Guide and collaborative VR experience screenshots. (a) Dive guide screenshot; (b) Participants watching the Dive Guide (Control); (c) Participants in the collaborative task (Graphic).

2.2 Measures

Participants completed a pre-survey before using the VR equipment or being assigned a condition. They completed a post-survey immediately following the conclusion of the Dive Guide experience.

Development and Validation of Agency Measures. Prior research illustrated how agency can be a multidimensional construct, reflecting varied definitions of agency as control over motor function or more broad learning activities[13]. Therefore, items were used that assess both these types of agency: ten items were adapted from [13] and [8]. A confirmatory factor analysis of the 10-item agency questionnaire was run to explore dimensions explaining the relationships between items. The multidimensional structure confirmed two constructs: a measure of agency over the VR experience (namely, VR agency) and a measure of agency over learning experience in VR (learning agency). The two-factor model was compared to a single-factor model with all 10 items and was statistically significantly better fit to the data ($\chi^2(1, 79) = 29.51, p < .001$). Table 2 depicts standardized loadings onto these two factors. The item referring to preference for deciding what to do on their own did not load onto the learning agency factor. This item was therefore dropped from the learning agency scale, which improved model fit without changing the other items' loadings. Fit indices were adequate for this final model ($CFI = .93$, $TLI = .91$, $RMSEA = .10$).

Analyses here utilized this five-item scale for VR agency ($\alpha = .86$) and this four-item scale for learning agency ($\alpha = .78$).

Other Measures. *Positive and negative affect (Pre and Post).* Participants' moods and emotions were assessed before and after the intervention through seven items from the Positive and Negative Affect Schedule (PANAS, Watson et al., 1988). They were asked to "please tell us how you feel right now," related to the items "interested," "distressed," "attentive," "ashamed," "active," "jittery," and "overwhelmed." Response options were on a 5-point Likert scale from "not at all" (score = 1) to "extremely" (score = 5).

Presence (Post). We adapted nine questions from the Presence Scale [14] to investigate participants' social, self, and environmental presence (e.g., "I felt as if I was inside the virtual world"). Three questions were asked for each type of presence. We computed a composite of each type of presence by averaging the corresponding questions (social $\alpha = .78$; self $\alpha = .79$; environmental $\alpha = .78$).

Learning (Pre and Post). A marine expert developed six multiple-choice questions to assess participants' knowledge and measure the effects of the intervention (question example: "Why are corals important for tropical marine life?"). Participants received one point for each correct answer, and no points for incorrect answers. A learning composite was created by averaging the six questions' scores.

Additionally, participants were asked at the pre-test to report demographic characteristics and their prior VR use. On the post-test they also answered questions about how close they felt to their group (*entitativity*) and discomfort level using the VR (*cybersickness*). We controlled for these characteristics as they are likely to influence how well a participant can interact with the experience (English level, VR experience) or have been shown contributors to how people experience VR (age, gender). For details of all the measures see [10].

Table 2. Confirmatory Factor Analysis.

	Standardized factor loadings	
Item	Factor 1: VR agency	Factor 2: Learning agency
My experiences and actions were under my control during the VR activity	0.701	
I had freedom to explore	0.845	
The VR felt interactive	0.722	
The VR activity allowed me to choose where to focus my attention	0.686	
The VR activity felt hands-on	0.806	
The VR activity allowed me to select what I was going to learn		0.844
The VR activity allowed me to make choices that influenced my learning outcomes		0.886
Being able to choose where to focus my attention was important for learning		0.435
I learned more when I controlled what to do		0.509
I preferred deciding what to do on my own than other people telling or showing me what to do		0.089

2.3 Participants

Participants were attendees from diverse backgrounds who enrolled in a session at an institutional program in March 2022. A total of 107 participants enrolled in the study, and 80 whose pre- and post-data were complete and could be matched are included in this analysis. Participants' ages varied from 19 to 69 years old (M = 26.34, SD = 10.09). 41 participants identified as female (51%), 38 as male (48%), and one as something else (1%). Participants identified their race as: 34% White, 30% Asian, 12% Latinx, 9% Black, 3% Middle Eastern, 6% more than one, and 6% declined to answer. They were from North America (46%), Asia (30%), Latin America (12%), and Europe (10%).

3 Results

To explore RQ1, *do different levels of interactivity encouraged in the environment predict variation in learners' sense of agency?,* a Welch two-sample T-test was performed comparing the mean level of the agency measures across each condition. Using the two measures of agency (VR agency and learning agency), we estimated the influence of the different treatment conditions on the users' agency. Means for each measure of agency are shown in Table 3 by treatment condition and day of the study. T-tests did not indicate a significant difference between the control and graphic conditions for mean VR agency ($t(39.99) = -0.02, p = .98$) or learning agency ($t(43.30) = 1.18, p = .24$). There was a significant difference between mean VR agency for the talk and graphic conditions for ($t(13.91) = -3.17, p < .001$) and the talk and control conditions ($t(19.42) = -2.84$, $p = 0.01$). No significant differences were found for mean learning agency between talk and graphic ($t(24.41) = 0.19, p = .85$) and between talk and control conditions ($t(29.96) = -0.92, p = .36$). The significant result for differences with the talk condition should be interpreted with caution as this condition was only used on the first day of the implementation and with a small sample ($n = 11$).

Table 3. Mean (Standard Deviation) of Agency Measures by Treatment Condition and Day.

	Day 1			Day 2			Day 3		
	Control	Graphic	Talk	Control	Graphic	Talk	Control	Graphic	Talk
VR agency	3.6 (0.9)	3.4 (0.7)	2.8 (1.0)	4.0 (0.9)	4.0 (1.0)		3.9 (1.1)	4.0 (0.8)	
Learning agency	3.9 (0.9)	2.8 (0.7)	3.5 (0.6)	3.4 (0.8)	3.5 (1.0)		3.8 (1.2)	3.8 (0.9)	

A simple linear regression model did not indicate a significant association between any of the conditions and either of the measures of agency when controlling for day of intervention (Table 4). Alternative models confirmed the robustness of these results, including random intercept estimates that better account for unbalanced groups, which estimated the same coefficients and significance levels. Together these results indicate there was little if any impact of the treatment conditions on users' sense of agency perception over the VR experience or their learning. The increased encouragement to interact with objects did not predict an increase in their agency perception.

Table 4. Linear regression results of association between agency and treatment condition, controlling for day of implementation.

	Dependent variable:	
	VR agency	Learning agency
Constant	3.49^{***}	3.31^{***}
Condition: Graphic	0.01	−0.26
Condition: Talk	−0.70	0.15
Day2	0.47	0.34
Day3	0.44	0.65^{*}
Observations	79	78
R^2 /Adjusted R^2	0.17/0.13	0.09/0.04
Residual Std. Error	0.91 (df = 74)	0.94 (df = 73)
F Statistic	3.91^{**} (df = 4; 74)	1.77 (df = 4; 73)
Note:	* p < .05, ** p < .01, *** p < .001	

To explore RQ2, *is sense of agency correlated with other subjective experiences VR learning environments, namely presence and emotions?*, Pearson correlations were estimated between the agency measures and positive and negative affect (pre and post) and presence.

Table 5. Correlations between agency measures and other subjective measures.

Pre-survey							
	Interested	Active	Attentive	Ashamed	Distressed	Jittery	Overwhelmed
VR Agency	0.27	0.22	0.25	0.27	−0.08	0.2	0.22
Learning Agency	0.4*	0.42*	0.34	0.22	0.03	0.27	0.17

Post-survey											
	Learning agency	Social-pres.	Self-pres.	Env-pres.	Interested	Active	Attentive	Ashamed	Distressed	Jittery	Overwhelmed
VR Agency	0.62***	0.59***	0.57***	0.64***	0.57***	0.47**	0.49***	−0.16	−0.02	−0.04	−0.02
Learning Agency		0.46**	0.39*	0.32	0.4*	0.6***	0.59***	−0.18	−0.05	0.02	−0.03
Note:		* p < .05, ** p < .01, *** p < .001									

As shown in Table 5, both agency measures were associated with indicators of a positive VR experience on the post-survey. VR agency was correlated with all three indicators of presence, meaning those with a higher sense of agency also felt more present with their peers, in their virtual body, and in the environment. It was also associated with all three positive emotions, meaning those with a higher sense of agency also felt more interested, active and attentive. VR agency was not associated with any of the pre-survey measures or negative emotions.

Learning agency was associated with social and self-presence, meaning those with higher learning agency also felt more present with their peers and in their virtual body but not necessarily in the environment. Learning agency was also correlated with all three positive emotions, meaning those with a higher sense of agency also felt more interested, active and attentive. Learning agency was also associated with feeling active and interested on the pre-survey (Table 5), indicating an association between feeling active and interested with being in control of their own learning before engaging in the VR experience.

Together this suggests VR and learning agency are associated with positive experiences in VR, feeling more positive emotions and a greater sense of presence.

To explore RQ3, *how is sense of agency associated with learning outcomes? Is agency associated linearly or non-linearly with learning outcomes?*, linear regression analyses estimated the association between learning outcomes and the sense of agency measures, controlling for individual characteristics (age, prior VR use, gender, English proficiency) and the day of implementation to account for design iterations. For example:

$$LearningPost_i = \beta_0 + \beta_1 Agency_i + \beta_2 LearningPre_i + \beta_3 Characteristics_i + \beta_4 Day_i + \beta_5 Condition + \in_i$$

Regression models with a quadratic term for agency were also estimated to assess whether sense of agency had a non-linear association with learning outcomes. For example:

$$LearningPost_i = \beta_0 + \beta_1 Agency_i + \beta_2 Agency_i^2 + \beta_3 LearningPre_i + \beta_4 Characteristics_i + \beta_5 Day_i + \beta_6 Condition + \in_i$$

Table 6 displays results for four regression models estimating both linear and quadratic associations between the agency measures and learning outcomes. Variance inflation factor was between 1 and 2 for all linear predictors in all models, ensuring multicollinearity was not an issue. Results indicated a significant negative linear relationship between learning agency and learning outcomes (Model 2). The results of the quadratic model for VR agency (Model 3) suggest a non-linear association between VR agency and learning outcomes, as the quadratic term is statistically significant, and the main effect is approaching significance ($p = .09$). ANOVA tests between the linear and quadratic models indicated the quadratic models best fit the data. We report this near-significant result because in this exploratory study the small sample with this number of predictors lowers the likelihood of observing significance, but the finding should be interpreted with caution.

These associations are depicted in Fig. 2. Panel A shows how as learning agency increases, learning outcomes decrease, controlling for individual factors and the day of implementation. Panel B illustrates that when VR agency is low, increases are associated with increased learning. However, the association reaches a peak when VR agency equals 2.7, after which heightened agency is associated with lower levels of learning.

Table 6. Regression results for linear and quadratic models.

	Dependent variable: Learning post-score			
	Linear		Quadratic	
	VR agency	Learning agency	VR agency	learning agency
	(Model 1)	(Model 2)	(Model 3)	(Model 4)
Constant	0.54^{+} (0.31)	0.62^{*} (0.26)	0.06 (0.38)	0.13 (0.36)
VR Agency	−0.05 (0.03)		0.27^{+} (0.16)	
Learning Agency		-0.07^{*} (0.03)		0.23 (0.17)
VR Agency^2			-0.05^{*} (0.02)	
Learning Agency^2				-0.05^{+} (0.02)
Learning Pre-Score	0.35^{*} (0.14)	0.30^{*} (0.13)	0.29^{*} (0.13)	0.29^{*} (0.13)
Graphic Condition	0.17^{**} (0.06)	0.17^{**} (0.06)	0.17^{**} (0.06)	0.16^{**} (0.06)
Talk Condition	−0.05 (0.10)	0.002 (0.09)	−0.02 (0.10)	−0.02 (−.09)
Age	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Prior VR Use	−0.01 (0.03)	−0.003 (0.02)	−0.01 (0.03)	−0.01 (0.02)
Gender: Male	−0.04 (0.05)	−0.04 (0.05)	−0.02 (0.05)	−0.04 (0.05)
Gender: Something Else	0.08 (0.23)	0.17 (0.22)	0.12 (0.22)	0.22 (0.22)
Cybersickness	-0.07^{*} (0.03)	-0.07^{*} (0.03)	-0.07^{*} (0.03)	-0.07^{*} (0.03)
English Skills	0.07^{+} (0.04)	0.06 (0.04)	0.07^{+} (0.04)	0.07^{+} (0.04)
Day 2	-0.19^{*} (0.08)	-0.19^{*} (0.07)	-0.16^{*} (0.08)	-0.19^{**} (0.07)
Day 3	-0.19^{**} (0.07)	-0.14^{+} (0.07)	-0.16^{*} (0.07)	-0.12^{+} (0.07)
Observations	78	77	78	77
R^2 /Adjusted R^2	0.34/0.22	0.38/0.27	0.38/0.26	0.42/0.30
Residual Std. Error	0.22 (df = 65)	0.21 (df = 64)	0.21 (df = 64)	0.20 (df = 63)
F Statistic	2.82^{**} (df = 12; 65)	3.32^{***} (df = 12; 64)	3.05^{**} (df = 13; 64)	3.46^{***} (df = 13; 63)
Note:	(Standard Error) + $p < .1$, * $p < .05$, ** $p < .01$, *** $p < .001$			

4 Discussion

This study explored data from a larger study on learning with collaborative VR to investigate sense of agency in such environments. Agency cohered into two distinct constructs, in which users felt a sense of agency over the VR and a distinct sense of agency over

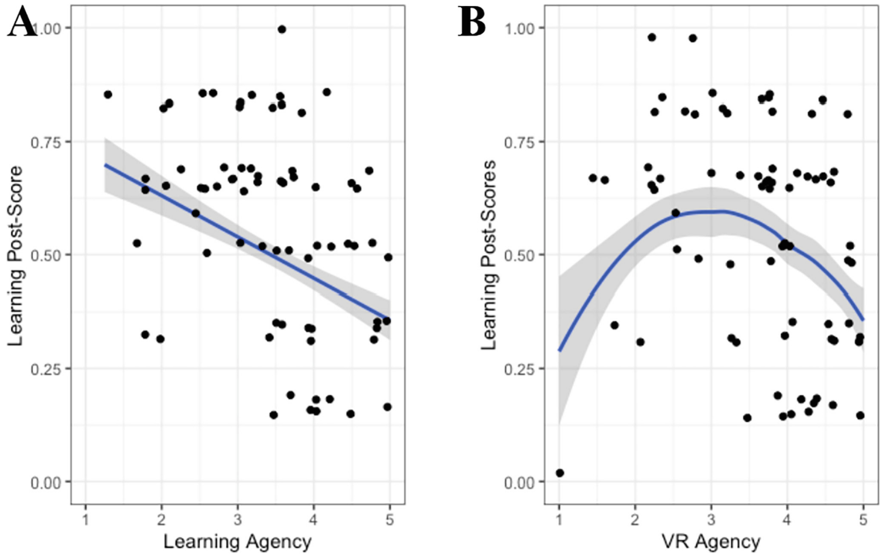

Fig. 2. Learning post-scores and sense of agency. The line visualizes the fitted relationship from regression results (see Table 6). Panel A shows a negative linear relationship between learning outcomes and learning agency. Panel B shows a non-linear (quadratic) relationship between learning outcomes and VR agency. *Note:* Points are jittered to display each individual observation.

their learning. Therefore, we constructed a 5-item measure of VR agency and a separate 4-item measure of learning agency which both exhibited internal consistency. This indicates sense of agency is multidimensional, and learners can experience different types of agency in a VR learning experience. In particular, there are distinctions between their sense of agency over the VR experience, such as exploring and interacting with the environment, and their sense of agency over their learning with that experience, such as being able to make choices about what they learned. Just as sense of presence is often measured across dimensions such as feeling present in the environment and feeling present in the virtual body, studies of agency should utilize measures specific to the type of agency they are interested in or aim to capture multiple dimensions of agency. Defining agency as feeling one's actions are self-generated (e.g. [15]) will yield different results than defining agency as being able to control one's learning goals and experience (e.g. [4]).

This study found that despite encouraging a greater degree of full-body interactivity, the treatment condition in which participants interacted with their peers and 3D objects was not associated with a higher perception of the level of either agency measure than the condition in which they only watched the dive. This finding is surprising and necessitates further investigation into the way interactivity impacts agency. It is possible that learners in the control condition focused on the agency they did have when responding to the questions, as they had the ability to move and look around even without being encouraged to do so. It's also possible that offering or encouraging more interactivity did not result in learners actually exploring or moving more. It is also possible that learners who experienced technical difficulty in the graphic condition felt less in control, negating any increase we may have observed. Future studies should include behavioral measures such as motion tracking to understand how activity in the VR impacts agency.

We did find that the agency measures were correlated with other indicators of having a positive experience in VR, including learners' sense of presence and positive emotions. This finding suggests that perceiving control over the VR experience and over learning may play a crucial role in learning in virtual environments, particularly related to the affective aspects of learning. Moreover, we found that learning agency had a negative, linear association with learning outcomes, suggesting that, in this specific VR experience, a higher perception of agency over learning choices corresponded to a lower retention of information about the overall experience. This finding indicates that in narration-rich VR learning environments, targeting conceptual knowledge, in which paying attention to the narration is important to recall information, feeling active and exploring the VR environment may compete with paying attention to the narration. Future studies should investigate the agency and recall relationship comparing experiences targeting conceptual or procedural knowledge.

Notably, we found that VR agency had a non-linear association with learning outcomes, and that when agency was low, increases in agency were associated with increases in learning outcomes. However, the relationship yielded a tipping point, where at the higher end of the scale increases in VR agency predicted lower levels of learning outcomes. This finding aligns with previous investigations about sense of agency and learning in medical emergencies training [16]. It highlights the intricacies of learning mechanisms within virtual reality (VR) and emphasizes that the learning experience in VR transcends the medium itself.

These results make several contributions to better understanding agency in VR learning environments and its relationship with VR design and learning outcomes. Our findings point to complexities in the association between how people interact in VR and their sense of agency. The design of this study was unique in that the varied conditions gave all the learners the same embodied representation and ability to move within the environment, but varied how they were encouraged to interact. We find that encouraging collaboration and interaction with 3D models did not increase either VR or learning agency. This could be because the graphic condition was more difficult to use and therefore learners felt less in control despite having the ability to interact more. It could also be due to a greater frequency of technical difficulties in the graphic condition, in which the 3D models increased the bandwidth needed and caused more glitching. These features may have interfered with learners' feelings of control, therefore not improving their agency perception over the learners who were not encouraged to move around and interact with objects. On the other hand, it could be that the control condition was successful at making learners feel as much agency as the graphic condition because the embodiment and ability to look and move around was more important than the specific interactive activities given to the graphic treatment. This may diverge from prior work that found interactivity was important for agency by comparing users who could interact with those watching a recording without a sense of embodiment [5, 6]. On the other hand, our findings align with prior studies that show learners can have a heightened sense of agency in experiences that are less interactive like 360-degree videos [8, 9], underscoring that interactivity in terms of hand and body movement is not equivalent to agency.

We also found that agency is associated with other subjective indicators of a positive experience in VR. VR agency correlated with three different presence measures and learning agency with self- and social-presence. Prior work has shown that greater levels of interactivity increases presence [5], but it is still unknown how agency and presence are related. Our findings suggest a relationship, but more research is needed to understand whether they are co-occurring due to the experience in the VR or one causes the other. Our finding that heightened agency in both measures was associated with feeling interested, attentive, and active lends support to models outlining how agency contributes to affective dimensions of learning as the mechanism through which they increase learning [1, 8]. This means increasing VR and learning agency could be an important mechanism to increase motivation and positive emotions.

The finding that learning agency is negatively associated with learning outcomes highlights another element of complexity in the role agency plays in learning with VR. It is possible that heightened agency helps engage affective dimensions of learning but interferes with retaining content and processing information. Learners who are in control of their experience may choose to focus on content or features of the activity that are not directly assessed on a content retention assessment. The finding that agency is also associated with positive emotions and presence indicates it may indicate a higher level of arousal and therefore cognitive load, which has been shown to hinder learning outcomes in terms of retaining information [17]. Our findings suggest that allowing more control over learning in VR could aim to increase learning outcomes other than content retention, as the experiences are less likely to encourage information processing and retention but likely to engage affective dimensions of learning. This echoes calls for more research to assess affective learning outcomes with VR [18].

The non-linear relationship between VR agency and learning outcomes suggests there are also complexities with how learners engage in VR and their learning. Our results illustrate that those who felt no ability to control their experience were likely to have lower learning outcomes, as were those who felt a great deal of agency over their environment. These learners likely faced different barriers: on the low-agency end not feeling engaged in the experience and on the high-agency end perhaps being distracted and choosing to focus on aspects unrelated to the content assessment. Our findings align with prior work that shows greater levels of movement within a VR experience hinders learning [7]. Our results suggest there may be a "sweet spot" for degree of agency in VR, as those who reported a moderate level of agency had the highest learning outcomes. The threshold in this study was a score of 2.7 out of a maximum of 5 on the VR agency scale. Supporting learners to take meaningful actions without becoming distracting may help maximize this association. Further, the association with greater presence and positive emotions also suggests greater VR agency may support affective learning outcomes more than content retention.

There are a number of practical implications from these findings. For one, educational VR can enhance agency even without encouraging a great deal of interactivity, as we found the learners in the control condition expressed equivalent levels of agency over learning and action as those in the graphic condition. Designers should also consider the learning goals of an experience when constructing interactive activities. Our results suggest giving learners more control and agency may compete with the demand on their attention to learn conceptual knowledge. Heightened agency may be better suited for other learning goals, like procedural skills and affective dimension such as intrinsic motivation and self-efficacy. The association between agency and other positive experiences in VR suggests it enhances learners experiences, and designers should experiment with how to make the most of this positive experience while also encouraging learning. Educators may choose to use agentic VR experiences to enhance these positive outcomes combined with other activities that enhance focus on conceptual knowledge.

Limitations. This study explored data collected on agency in a larger experiment with collaborative VR environments, and therefore was not designed to study the causal impact of agency on learning or VR designs on agency. Further, this was a design-based research study whose implementation iterated day-to-day. While we utilized controls for the day of implementation, the experimental conditions were not highly controlled. Future research should experiment with varied forms of interactivity and investigate the impact of agency on learning more systematically. More research with larger samples should also investigate these associations to understand how generalizable they are, particularly associations such as the non-linear relationship between VR agency and learning, which approached statistical significance but may be easier to observe in a larger sample. The sample was also a self-selected group interested in VR. There may be different results with more experienced VR users or those who are not already interested in it. Further, our findings are applicable for this specific VR experience which may differ from others that have less collaboration or other designs and learning activities. Investigating questions like this in other VR experiences would help understand their generalizability. Further, including behavioral measured described in the discussion would improve our understanding of agency related to behavior in addition to the subjective self-report measures.

5 Conclusion

This study investigated the nuanced aspects of agency within narration-rich, collaborative virtual reality (VR) learning environments. First, two components of agency in VR were identified: agency towards learning (learning agency) and agency over the VR (VR agency). Varied conditions of a VR experience that encouraged learners to interact with the environment and each other did not impact the sense of agency learners reported. A non-linear association between VR agency and learning outcomes suggested moderate agency levels correlating with the highest learning outcomes. However, heightened learning agency was negatively associated with retention, revealing a potential trade-off between exploration in VR and content retention in narration-rich VR environments. The results highlight complex relationships between interactivity, agency, and learning that have not been fully explored in prior literature. Further research is needed to understand the intricate dynamics of agency in VR learning environments and their implications for instructional design.

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References

1. Makransky, G., Petersen, G.B.: The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based Model of Learning in Immersive Virtual Reality. Educ. Psychol. Rev. (2021). https://doi.org/10.1007/s10648-020-09586-2
2. Johnson-Glenberg, M.C.: Immersive VR and education: embodied design principles that include gesture and hand controls. Frontiers in Robotics and AI **5** (2018). Accessed: 12 Dec. 2022. https://doi.org/10.3389/frobt.2018.00081
3. Jicol, C., et al.: Effects of emotion and agency on presence in virtual reality. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1–13. ACM, Yokohama Japan (2021). https://doi.org/10.1145/3411764.3445588
4. Ryan, M.R., Deci, E.L.: Self-Determination Theory and the Facilitation of Intrinsic Motivation, Social Development, and Well-Being, American Psychologist, p. 11 (2000)
5. Petersen, G.B., Petkakis, G., Makransky, G.: A study of how immersion and interactivity drive VR learning. Comput. Educ. **179**, 104429 (2022). https://doi.org/10.1016/j.compedu.2021.104429
6. Johnson-Glenberg, M.C., Bartolomea, H., Kalina, E.: Platform is not destiny: embodied learning effects comparing 2D desktop to 3D virtual reality STEM experiences. J. Comput. Assist. Learn. **37**(5), 1263–1284 (2021). https://doi.org/10.1111/jcal.12567
7. Queiroz, A.C.M., Fauville, G., Abeles, A.T., Levett, A., Bailenson, J.N.: The efficacy of virtual reality in climate change education increases with amount of body movement and message specificity. Sustainability **15**(7), Art. no. 7 (2023). https://doi.org/10.3390/su15075814
8. Queiroz, A.C.M., Fauville, G., Herrera, F, da S. Leme, M.I., Bailenson, J.L.: Do Students Learn Better With Immersive Virtual Reality Videos Than Conventional Videos? A Comparison of Media Effects With Middle School Girls. Technology, Mind, and Behavior **3**(3) (2022). https://doi.org/10.1037/tmb0000082
9. McGivney, E.: The Impact of Interactivity and Identity on Learners' Sense of Agency in Virtual Reality Field Trips, Under Review
10. Queiroz, A.C.M., et al.: Collaborative tasks in immersive virtual reality increase learning. In: Proceedings of the 16th International Conference on Computer-Supported Collaborative Learning, International Society of the Learning Sciences (2023)
11. Barab, S., Squire, K.: Design-based research: putting a stake in the ground. J. Learn. Sci. **13**(1), 1–14 (2004). https://doi.org/10.1207/s15327809jls1301_1
12. ENGAGE (2022). https://engagevr.io/
13. McGivney, E.: Promoting learning, agency, and motivation in STEM classrooms with virtual reality field trips, Unpublished doctoral dissertation. Harvard University, Cambridge, MA (2023)

14. Han, E., et al.: People, places, and time: a large-scale, longitudinal study of transformed avatars and environmental context in group interaction in the metaverse. J. Comp.-Mediated Comm. **28**(2), zmac031 (2023). https://doi.org/10.1093/jcmc/zmac031
15. Polito, V.A., Barnier, A.J., Woody, E.Z.: Developing the sense of agency rating scale (SOARS): an empirical measure of agency disruption in hypnosis. Consciousness and Cognition **22**(3), 684–696 (2013). https://doi.org/10.1016/j.concog.2013.04.003
16. Mühling, T., et al.: Virtual reality in medical emergencies training: benefits, perceived stress, and learning success. Multimedia Syst. **29**(4), 2239–2252 (2023). https://doi.org/10.1007/s00530-023-01102-0
17. Parong, J., Mayer, R.E.: Cognitive and affective processes for learning science in immersive virtual reality. J. Comput. Assist. Learn. **37**(1), 226–241 (2021). https://doi.org/10.1111/jcal.12482
18. Hamilton, D., McKechnie, J., Edgerton, E., Wilson, C.: Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design. J. Comput. Educ. **8**(1), 1–32 (2021). https://doi.org/10.1007/s40692-020-00169-2