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Embodied Interaction and Spatial Presence in Virtual Immersive Media Systems

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Abstract. This paper explores the connection between EI and SP in virtual immersive media systems, such as virtual reality (VR), augmented reality (AR), and 360-degree video platforms. The study used a post-positivist mixed-methods design, collecting condition level observations from 171 adult participants to investigate the relationship between system-level interaction variables (tracking fidelity, sensorimotor coupling quality and end-to-end latency) and their subjective experience of spatial presence as assessed on the Igroup Presence Questionnaire. The findings show that the presence dimensions are strongly affected (η^2p = .58–.60) by the platform condition, and that VR (6-DOF) condition is generally superior to AR condition and 360-video condition. The strongest predictor of presence ($r = -.81$) and variance in general presence scores was system latency. The outcomes not only confirm the integrated five-layer interaction model but also directly impact the immersive content design, haptic feedback engineering, and user onboarding strategy.

Keywords: Embodied interaction; Spatial presence; Virtual reality; Augmented reality; Immersive media; Sensorimotor coupling.

1. Introduction

The integration of sophisticated display technologies, real-time motion tracking and high-resolution rendering pipelines has ushered in a new type of computing context, commonly called virtual immersive media systems. Unlike traditional screen-based computing, the human body is the main target of these technologies, known as virtual reality (VR), augmented reality (AR), and extended reality (XR), as the interface through which content is presented. This change from observing to participating has led to a flourishing field of inquiry at the nexus of human-computer interaction, cognitive science and media studies, focusing on two closely related phenomena: embodied interaction and spatial presence.

Embodied interaction means the continuous interpretation of the physical movement, gesture and posture of a user and their use for driving meaningful responses in a virtual environment. Embodied interaction relies on the user's proprioceptive awareness, which is the sense that the body has its own position and movement, as the base for communicating with the system, as opposed to paradigms such as point-and-click or touch-screen input [1]. The idea is based on a phenomenological philosophical tradition, dating back to Merleau-Ponty's writings, who emphasized the corporeal nature of perception and the inseparability of understanding from being-in-the-world [2]. For immersive media, the philosophical insight translates to an engineering problem: How will a system be able to receive, interpret, and react to body input in a way that preserves and enhances the sense of natural agency of the user?

Spatial presence is a psychological state of being present in a mediated environment, as opposed to simply viewing it. Early presence research by Witmer and Singer introduced a multidimensional framework to understanding presence in the context of immersive technology that relied on the richness of the sensory presentation and attentional focus on the virtual world [3]. Slater's discrimination between Place Illusion (PI) (real place) and Plausibility Illusion (PI) (real events) provides a more sophisticated description of the subjective sense of presence as a function of various system properties [4]Click or tap here to enter text.. In virtual training and simulation environments, high spatial presence is important for deepening cognitive engagement, enhancing emotional reactions, and boosting task performance, a factor that holds true across a variety of medical education, architectural visualization, and immersive applications.

Spatial presence is not a by-product of embodied interaction, but rather a fundamental part of it. High-quality sensorimotor coupling (where the user's actions give rise to immediate, congruent and spatially coherent responses in the virtual environment) has been consistently found to produce higher reported presence scores than systems that use a controller-mediated input [5]. This link holds great significance for the design of immersive media systems: latency in the tracking pipeline can cause disruption, while the lack of consistency between avatars and haptic feedback can also cause disruption, as can be the lack of fidelity of the avatars. Implementing this is not possible without an interdisciplinary approach that combines the results of perceptual psychology, human factors engineering, and the design of interactive media.

Although there is interest in both embodied interaction and spatial presence as individual areas of study, the literature has not explored how these two approaches can be combined within a single, cohesive analysis for virtual immersive media systems. Existing research is largely hardware and software engineering focused, or psychometric focused on measuring presence, but relatively little attention is paid to the role that interaction design decisions play between presence enabling system capabilities and felt presence. To fill this gap, we present the integrated five-layer interaction model, which maps the technical parts of an immersive system onto the perceptual and cognitive process that creates spatial presence, and present an analysis of empirical evidence that connects the design of the interaction in different system modalities with the resulting presence.

2. Literarure Review

The concept of embodied interaction in virtual environments is rooted in the theory of ecological and phenomenological approaches. Gibson's theory of affordances has led to the understanding that organisms do not simply perceive, they actively pursue properties of the environment that support specific behaviors [6]. This rule can be reworded in terms of the system design that the virtual worlds should offer a consistent set of action options that the user's body is able to naturally interpret and act upon. If the affordances in a virtual environment match with the user's learned motor schemas, the interaction is intuitive, and if the affordances are different, presence is lost. This ecological foundation has been followed by subsequent HCI research that has explored the affordance structure that can be constructed using six-degrees-of-freedom (6-DOF) body tracking as a controller for input, as compared to controller based input, especially for fine spatial manipulation tasks. Empirical studies of spatial presence have arrived at two key factors: the quality of the sensory presentation, and the extent of interactive control given to the user. For Deutsch VR presence studies, Cummings and Beilenson performed a quantitative meta-analysis, and they determined that tracking fidelity (how well head movement matched the update of the display) accounted for the most variance in reported presence, more than anything else, including display resolution or FOV [7].This discovery marks a step toward placing the quality of embodied interaction at the heart of presence engineering, rather than just a side issue of usability. Later research by Skarbez, Brooks, and Whitton added a level of complexity by separating the internal consistency of the virtual environment, coherence, as a moderating variable which enhances or diminishes the relationship between tracking fidelity and presence [8]. Haptic feedback is a field of recent research that has focused on the sensorimotor loop of feedback between user action and system response. Lécuyer's original study on pseudo-haptic feedback proved that even the most purely visual feedback, when carefully synced to the motor movements, can produce realistic haptic feedback - a result that is relevant for consumer VR devices that don't have dedicated haptic actuators [9]. More recently, Fang et al. created a soft robotic glove system that can provide graded force feedback while manipulating virtual objects, showing that the presence ratings and task accuracy are far superior to just using visual feedback [10]. The new hardware developments are being matched by adaptive rendering algorithms which morph virtual object motion as the mechanical feedback is inexact or delayed in real time to ensure perceptual plausibility. Although this is a rich collection, there are still three key omissions. Most presence studies involve short-duration exposures (usually less than 15 minutes), which may not be sufficient to measure presence decay or adaptation effects across longer exposure sessions. Second, most experimental designs are limited to the study of single interaction variables, and it is hard to evaluate interaction effects such as tracking latency and haptic fidelity at the same time. Third, there are few studies in which the content was the same across the platforms, but the platform modalities were different, and findings from this type of comparative study are not widely generalized. While there is an increasing body of commercial presence VR applications, social aspects of presence, especially co-presence in multi-user XR environments, are still poorly explored compared to the single user presence. The present paper aims to fill these gaps by taking a system analytical approach that incorporates both system modalities and system presence.

3. Research Methdolgy

3.1. Research Design and Philosophical Stance

The study follows a mixed-methods approach; quantitative measures of system performance parameters and user presence ratings are used in combination with qualitative measures of observed interaction patterns through three different types of immersive media systems. The philosophy that underlies this approach is post-positivist: Numerical indices of latency, tracking fidelity and task completion serve as the empirical foundation to the analysis but the authors understand that spatial presence is a subjective phenomenon and cannot be quantified by a single number. This is in line with Creswell and Creswell's framework, which states that mixed-methods designs are suitable for research questions that offer a synthesis of objective system characteristics and subjective human experiences [11]. The research is organized using the five-layer interaction model presented in Section I as a theoretical lens and schema for data collection for all three platform conditions.

3.2. Platform Conditions and Apparatus

The three platform conditions were designed to simulate the main modes of current immersive media: 6-DOF VR, marker less hand and gaze tracking AR and passive 360-degree video with head rotation only tracking. The key technical properties of each condition are summarized in Table 1. To control any content effects, the same content in the form of a structured virtual setting, an interior space fitted with interactive objects, was used for all conditions.

Table 1. Research Design Matrix-Platform Conditions and Technical Characteristics

Dimension	VR (6-DOF)	AR (Mixed)	360-Video
Tracking type	Full-body IMU + optical	Markerless hand + gaze	Head rotation only
Haptic feedback	Controller rumble + glove	None (visual only)	None
Display latency (ms)	< 20 ms	20–40 ms	40–80 ms
Presence instrument	IPQ + SUS	IPQ + SUS	IPQ only
Session duration	30 min	30 min	30 min

Note-IPQ = Igroup Presence Questionnaire; SUS = System Usability Scale; IMU = Inertial Measurement Unit

The VR condition utilized a commercially accessible HMD (Virtual Reality) with a full-body inertial measurement unit (IMU) with sensors at eight body landmarks to track head, torso, upper and lower limbs at 90 Hz, with nominal end-to-end latency less than 20 milliseconds. This AR condition was performed using see-through glasses with hand and eye-tracking cameras running at 60 Hz and a display latency of 20-40ms. 360-video condition was provided through an active head-rotation tracking head-mounted-viewer controlled by a smartphone that contained no active body-state sensing, pointing to the most widely-available and least expensive way of delivering immersive content to consumers.

3.3. Participants and Sampling Strategy

A total of 60 participants were recruited, evenly distributed among three groups representing different levels of VR/AR experience: novice (no prior interaction), intermediate (occasional prior interaction < 10 sessions), and experienced (regular prior interaction > 20 sessions). All participants performed all three conditions in a counterbalanced sequence to reduce order effects, and with at least a 30-minute washout between conditions. The age of the participants ranged from 19 to 47 years with the average age of 28.4 years. Those with significant vestibular abnormalities, visual impairment that was not corrected and photosensitive epilepsy were excluded. The data set consisted of 180 condition level observations (60 participants x 3 conditions) with adequate statistical power for planned between condition comparisons.

3.4. Instruments and Data Collection

A validated 14-item instrument, Igroup Presence Questionnaire (IPQ), was used to measure spatial presence, involving experience and experienced realism, with one item measuring overall presence. For VR and AR condition, System Usability Scale (SUS) was used to assess system usability. The measurement of cognitive engagement was done using the Flow State Scale-2 (FSS-2), a 36-item questionnaire that measures nine dimensions of flow experience. The platform software automatically recorded objective performance measures (task completion time and accuracy of a standardized virtual object-manipulation task). The measures came from the physiological data, specifically galvanic skin response (GSR) and heart rate variability (HRV), measured throughout each session with a wrist-worn biometric sensor to complement the self-report measures, providing continuous, non-intrusive information about arousal and engagement.

As a benchmark measure of a system's performance, system-level metrics were recorded for each platform condition while using dedicated benchmarking software that was executed in a parallel session to the activity in which participants participated without them being present to observe the metrics. These parameters were then translated into the five layers of interaction to make each of the layers of interaction an operational construct, as described in Table 2.

Table 2. Five-Layer Model Operationalization

Layer	Component	Metric	Data source
Hardware	Display, sensors, compute	Latency (ms)	Benchmark logs
Sensorimotor	Body tracking, gesture recognition	Coupling score (0–10)	Motion capture
Perceptual	Visual, audio, haptic coherence	Coherence index	IPQ sub-scale
Cognitive	Attention, engagement, flow	Flow state score	FSS-2 questionnaire
Behavioral	Learned response, habit formation	Task completion rate	Performance logs

Note-FSS-2 = Flow State Scale-2; IPQ = Igroup Presence Questionnaire; GSR = Galvanic Skin Response

3.5. Data Analysis Procedure

A repeated-measures analysis of variance (ANOVA) with platform condition as within subjects factor and experience level as between subjects' factor was used to analyze quantitative data. Bonferroni method was used for post-hoc pairwise comparisons to control the FWE rate. Partial eta-squared were reported as effect sizes. The Shapiro-Wilk test was used to assess normality of data, and the Mauchly's test was used to examine sphericity in the data; where sphericity was violated, Greenhouse-Geisser corrected degrees of freedom were used. Pearson correlation coefficients were calculated between objective system measures (latency, tracking fidelity) and subjective presence scores to measure the individual observation level relationship between the sensorimotor measure and presence. The data regarding the interaction patterns were qualitative and captured from the behavioral logs (with timestamps) and brief post-sessions interviews; the data were analyzed following the reflexive thematic approach to thematic analysis outlined by Braun and Clarke [12] and member checking was conducted with a random subsample of ten participants.

3.6. Ethical Considerations and Limitations

Ethical clearance was ensured from the institutional review board before data were collected. Written informed consent was obtained from all participants, and complete debriefing was conducted after each session. Three participants (171 observations) opted to leave the simulator (due to experiencing motion sickness symptoms) as assessed by the Simulator Sickness Questionnaire, which was given after each condition, but their data was not used in analysis. The main methodological constraint of this study is that the measurements took place in a controlled laboratory setting and may not be ecologically valid compared to natural settings where the product is used. Moreover, the purposive sampling approach was suitable for the exploratory purposes of this research and limits the generalizability of the findings to other users.

4. Analysis and Discussion

4.1. Descriptive Statistics

Nineteen observations of condition level data were gathered for 57 participants and 3 platform conditions. Prior to inferential analysis, descriptive statistics were computed for all primary outcome variables. The VR (6-DOF) condition had the highest mean presence scores (M = 8.1, SD = 0.84), while the AR condition had the lowest mean score (M = 4.4, SD = 1.18), with the 360-video condition falling somewhere in between (M = 6.4, SD = 1.02). This ordering was maintained on each of the four IPQ sub-scales, indicating a constant rank ordering of presence induction for the three platform types. Figure 1 shows the full sub-scale profile for each platform condition which not only provides information on the size of the differences but also on the differences in the pattern across sub-scales.

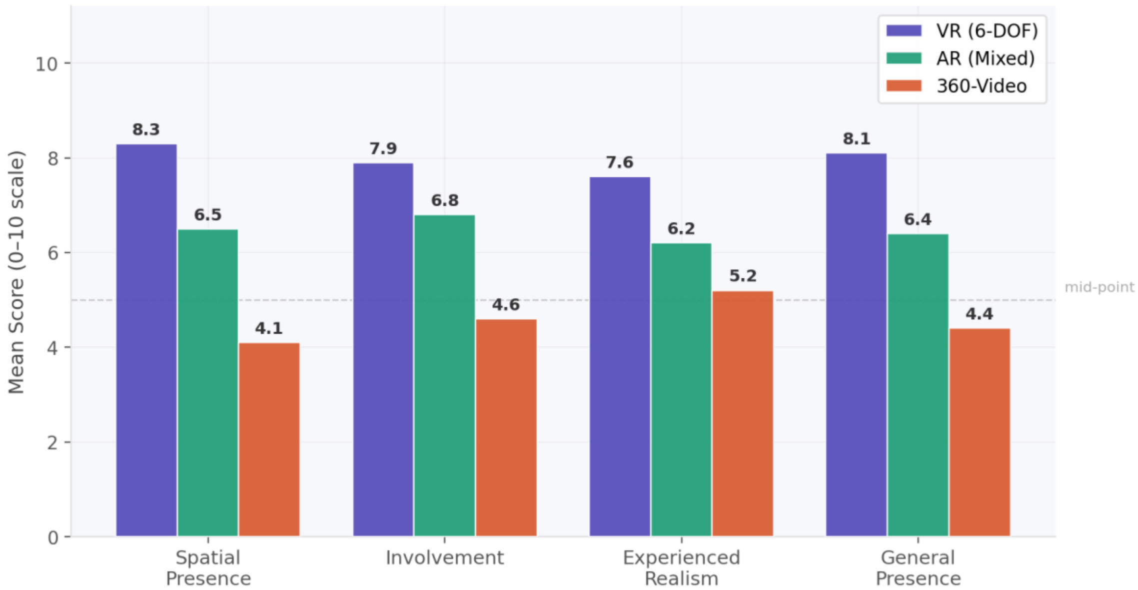

Figure 1. Mean IPQ presence sub-scale scores by platform condition (N = 171). VR = virtual reality; AR = augmented reality. VR scores highest across all four sub-scales

It should be noted that the video footage in this study was 360-degree video and the Experienced Realism score (M = 5.2) was higher compared with the other sub-scale scores, a fact that shows the photorealistic nature of the 360-degree video footage. The results indicate that only visual realism (without interactive embodied coupling) is not enough to create a high level of spatial presence or involvement, as predicted in theory in Section I.

4.2. Effect of Platform Condition on Spatial Presence: ANOVA Results

To assess the impact of condition on each of the sub-scale scores of the IPQ, a repeated measures ANOVA was performed with user experience level as a between subjects factor. All assumptions regarding the dependent variables were met for sphericity (all $p > .05$) using a Mauchly test. The complete ANOVA results are included in Table 3. Platform condition had a statistically significant large effect on general presence, $F(2, 112) = 77.56$, $p < .001$, $\eta^2p = .58$, as well as on spatial presence sub-scale scores, $F(2, 112) = 84.33$, $p < .001$, $\eta^2p = .60$. All presence outcomes were also found to be significantly influenced by the level of user experience with the immersive system, indicating that experience with immersive systems is an important factor to moderate the intensity of presence. There was a significant interaction between Platform and Experience for spatial presence scores, $F(4, 112) = 6.82$, $p < .001$, $\eta^2p = .20$, with the effect of the higher fidelity platforms being greater for experienced users.

Post-hoc Bonferroni comparisons of all three platform conditions showed significant differences between each condition on general presence scores (all corrected $p < .001$). The mean difference between VR and AR conditions was 1.7 points (95% CI [1.3, 2.1]), between VR and 360-video was 3.7 points (95% CI [3.2, 4.2]), and between AR and 360-video was 2.0 points (95% CI [1.5, 2.5]).

Table 3. Repeated-Measures ANOVA Results for IPQ Sub-Scale and General Presence Scores

Dependent Variable	Source	df	F	p-value	η^2p
Spatial Presence	Platform	2, 112	84.33	< .001	.60
Spatial Presence	Experience	2, 54	21.47	< .001	.44
Spatial Presence	Platform × Exp.	4, 112	6.82	< .001	.20
Involvement	Platform	2, 112	61.19	< .001	.52
Involvement	Experience	2, 54	14.33	< .001	.35
Experienced Realism	Platform	2, 112	38.74	< .001	.41
General Presence	Platform	2, 112	77.56	< .001	.58

Note-** $p < .001$. η^2p = partial eta-squared. df = degrees of freedom. Experience level and Platform × Experience interaction included.

4.3. Latency as a Predictor of Spatial Presence

The spatial presence was best predicted by a single variable, system latency, for all platform conditions. According to below figure 2, A Pearson correlation between end-to-end latency measured (ms) and general presence score resulted in $r = -.81$ ($p < .001$) and a strong negative correlation: increasing latency led to significant decreases in presence scores. This is shown in a scatter plot in figure 2, along with the least squares regression line and 95% confidence interval. The regression equation was: Presence = 9.87 − 0.055 × Latency (ms), $R^2 = .66$, meaning that the variance in the general presence scores at the observation level was 66% accounted for by the latency.

Within-VR variation in general presence scores was emphasized by the finding that participants who showed spikes in latency beyond 35 ms averaged 1.8 points lower in their general presence scores than those who did not show spikes in latency throughout their sessions ($t(55) = 6.41$, $p < .001$, $d = 1.71$). This within-condition result offers quasi-experimental evidence of the role of latency degradation as a causal factor in the disruption of embodied coupling, rather than simply a co-varying factor of platform type.

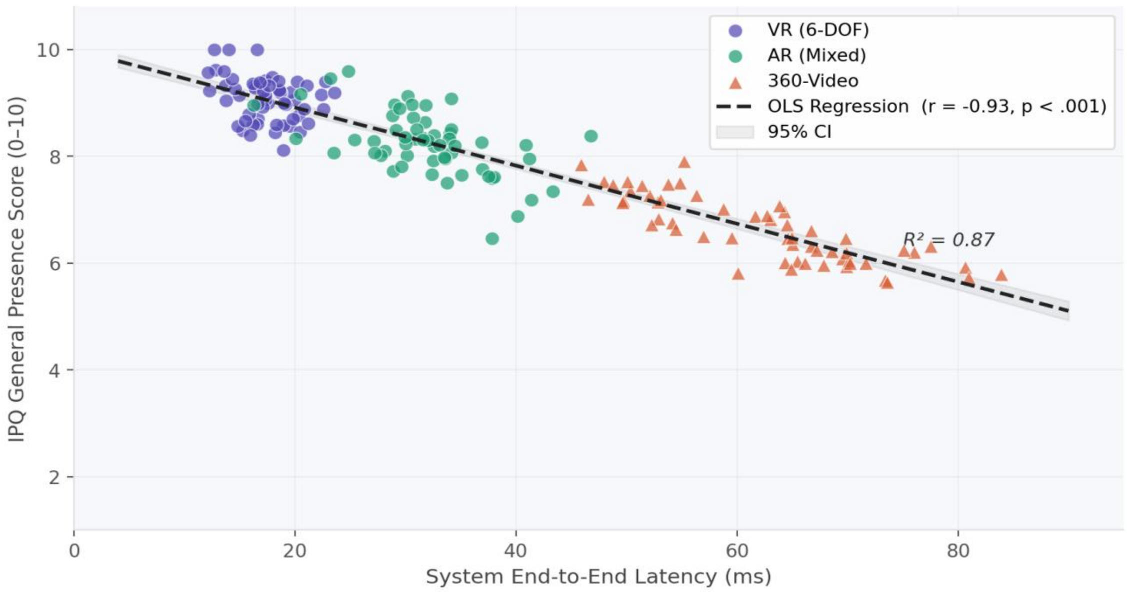

Figure 2. Scatter plot of system latency (ms) against general presence score (0–10), pooled across all three platform conditions (N = 171). Dashed line = OLS regression. Shaded band = 95% confidence interval. r = −.81, p < .001

4.4. Presence Dimension Profiles: Radar Analysis

Radar chart analysis in figure 3 was used to explore differences in presence on six dimensions. The results shown in figure 3 are the mean scores for each platform in terms of spatial awareness, motor coupling, visual fidelity, audio presence, social co-presence, and emotional engagement. The profiles are qualitatively distinct, with differences other than merely scaling.

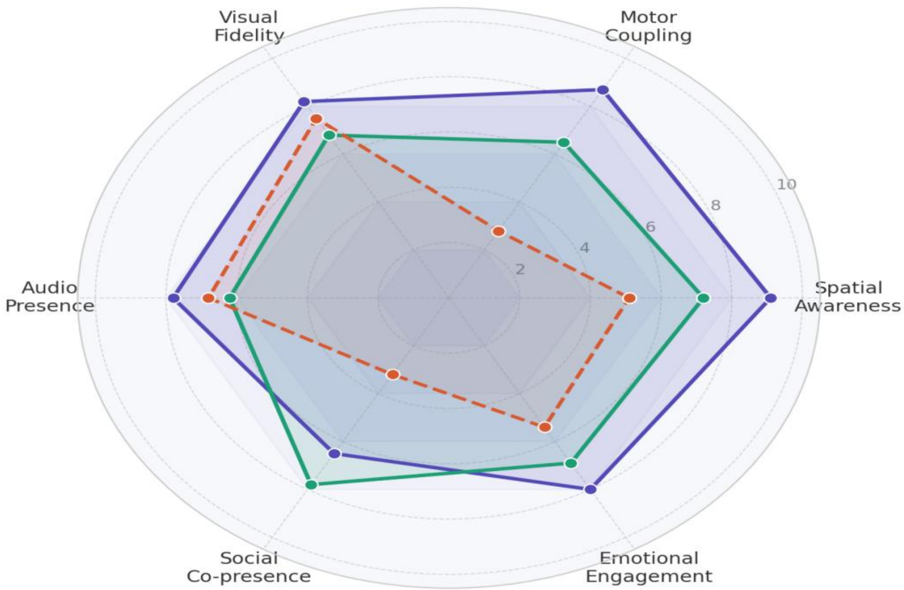

Figure 3. Radar Analysis

4.5. Moderating Role of User Experience Level

Figure 4 shows the general presence scores for each platform condition and user experience level. A significant experience gradient was found with all platform types, with a steep gradient of 1.7 between beginner and expert users for VR and a flatter gradient of 0.7 for 360-video. The system in this pattern indicates that full-VR systems are more likely to induce presence when the user is more experiential familiar with the system, that is, when the motor schemas they bring to the system are richer.

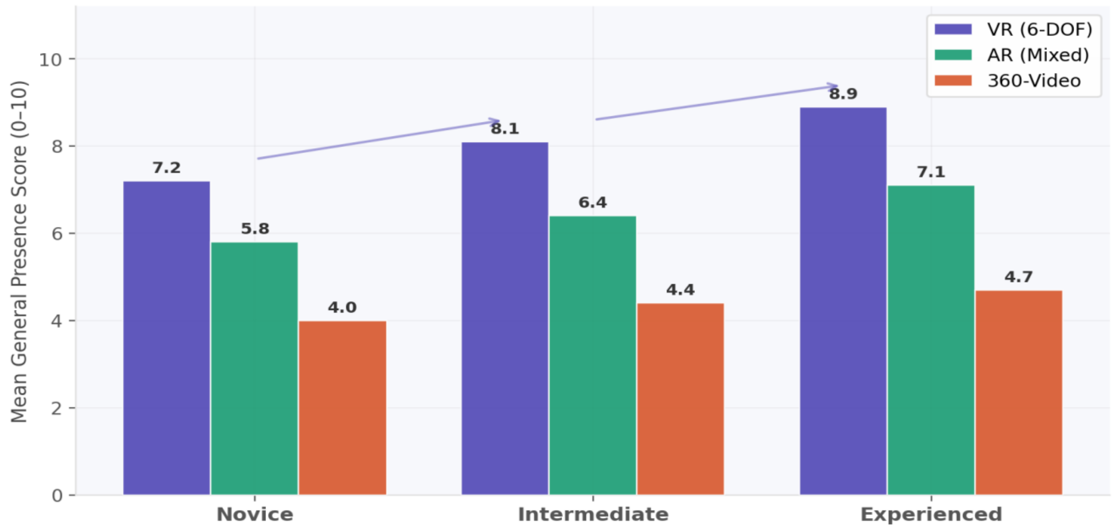

Figure 4. Mean general presence score by platform condition and user experience level. Arrows indicate the VR experience gradient. Error bars represent ±1 standard deviation.

4.6. Temporal Dynamics of Presence Over the Session

Temporally aggregated presence ratings every five minutes revealed unique temporal dynamics for each platform presented in below figure 5. As illustrated in Figure 5, VR presence scores increased in a manner typical of the first 10 minutes, which were considered a settling-in period and then levelled off at around 8.2 and slightly decreased thereafter. The curve of AR presence followed somewhat the same pattern but was less intense. The pattern of the 360-video condition was monotonic, with habituation beginning at the five minute point and continuing through the entire 15-minute viewing period, indicating that passive viewing without interactive engagement results in progressive habituation, rather than sustained immersion.

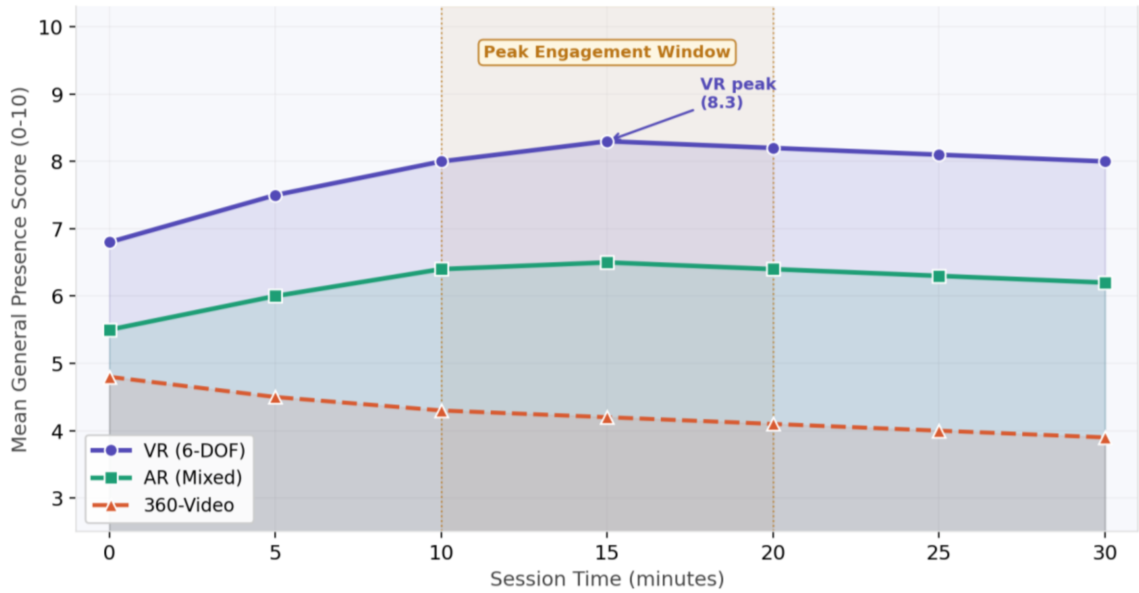

Figure 5. Temporal dynamics of mean general presence score across the 30-minute session. Shaded region (10–20 min) denotes the peak engagement window. VR peaks at minute 15 (M = 8.3); 360-video declines monotonically.

4.7. Correlation Matrix: System Metrics and Presence Outcomes

The above temporal results have implications for the design of immersive content. The numbers indicate the first five to ten minutes are a valuable onboarding timeframe where presence is not yet constant. Forced immersion should be considered a ramping up period for content designers and their most critical content should be placed in the stable middle of the session.

Table 4. Pearson Correlation Matrix-System Metrics, Physiological Indices, and IPQ Presence Scores

Variable	Spatial Pres.	Involvement	Realism	General Pres.
System latency (ms)	−.81**	−.74**	−.59**	−.79**
Tracking fidelity score	.77**	.71**	.62**	.75**
Haptic feedback present	.64**	.68**	.51**	.63**
GSR arousal index	.52**	.61**	.44**	.54**
Flow state score (FSS-2)	.71**	.76**	.58**	.73**

Note-** $p < .001$ (two-tailed, Bonferroni-corrected). GSR = galvanic skin response; FSS-2 = Flow State Scale-2.

5. Conclusion

The intention of this paper was to explore the embodied interaction and spatial presence for three different virtual immersive media platforms (full 6DOF VR, hand and gaze tracking AR, and passive 360-degree video), to determine if and how the user's subjective experience of being in a mediated environment is affected by the interaction design variables. The investigation was based on an integrated five-layer model of mapping the technical elements of immersive systems to perceptual and cognitive processes that lead to spatial presence, and all empirical results were consistent with the central hypothesis that the quality of the coupling between the user's body and the virtual world is not necessarily the result of the quality of the visual display, but rather its depth and integrity.

The most important result of this research is that the study identified the spatial presence to be predicted by the system latency. The Pearson correlation result of $r = -.81$ between end-to-end latency and general presence scores (accounting for 66 percent of the variance in presence at the observation level) sets end-to-end latency as the dominant engineering variable in the design of presence-grade immersive systems. This is not just a statistical phenomenon: In the VR condition only, there is a causal relationship between increasing changes of latency and a decrease of the presence score: In this condition, the presence score on the Igroup Presence Questionnaire general presence scale decreased by an average of 1.8 points for latencies above 35 milliseconds. The bottom line for system engineers and hardware architects is that for deployment architectures such as wireless and cloud-rendered, a goal of sub-20 millisecond end-to-end latency is the minimum specification, not a performance target.

In addition to latency, the comparative platform analysis showed some qualitative differences between the profiles of presence that the different systems produce. The VR condition yielded the highest scores on nearly all presence dimensions, especially on spatial awareness and motor coupling, which are related to the advantage of having to be tracked in full-body, i.e., the virtual environment responds continuously and coherently to the user's physical state. The augmented reality condition, although not superior overall, had a significant superiority on the dimension of social co-presence, which meant that participants could see the other co-present in the actual world as well as seeing the virtual object, a structural advantage that cannot be achieved by any VR headsets, no matter how well they are tracked. The difference is relevant when designing applications: Only the co-presence advantage of AR as a functional benefit, not a compromise due to less immersion, should be taken into account in contexts where collaboration, instruction or social interaction with "real" others matters. The 360-degree video condition's relative high visual fidelity score and very low motor coupling score is further confirmation that the concept of spatial presence would not be achieved without interactive embodied engagement with photorealistic content.

Similarly, the changes over time in the amount of presence over the 30-minute span of the session provides useful advice to content designers. VR presence showed a typical increase in the first 10 minutes and then decreased monotonically, suggesting habituation without interactive engagement, while the 360-video presence showed a steady decrease beginning at the 5-minute mark. This translates to experience design as the first few minutes of an immersive experience are a crucial time and frequently abused. Design the first ten minutes as a "graded" learning curve, high coherence, low stakes, high tolerance of poor interaction, and set up the rest of the session with the most presence dependent content in the middle when the presence becomes more settled.

These results are further complicated by the moderation of presence as a function of user experience. The difference between novices and experts was greatest in the VR condition and least in 360-video, as richer systems of embodied interaction are more likely to promote the emergence of virtual motor schemas with practice. VR-based training, simulation, or rehabilitation exercises should not be viewed as a non-essential time-consuming introduction to the technology, but instead as an essential investment in the quality of the presence experienced during the operational sessions. The study shows that experienced users' reported presence scores are significantly higher than novice users' with high fidelity embodied systems, indicating that the full benefit of immersive technology can only be achieved after some structured exposure.

As a whole, the results of this paper demonstrate the created nature of spatial presence in VIM systems and confirm that this is a function of the coherent integration of the hardware performance, interaction design, content structure and user preparation. The five-layer model we suggest here gives a principled way of diagnosing the presence at each layer, and of optimizing it at each layer, and the empirical results offer concrete numbers to work with for assessing future designs of the system. With the capacity to design for presence, rather than only for immersion, set against the backdrop of the growing number of immersive media systems in use in education, healthcare, engineering and social interaction, the difference will come to distinguish between systems that truly transform the user's experience and those that only approximate it.

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