

PAPER

A Virtual Reality Simulator for 30° Laparoscopic Camera Navigation Training: Psychometric and Kinematic Evaluation of Early Practice

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ABSTRACT

Minimally invasive surgery requires precise visuomotor coordination under indirect vision, fulcrum-mediated instrument motion, and constrained camera handling. Training in 30° laparoscopic camera navigation is clinically relevant but remains difficult to deliver at scale because conventional systems are equipment-dependent and often provide limited objective feedback. The objective of this simulator-based study was to evaluate SECMA, a portable virtual reality (VR) simulator for 30° laparoscopic camera-navigation training, through the joint analysis of structured user-perception data and simulator-derived kinematic performance metrics. The study did not involve clinical trials, patient data, clinical outcomes, or intraoperative performance assessment. The system integrates a mechanically informed interface, real-time stereoscopic visualization, standardized target-centering and horizon-alignment tasks, and continuous six-degree-of-freedom telemetry. Participants with heterogeneous laparoscopic experience completed repeated practice trials and an 11-item ordinal questionnaire. User-perception data were analyzed using a multidimensional graded-response item response theory model, yielding three latent dimensions: perceived realism, utility/interface/feedback, and attitudes toward adoption. Kinematic data were summarized into temporal, spatial, and angular descriptors and analyzed using mixed-effects models. Early practice was associated with shorter completion time and improved path efficiency, while expert–novice differences remained evident. Among the latent perception dimensions, utility/interface/feedback was the most consistently measured and showed the clearest association with path efficiency. These findings support SECMA as a portable, telemetry-rich simulator for laparoscopic camera-navigation training and illustrate how psychometric and kinematic evidence can be integrated to evaluate digital surgical simulators beyond face realism alone.

KEYWORDS

biomedical engineering, surgical simulation, virtual reality (VR), 30° laparoscopic camera navigation, minimally invasive surgery, psychometrics, item response theory, kinematic assessment, telemetry, medical training

Guzmán Montoto, J. I., Herrera-Marín, M., Donoso Carrasco, C. A., Marinkovic Gómez, B., Rodríguez Beltrán, C. I., Trigo Vilches, R. (2026). A Virtual Reality Simulator for 30° Laparoscopic Camera Navigation Training: Psychometric and Kinematic Evaluation of Early Practice. *International Journal of Online and Biomedical Engineering (iJOE)*, 22(10), pp. 22–46. <https://doi.org/10.3991/ijoe.v22i10.62228>

Article submitted 2026-05-14. Revision uploaded 2026-06-24. Final acceptance 2026-06-29.

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1 INTRODUCTION

Minimally invasive surgery has transformed operative care by reducing tissue trauma, shortening recovery time, and improving postoperative outcomes in multiple clinical domains. At the same time, it introduces a demanding human–technology interface: the surgeon and the assistant operate through long instruments, indirect two-dimensional or stereoscopic visualization, constrained trocar access, and camera-mediated perception of the operative field. In this setting, the laparoscopic camera is not a passive imaging device. It is a central component of the surgical workflow because it determines the visual frame within which dissection, exposure, instrument coordination, and team communication occur.

Training the operator responsible for camera navigation is therefore a biomedical engineering problem as much as a pedagogical one. The task requires sustained visuomotor control, depth regulation, angular stabilization, and continuous alignment of the field of view. In 30° laparoscopy, this challenge is intensified because the optical axis is oblique: rotating the scope changes the visual direction, while shaft manipulation changes position and perspective. The trainee must learn a coupled mapping between proximal hand motion, distal camera motion, and screen-based visual consequence. Poor camera control can degrade visualization, increase cognitive load for the operating team, and interfere with procedural fluency [1]–[5].

Simulation-based training has become a standard strategy for reducing the risks and costs associated with early procedural learning. However, conventional box trainers and high-fidelity laparoscopic simulators have complementary limitations. Box trainers are accessible and clinically intuitive but often require expert supervision and provide limited quantitative feedback. High-end simulators can provide rich virtual environments and automated scoring but are frequently expensive, institution-bound, and less scalable in resource-constrained educational settings [6]–[8]. These limitations motivate the development of portable, low-cost, and instrumented systems that preserve clinically relevant interaction constraints while generating objective performance data.

Virtual reality (VR) is increasingly used in medical and surgical education, but its educational value cannot be inferred from immersion or visual realism alone. A simulator is useful only if it reproduces action-relevant constraints, supports structured practice, and produces interpretable evidence of behavioral adaptation [9]–[12]. In the specific case of laparoscopic camera navigation, the key question is not whether the system looks like an operating room, but whether it captures enough of the embodied control problem to support measurable practice, expert–novice discrimination, and meaningful feedback.

The SECMA platform (*Sistema de Entrenamiento Portátil para Cirugías de Mínimo Acceso*) was developed to address this need. Previous work demonstrated the feasibility of portable, telemetry-rich VR training for minimally invasive skills [13]. The present manuscript aligns the system with the scope of online and biomedical engineering by emphasizing its role in laparoscopic camera-navigation training, its measurement architecture, psychometric validity evidence, and kinematic sensitivity to early practice.

The central objective of this study is to evaluate a portable VR-based simulator for 30° laparoscopic camera-navigation training through the joint analysis of user-perception data and objective kinematic performance. The validation evidence reported here is explicitly simulator-based: it refers to psychometric structure,

early practice sensitivity, expert–novice discrimination, and simulator-derived motion metrics. It does not constitute a clinical trial, and it does not claim validation against patient outcomes or intraoperative performance. The study addresses four questions. First, can a compact mechanical–VR system preserve the core action constraints of 30° laparoscopic camera manipulation? Second, does the standardized task elicit measurable early practice effects and expert–novice differences? Third, can user perception be represented as a structured multidimensional latent construct rather than as a single satisfaction score? Fourth, are latent perceptions of utility, interface quality, and feedback associated with objective behavioral efficiency?

The contribution is methodological and relevant to biomedical engineering. Technically, the paper describes a portable system that combines a mechanically informed interface, real-time VR rendering, continuous six-degree-of-freedom telemetry, and automated data capture. Analytically, it integrates multidimensional item response theory and mixed-effects kinematic modeling. Educationally, it provides evidence that portable VR can support objective assessment of a clinically relevant but under-instrumented component of minimally invasive surgery.

2 RELATED WORK

2.1 Surgical simulation and laparoscopic skills training

Simulation-based education is widely used to support procedural learning before trainees operate on patients. In laparoscopic surgery, simulation has been used to develop psychomotor skills, hand–eye coordination, bimanual control, and proficiency-based progression [9], [14]–[16]. Validation studies have traditionally focused on content validity, construct validity, concurrent validity, and predictive value for later performance [17], [18]. More recent work emphasizes the importance of scalable and affordable platforms that can extend training outside specialized simulation centers [19]–[21].

Camera navigation has received less attention than tasks such as peg transfer, suturing, or knot tying, even though it is essential for procedural visualization. Existing studies show that laparoscopic camera navigation can be trained and assessed in both physical and virtual environments, including tasks involving deviated optical angles and camera-control-specific protocols [3], [4], [22]–[24]. Nevertheless, many platforms still depend on instructor observation, endpoint completion, or global time scores, and they rarely integrate user-perception modeling with objective kinematic telemetry.

2.2 VR as a biomedical engineering platform

In biomedical engineering, VR should be understood not only as a display technology but also as an integrated sensing, interaction, and feedback platform. For surgical training, this distinction is critical. Visual realism may support acceptance and ecological credibility, but skill acquisition depends strongly on interaction fidelity: whether the physical and virtual controls reproduce the constraints, contingencies, and feedback loops that shape the target task [25]–[28]. A low-cost simulator can therefore be scientifically valuable if it preserves clinically meaningful action–effect relations and records objective performance data.

This perspective is particularly relevant to 30° laparoscopic camera handling. The camera operator must coordinate shaft insertion, fulcrum-mediated angular motion, optical rotation, image centering, and horizon stabilization. A VR simulator for this task should therefore reproduce a constrained motor-control problem rather than merely provide a visual scene. The present system adopts this principle by combining a physical interface with real-time VR control and telemetry logging.

2.3 Psychometric and kinematic assessment in digital training systems

A recurring limitation in simulation studies is the separation between subjective evaluation and objective performance analysis. Questionnaires are often treated as ancillary satisfaction instruments, while motion data are reduced to a few global metrics. This separation makes it difficult to understand whether perceived system qualities are related to actual behavior. In human-centered biomedical engineering, user perception should be measured with the same care as kinematic performance, because interface clarity, feedback quality, and perceived usefulness can shape engagement and motor organization [10], [29], [30].

The present study addresses this gap by modeling post-task user perception with multidimensional graded-response item response theory (IRT) and linking the resulting latent scores to repeated-measures kinematic outcomes. This approach provides a structured way to distinguish perceived realism, perceived utility/interface/feedback, and adoption-related attitudes while evaluating whether those dimensions are associated with temporal and spatial efficiency.

3 MATERIALS AND METHODS

3.1 System overview

SECMA is a portable VR-based platform for minimally invasive surgery training. For the 30° laparoscopic camera-navigation module, the system combines three layers: a physical interaction layer, a VR training and evaluation layer, and a backend data-management layer. The physical layer provides a compact mechanical interface that approximates trocar-constrained camera manipulation. The VR layer maps user motion into a standardized virtual task and provides real-time visual feedback. The backend layer stores trial-level telemetry, event markers, and derived metrics for downstream analysis.

Figure 1 situates the proposed platform relative to a reference laparoscopic camera system and a conventional physical training configuration. The figure is included only to contextualize the components and handling constraints that motivated the simulator design. It does not depict a clinical trial, patient intervention, or source of clinical data. The intention of SECMA is not to reproduce the entire operating-room ecosystem but to preserve the interaction constraints most relevant to camera manipulation and make them measurable in a portable simulator.

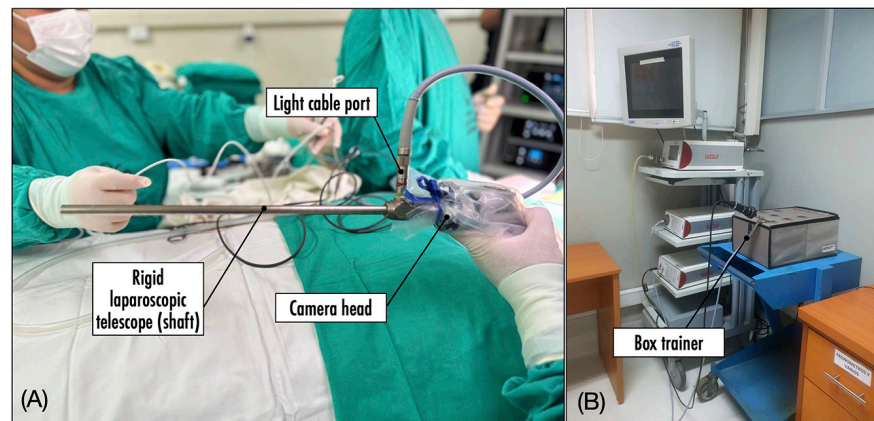


Fig. 1. Reference configuration for laparoscopic camera-navigation training: (A) Representative rigid laparoscope showing the telescope shaft, camera head, and light cable port, included to illustrate the components and handling constraints that the simulator aims to reproduce; (B) Conventional laparoscopic tower and box trainer used to contextualize camera handling in minimally invasive surgery training

Note: The images are illustrative reference material and were not obtained from clinical procedures; no patient data are shown.

3.2 Mechanical interface and task-specific design rationale

The physical assembly consists of a telescopic shaft mounted on a compact base with a jointed structure that approximates the trocar pivot. Meta/Oculus Quest controllers are attached through modular connectors that map hand motion to distinct but coordinated control channels. The resulting interface approximates the main degrees of freedom required for laparoscopic camera navigation: pitch, yaw, roll, axial translation, optical redirection, and horizon management.

The design rationale is task-specific rather than purely graphical. In clinical laparoscopy, the camera operator manipulates a rigid optical instrument through a small access point. This creates a fulcrum effect in which proximal hand displacement and distal image motion are coupled in a non-intuitive way. The system therefore emphasizes action-relevant fidelity: the preservation of clinically meaningful movement constraints and visual consequences. Figure 2 shows the physical interface and representative system use.

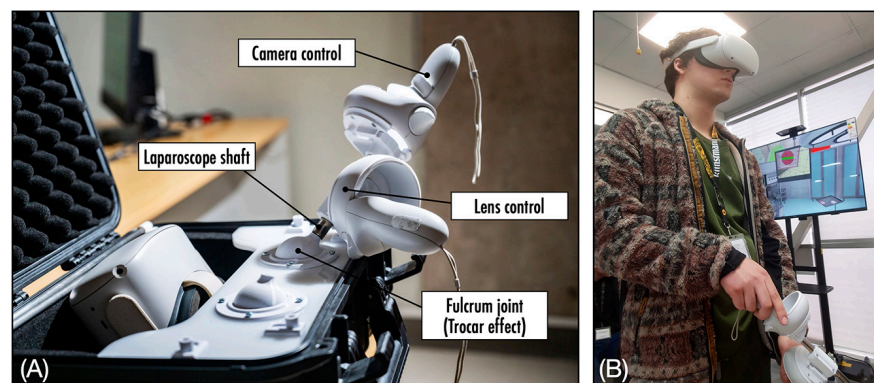


Fig. 2. Physical interface and representative use of the SECMA 30° camera-navigation platform: (A) Portable mechanical interface showing the laparoscope shaft, control modules, and fulcrum-like joint; (B) Example of participant interaction with the system during the virtual training task

Note: The interface was designed to preserve the embodied constraints of angled laparoscopic camera manipulation in a compact and low-cost device.

3.3 Decoupled control logic

A distinctive property of the system is its decoupled control structure. In 30° laparoscopy, image direction depends not only on where the shaft points but also on how the angled optic is rotated. The operator must therefore manage two related but separable goals: directing the field of view and maintaining a usable horizon. SECMA reproduces this burden by assigning camera orientation, optical redirection, and horizon stabilization to coordinated hand actions. This design requires participants to form a stable internal mapping between physical manipulation and visual consequence.

3.4 Immersive visual implementation and technical characteristics

The task was implemented as an immersive first-person VR experience. The virtual viewpoint corresponded to the operative camera perspective rather than to an external observer perspective. The headset provided stereoscopic rendering and six-degree-of-freedom tracking of the head and controllers. The module used real-time visual cues for target centering and stripe alignment. These cues were not intended to increase photorealism; rather, they were designed to support interpretable feedback during skill execution.

The Meta Quest 2 headset provides a nominal resolution of 1832×1920 pixels per eye and supports refresh rates of 72, 90, and 120 Hz depending on configuration [31]. The present system used six-degree-of-freedom controller tracking. Eye tracking was not available and was not used. End-to-end latency and optical field of view were not independently benchmarked in this study; therefore, claims are restricted to nominal device specifications and observed real-time operation within the expected performance envelope for interactive VR applications [32].

3.5 System architecture

The complete SECMA architecture is shown in Figure 3. The simulator core integrates the physical interface with the real-time VR task. During each trial, interaction data are acquired continuously and transmitted to the backend layer. This architecture supports storage, report generation, quantitative assessment, and future AI-based feedback modules. The system therefore functions not only as a training simulator but also as a simulation-based data-acquisition and assessment platform.

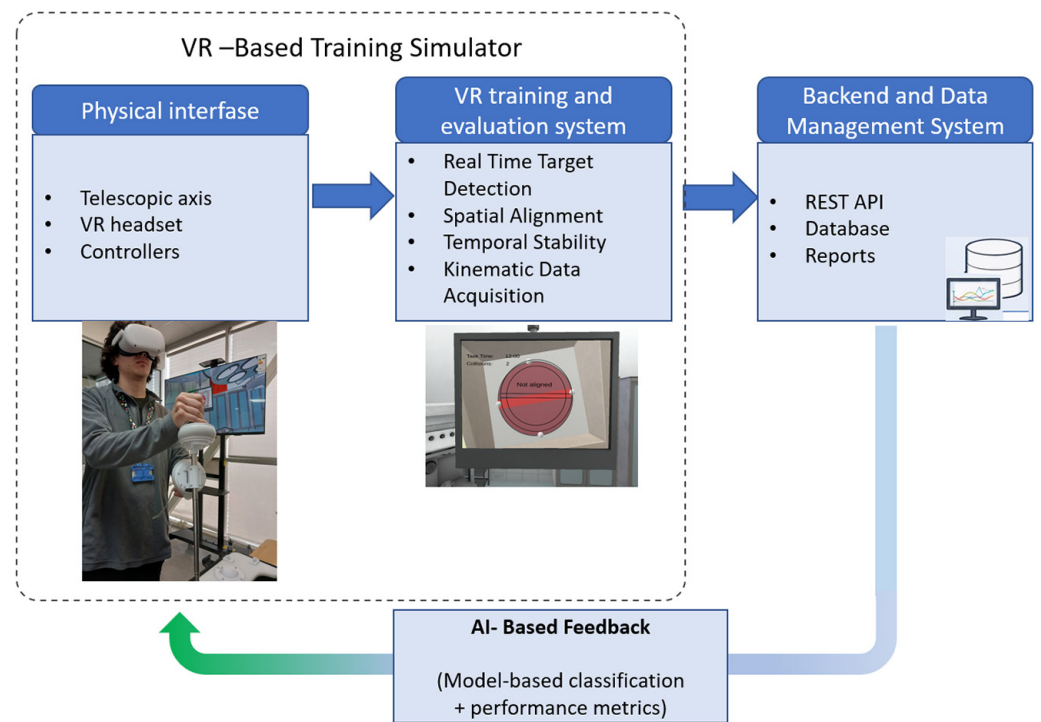


Fig. 3. Architecture of the SECMA VR-based laparoscopic camera-navigation training platform

Note: The simulator core combines the physical interface and the VR training and evaluation system. Interaction data are continuously acquired and transferred to backend storage, enabling report generation, quantitative analytics, and future AI-based feedback.

3.6 Standardized camera-navigation task

The virtual task was designed to reproduce the perceptual and motor demands of 30° laparoscopic camera navigation. Participants were required to coordinate translational and rotational camera movements while maintaining a sustained visual-alignment condition. The virtual scene contained six open containers placed at different positions and orientations within a bounded workspace. Each container included a circular red target crossed by a horizontal stripe. For each target, the participant had to approach the container and satisfy two simultaneous visual criteria: target centering and horizon alignment. Importantly, task evaluation was performed in the image plane of the virtual endoscopic camera rather than through a purely three-dimensional distance criterion. Each target was represented by four control points in three-dimensional space. These points were projected onto the normalized image plane of the virtual endoscopic camera, located at the distal tip of the instrument and configured to emulate a 30° laparoscopic lens, using Unity's `WorldToViewportPoint` function.

Let $\mathbf{u}_i(\mathbf{t}) \in \mathbb{R}^2$, $i = 1, \dots, 4$, denote the projected image-plane coordinates of the four target control points at time $\mathbf{t}$. A predefined circular ring region in the normalized image plane was denoted by Ω . The number of projected control points lying inside this region was computed as $N(\mathbf{t}) = \sum_{i=1}^4 \mathbf{1}\{\mathbf{u}_i(\mathbf{t}) \in \Omega\}$. Target centering was considered successful when all four projected control points were contained within the ring region, that is, when $N(\mathbf{t}) = 4$. This criterion ensured that centering was assessed according to the visual appearance of the target in the endoscopic image, rather than according to Euclidean proximity in the three-dimensional virtual environment.

Horizon stabilization was assessed from the projected orientation of the target stripe. Two control points, denoted by $\mathbf{p}_3$ and $\mathbf{p}_4$, were defined in three-dimensional space to represent the horizontal direction of the target. These points define the reference orientation of the target in the virtual scene. At time $\mathbf{t}$, the points were projected onto the normalized image plane of the virtual endoscopic camera, yielding coordinates $\mathbf{u}_3(\mathbf{t})$ and $\mathbf{u}_4(\mathbf{t})$. The apparent stripe direction in the image was

then represented by the unit vector $\mathbf{h}(\mathbf{t}) = \frac{\mathbf{u}_4(\mathbf{t}) - \mathbf{u}_3(\mathbf{t})}{\|\mathbf{u}_4(\mathbf{t}) - \mathbf{u}_3(\mathbf{t})\|}$. This vector describes the

orientation of the stripe as perceived through the camera view and is therefore used to quantify horizon stabilization. The angular deviation of this projected direction from the horizontal image axis was then computed as $\theta(\mathbf{t}) = \cos^{-1}(|\mathbf{h}(\mathbf{t}) \cdot \mathbf{e}_x|)$, where $\mathbf{e}_x = (1, 0)$ denotes the horizontal unit vector of the image plane. Horizon alignment was considered acceptable when $\theta(\mathbf{t}) < \epsilon_\theta$. A target was marked as completed only when both criteria, full target centering and acceptable horizon alignment, were satisfied simultaneously and maintained continuously for at least three seconds. Once this temporal persistence condition was met, the system registered the target as completed and the participant advanced to the next target.

This image-plane formulation was chosen to make the assessment consistent with the visual information available to the user during laparoscopic navigation. In clinical camera handling, the operator acts primarily on the basis of the endoscopic image rather than on direct access to the three-dimensional geometry of the operative field. By evaluating centering and horizon stabilization after projection onto the virtual camera plane, the task better captures the perceptual basis of 30° laparoscopic camera control. The three-second persistence criterion also prevents brief or accidental alignments from triggering task completion, thereby improving the robustness and reliability of the automated evaluation.

3.7 Telemetry and event logging

During each trial, the system recorded time-stamped six-degree-of-freedom telemetry comprising camera-tip position (x, y, z), quaternion orientation (q_w, q_x, q_y, q_z), and event markers for target acquisition and alignment validation. The nominal sampling rate was 80–100 Hz, sufficient to capture both trajectory geometry and short bursts of angular reorientation. This telemetry architecture made it possible to replace binary completion or subjective instructor judgment with reproducible trial-level kinematic descriptors.

3.8 Participants and study design

Participants were recruited to span a range of laparoscopic experience. The novice group comprised medical students or junior trainees without routine hands-on experience in laparoscopic camera handling. The expert group comprised board-certified surgeons or senior residents with prior exposure to minimally invasive procedures and regular use of laparoscopic visualization systems.

Each participant completed a short familiarization period followed by three recorded practice repetitions of the six-target camera-navigation task. After the interaction session, participants completed an 11-item ordinal questionnaire

focused on their experience with the system. The dataset therefore contained two linked layers: participant-level perception data and trial-level motion data. All analyzed data were generated inside the SECMA VR simulator; no patient data, intraoperative video, clinical imaging, or clinical outcome data were collected.

Because the questionnaire was administered after task execution, the relationship between latent perception scores and performance was interpreted as associative rather than causal. More favorable evaluations may reflect better perceived interface quality, but they may also be influenced by prior ability, motivation, technological familiarity, or the participant's own performance during the task.

3.9 Questionnaire design

The questionnaire targeted three conceptual domains: perceived realism of the virtual environment and camera-control experience; perceived utility, interface clarity, guidance, feedback, and ease of configuration; and adoption-related attitudes, including motivation, perceived importance, and willingness to reuse the system. All responses were ordinal, with higher categories indicating more favorable evaluation. Item-wise response distributions were inspected before model fitting to identify sparse categories, skewness, and possible ceiling tendencies. Polychoric correlations were used to summarize latent associations between items.

3.10 Multidimensional graded-response IRT model

Let Y_{ij} denote the ordinal response of participant i to item j . Under the graded-response formulation,

$$\Pr(Y_{ij} \geq k | \theta_i) = \text{logit}^{-1}(a_j^\top \theta_i - b_{jk}),$$

where $\theta_i = (\theta_{i1}, \theta_{i2}, \theta_{i3})^\top$ is the participant-specific latent vector, a_j is the discrimination vector, and b_{jk} are ordered category thresholds. The three dimensions were interpreted as F1: realism, F2: utility/interface/feedback, and F3: attitudes/adoption.

Models were estimated in R using the **mirt** package [33]. In addition to the pre-specified three-factor model, one- and two-dimensional graded-response alternatives were estimated for comparison. Global fit was summarized with M2-based indices when available, and local dependence was examined using Q3 residuals. An expected a posteriori factor score was extracted for downstream mixed-effects modeling.

The multidimensional structure was interpreted as a theory-guided representation rather than as a finalized psychometric instrument. This conservative interpretation is important because the questionnaire was short and the sample size was modest for highly parameterized latent modeling.

3.11 Exploratory dimensionality assessment

Dimensionality checks were carried out to verify that the response structure was empirically compatible with a multidimensional interpretation. These checks included scree inspection, parallel analysis, and exploratory factor analysis of the polychoric matrix using oblique rotations. Their purpose was not to establish a final

scale but to determine whether the confirmatory structure was broadly consistent with the observed item geometry.

The diagnostic outputs from these exploratory checks are summarized in Figure 4, which combines item-level response distributions with the polychoric correlation structure used to evaluate whether the questionnaire supported a multidimensional interpretation.

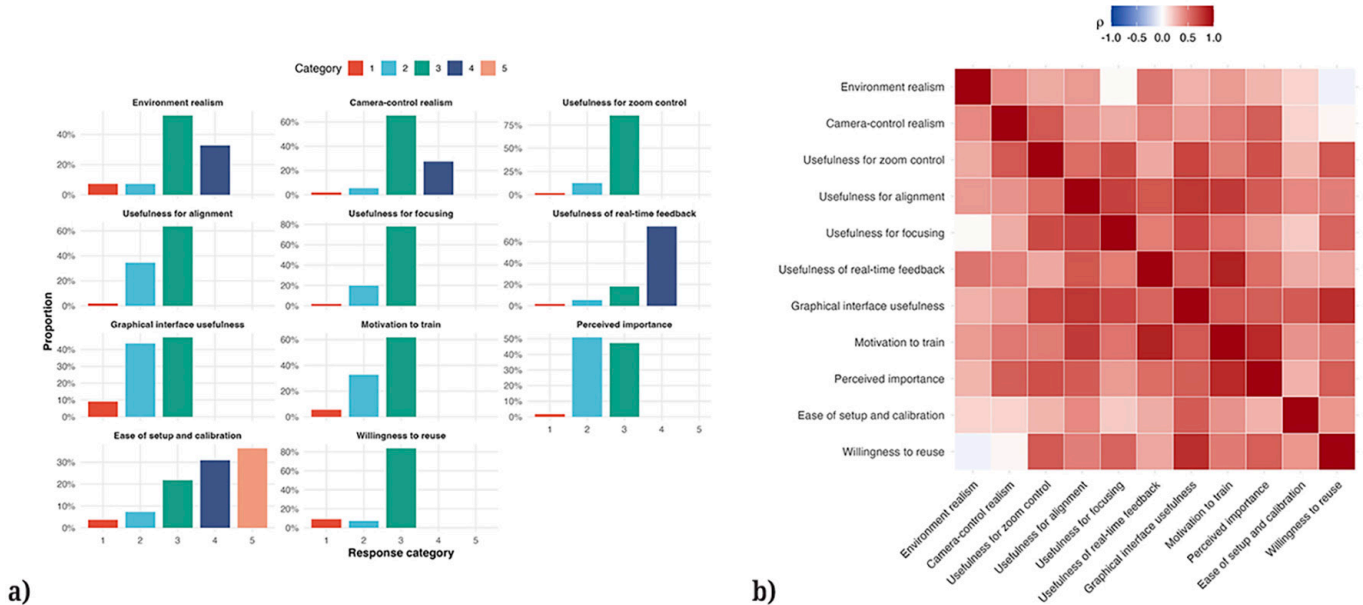


Fig. 4. Psychometric structure of the post-task questionnaire: (A) Ordinal response distributions by item, ordered by construct, showing favorable evaluations without complete ceiling collapse; (B) Polychoric correlation matrix, showing a coherent block among utility/interface/feedback items and a related but distinguishable realism component

3.12 Kinematic preprocessing and outcome selection

Raw telemetry trajectories differed in duration and number of samples across participants and trials. Each trajectory was sorted by timestamp, duplicate timestamps were removed, finite-valued pose records were retained, and quaternion representations were normalized when required. Translational increments were used to derive path length, direct displacement, speed, and path-efficiency descriptors. Quaternion increments and Euler-angle reconstructions were used to derive angular-speed and orientation-stability descriptors.

The primary outcomes were total completion time and path efficiency. Total completion time was defined as the elapsed time from trial onset to completion of the sixth target. Path efficiency was defined as

$$\text{Path efficiency} = \frac{\|x_{\text{end}} - x_{\text{start}}\|}{\sum_t \|x_{t+1} - x_t\|}.$$

This metric increases when the translational path becomes more geometrically economical. Secondary outcomes were excess path, defined as total path length minus direct displacement, and angular P95, defined as the 95th percentile of instantaneous angular speed. This compact outcome set was chosen because it captures temporal efficiency, translational economy, and upper-end orientational control while avoiding overreliance on a single omnibus tortuosity score.

3.13 Mixed-effects models

Early practice-related change was analyzed using linear mixed-effects models. For each outcome, the baseline model was

$$Y_{ij} = \beta_0 + \beta_1 \text{Practice}_j + \beta_2 \text{Group}_i + u_i + \varepsilon_{ij},$$

where u_i is a subject-specific random intercept. Psychometric-linked models added F1, F2, or F3 as participant-level covariates. A model including all three factors was also estimated. Exploratory models examined practice-by-factor interactions, but these were interpreted conservatively.

Models were fitted in R using lme4, with inferential summaries based on the lmerTest workflow [34], [35]. Model comparison relied primarily on AIC, interpreted jointly with effect estimates and confidence intervals.

3.14 Ethics and AI-assisted preparation disclosure

All procedures involving human participants were reviewed and approved by the corresponding institutional ethics committee (approval No. 11102023JGM) and were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before data collection.

Generative AI tools were used to support language editing, clarity, and journal-style refinement during manuscript revision. All scientific content, analyses, interpretations, references, and final wording were reviewed by the authors, who remain fully responsible for the submitted manuscript.

4 RESULTS

4.1 Response distributions and latent response structure

Item-level response distributions showed globally favorable evaluation of the SECMA module but did not show complete ceiling collapse (see Figure 4A). Realism-related items retained greater dispersion, whereas several utility, motivation, and reuse items were shifted toward higher response categories. This pattern suggests that participants did not respond through a single undifferentiated positive halo.

The polychoric correlation matrix supported this interpretation (see Figure 4B). Interface clarity, usefulness, feedback, and motivational engagement formed a coherent block of positive associations, consistent with a shared latent utility/interface/feedback construct. Realism items correlated with this block but remained partially separable.

4.2 IRT model comparison and empirical reliability

Table 1 summarizes the comparative fit of one-, two-, and three-dimensional graded-response models. The three-factor specification was retained because it aligned with the conceptual organization of the questionnaire and provided a behaviorally useful decomposition of perception into realism, utility/interface/feedback, and adoption-related attitudes. However, the 3D model did not dominate the lower-dimensional alternatives according to all global-fit indices. It showed

higher AIC/BIC and less favorable M2-based summaries than the 1D and 2D alternatives in the present sample. The retained structure should therefore be interpreted as a theory-guided analytic representation, not as a definitive psychometric endpoint.

Table 1. Comparative fit indices for graded-response IRT models

Model	AIC	BIC	logLik	M2	df	RMSEA	SRMSR
1D-GRM	911.70	987.98	−417.85	54.92	28	0.133	0.109
2D-GRM	912.13	990.41	−417.06	52.39	27	0.132	0.110
3D-GRM	943.64	1023.93	−431.82	78.61	26	0.194	0.261

Empirical reliability of the extracted factor scores was acceptable for participant-level latent summaries, with values of 0.678 for F1, 0.753 for F2, and 0.774 for F3 (Table 2). F2 and F3 were therefore more stable latent summaries than F1 in this dataset.

Table 2. Empirical reliability of the three latent dimensions in the retained 3D-GRM

Factor	Empirical Reliability
F1 (Realism)	0.678
F2 (Utility/Interface/Feedback)	0.753
F3 (Attitudes/Adoption)	0.774

4.3 Item parameters and measurement information

The item parameters of the retained 3D-GRM are reported in Table 3. The two realism items loaded on F1 with moderate to strong discrimination, especially camera-control realism. The utility/interface items showed consistently strong discrimination on F2, particularly usefulness for alignment, usefulness for focusing, and graphical interface usefulness. The adoption-related items showed strong discrimination on F3, especially motivation to train and perceived importance. Ease of setup and calibration loaded on F3 but showed lower discrimination than the core motivational items.

Table 3. Item discrimination and threshold parameters from the retained three-factor graded-response model

Item	a_1	a_2	a_3	b_1	b_2	b_3	b_4
Environmental realism	1.020	0.000	0.000	−2.969	−2.098	0.852	
Camera-control realism	3.002	0.000	0.000	−2.660	−1.788	0.737	
Usefulness for zoom control	0.000	1.813	0.000	−3.106	−1.515		
Usefulness for alignment	0.000	3.368	0.000	−2.468	−0.370		
Usefulness for focusing	0.000	2.575	0.000	−2.626	−0.919		
Usefulness of real-time feedback	0.000	1.363	0.000	−3.636	−2.406	−1.030	
Graphical interface usefulness	0.000	3.377	0.000	−1.518	0.078		
Motivation to train	0.000	0.000	3.967	−1.831	−0.324		
Perceived importance	0.000	0.000	8.197	−2.392	0.039		
Ease of setup and calibration	0.000	0.000	0.600	−5.708	−3.691	−1.295	0.999
Willingness to reuse	0.000	0.000	1.063	−2.642	−1.911		

Note: Blank cells indicate that a response category threshold was not required for that item in the fitted model.

The information functions further clarified the role of each latent dimension (see Figure 5). F2 distributed information over a broader interval of below-average to near-average latent values, whereas F1 and F3 showed more localized information peaks. This supports the interpretation that utility/interface/feedback was the most consistently measured dimension in the questionnaire.

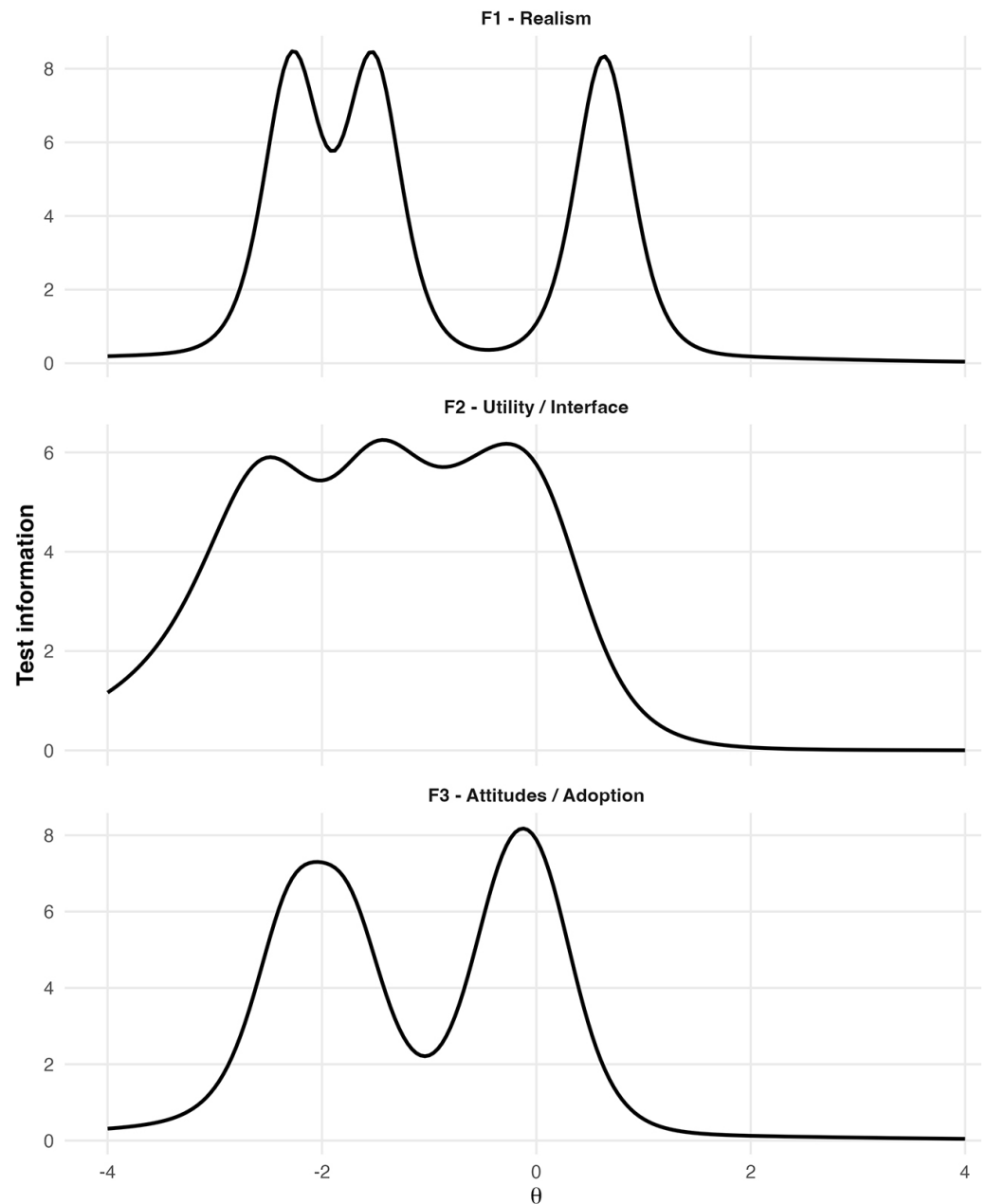


Fig. 5. Test information by latent dimension in the retained three-factor graded-response model

Note: F2 (Utility/Interface/Feedback) provides the broadest and most even information across the central portion of the latent continuum, whereas F1 and F3 show more localized peaks.

4.4 Residual local dependence

Residual Q3 diagnostics indicated that most item pairs did not show problematic local dependence, but several pairs stood out. The largest residual association was observed between usefulness of real-time feedback and motivation to train ($Q3 = 0.504$), followed by graphical interface usefulness with ease of setup/calibration ($Q3 = 0.344$) and graphical interface usefulness with willingness to reuse ($Q3 = 0.289$). These patterns indicate that some items share additional covariance beyond the targeted latent dimensions, likely because they reflect overlapping aspects of usability and engagement. This finding reinforces the conservative interpretation of the questionnaire as an informative but preliminary measurement layer.

4.5 Early practice effects in temporal and spatial performance

Across the three recorded repetitions, participants showed clear early practice-related improvement. Total completion time declined across repetitions, while experts remained systematically faster than novices. In the baseline model, practice was associated with lower log-total time ($\beta = -0.173$, $SE = 0.032$, 95% CI $[-0.238, -0.108]$, $p < 0.001$), and novice status was associated with slower performance ($\beta = 0.618$, $SE = 0.109$, 95% CI $[0.396, 0.840]$, $p < 0.001$).

Path efficiency also increased across repetitions, indicating more economical translational organization. In the baseline model, path efficiency improved with practice ($\beta = 0.0216$, $SE = 0.0086$, 95% CI $[0.0045, 0.0387]$, $p = 0.014$) and was lower in novices ($\beta = -0.0639$, $SE = 0.0210$, 95% CI $[-0.1066, -0.0213]$, $p = 0.004$). These results show that the task was both practice-sensitive and expertise-sensitive.

Descriptive summaries for the primary and selected secondary outcomes are reported in Table 4. The same early-practice pattern is visualized in Figure 6 for total completion time and in Figure 7 for path efficiency, showing the temporal reduction and spatial-efficiency improvement across repetitions by expertise group.

Table 4. Descriptive summaries of the primary and selected secondary outcomes by expertise group and practice repetition

Group	Practice	Total Time (s)	Path Efficiency	Angular P95	Horizon Instability
Expert	2	86.30 (40.02)	0.149 (0.093)	1.743 (0.740)	0.739 (0.172)
Expert	3	69.11 (27.31)	0.168 (0.101)	1.882 (0.920)	0.762 (0.135)
Expert	4	55.97 (17.52)	0.193 (0.090)	1.714 (0.833)	0.834 (0.354)
Novice	2	143.29 (66.26)	0.102 (0.048)	1.681 (0.781)	0.820 (0.211)
Novice	3	102.37 (53.85)	0.117 (0.054)	1.475 (0.630)	0.731 (0.221)
Novice	4	86.84 (56.73)	0.119 (0.042)	1.489 (0.615)	0.770 (0.198)

Notes: Values are means (SD). Practice labels 2, 3, and 4 denote the three recorded repetitions; Practice 1 was the familiarization trial and was not included in the recorded analysis.

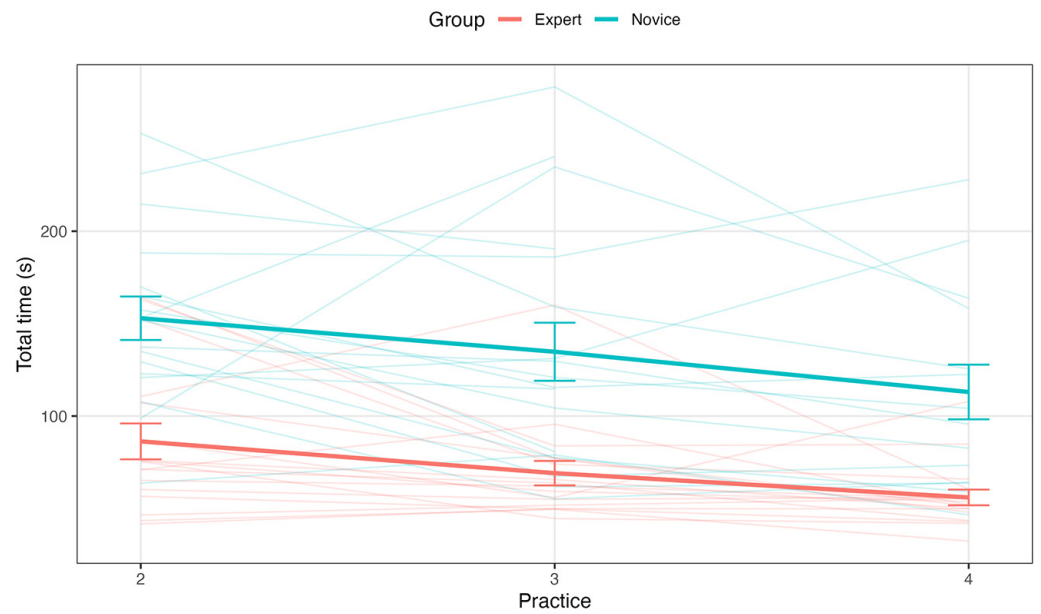


Fig. 6. Total completion time across practices

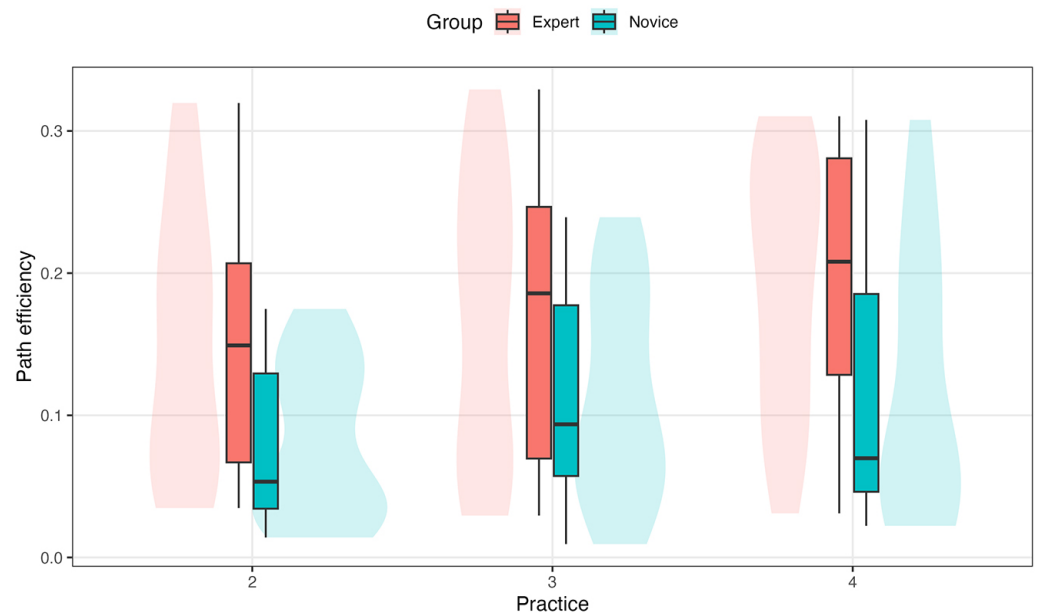


Fig. 7. Path efficiency across practices

4.6 Psychometric associations with objective performance

The psychometric and kinematic layers were linked through mixed-effects models that included latent factor scores as participant-level covariates. The clearest pattern emerged for F2, the utility/interface/feedback dimension. For log-total time, the best-fitting psychometric variant by AIC was the F2 main-effects model (AIC = 62.12 versus 63.23 for F1 and 63.14 for F3 within the linked subset). The F2 coefficient was directionally consistent with faster performance at higher F2 values, although the

confidence interval crossed zero ($\beta = -0.0930$, $SE = 0.0720$, 95% CI $[-0.242, 0.056]$, $p = 0.209$).

For path efficiency, the association with F2 was clearer. In the F2 main-effects model, higher F2 scores were associated with higher path efficiency ($\beta = 0.0292$, $SE = 0.0124$, 95% CI $[0.0037, 0.0546]$, $p = 0.026$), while practice remained positively associated with path efficiency ($\beta = 0.0287$, $SE = 0.0102$, 95% CI $[0.0081, 0.0492]$, $p = 0.007$). The F2 model also improved AIC relative to the other one-factor additions within the linked subset. Thus, the most consistent psychometric signal was an overall association between perceived utility/interface/feedback and more economical translational behavior, rather than a moderation of the practice slope.

The fixed-effect estimates for the main primary-outcome models are reported in Table 5, and the AIC comparison across candidate psychometric-linked models is summarized in Table 6. The corresponding marginal predictions are displayed in Figure 8 for path-efficiency differences and in Figure 9 for total-time differences, providing a visual summary of the association between latent perception scores and objective simulator performance.

Table 5. Selected mixed-effects results for the primary outcomes

Outcome	Term	Estimate	SE	95% CI	<i>p</i>
Baseline model for log-total time					
	Practice	−0.1730	0.0325	[−0.2379, −0.1081]	<0.001
	Novice group	0.6182	0.1094	[0.3960, 0.8404]	<0.001
F2 main-effects model for log-total time					
	Practice	−0.1766	0.0391	[−0.2553, −0.0979]	<0.001
	Novice group	0.5895	0.1434	[0.2931, 0.8858]	<0.001
	F2	−0.0930	0.0720	[−0.2418, 0.0558]	0.209
Baseline model for path efficiency					
	Practice	0.0216	0.0086	[0.0045, 0.0387]	0.014
	Novice group	−0.0639	0.0210	[−0.1066, −0.0213]	0.004
F2 main-effects model for path efficiency					
	Practice	0.0287	0.0102	[0.0081, 0.0492]	0.007
	Novice group	−0.0557	0.0246	[−0.1065, −0.0050]	0.033
	F2	0.0292	0.0124	[0.0037, 0.0546]	0.026

Note: Baseline models were fitted on the full trial-level feature file; psychometric-linked models were fitted on the linked complete-case subset.

Table 6. AIC comparison across mixed-effects models for the primary outcomes within the linked psychometric subset

Outcome	Base	F1 Main	F2 Main	F3 Main	All Main	F1 Int	F2 Int
Log-total time	75.24	63.23	62.12	63.14	66.07	63.86	64.05
Path efficiency	−212.88	−142.98	−145.70	−141.61	−141.75	−141.47	−143.70

Notes: The Base model was fitted on the full trial-level dataset and its AIC is shown for reference only. All psychometric-linked models were fitted on the same linked complete-case subset; therefore, direct AIC comparisons should be restricted to these models. Lower AIC indicates better relative fit among models fitted to the same observations.

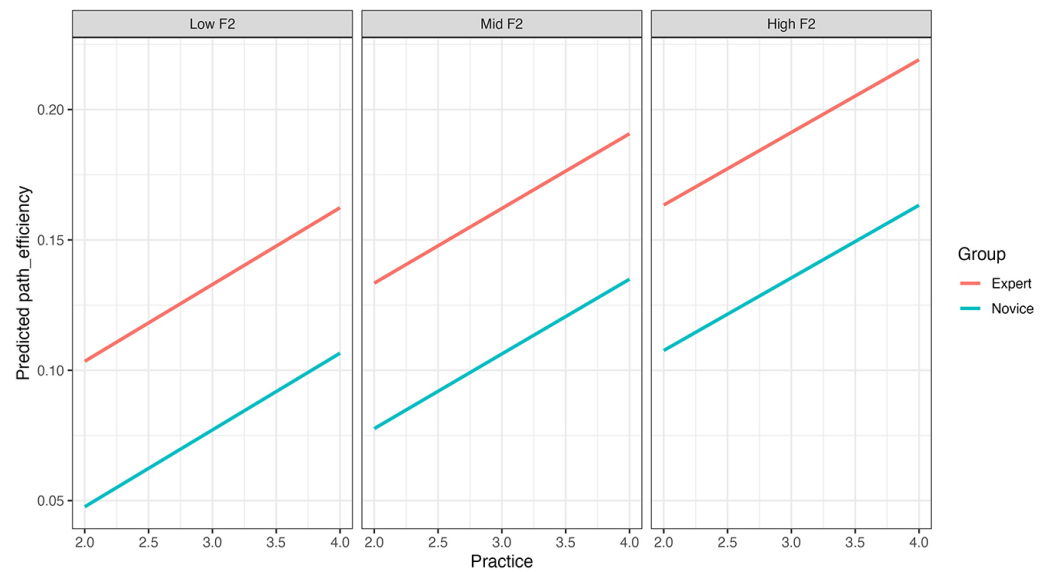


Fig. 8. Marginal predictions

Note: Path-efficiency differences.

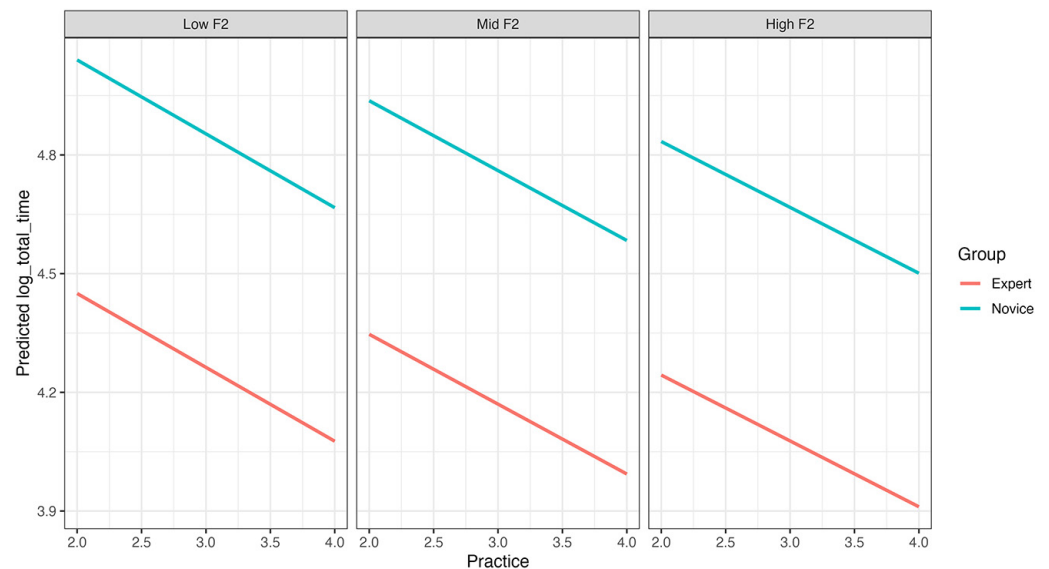


Fig. 9. Marginal predictions

Note: Total-time differences.

4.7 Secondary kinematic descriptors

Among the secondary outcomes, excess path behaved consistently with the primary spatial results. It decreased with practice and remained higher among novices, indicating that repeated exposure reduced redundant translational travel. In the baseline model, practice was associated with lower log-excess path ($\beta = -0.148$, $SE = 0.036$, 95% CI $[-0.220, -0.076]$, $p < 0.001$), and novice status was associated with higher excess path ($\beta = 0.518$, $SE = 0.111$, 95% CI $[0.292, 0.744]$, $p < 0.001$). The best-fitting model for this outcome by AIC was the F1 interaction model, but the interaction estimate did not clearly exclude zero ($\beta = -0.0857$, $SE = 0.0451$, 95% CI $[-0.176, 0.005]$, $p = 0.064$), so this result should be regarded as suggestive.

Angular P95 captured a different dimension of movement style by summarizing upper-end rotational bursts during camera reorientation. It was not strongly practice-sensitive, but novices showed lower log-angular P95 than experts in the baseline model ($\beta = -0.273$, $SE = 0.106$, 95% CI $[-0.487, -0.059]$, $p = 0.014$). Exploratory model comparison suggested that F3 may be more relevant to angular-control descriptors than to the primary temporal and spatial outcomes, although these associations were weaker than the F2–path-efficiency relationship.

The practice trajectories for these secondary descriptors are shown in Figure 10 and Figure 11. Figure 10 summarizes log excess path across repetitions, whereas Figure 11 summarizes angular P95, illustrating that secondary translational and rotational descriptors captured movement-style differences beyond total time alone.

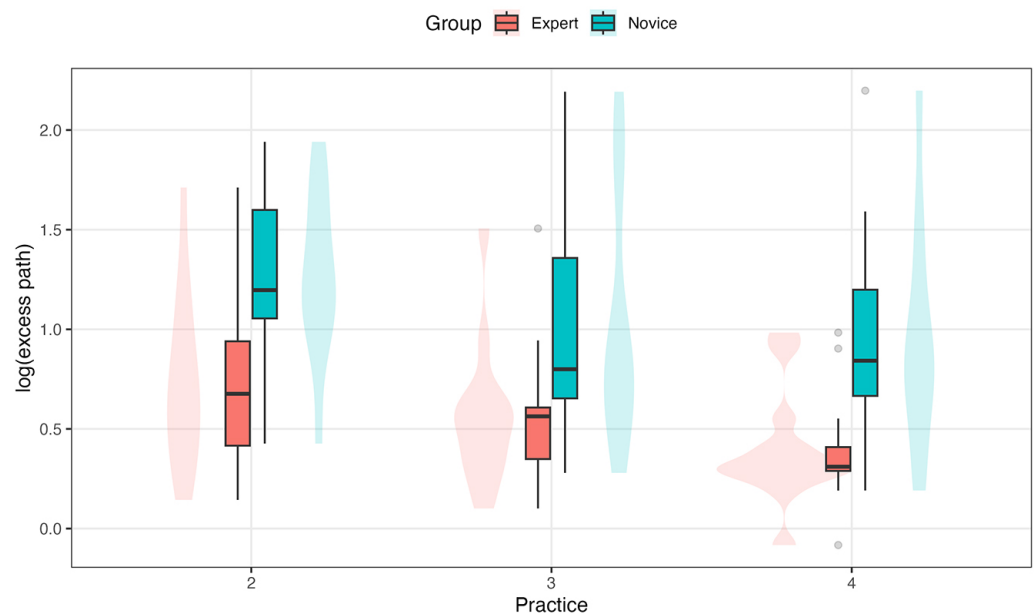


Fig. 10. Log excess path across practices

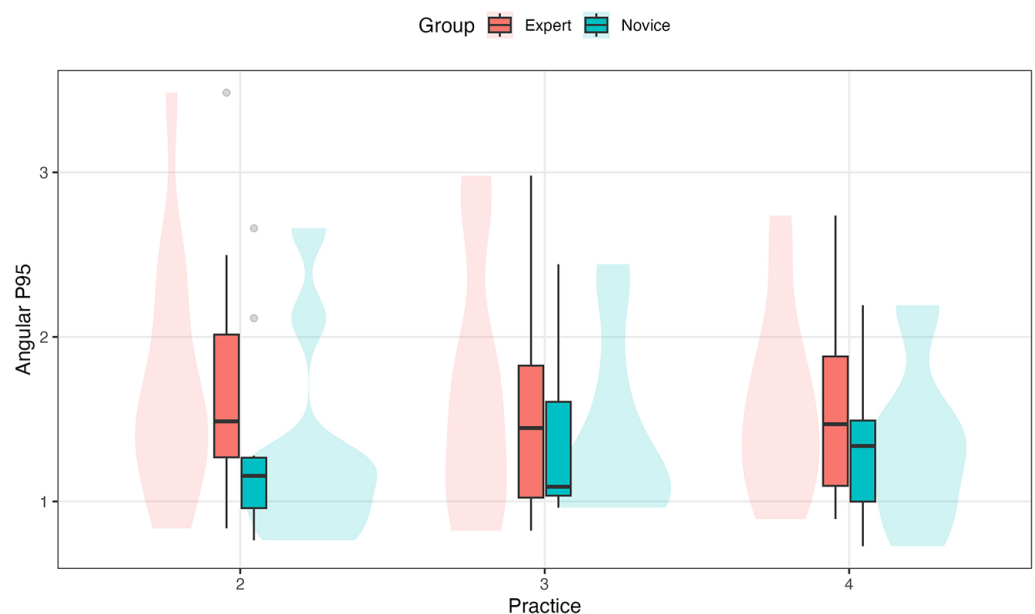


Fig. 11. Angular P95 across practices

5 DISCUSSION

5.1 Relevance of the SECMA camera-navigation module for surgical simulation

This study presents SECMA as a portable VR-based training system for a clinically meaningful component of minimally invasive surgery: 30° laparoscopic camera navigation. The results support three main conclusions. First, the simulator task is sensitive to early practice, as shown by reductions in completion time and improvements in path efficiency. Second, the task preserves expertise-related contrasts, with experts performing faster and more efficiently than novices. Third, user perception is structured and behaviorally relevant: the utility/interface/feedback dimension was the most consistently measured latent factor and showed the clearest association with path efficiency.

The significance of the system lies in its integration of training and measurement within a portable simulator. Conventional camera-navigation practice often depends on physical equipment and instructor observation. SECMA provides an alternative that records dense motion telemetry and supports quantitative analysis. The present evidence should be interpreted as simulator-based validation evidence, not as clinical validation. Within that scope, the results are relevant for distributed surgical education, competency tracking, and future adaptive feedback systems.

5.2 From face realism to measurable training value

A central implication of the study is that simulator evaluation should move beyond face realism alone. Realism remains important because it affects credibility and acceptance, but it is not sufficient. In the present data, the most behaviorally meaningful latent dimension was not realism itself but perceived utility, interface clarity, and feedback. This finding aligns with the concept of action-relevant fidelity: the system must preserve the interaction constraints that organize the target skill and provide feedback that users can interpret during practice.

For biomedical engineering, this distinction is practical. A low-cost VR simulator may be educationally valuable if it captures the correct control problem and records objective performance data, even if it does not reproduce every visual or tactile feature of the operating room. Conversely, a visually sophisticated simulator may be less useful if its interface is opaque or its feedback does not support learning.

5.3 Interpretation of the kinematic outcomes

In practical terms, the kinematic outcomes can be understood as indicators of how efficiently participants controlled the virtual laparoscopic camera during the task. Total completion time reflects how long it took to complete the full sequence of targets. Path efficiency indicates whether the camera followed a more direct and economical trajectory. Excess path represents unnecessary additional movement, while angular P95 captures abrupt rotational adjustments during camera reorientation. These descriptors help translate raw motion telemetry into performance evidence that can be understood by readers without specialized experience in kinematic modeling.

Total completion time was the most robust indicator of early adaptation, but time alone cannot explain how performance changes. Path efficiency and excess path provide complementary information by describing whether users complete the task with more economical translational motion. Angular P95 captures upper-tail rotational bursts and therefore reflects orientational control rather than simple path economy.

This outcome set is better aligned with the mechanics of 30° camera navigation than a single global tortuosity measure. Camera handling requires efficient translation, stable visual framing, and controlled rotation. The selected metrics therefore provide a compact but clinically interpretable summary of performance organization.

5.4 Psychometric transparency

The psychometric analysis is a strength of the study because it avoids treating the questionnaire as a simple satisfaction score. The multidimensional IRT model made it possible to separate perceived realism, utility/interface/feedback, and adoption-related attitudes. At the same time, the model-comparison results and local-dependence diagnostics show that the measurement instrument is preliminary. The retained 3D-GRM is useful for interpretation but should not be considered a finalized scale.

This transparent reporting is important for future development. The current questionnaire can be refined by expanding item coverage, reducing local dependence among usability and engagement items, and adding validated constructs such as presence, workload, cybersickness, and prior VR familiarity. Such refinements would strengthen the ability to relate user experience to objective skill acquisition.

5.5 Implications for online and biomedical engineering

The study is well aligned with the scope of online and biomedical engineering because the platform combines remote-compatible training, digital interaction, biomedical task design, and quantitative analytics. Recent work in technology-enhanced learning further supports this positioning. VR/AR-based mobile interaction has been proposed as a practical approach for virtual simulation training in higher education [36], while recent bibliometric evidence documents the growing role of virtual, augmented, and mixed reality technologies in STEM education [37]. In medical education specifically, VR technology and online teaching systems have been evaluated as tools for supporting medical students' training in contexts where flexible and digitally mediated learning environments are required [38]. SECMA can support distributed practice outside conventional skills laboratories, and its backend architecture enables storage, monitoring, and future data-driven feedback. In this sense, the platform should be understood not only as a VR simulator but also as an online surgical training and assessment system.

The results also suggest a design priority for future systems: investments in calibration, interface clarity, feedback timing, and interpretable guidance may yield greater training value than visual realism improvements alone. These system-level properties are measurable and can be experimentally manipulated in future studies.

5.6 Limitations

Several limitations should be acknowledged. First, the association between psychometric scores and performance is observational. Because the questionnaire was administered after task execution, higher F2 scores may reflect better interface experience, better performance, or both. Second, the practice horizon was short. Three recorded repetitions are sufficient to detect early adaptation but do not establish long-term retention, transfer to physical trainers, or transfer to clinical camera handling. Third, the sample size was modest for complex psychometric modeling and for detecting small practice-by-factor interactions.

Fourth, the questionnaire showed favorable response distributions and some local dependence among usability and engagement items. The instrument should therefore be refined before it is used as a definitive scale. Fifth, the study did not directly measure presence, cybersickness, workload, prior VR exposure, or baseline visuospatial ability. Sixth, the system did not instrumentally benchmark end-to-end latency or field of view. Finally, and most importantly for interpretation, this study does not establish predictive validity for clinical performance or patient outcomes. It shows that the system is practice-sensitive, expertise-sensitive, and analytically informative within the simulated environment.

5.7 Future work

Future studies should evaluate longer training protocols, delayed retention, and transfer to physical box trainers or supervised clinical camera-navigation tasks. Experimental manipulation of feedback cues would make it possible to test whether perceived utility/interface/feedback can be improved and whether such improvements affect objective performance. The psychometric instrument should be expanded and validated in larger samples. Target-level analyses, horizon-alignment error, and segment-wise kinematic decomposition would provide a more detailed description of the control strategies used by trainees.

6 CONCLUSION

This simulator-based study evaluated a portable VR system for 30° laparoscopic camera navigation within a biomedical engineering framework centered on training, measurement, and objective performance analytics. SECMA combines a mechanically informed interface, immersive visualization, standardized task design, six-degree-of-freedom telemetry, and psychometric assessment. The system elicited measurable early practice effects and preserved expert–novice differences. The integrated analysis further showed that perceived utility, interface quality, and feedback were more strongly related to path efficiency than perceived realism alone.

The main contribution is therefore not only a portable VR simulator but a reproducible framework for evaluating simulator-based surgical training technologies through the joint analysis of structured user perception and kinematic behavior. This approach is relevant for online surgical education, low-cost simulation, and the development of data-driven feedback systems for minimally invasive surgery training.

7 ACKNOWLEDGMENTS

The authors acknowledge the support of the participating trainees and faculty collaborators, as well as the broader SECMA development team.

8 FUNDING

This work was supported by ANID FONDEF I+D 2023, Project IT23I0018.

9 DATA AVAILABILITY

The datasets and code supporting the findings of this study are available from the corresponding author upon reasonable request.

10 AUTHOR CONTRIBUTIONS

J.I.G.M. contributed to simulator conception, hardware development, task design, and manuscript revision. M.H.-M. developed the analytical framework, organized the psychometric and kinematic integration, performed the statistical modeling and result synthesis, and led manuscript preparation. C.A.D.C. provided surgical expertise for the definition of the camera-navigation task, participated in study execution, and critically reviewed the manuscript. B.M.G. contributed to the conceptualization of the exercise and to experimental organization. C.I.R.B. contributed to the conception, design, and evaluation of the mechanical interface. R.T.V. contributed to the design and implementation of the simulator management software and to the services required for integration with the data-acquisition and analysis pipeline. All authors reviewed and approved the final version of the manuscript.

11 CONFLICT OF INTEREST

The authors declare no conflict of interest.

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