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PAPER

Bridging Distances: Virtual Collaboration in Remote Laboratories for Real-World Teamwork Simulation

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ABSTRACT

With the prevalence of virtual and remote laboratories (VRLs) in higher education and the COVID-19 pandemic, there is an increasing demand for stringent evidence of their collaborative design. It explores the key success factors determining virtual teams' effectiveness amongst 363 undergraduate students from the University of Sousse, Tunisia, who participated in VRL-based coursework through their pandemic-implemented remote learning experience. Using a quantitative cross-sectional survey study and multiple regression, we reveal communication quality ($\beta = 0.47$, $p < .001$) and digital tool integration ($\beta = 0.31$, $p < .001$) as the biggest predictors of virtual team effectiveness, accounting for 58.3% of outcome variance ($R^2 = .583$, $F(4,358) = 124.7$, $p < .001$). However, neither task allocation nor collaboration had independent significant impact on multivariate models, which implies a mediation between communicative and technological infrastructure. Embedded into Industry 4.0 requirements and the current Metaverse-Enhanced Learning Ecosystem (MELE) framework, our results provide recommendations and specific design points for next-generation VRL platforms that focus on synchronous co-experimentation, adaptive AI-driven guidance, and communicative scaffolding. This study advances the empirical literature on virtual teamwork in STEM education and proposes a design approach grounded in evidence for collaborative remote laboratory environments.

KEYWORDS

virtual collaboration, remote laboratories, teamwork simulation, engineering education, active learning, Industry 4.0, collaborative tools, gamified learning, adaptive virtual spaces, computer-supported collaborative learning, CSCL, virtual and remote laboratories (VRL), online engineering, metaverse-enhanced learning, virtual distance, synchronous collaboration

1 INTRODUCTION

In response to traditional hands-on laboratory facilities' well-documented limitations, virtual and remote laboratories (VRLs) have found their way into education as a response to these obstacles: costs are too expensive, people cannot walk into them,

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and there is a lack of scalability [1]–[3]. To a significant extent, VRL facilities have changed the face of STEM teaching. They allow students to participate in experimenting at a distance without losing the practical feeling that laboratory education does provide them with, and as a result, through VRLs particularly, STEM—particularly in engineering, science, and technology—particularly centers around hands-on work experiments, which forms part of developing skills [4], [5]. The COVID-19 pandemic additionally forced institutions worldwide to roll out virtual laboratory experiments on a mass scale within weeks, thereby revealing both their considerable value to potential users and persistent limitations in joint designing for teachers and users [4] as well as the need for a new method of teaching or service providers themselves. One of the key problems in this development is the effective facilitation of cooperative learning in the VRL environment. Although role-based interaction, synchronous communication tools, and group awareness mechanisms have been incorporated over the years to mimic realistic teamwork context [1], [3], [5], these collaborative affordances are still underdeveloped and have variable assessment [3]. Current studies cover technical implementations—multi-site access, platform integration, mixed reality group awareness [18] for teamwork—but have not focused on the way in which VRL environments can explicitly emulate teamwork in a professional environment and provide a tangible impact on the effects of its use. This gap is important: In a world where Industry 4.0 paradigms increasingly call for graduates who are capable of distributed, technology-mediated collaboration [6], the lack of evidence-based collaborative design frameworks for VRLs is a serious pedagogical gap. The problem is aggravated with the virtual distance. Lojeski and Reilly [17] identify three mutually reinforcing constructs of virtual distance—physical, operational, and affinity—that eat away at the richness of communication, interpersonal trust, and coordination in distributed teams. These dimensions are particularly pressing to VRL-based teamwork, but their implications in remote laboratory settings have so far not been adequately evaluated empirically on a broader scale. Similarly, although VRLs are spaces for gamified learning, adaptive environments, and immersive virtual environments [6] and incubators for 21st-century competencies like critical thinking and technology skills [7], the precise organizational and communicative elements that affect the success or failure of virtual teams in such environments (or the lack thereof) are still unfulfilled. The objectives of this article fill this void by addressing the above-mentioned gaps with a large-scale quantitative study conducted at the University of Sousse, Tunisia, and its first regression-based model of virtual team effectiveness in a VRL context. Not only does this paper quantify the relative contributions of varying dimensions of communication quality, integration of digital tools, assignment of tasks, and collaboration to the overall team effectiveness of the group, but it will also help contextualize its findings within the Metaverse-Enhanced Learning Ecosystem (MELE) [6], generating actionable design recommendations for next-generation VRL platforms—extending VRL research towards professional and industrial teamwork training, which is sorely lacking in the existing literature. The rest of the paper is organized as follows: Section II provides a summary of relevant work; Section III outlines the methodology; Section IV describes the results and discussion of the findings; and Section V discusses design implications and future research.

2 RELATED WORK

The evolution of laboratory education towards virtuality and virtual learning, especially with the impact of technology and external problems such as the

COVID-19 pandemic, brings about a complete movement towards remote and virtual. Virtual labs that are typically developed using commercially made game engines like the "Source" engine offer a high degree of immersion to students and encourage them to contribute to the learning process by stimulating various modes of learning and collaboration. They make resource development infeasible and allow educators to work within infrastructure, limiting their resource development to improving the interactive elements and engaging people with existing infrastructure to a minimum [8], [9], as their platform is provided through the infrastructure to enhance the experience. In the same vein, virtual reality (VR) and augmented reality (AR) technology have been utilized to deliver digital labs to remotely build labs that model physical experiential learning. Digital twins of their robotic arms in VR with robotic arm platforms enable students to run experiments remotely and encourage collaboration between institutions and time zones [10]. Remote laboratories, where students connect with real equipment over the Internet, have also gained popularity. These labs use software tools such as MATLAB, LabVIEW, and Arduino for remote control and data acquisition of experiments to verify conceptually sound theory through experiments [11], [12]. A unique feature of remote labs is collaborative learning, imitating group dynamic typical of conventional labs and aiding in practicing teamwork and problem-solving [13]. Hybrid models including in-person and remote participation have proved to be an especially ideal solution to the challenge of preserving the educational quality during the pandemic. This course took a hybrid route; students could participate in either in-person or remote work while also creating a team [14]. Moreover, international initiatives involving remotely programming robotic systems have shown promise as a means to enhance technical skill as well as collaborative skill [15], [16]. At the intersection of collaborative learning and virtual distance, Lojeski and Reilly [17] identified three dimensions of virtual distance—physical, operational, and affinity—that increase the communicative and socio-emotional challenges of distributed teams. These dimensions have direct implications for VRL-based teamwork in which students work together across both physical and affective distances. One positive avenue to address these challenges is mixed reality systems with mechanisms of group awareness [18]. Such progress shows the significant effects of virtual and remote labs in making laboratory education more accessible, interactive, and collaborative and also highlights gaps in design that this study empirically addresses.

3 METHODOLOGY

3.1 Research context and setting

The study was done at the University of Sousse, Tunisia, one of the leading public universities in the country, encompassing multiple higher institutes in engineering, technology, and applied sciences. This research was conducted in the academic year 2020–2021, when on-campus activity was curtailed in the wake of the COVID-19 pandemic. To cope with this disruption, the University of Sousse quickly transitioned its laboratory-based classes to completely virtual and remote modalities with the support of a variety of digital collaboration platforms—including Microsoft Teams, Moodle, and discipline-specific VRL environments—that were designed to preserve pedagogical continuity. Such a context offered a unique opportunity to observe virtual teamwork in VRL environments under real, not simulated, conditions of enforced remote collaboration.

3.2 Participants and sampling

A total of N = 363 undergraduate students were sampled from the three faculties of the University of Sousse: the Higher Institute of Applied Sciences and Technology of Sousse (ISSAT Sousse), the Higher Institute of Technological Studies of Sousse (ISET Sousse), and the National Engineering School of Sousse (ENISo). Participants were enrolled in second- and third-year programs in electrical engineering, computer science, industrial automation, and applied physics—disciplines in which laboratory experimentation constitutes a core component of the curriculum. The sampling was purposive: only students who had participated in at least one structured virtual team project within a VRL environment during the academic year were eligible to participate. This criterion ensured that all respondents had direct, comparable experience of the phenomenon under investigation. The sample comprised 241 male students (66.4%) and 122 female students (33.6%), with a mean age of 21.3 years (SD = 1.4). Participation was voluntary, anonymous, and carried no academic consequence. Ethical clearance was granted by the institutional research ethics committee of the University of Sousse.

3.3 Data collection instrument

Data were gathered through a self-administered structured online survey distributed on the Moodle learning management system that is already used by the participating institutes. This tool comprised five thematic areas of information: (1) demographics and level of academic attainment; (2) perceived benefits of virtual teamwork; (3) barriers encountered in virtual collaboration; (4) quality and integration of digital tools; and (5) overall virtual team effectiveness. The questionnaire was piloted with a convenience sample of 30 participants who were excluded from the main study, and items were adjusted for clarity according to an assessment of the pilot input. The final instrument was made available in French and English to accommodate the language needs of our student population. Four independent constructs were operationalized using validated multi-item Likert scales (1 = Strongly Disagree to 5 = Strongly Agree):

- Communication Quality (CQ): assessed both the clarity, frequency, and responsiveness of virtual communication channels used in student teams, including synchronous video conferencing and asynchronous messaging tools.
- Digital Tool Integration (DTI): measured the degree to which the VRL technological environment was perceived as supportive, intuitive, and well integrated with team workflows.
- Task Allocation (TA): evaluated team members' perceived fairness, clarity, and transparency about sharing tasks.
- Collaboration (COL): assessed levels of active, reciprocal, and equitable involvement through joint laboratory tasks among team members.

The dependent variable, Virtual Team Effectiveness (VTE), was assessed by means of a composite six-item scale with quality of collective task completion, perceived contribution to learning outcomes, extent of team goal attainment, satisfaction level of team members, project-completion deadline status, and perceived team cohesion. Internal consistency of all multi-item scales was satisfactory

(Cronbach's α = .73 to .86), and construct validity was ensured by confirmatory factor analysis (CFA) performed on AMOS v.24 with all factor loadings > .60 and RMSEA < .06.

3.4 Statistical analysis procedure

All analyses were conducted in IBM SPSS Statistics v.26. First, descriptive statistics were computed for all study variables. Pearson product-moment correlations were subsequently computed to test for bivariate associations between each independent variable and VTE and between predictors. Next, a hierarchical multiple regression model was specified in which we entered the four predictors simultaneously to determine their contribution to VTE variance while controlling for shared variance across variables. The standardized regression coefficients (β), unstandardized coefficients (B), standard errors (SE), t-statistics, and associated p-values are reported. The threshold for significance was set at $\alpha = .05$ (two-tailed). Multicollinearity was assessed using Variance Inflation Factor (VIF) statistics; all VIF values were below 3.0, with no evidence of troubling collinearity among predictors.

4 RESULTS AND DISCUSSION

4.1 Benefits and challenges of virtual teamwork

In Figure 1, we show endorsement rates for perceived benefits and challenges of the University of Sousse student sample. Benefits: Scheduling flexibility (78.5%), leveraging of diverse expertise (71.3%), and geographic barrier elimination (68.4%) are aligned with the collaborative affordances of synchronous VRL platforms [5]. By contrast, the greatest challenges were the absence of face-to-face interaction (82.1%), trust-building difficulties (69.7%), and real-time coordination failures (64.2%), confirming the virtual distance constructs established in the literature [17].

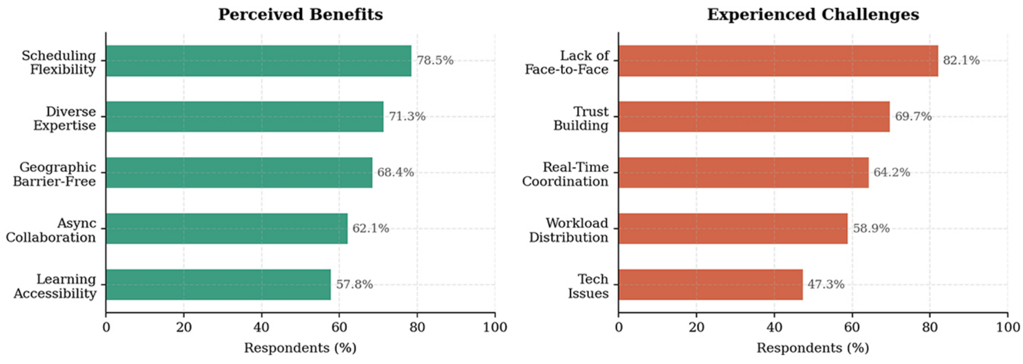

Fig. 1. Perceived benefits (left) and challenges (right) of virtual teamwork (N = 363)

4.2 Bivariate correlations

Table 1 and Figure 2 present the Pearson correlation matrix. CQ exhibited the strongest bivariate association with VTE ($r = .68$, $p < .001$), followed by DTI ($r = .55$), COL (r = .42), and TA (r = .38). Moderate inter-predictor correlations indicate limited multicollinearity risk.

Table 1. Pearson correlation matrix (N = 363)

Predictor	(1)	(2)	(3)	(4)	(5)
1. VTE	–	.68**	.55**	.42**	.38**
2. CQ	.68**	–	.61**	.49**	.35**
3. DTI	.55**	.61**	–	.44**	.40**
4. COL	.42**	.49**	.44**	–	.53**
5. TA	.38**	.35**	.40**	.53**	–

Note: **p < .001. VTE = Virtual Team Effectiveness; CQ = Communication Quality; DTI = Digital Tool Integration; COL = Collaboration; TA = Task Allocation.

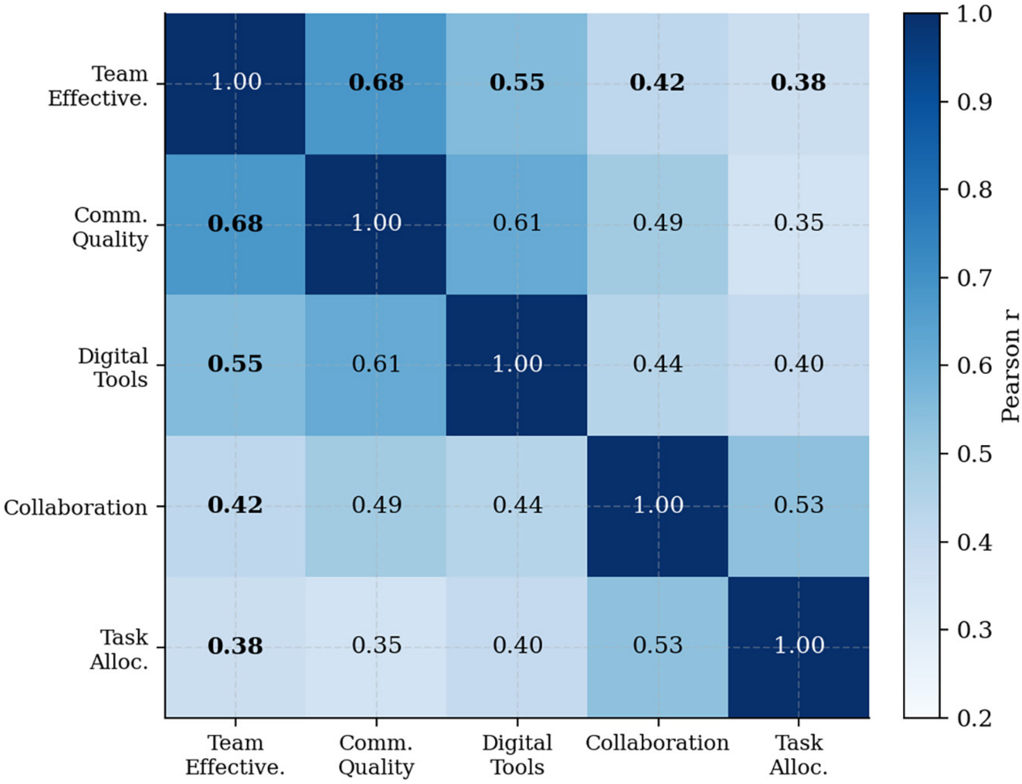

Fig. 2. Pearson correlation heatmap

Note: Darker shading indicates stronger positive association.

4.3 Multiple regression results

Table 2 presents the full regression model. CQ (β = 0.47, p < .001) and DTI (β = 0.31, p < .001) were significant positive predictors, together explaining 58.3% of VTE variance (R^2 = .583, F(4,358) = 124.7, p < .001). Neither TA (β = 0.08, p = .14) nor COL (β = 0.11, p = .09) reached significance as independent predictors.

Table 2. Multiple regression predicting virtual team effectiveness

Predictor	(1)	(2)	(3)	(4)	(5)
Communication Quality	0.49	0.06	.47	8.21	< .001
Digital Tool Integration	0.30	0.05	.31	5.87	< .001
Collaboration	0.10	0.06	.11	1.70	.09
Task Allocation	0.07	0.05	.08	1.48	.14

Notes: $R^2 = .583$; adj. $R^2 = .574$; $F(4,358) = 124.7$, $p < .001$; β = Standardized coefficient.
Dependent variable: VTE.

Figures 3 and 4 provide a graphical representation of the regression results. Figure 3 presents the standardized regression coefficients (β) with their 95% confidence intervals, highlighting communication quality and digital tool integration as the strongest significant predictors of virtual team effectiveness. Figure 4 illustrates the cumulative variance explained at each step of the hierarchical regression, showing the contribution of digital tool integration and the limited incremental contribution of collaboration and task allocation.

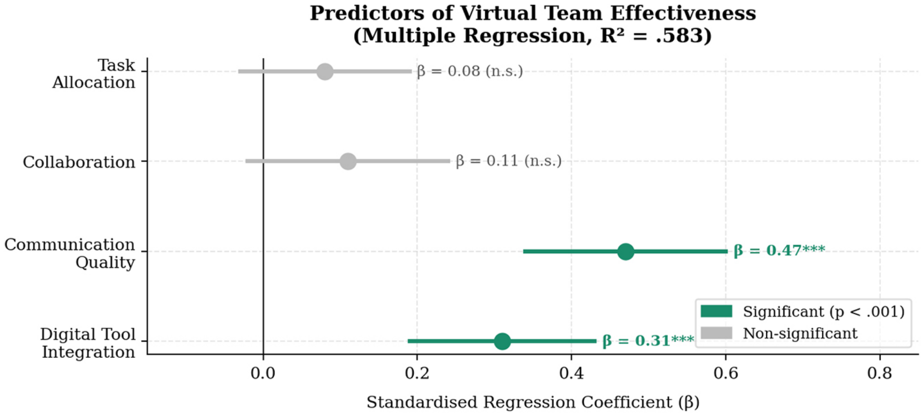

Fig. 3. Forest plot of standardized β with 95% CI

Note: Teal = significant ($p < .001$); grey = n.s.

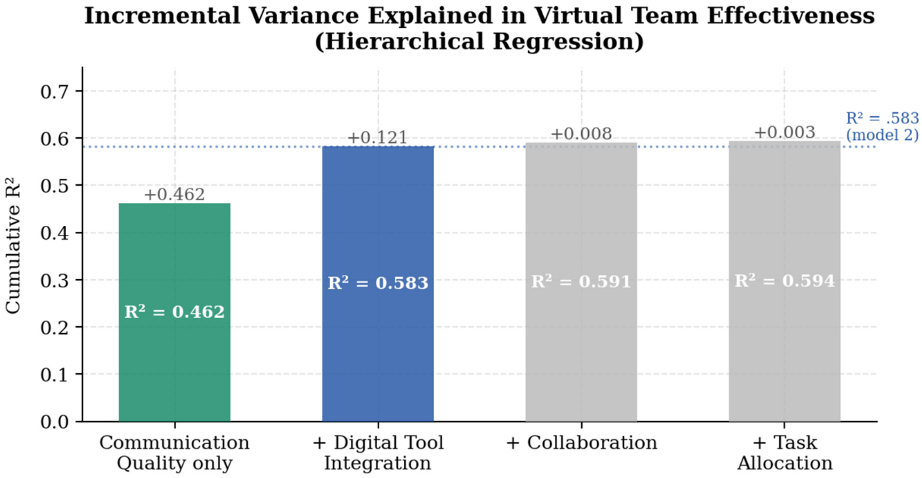

Fig. 4. Cumulative R^2 at each hierarchical regression step

4.4 Mediation hypothesis and conceptual model

The fact that TA and COL appear not significant in multivariate models does not mean they are irrelevant. On the contrary, their impact on VTE appears mediated by both CQ and DTI: teams that communicate well in well-designed technological environments spontaneously create functional task allocation and collaborative norms, without any additional formal structural intervention [3]. This insight aligns with CSCL theory that technology-mediated communication scaffolds provide a proximal way coordination and role differentiation are achieved. Figure 5 presents the proposed conceptual model.

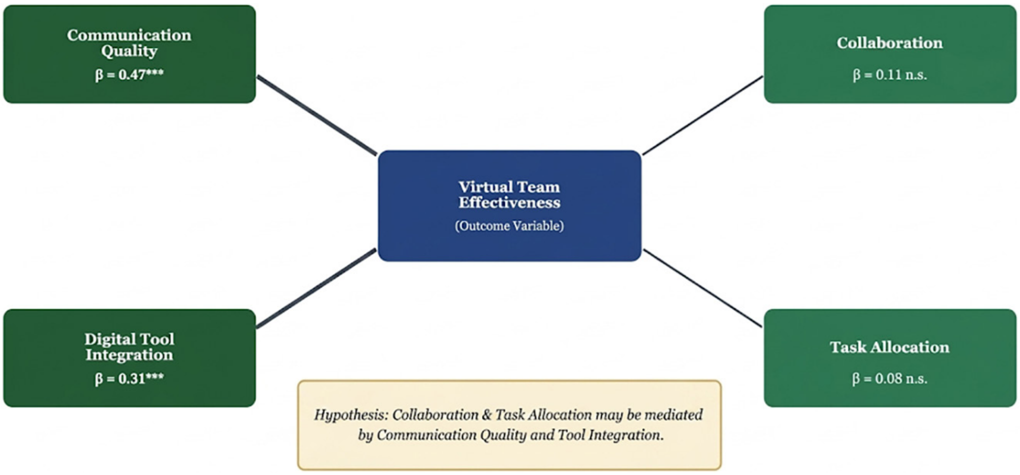

Fig. 5. Conceptual model: regression paths and proposed mediation hypothesis

4.5 Design and pedagogical implications

Therefore, given the centrality of DTI as a basis for a design philosophy leaning towards cooperating functionalities (e.g., synchronous co-experimentation interfaces, real-time data sharing, and group awareness dashboards) as central features of VRL [3], [1]. According to the MELE framework [6], future VRL systems should integrate AI-driven monitoring of team interaction patterns and initiate targeted interventions when coordination difficulties are detected. This is consistent with the gamified and adaptive learning trends [6] highlighted as critical VRL innovations [9]. The focus on CQ implies that VRL pedagogies must build not merely technical competences but also communicative competence. As noted previously, we recommend that instructors provide the development of structured communicative protocols, regular synchronous touchpoints, and reflective exercises based on team development models, which have been illustrated in hybrid laboratory settings [14] that could aid in building meta-communicative awareness within virtual teams.

5 CONCLUSION

The results demonstrate that communication quality and digital tool integration are the top two predictors of virtual team effectiveness among undergraduate students in VRL coursework, explaining 58.3% of the variance in the results. The findings extend the empirical literature describing collaborative VRLs, offer evidence-guided recommendations to inform the design of next-generation platforms, and help develop a mediation hypothesis based on previously inconsistent findings on task allocation and collaborative structure. Limitations include the cross-sectional design, reliance on self-report measures, single-national sample, and the extraordinary pandemic context. Furthermore, future research could use longitudinal designs and objective behavioral measurements from VRL interaction logs, cross-national samples, and formal mediation modeling to establish a generalizable evidence base for collaborative VRL design. As the boundaries between conventional and online learning draw ever closer, ensuring real, efficient collaboration across online spaces will come to be regarded as a key metric for educational quality. The findings from this work indicate the communicative and technological components on which this kind of capability is built.

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