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Student achievement and perceptions of virtual reality compared to light microscopy in blood cell identification: Pilot study in laboratory technology education

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ABSTRACT

Introduction: In modern health sciences education, the emergence of virtual reality (VR) has introduced new approaches to learning; however, its application in the study of blood cell morphology remains underexplored. This study aimed to compare student performance and the time required for blood cell identification using light microscopy (LM) and VR, as well as to assess students' perceptions of VR and their readiness for its integration into the teaching process.

Methods: This pilot study used a within-subject comparative design involving two modalities (LM and VR). It was conducted at the Institute for Health Development, University of Sarajevo – Faculty of Health Studies, during April and May 2026 and included 24 participants. The study protocol encompassed the digitization of hematological preparations, the development of VR and web applications, and comparative testing.

Results: The use of VR resulted in a statistically significantly higher overall percentage of correct cell identifications compared with LM (73.9% vs. 58.0%; $p < 0.001$). By cell lineage, participants using VR achieved significantly higher accuracy in identifying cells of the erythroid lineage (80.3% vs. 65.9%; $p < 0.001$) and leukocytic lineage (67.4% vs. 49.2%; $p < 0.001$). The time required for blood cell identification was reduced by 26.7% with VR across all three cell lineages. Participants showed positive attitudes toward VR, with an increase of 0.35 in the overall post-test score (95% CI: 0.15-0.55; $p = 0.002$).

Conclusion: VR demonstrated potential as a useful tool for blood cell identification, particularly by enabling detailed visualization of morphological characteristics in cells of the erythroid and leukocytic lineages. High ratings for ease of use, despite limited prior VR experience, suggest that integrating VR into the educational process is both feasible and practical, with minimal additional burden on students and teaching staff.

Keywords: Students; light microscopy; virtual reality; blood cells

INTRODUCTION

The transition of the healthcare sector toward Healthcare 4.0 and the entry of Generation Z into higher education require a systematic review and adaptation of traditional teaching models (1,2). In this context, the education of future university-trained laboratory professionals, within curricula that rely heavily on morphological analysis, faces complex challenges. Curriculum evaluation and modernization are key pre-requisites for aligning educational outcomes with the dynamic demands of the modern work

environment. However, the introduction of advanced visualization modalities into practical teaching on blood cell morphology requires substantial material resources, which represents a significant barrier in resource-limited countries. A lack of equipment and continued reliance on conventional teaching methods can jeopardize the acquisition of essential practical skills and competencies and, consequently, reduce graduates' competitiveness in the international labor market (3-6).

Existing curricula and programs for the study of blood cell morphology are predominantly based on conventional light microscopy (LM) as the primary visualization modality in practical teaching. Although LM remains the "gold standard" in diagnostic practice, it is subject to subjective interpretation and optical limitations, requires considerable

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time, and makes retrospective analysis and archiving difficult. In addition, the precise identification of atypical cell shapes is often hindered by the difficulty of perceiving fine structural details and spatial depth simultaneously, largely because of the shallow depth of field and narrow field of view of conventional LM (7-11).

In modern higher education in the health sciences, immersive technologies have become a priority for improving practical skills and competencies. The advent of virtual reality (VR) has introduced transformative approaches to learning by creating immersive, interactive environments that effectively bridge the gap between theoretical knowledge and practical application (12). Grounded in the principles of experiential learning and cognitive load reduction, VR facilitates the differentiation of morphologically similar blood cells, supports the formation of mental maps and, according to previous research, increases knowledge retention rates by up to 75% (13-15). Despite technical and infrastructural challenges (14), VR has significant potential to overcome the methodological shortcomings of LM and is a key candidate for integration into modern higher education standards (16).

However, the application of VR in education on blood cell morphology remains insufficiently researched globally. To our knowledge, this is also the case in Bosnia and Herzegovina and the wider Western Balkans region. Before undertaking a formal revision and structural transformation of higher education curricula, it is necessary to evaluate empirically whether the introduction of new technologies is justified and effective. In an effort to address this scientific gap and provide an empirical basis for future curricular reforms, this pilot study aimed to examine (1) students' success rate and the time required for blood cell identification using LM versus VR, (2) the subjective validity of VR, and (3) students' readiness for its integration into the teaching process.

METHODS

The pilot study was designed as a within-subject comparative study with two modalities within the group (LM modality and VR modality). It was conducted at the Institute for Health Development of the University of Sarajevo – Faculty of Health Studies during April and May 2026.

The initial sample comprised all students enrolled in the eighth semester ($n = 29$) of the 2025/2026 academic year in the Laboratory Technology study program at the University of Sarajevo – Faculty of Health Studies. The inclusion criteria were active 4th-year student status; successful completion of laboratory hematology courses taken up to and including the fifth semester; absence of neurological or vestibular disorders and pregnancy; and provision of voluntarily signed informed consent. The exclusion criteria were extended non-coursework status (i.e., completion of all coursework and examinations without having defended the final thesis); failure to pass laboratory hematology courses; a confirmed neurological or vestibular disorder; pregnancy; declining participation; and an increased risk of adverse reactions according to the VR device manufacturer's guidelines (Meta Platforms, Inc.) (17). Of the initial 29 students, four were excluded at baseline: Two declined to participate,

one did not meet the eligibility criteria because of pregnancy, and one did not meet them because of a neurological condition. One additional participant withdrew during the experiment because of VR-induced nausea. Consequently, the final sample of participants who completed the full study protocol comprised 24 students.

To ensure methodological rigor and the reliability of the data, the research procedure was structured into three main phases. The first phase involved the selection and digitization of a representative sample of hematological preparations; the second focused on the development of a dedicated demo VR application; and the third comprised direct testing of participants according to a pre-defined protocol. The protocol included a pre-test, LM testing, a washout period, VR testing, and a post-test.

In the first phase, the archive of hematological preparations used in teaching was systematically reviewed. The archive included preparations representing physiological and various pathological conditions. Preparations were selected according to pre-defined criteria (18). Following selection, the principal investigator performed microscopic analysis using an Olympus CX33 light microscope (Olympus Corporation, Tokyo, Japan) under oil immersion at 1000 $\times$ total magnification (100 $\times$ objective). A total of 30 digital images representing erythroid, leukocyte, and thrombocytic lineages, encompassing various stages of maturity and morphological characteristics, were selected for the study (Table 1). The selection was aligned with the teaching units in the laboratory hematology course syllabus and the official nomenclature of the International Council for Standardization in Haematology (19). The selected blood cells were digitized using a Moticam X5 digital camera (Motic, Xiamen, China). Motic Images Plus software (Motic, Xiamen, China), a Dell P2725H monitor (Dell Technologies, Round Rock, TX, USA), and a connected Dell Pro Slim QCS1250 computer (Dell Technologies, Round Rock, TX, USA) were used for image processing, quality control, and analysis.

The second phase involved the development of an interactive virtual environment and a supporting demo VR application for the experimental sessions. The virtual environment ran on a Meta Quest 3 VR headset (Meta Platforms, Menlo Park, USA), with a display resolution of 2064 $\times$ 2208 pixels per eye. The creation of participant profiles, monitoring of tests, and randomization of the presentation order of digitized blood cell images within the VR application were managed in real time via a Samsung Galaxy

TABLE 1. Overview of selected blood cells for identification using light microscopy and virtual reality

Erythroid lineage	Polychromatophilic erythroblast, acidophilic erythroblast, erythrocyte with pathological inclusion (<i>Plasmodium malariae</i> , ring shape), echinocyte, codocyte (target cell), spherocyte, stomatocyte, dacrocyte, elliptocyte, schizocyte and basophilic stippling
Leukocytic lineage	Myeloblast, promyelocyte, myelocyte, metamyelocyte, band, neutrophil, eosinophil, basophil, hypersegmented neutrophil, promonocyte, monocyte, prolymphocyte, lymphocyte, granular lymphocyte, reactive lymphocyte, plasma cell and trichocyte
Thrombocytic lineage	Thrombocyte and giant thrombocyte

Tab A9 8.7-inch tablet (Samsung Electronics, Suwon, South Korea).

The demo VR application enabled participants to review high-resolution digitized microscopic images of blood cells in an immersive environment. While participants viewed the images, the researcher simultaneously controlled the session content and monitored identification accuracy through a companion web application. The web application's main functions included managing participant profiles and image galleries, initiating VR sessions, and reviewing results, time spent on each task, and dates of previous examinations. This design enabled the application to run on a standard tablet without additional software installation. The immersive component was developed in Unity (version 2022.3.15f1; Unity Technologies, San Francisco, USA) for Meta Quest devices, with the aim of providing an intuitive, ergonomically adapted interface for viewing images in an immersive environment.

The experimental part of the study comprised five successive steps following a within-subject design.

Initial assessment (pre-test)

During the initial assessment, all participants completed a pre-test questionnaire evaluating their experiences, expectations, and perspectives on the use of VR in the education of laboratory professionals. A modified questionnaire adapted from Mergen et al. (2023) was used (20). Originally intended for medical students, the questionnaire was translated into Bosnian with the author's consent and adapted to the Laboratory Technology study program curriculum. It consisted of 18 questions grouped into three categories: (a) Demographic characteristics (age and gender), (b) previous experience with VR, and (c) evaluation of the potential of VR in education. The questionnaire's internal consistency was assessed using Cronbach's α coefficient with a bootstrap 95% confidence interval (CI): Pre-test $\alpha = 0.872$ (95% CI: 0.709-0.932) and post-test $\alpha = 0.868$ (95% CI: 0.710-0.905). Participants' attitudes toward the use of VR in education and its potential for developing practical skills were evaluated on a numerical scale from 1 to 5, while attitudes toward long-term sustainability were assessed on a scale from 1 to 10, preserving the measurement scales of the original questionnaire. Participants were also instructed not to review the material or consult additional literature on laboratory hematology throughout the experimental period, to minimize the influence of external factors on the final results.

Session 1: Knowledge testing using LM

In the first experimental session, slides containing the selected blood cells (Table 1) were placed on the stage of a light microscope and examined under oil immersion using a 100 $\times$ objective. The fields of view containing the target cells had been marked in advance by the principal investigator to ensure traceability and repeatability of measurements. Slides were labeled with unique codes to prevent participants from memorizing their order and sharing answers. A different randomized order of cell presentation was used for each participant to minimize potential bias. Participants observed the cells individually and recorded their responses

on the forms provided, using self-generated anonymized codes. The time required to identify each blood cell was measured using a digital stopwatch.

Washout period

A 1-month washout period was applied between the two knowledge-testing sessions to minimize the learning effect and reduce the likelihood that participants would remember specific morphological characteristics of the preparations. Because all participants completed the modalities in the same sequence (LM followed by VR), this interval was intended to reduce the potential carryover effect.

Session 2: Knowledge testing using VR

In the second experimental session, participants identified blood cells using VR. Before testing began, all participants received standardized instructions on handling and adjusting the VR device. During testing, participants stood and had freedom of movement and interaction within a defined laboratory space. Blood cell identification in the immersive environment comprised four successive subphases: Preparation and selection, immersion, response recording, and data storage.

In the first subphase, an individual participant profile was created through the management web application, and the appropriate album of digitized images was selected. The application automatically randomized the display order of the image files using an integrated randomization algorithm, thereby reducing potential bias related to presentation order. The second subphase involved immersion: Using the VR device, the participant passed through a virtual portal in mixed reality, which activated an evaluation carousel of high-resolution digitized images. In the third subphase, the participant identified the blood cell through visual inspection in the immersive environment and reported the answer verbally. The researcher then recorded whether the response was correct or incorrect through the web application. The system automatically measured and recorded the time spent on each image file. The fourth subphase involved automatic data storage: Identification accuracy, time spent, and session history were stored in the device's local database.

Final assessment (post-test)

Following the respective LM and VR sessions, participants rated image quality, their diagnostic confidence in cell identification, and the ease of use of each modality on a numerical scale from 1 to 10. These evaluation parameters were adapted from Farahani et al. (2016) (21). After completing the experimental protocol, participants completed the post-test version of the modified questionnaire adapted from Mergen et al. (2023) (20), concluding the data collection phase.

Before the study began, all participants received detailed information about its aims, procedures, and potential benefits and risks. They then voluntarily signed an informed consent form and retained the right to withdraw at any stage without consequences. To protect anonymity and personal data, participants independently generated unique codes intended to prevent re-identification by third parties and the research team. All study procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki.

The procurement of research equipment was financially supported by the Ministry of Education and Science of the Federation of Bosnia and Herzegovina as part of the Public Call for Co-financing of Scientific Research and Research and Development Projects in 2025.

Statistical analyses were performed using the Statistical Package for the Social Sciences, version 27 (IBM Corp., Armonk, NY, USA). Blood cell identification accuracy was coded as a binary variable (1 = correct answer; 0 = incorrect answer), while identification time was measured in seconds to decimal precision. Categorical data are presented as absolute and relative frequencies (%). Continuous variables were described using parametric measures, the arithmetic mean (M) $\pm$ standard deviation (SD), and non-parametric measures, the median (Mdn) and interquartile range (IQR). The Wilcoxon signed-rank test was used to compare paired samples. The association between the identification modality and accuracy was analyzed using logistic regression with cluster-robust standard errors at the participant level. Logistic regression results are expressed as odds ratios (OR) with corresponding 95% CI. Agreement between modalities was evaluated using Cohen's kappa (κ) coefficient and interpreted as follows: <0.20 (poor), 0.21-0.40 (mild), 0.41-0.60 (moderate), 0.61-0.80 (significant), and 0.81-1.00 (very good) (22). All tests were two-tailed, and statistical significance was set at $p < 0.05$.

RESULTS

The mean age of the participants was 23 ± 1.77 years. Nineteen participants (79.2%) were female, and five (20.8%) were male. Of the total sample ($n = 24$), four participants (16.7%) had prior experience with VR, exclusively through gaming (Figure 1).

Table 2 presents the results of the comparison of blood cell identification accuracy between LM and VR. The use

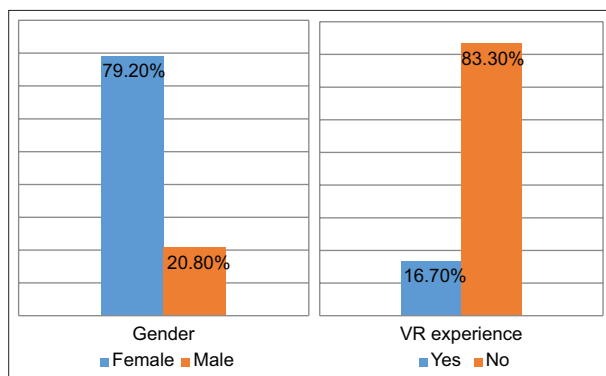


FIGURE 1. Gender distribution and previous experience of participants in using virtual reality.

of VR resulted in a statistically significant increase in the overall percentage of correct cell identifications compared with LM (58.0%; $p < 0.001$). The logistic regression model showed that subjects in the VR environment were twice as likely to correctly identify cells overall (OR = 2.05; 95% CI 1.67-2.52; $p < 0.001$). When analyzed by cell lineage, subjects using VR achieved significantly higher accuracy in identifying cells of the erythroid lineage (80.3% vs. 65.9%; $p < 0.001$) and cells of the leukocytic lineage (67.4% vs. 49.2%; $p < 0.001$). Although a similar effect was observed for cells of the thrombocytic lineage (93.8% vs. 87.5%), this difference was not statistically significant ($p = 0.317$). The probability of correct identification was approximately twice as high with VR for the erythroid lineage (OR = 2.09; 95% CI 1.46-2.99; $p < 0.001$) and the leukocytic lineage (OR = 2.13; 95% CI 1.64-2.76; $p < 0.001$). No statistically significant difference between the two modalities was observed for the thrombocytic lineage ($p = 0.337$).

The use of VR significantly reduced the time required to identify blood cells across all three cell lineages (Table 3). The overall mean identification time with LM was 18.97 ± 7.08 s, whereas VR reduced this to 13.90 ± 4.58 s, representing a 26.77% reduction ($p = 0.011$). The greatest difference in identification speed was observed for cells of the thrombocytic lineage, with subjects identifying these cells in an average of 9.69 ± 5.90 s using VR, compared with 19.13 ± 13.22 s using LM, representing a 49.34% reduction (95% CI: -15.58 to -4.08; $p = 0.003$). Statistically significant reductions in identification time with VR were also observed for cells of the leukocytic lineage (27.78%; $p = 0.012$) and cells of the erythroid lineage (20.33%; $p = 0.034$).

Inter-method agreement in blood cell identification accuracy between LM and VR was evaluated using Cohen's kappa (κ) coefficient and is presented in Table 4. The overall percentage agreement between LM and VR was 64.7% (95% CI: 61.2-68.2%), with an overall Cohen's κ of 0.235 (95% CI: 0.171-0.303), indicating mild agreement between the two modalities.

By cell lineage, the most consistent agreement between modalities was observed for the leukocytic lineage ($\kappa = 0.220$; 95% CI: 0.130-0.319), whereas the lowest was recorded for the erythroid lineage ($\kappa = 0.197$; 95% CI: 0.088-0.307). For the thrombocytic lineage, a kappa paradox was observed, characterized by a high percentage of raw agreement (81.2%) alongside a negative Cohen's κ ($\kappa = -0.091$; 95% CI: -0.155-0.027).

Table 5 shows the subjects' evaluations of image quality, diagnostic confidence, and ease of use for LM and VR.

TABLE 2. Comparison of blood cell identification accuracy between light microscopy and virtual reality

Cell lineage	Light microscopy		Virtual reality		p^a	OR VR versus LM (95% CI)	p^b
	n	%	n	%			
Erythroid lineage	174/264	65.9	212/264	80.3	<0.001	2.09 (1.46-2.99)	<0.001
Leukocytic lineage	201/408	49.2	275/408	67.4	<0.001	2.13 (1.64-2.76)	<0.001
Thrombocytic lineage	42/48	87.5	45/48	93.8	0.317	2.14 (0.45-10.14)	0.337
Total	417/720	58.0	532/720	73.9	<0.001	2.05 (1.67-2.52)	<0.001

n: Number of correct answers per cell line, OR: Odds ratio, CI: Confidence interval, ^a: Wilcoxon signed-rank test, ^b: Logistic regression with cluster-robust standard errors at the subject level, Bold values indicate statistically significant differences ($p < 0.05$).

TABLE 3. Comparison of blood cell identification time in seconds using light microscopy and virtual reality

Cell lineage	Light microscopy		Virtual reality		Difference (95% CI)	Difference (%)	<i>p</i> ^a
	M±SD	Mdn (IQR)	M±SD	Mdn (IQR)			
Erythroid lineage	17.71±6.62	17.03 (13.12-22.49)	14.11±4.54	13.67 (11.07-17.30)	-3.60 (-6.56 to -0.45)	-20.33	0.034
Leukocytic lineage	19.77±7.87	20.01 (14.56-24.28)	14.26±5.99	13.19 (9.63-19.62)	-5.51 (-9.58 to -1.21)	-27.87	0.012
Thrombocytic lineage	19.13±13.22	15.90 (11.13-22.89)	9.69±5.90	7.98 (5.22-13.87)	-9.44 (-15.58 to -4.08)	-49.34	0.003
Total time	18.97±7.08	19.44 (14.81-23.30)	13.90±4.58	13.76 (9.78-17.87)	-5.08 (-8.71 to -1.80)	-26.77	0.011

SD: Standard deviation, M: Mean, Mdn: Median, IQR: interquartile range, CI: Confidence interval, ^a: Wilcoxon signed-rank test for dependent samples, Bold values indicate statistically significant differences ($p < 0.05$)

TABLE 4. Cohen's kappa coefficient of agreement between modalities by cell lineage

Cell lineage	Agreement		Cohen κ (95% CI)
	%	95% CI	
Erythroid lineage	67.7	61.8-73.2	0.197 (0.088 to 0.307)
Leukocytic lineage	60.8	55.9-66.1	0.220 (0.130 to 0.319)
Thrombocytic lineage	81.2	70.8-91.7	-0.091 (-0.155 to -0.027)
Total	64.7	61.2-68.2	0.235 (0.171 to 0.303)

CI: Confidence interval, κ : Kappa coefficient

Participants rated VR higher on average than LM in all categories. The largest difference was in diagnostic certainty, where VR was rated significantly better than LM, with a mean difference of 2.88 (95% CI 1.94-3.79; $p < 0.001$).

The results indicate that participants had positive attitudes toward the use of VR, with a statistically significant increase in the total post-test score of 0.35 (95% CI: 0.15-0.55, $p = 0.002$). Statistically significant improvements ($p < 0.05$) were observed in four of the eight attitudes analyzed (Table 6). The largest increases were observed in attitudes regarding the need to integrate VR into the curriculum (0.67; 95% CI: 0.38-0.96, $p = 0.001$), performing complex analyses (0.50; 95% CI: 0.12-0.86, $p = 0.027$) and the general advantages of VR (0.50; 95% CI: 0.21-0.83, $p = 0.012$). Perceptions of the long-term sustainability and impact of VR also increased by 1.17 (95% CI: 0.29-1.79, $p = 0.004$).

According to the research results (Table 7), the main advantage in the post-test was the opportunity to develop and use simulations (from 70.8% to 91.7%), while the development of manual skills remained the least represented (29.2%). In terms of shortcomings, the perception of potential health problems decreased from 41.7% to 16.7%, and of technical requirements from 54.2% to 33.3%. The only statistically significant change was observed in the proportion of participants who believe that VR has no shortcomings, which increased from 4.2% to 33.3% ($p = 0.016$).

DISCUSSION

Various educational models are currently used to train health professionals; however, research evaluating virtual systems for teaching students of Laboratory Technology to identify the morphological characteristics of blood cells remains limited. In Bosnia and Herzegovina, this gap does not reflect a lack of initiative among academic staff to modernize teaching. Rather, it stems primarily from limited material and financial resources and, consequently, insufficient investment in modern educational infrastructure. In this context, our pilot study is the first within-subject

comparative study in this field to evaluate the accuracy and speed of identifying the morphological characteristics of blood cells using VR compared with conventional LM.

Female participants predominated in our sample (79.2%), consistent with previous research (23) and the World Health Organization data indicating that women account for approximately 70% of the global health workforce (24). This gender distribution reflects the composition of the profession but also limits a more detailed analysis of potential gender differences in the acceptance of new technologies. Although the sociodemographic factors influencing the choice of this profession have not been fully clarified, larger future studies with more balanced samples should examine their potential influence on the acceptance and perception of advanced educational technologies.

The pre-test and post-test analyses showed statistically significant improvements in participants' attitudes in four of the eight dimensions examined. The greatest improvement was observed in support for integrating VR into the curriculum ($p = 0.001$), consistent with recent regional research on the implementation of VR in teaching (16,25). Although 83.3% of participants had no prior experience with VR, they showed considerable openness to trying it. Similar findings were reported by Mergen et al. (20) and Reist et al. (26), whose studies found that 95.2% of students supported introducing VR into courses focused on developing practical skills. Regarding perceived shortcomings, 54.2% of participants initially identified technical requirements as a concern; after direct experience in a VR environment, this proportion decreased to 33.3%. The proportion of participants who believed that VR had no shortcomings also increased significantly, from 4.2% to 33.3% ($p = 0.016$).

In our study, VR produced higher overall accuracy in blood cell identification than LM (73.9% vs. 58.0%, $p < 0.001$), particularly for the erythroid ($p < 0.001$) and leukocyte lineages ($p < 0.001$). Liu et al. (2025) (27) reported a similar finding: Accuracy in leukocyte identification was 30% higher with digital platforms than with LM. Because our study included cells at different stages of maturity and with various pathological features, these findings suggest that VR offers an advantage in displaying morphological characteristics such as chromatin structure, granule and cytoplasmic staining, and nuclear and cell shape. Memmott et al. (2024) (28) also emphasized the importance of these features in morphological diagnosis. Their machine learning models (Random Forest) suggest that integrating advanced morphological algorithms into VR in the future could further improve learning and diagnostic accuracy.

TABLE 5. Subjective evaluation of the participants on image quality, diagnostic confidence and ease of use

Parameter	Light microscopy M±SD	Virtual reality M±SD	Difference (95% CI)	p ^a
Image quality	8.21±3.05	9.46±0.88	1.25 (0.08-2.31)	0.016
Diagnostic confidence	5.92±1.93	8.79±1.53	2.88 (1.94-3.79)	<0.001
Ease of use	7.71±2.40	9.58±0.78	1.88 (1.08-2.77)	0.001

M: Mean, SD: Standard deviation, ^a: Wilcoxon signed-rank test for dependent samples, Bold values indicate statistically significant differences ($p < 0.05$)

TABLE 6. Participants' views on the application of virtual reality in the education of laboratory professionals (pre-test vs. post-test)

Attitude	Pre-test M±SD	Post-test M±SD	Difference pre-post (95% CI)	p ^a
Application in the educational process				
VR would improve education	4.50±0.59	4.88±0.34	0.38 (0.12-0.67)	0.013
VR should be integrated into the curriculum	4.17±0.87	4.83±0.48	0.67 (0.38-0.96)	0.001
I would take a course that uses VR	4.83±0.48	4.92±0.41	0.08 (0.00-0.21)	0.157
VR has a major advantage over conventional methods	4.46±0.78	4.96±0.20	0.50 (0.21-0.83)	0.012
Potential in skill development				
Sample Processing in VR	4.00±0.98	4.17±0.96	0.17 (-0.25-0.58)	0.479
Complex Analysis in VR	3.75±0.85	4.25±0.99	0.50 (0.12-0.86)	0.027
Patient Communication in VR	3.04±1.00	3.17±1.13	0.12 (-0.33-0.52)	0.571
Teamwork in VR	3.71±1.00	4.08±1.02	0.38 (0.00-0.71)	0.067
Scale: 1-5 (average of 8 items)	4.06±0.57	4.41±0.54	0.35 (0.15-0.55)	0.002
Long-term sustainability/impact Scale: 1-10	7.83±1.55	9.00±1.14	1.17 (0.29-1.79)	0.004

^a: Wilcoxon signed-rank test for dependent samples. VR: Virtual reality, SD: Standard deviation, CI: Confidence interval, Bold values indicate statistically significant differences ($p < 0.05$)

TABLE 7. Analysis of the advantages and disadvantages of applying virtual reality in education (pre-test vs. post-test)

Variable	Pre-test		Post-test		p
	n	%	n	%	
Advantages					
Broad simulation possibilities	17	70.8	22	91.7	0.125
Repeatable scenarios	12	50.0	11	45.8	1.000
Depiction of rare diseases	11	45.8	12	50.0	1.000
Interactive first-person learning	21	87.5	17	70.8	0.289
Development of manual skills	8	33.3	7	29.2	1.000
Competence improvement	14	58.3	14	58.3	1.000
Disadvantages					
Health problems	10	41.7	4	16.7	0.109
Technical requirements/ competences	13	54.2	8	33.3	0.180
Technical error susceptibility	11	45.8	6	25.0	0.125
Unrealistic experience	2	8.3	1	4.2	1.000
No disadvantages	1	4.2	8	33.3	0.016

Bold values indicate statistically significant differences ($p < 0.05$)

Several factors may explain the observed advantages of immersive technologies over conventional LM. When using LM, students often spend considerable time locating the target cell, which can complicate identification and create uncertainty about whether they have found the correct cell. In contrast, VR and its additional tools provide precise visual guidance to a specific cell, which is not available with conventional LM. Han et al. (2020) (29) reported similar observations, emphasizing that visual guidance helped direct attention and reduce cognitive load, particularly among participants with less prior knowledge. Regarding task completion time, a study conducted in Finland found

that beginners using VR completed tasks significantly faster and made fewer errors than the control group (30). Importantly, identification time was measured differently across the two modalities in our study. The observed difference in identification time therefore reflects the complete identification task under each modality and should not be interpreted solely as a difference in the speed of recognizing cell morphology. Finally, the results of our logistic regression analysis indicate that the modality used was significantly associated with blood cell identification accuracy, regardless of participants' prior experience with VR.

Analysis of agreement between LM and VR showed slight agreement with positive Cohen's κ values for the leukocyte and erythroid lineages. In contrast, the thrombocytic lineage showed a paradoxical finding previously documented in the literature (22). The negative coefficient reflects the kappa paradox, driven primarily by pronounced asymmetry in the marginal distributions. When responses are heavily concentrated in a single majority category, expected chance agreement can exceed observed agreement. In contrast, the larger number of diagnostic categories in the leukocyte ($n = 15$) and erythroid ($n = 13$) lineages distributed responses more evenly, lowering expected chance agreement and allowing Cohen's κ values of 0.220 and 0.197, respectively, to reflect inter-method agreement more reliably. Participants' subjective assessments favored VR over LM across all three evaluated parameters: Image quality, diagnostic confidence, and ease of use. We believe that these dimensions influence blood cell identification accuracy because the VR environment provided higher resolution and a wider field of view while minimizing external distractions. Our results differ in part from those of Farahani et al. (2016) (21), who reported

lower participant ratings of image quality in VR and no statistically significant difference in diagnostic confidence ($p > 0.05$). Rapid advances in VR hardware over the past decade, as well as differences in participants' backgrounds and prior training, may explain this discrepancy. Overall, these findings suggest that modern, high-resolution VR systems may improve students' perceived competence and confidence in identifying blood cell morphology.

Participants also rated VR as significantly easier to use. This finding contrasts with expectations based on the technology acceptance model (TAM) and the general extended TAM for E-learning, in which prior experience is typically considered an important predictor of perceived ease of use and usefulness (31). Our findings suggest that an intuitive visual interface and a realistic immersive environment may offset a lack of prior VR experience. Furthermore, Generation Z learners show a strong preference for visual media over text-based content, supporting the potential of VR to align with their learning preferences and shorter attention spans (1). These findings are encouraging for integrating VR into practical teaching on blood cell morphology. They suggest that new visualization modalities may be introduced without placing substantial additional cognitive or technical demands on students. However, the highly positive perceptions observed may also reflect a "novelty effect," or short-term enthusiasm following initial exposure to an innovative approach (32). This possibility warrants further investigation. Overall, our results support further integration of VR into teaching and align with present trends toward using digital technologies, artificial intelligence tools, and simulation in health care and education (33). Larger longitudinal studies are needed to evaluate the long-term educational value and practical benefits of this approach.

CONCLUSION

Students in the Laboratory Technology program demonstrated a high level of openness to integrating VR into education, providing a foundation for the development of VR-assisted instructional modules. The pilot study results indicate that VR is a useful modality for visualizing morphological characteristics of cells in the erythroid and leukocyte lineages. High ease-of-use ratings, despite students' limited prior experience with immersive technologies, suggest that incorporating VR into the curriculum is feasible without imposing a substantial additional burden on students or teaching staff.

LIMITATIONS

The limitations of this single-center pilot study primarily relate to the relatively small sample size, as participants were recruited exclusively from a single cohort at one higher education institution. Nevertheless, the volume of analyzed cell items provided a solid foundation for our analytical model, though future research with larger student populations is recommended to confirm these findings. In addition, the experimental protocol strictly prohibited participants from reviewing learning material during testing, which may have influenced performance. A crucial study design limitation lies in the fixed testing order; because all participants completed blood cell identification in the VR environment before testing

under LM, a potential learning or familiarization effect cannot be entirely excluded. Consequently, future research in this domain should incorporate randomized sequence allocation or counterbalancing to control for order-dependent biases. Finally, this study did not evaluate the long-term retention of morphological identification skills, limiting definitive conclusions regarding the durability of the educational impact. Longitudinal studies are therefore required to assess knowledge retention over time and the practical transfer of competencies into real-world clinical laboratory practice.

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DECLARATION OF INTERESTS

Authors declare no conflicts of interests.

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