ORIGINAL ARTICLE

Volume 18 No. 3 2026

DOI: 10.21315/eimj2026.18.3.2

ARTICLE INFO

Submitted: 21-09-2024
Accepted: 13-06-2026
Online: 30-09-2026

A Preliminary Evaluation of the e-Learning for Renal Applied Pharmacology Tool for Enhancing Pharmacology Learning: A Pilot Quasi-Experimental Study

Siti Yusrina Nadihah Jamaludin[1], Nur Khadijah Muhamad Jamil[1], Yasrul Izad Abu Bakar[2,3], Siti Fadziyah Mohamad Asri[2], Marwan Saad Abdulrahman Azzubaidi[1]

[1]*Department of Pharmacology, Faculty of Medicine, Universiti Sultan Zainal Abidin, Medical Campus, Terengganu, MALAYSIA*

[2]*Department of Anatomy and Physiology, Faculty of Medicine, Universiti Sultan Zainal Abidin, Medical Campus, Terengganu, MALAYSIA*

[3]*Department of Medical and Health Professionals Education, Faculty of Medicine, Universiti Sultan Zainal Abidin, Medical Campus, Terengganu, MALAYSIA*

To cite this article: Jamaludin SYN, Jamil NKM, Abu Bakar YI, Mohamad Asri SF, Azzubaidi MSA. A preliminary evaluation of the e-learning for renal applied pharmacology tool for enhancing pharmacology learning: a pilot quasi-experimental study. Education in Medicine Journal. 2026;18(3): 19–34. https://doi.org/10.21315/eimj2026.18.3.2

To link to this article: https://doi.org/10.21315/eimj2026.18.3.2

ABSTRACT

Electronic learning (e-learning) or online learning in medical education has become increasingly prevalent, especially during the COVID-19 pandemic. However, poor student engagement and reduced motivation are among the critical challenges associated with online learning. The e-learning for Renal Applied Pharmacology (e-RAP) is a new technology-enhanced learning tool that includes a nephron image augmented with several Quick Response (QR) codes. It allows students to access relevant QR-linked educational materials prepared by the teachers. This quasi-experimental pilot study examined whether use of the e-RAP tool was associated with differences in cognitive performance, engagement, and motivation among 105 preclinical medical students at Universiti Sultan Zainal Abidin (UniSZA), Malaysia. Participants in the intervention group (Year 2, n = 45) used the e-RAP tool, while the control group (Year 1, n = 60) received conventional teaching. Cognitive performance, engagement, and motivation scores were measured using pre- and post-test multiple-choice questions (MCQ), the Burch Engagement Survey for Students, and the Motivated Strategies for Learning Questionnaire, respectively. Both groups demonstrated improvements in mean cognitive scores from pre- to post-test MCQ, with greater gains in the intervention group than in the control group. The intervention group was also associated with higher emotional and cognitive engagement (both in and out of class) and higher scores in several motivational domains, including intrinsic value, cognitive strategy use, and self-regulation. Although groups differed by academic year, baseline knowledge was comparable. Taken together, these preliminary findings suggest that e-RAP use may be associated with differences in cognitive performance, engagement, and motivation.

Keywords: *e-Learning, Cognitive performance, Engagement, Motivation, Pharmacology*

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CORRESPONDING AUTHOR

Siti Yusrina Nadihah Jamaludin, Department of Pharmacology, Faculty of Medicine, Universiti Sultan Zainal Abidin, Medical Campus, 20400 Kuala Terengganu, Terengganu, Malaysia

Email: yusrina2012@gmail.com

INTRODUCTION

Technology can be a powerful tool for revolutionising learning. Technology-enhanced learning refers to the use of technology in learning and instructional strategies to create improved learning experiences (1). In recent years, medical education has increasingly incorporated technology into teaching and learning methods, recognising the need for innovative approaches to engage modern medical students and enhance educational outcomes (2,3). E-learning in medical education, defined as the use of internet technologies to improve knowledge and performance (4), offers advantages, including easy access to materials, simultaneous distribution of digital content, and promotion of a learner-centred environment (4,5). Effective integration of these tools in educational settings is crucial to transforming education and improving student learning.

Online learning is not new in medical education; however, the COVID-19 pandemic accelerated its adoption, often replacing traditional face-to-face teaching (6). An integrative review of 38 studies reported generally positive attitudes among medical students towards technology-enhanced learning, valuing it both as an information and communication medium (7). However, studies investigating the impact of the COVID-19 pandemic have identified barriers, including poor communication, technical difficulties, reduced motivation and limited engagement (8–11). For example, a large cross-sectional study involving 2,100 undergraduate medical students conducted by Zhang et al. (12) found that online education is not the best approach in the post-epidemic era, at least for evidence-based medicine courses, given its lack of advantage in fostering motivation and comprehension compared to the blended or face-to-face teaching approach. These findings underscore the need for continuous refinement of technology-enhanced learning strategies to improve students' learning experiences.

The undergraduate medical programme (MBBS) at the Faculty of Medicine, Universiti Sultan Zainal Abidin (UniSZA), Terengganu, Malaysia, consists of a two-year preclinical phase covering basic medical sciences and a three-year clinical phase (13). During the preclinical phase, students learn core disciplines including anatomy and pharmacology. Anatomy focuses on the structures and organs of the human body, essential for safe clinical practice (14), while pharmacology addresses drug-receptor interactions, mechanisms of drug action, metabolism, and therapeutics (15). Both subjects are fundamental not only for medical students but also for those in other health care programmes, such as pharmacy and nursing. There is, therefore, a growing need to enhance the teaching of these disciplines through effective strategies that better prepare them for professional practice (16).

Effective pharmacology teaching often requires linking concepts with other basic sciences, such as physiology and pathophysiology (17). In renal pharmacology, this involves reinforcing students' understanding of nephron anatomy alongside site-specific drug actions. Instructional tools that highlight such cross-disciplinary connections can simplify complex concepts and enhance learning. Technology-enhanced strategies, such as Quick Response (QR) codes, offer practical ways to support this interconnected knowledge by providing immediate access to relevant resources (18).

QR codes in medical education improve access to online resources and foster peer learning in flipped or blended classrooms (19). Building on this, the e-learning tool for Renal Applied Pharmacology (e-RAP) uses QR codes to promote self-directed learning (20) and reduce cognitive load (21) during complex renal pharmacology study. Although QR codes and e-learning tools enhance access to digital resources, increased accessibility alone does not guarantee meaningful cognitive integration. In renal pharmacology education, students are required to connect nephron anatomy, physiology, and site-specific drug mechanisms, which are interrelated concepts often delivered in parallel yet dispersed across separate instructional materials. Such fragmented delivery increases cognitive processing demands and may hinder schema development, highlighting the need for structured conceptual integration.

Renal pharmacology involves processing multiple interacting elements, including nephron segment differentiation, transport mechanisms, and pharmacodynamic targets (22). Without structured scaffolding, students may struggle to organise and integrate the complex concepts inherent in renal pharmacology. Guided self-directed learning therefore necessitates intentional instructional design that supports learners in managing intrinsic complexity while maintaining learner autonomy (23). Within this framework, embedded case-based learning can serve as an integral scaffolding mechanism, prompting students to apply foundational anatomical and pharmacological knowledge to clinically meaningful contexts (24). Rather than functioning as a separate instructional component, case-based activities can be integrated into knowledge-consolidation frameworks to facilitate schema construction and promote deeper conceptual integration (25).

Cognitive Load Theory (CLT) emphasises that working memory is limited, and thus, instructional design should reduce unnecessary demands while supporting meaningful learning (26). From a CLT perspective, renal pharmacology represents high intrinsic load (IL) due to its inherent conceptual complexity. The e-RAP tool was therefore designed as a guided self-directed learning resource aligned with CLT principles. IL is managed by segmenting content according to nephron regions and explicitly linking each drug class to its anatomical site of action. Colour-coded QR codes embedded in a custom nephron image provide access to interconnected knowledge presented in simplified lecture notes, mnemonics, and an educator-prepared animation video, all from a single consolidated source (Figure 1). Extraneous load (EL) is addressed by reducing split-attention effects; instead of navigating multiple sources, learners access QR-linked materials embedded within a single nephron-based visual scaffold (21). Germane load (GL) is supported through embedded case-based learning with guided feedback, encouraging active schema construction rather than isolated memorisation (21,26). By combining anatomical localisation, pharmacological mechanisms, CLT-informed segmentation, and case-based scaffolding into a single structured interface, e-RAP addresses the instructional gap in cross-disciplinary knowledge integration rather than simply offering digital access.

As a student-centred learning tool, e-RAP has the potential to enhance engagement and motivation, thereby potentially supporting learning performance. Engagement is critical for effective learning in basic medical sciences (27), encompassing students' participation, investment, and commitment (28). Motivation, with its multiple components, is likewise essential for academic success (29), particularly given the intensive nature of the medical course (30). By assessing students' cognitive performance, engagement and motivation, this pilot study aimed to evaluate the association between use of the e-RAP tool and students' learning. We hypothesised that students using the e-RAP tool would demonstrate higher cognitive performance, greater engagement, and improved motivation than those receiving conventional teaching. Understanding the influence of e-RAP on these aspects can inform evidence-based educational practices and guide future development of technology-enhanced learning tools.

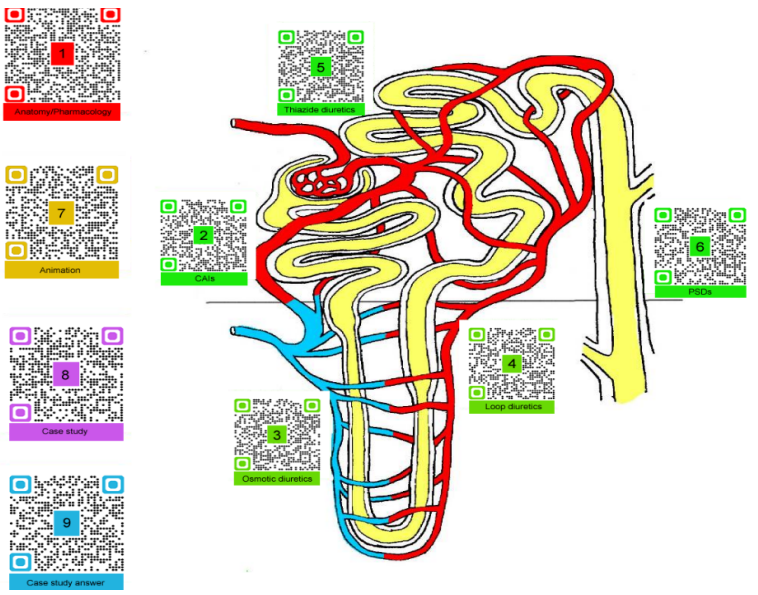


Figure 1: e-RAP, combining nephron anatomy with pharmacological concepts. QR codes (1 to 9) represent sequential learning from foundational content to diuretic classes, mapped to nephron segments, followed by case-based application and answer review.

METHODS

Development of the e-RAP Tool

The e-RAP tool was jointly developed by pharmacology and anatomy educators at UniSZA to promote self-directed learning. It was conceptualised in response to informal student feedback on difficulties in linking nephron anatomy with site-specific drug actions in conventional teaching. A custom nephron diagram was created with colour-coded QR codes linking to educator-created materials: simplified notes covering the functional microanatomy of the nephron and the pharmacology of diuretics; an animation visualising drug movement; mnemonics for memory support; and case-based self-assessments with feedback. The anatomy content was intentionally limited to functional microanatomy, designed to complement rather than compete with the tool's pharmacological emphasis. All educational resources were curated by subject-matter experts among the researchers to ensure relevance, accuracy, and alignment with the faculty-defined learning outcomes. The e-RAP tool was designed for easy access on smartphones and tablets, with QR codes enabling immediate access to digital resources via built-in cameras or commonly available scanning apps. While most students accessed the tool on their mobile devices, the resources were also accessible on other platforms via standard web browsers, supporting flexible use across devices. In a small-scale user acceptance test with 20 non-participating students, e-RAP was rated highly for usability, content relevance, and overall satisfaction. Although static in delivery, the e-RAP tool supported embedded interactivity through on-demand access to multimedia content and self-assessment activities, fostering personalised learning experiences.

Research Design

Randomisation was not feasible due to logistical and ethical constraints within the teaching schedule and cohort structure. Therefore, this study employed a quasi-experimental framework involving Year 1 (control) and Year 2 (intervention) students to provide a non-randomised pilot evaluation of the e-RAP learning tool in relation to preclinical medical students' learning process.

Participants

A total of 105 preclinical medical students (Academic Session 2023/2024) from the Faculty of Medicine, UniSZA, were enrolled, comprising 60 first-year (control) and 45 second-year (intervention) students. No probability sampling method was applied; all available samples that fulfilled the criteria were included due to the limited sampling frame. The control group received a conventional teaching method comprising face-to-face didactic lectures delivered by two subject lecturers (anatomy and pharmacology) in a computer laboratory setting on the functional microanatomy of the nephron and the pharmacology of diuretics, respectively. These sessions lasted one hour and included verbal explanations using standard lecture slides, without additional interactive components or online materials. The intervention group participated in a one-hour e-RAP session, beginning with a review of the nephron diagram to familiarise themselves with its segmental structure, followed by sequential scanning of QR codes corresponding to each nephron segment. They then engaged with the linked simplified notes, animation video, and case-based self-assessment activities in the prescribed order. Although the learning remained self-paced, this structured sequence was implemented to scaffold conceptual integration between anatomical and pharmacological concepts.

Participants were grouped by academic year based on pre-existing cohorts from the 2023/2024 session, without randomisation, matching, or stratification. Baseline comparability between groups was assessed using pre-test scores. All participants had no prior exposure to the topic, and none were repeaters, ensuring equal baseline exposure to the content. The characteristics of each group are shown in Table 1.

Table 1: Demographic characteristics of study participants (n = 105)

Demographic variable	n (%)		*p*-value
	Intervention group	Control group	
Total participants	45	60	
Gender			0.443[a]
Male	14 (31.1)	23 (38.3)	
Female	31 (68.9)	37 (61.7)	
Ethnicity			0.744[b]
Malay	35 (77.8)	44 (73.3)	
Indian	8 (17.8)	14 (23.3)	
Chinese	2 (4.4)	2 (3.3)	

Notes: [a] Pearson chi-square test; [b] Fisher's exact test

Research Instruments and Data Collection

A set of predesigned, vetted MCQs containing nine questions (two anatomy and seven pharmacology) related to the e-RAP content, developed by the research team, was employed in this study. The MCQ items were vetted by a medical educationist (YIAB), an anatomist (SFMA) and three pharmacologists (SYNJ, NKMJ, and MSAA) to ensure their validity and reliability before the execution of this study. Two types of MCQ tests were administered via Google Forms: the pre-test and the post-test. The pre-test MCQ assessed students' baseline knowledge before exposure to conventional teaching or the e-RAP intervention, while the post-test MCQ evaluated their cognitive performance after exposure to conventional teaching or the e-RAP intervention. To prevent cross-discussion among students that could cause data contamination, the intervention phase of the study was conducted and monitored by researchers at the computer laboratories in the Faculty of Medicine, UniSZA. Initially, all participants were asked to answer a pre-test MCQ before being assigned to the respective teaching method. This was followed by the learning stage for one hour, where participants were introduced to either the e-RAP tool (i.e., participating students were initially briefed by the principal investigator on how to access and navigate the e-RAP tool) or received the conventional face-to-face didactic lectures delivered by two subject lecturers (anatomy and pharmacology) in a computer laboratory setting.

Students in the intervention group accessed the e-RAP tool via mobile devices or institutional computers, and were instructed to explore the content at their own pace. Although the researchers were present to supervise and assist with any technical issues, no direct teaching or facilitation was provided during this one-hour learning session to preserve the student-centred nature of the intervention. Then, all participants were asked to answer a post-test MCQ after the learning stage, which evaluated cognitive performance after the intervention. The test contained the same nine questions as the pre-test MCQ, with slight paraphrasing and question reshuffling to mitigate potential recall bias. The immediate post-test was selected to assess immediate knowledge acquisition, rather than long-term knowledge retention following the intervention. Both the pre-test and post-test MCQ were administered in a supervised computer laboratory setting to prevent cross-group contamination and external influences. Participants were awarded one point for each correct answer and received no penalty for each incorrect answer. A higher score indicated better cognitive performance or ability. The improvement from the pre-test MCQ to the post-test MCQ was regarded as the basis for students' cognitive performance (i.e., knowledge acquisition) in the cognitive learning domain.

Subsequently, all participants were asked to complete two validated questionnaires, with high internal consistency (i.e., Cronbach's alphas well above the recommended 0.7 threshold): the Burch Engagement Survey for Students (BESS) (31) and the Motivated Strategies for Learning Questionnaires (MSLQ) (32). Both were administered in their published, unmodified forms via Google Forms for non-commercial, ethics-approved academic research. No explicit restrictions on their academic use were stated in the original publications. Both BESS and MSLQ have been widely used in medical education research (33–35). BESS comprises 24 items assessing emotional, physical and cognitive engagement (in class and out of class) on a 5-point Likert scale (31). In contrast, MSLQ included 44-item survey questions measuring two main dimensions: (a) Motivational Beliefs (22 items) and (b) Self-Regulated Learning Strategies (22 items) with a 7-point scale (32).

Statistical Analysis

Comparisons of demographic data between the intervention and control groups were conducted using Pearson's chi-square test or Fisher's exact test, depending on expected cell counts. Specifically, Fisher's exact test was applied when the expected count of less than five was more than 20%; otherwise, Pearson's chi-square test was applied. Repeated Measures Analysis of Variance (RM ANOVA) was employed to assess mean differences in cognitive scores: (a) within each group over time (time effect), (b) between groups (intervention effect), and (c) between groups based on time (time-intervention interaction). The assumptions of RM ANOVA were evaluated, including normality of residuals (assessed using histograms), homogeneity of variances (examined by plotting residuals against predicted values), and compound symmetry. Independent *t*-tests were used to compare engagement and motivation scores between the intervention and control groups. Results are presented as means ± standard deviations (SD), along with 95% confidence intervals (CIs). A *p*-value less than 0.05 was considered statistically significant. All analyses were conducted using IBM SPSS Statistics, version 29.0.

RESULTS

Participant Characteristics

Of the 119 students invited to participate in the study, 105 (88.2%) participated, representing 88.2% of the total cohort (Table 1). The majority of participants in both groups were female. Regarding ethnicity, most participants were Malay, followed by Indian and Chinese. The distribution of gender and ethnicity was comparable between the intervention and control groups.

Effect on Cognitive Performance

The pre-test scores did not differ significantly between the intervention and control groups ($p = 0.059$), indicating comparable baseline knowledge. Table 2 summarises the within-group analysis of cognitive scores over time. Statistically significant improvements in mean cognitive scores were observed from pre- to post-test in both the intervention and control groups ($p < 0.001$). While both groups showed increased scores following their respective instructional methods, the intervention group, which received the e-RAP tool, demonstrated a more pronounced improvement compared to the control group, which received only standard didactic lectures.

Table 2: Comparison of cognitive scores within each group based on time (time effect)

Comparison	Intervention group		Control group	
	MD [95% CI]	*p*-value	MD [95% CI]	*p*-value
Pre – Post intervention scores	−3.42 (−4.06, −2.79)	< 0.001	−2.05 (−2.52, −1.58)	< 0.001

Notes: Within-group analysis was conducted using RM ANOVA, followed by pairwise comparisons with Bonferroni-adjusted 95% confidence intervals. Mean differences (MD) were reported, and a significance level of $p < 0.05$ was applied.

Table 3 presents the between-group comparison of overall mean cognitive score differences, reflecting the main intervention effect. A statistically significant difference was found between the intervention and control groups ($p < 0.001$). The intervention group achieved a higher mean cognitive score (5.47) than the control group (4.09), suggesting an association between e-RAP tool use and higher cognitive performance.

Table 3: Comparison of overall mean difference of cognitive scores between intervention and control groups (intervention effect)

Variable	Mean (SD)		MD [95% CI]	*p*-value
	Intervention group	Control group		
Cognitive scores	5.47 (1.11)	4.09 (1.87)	1.38 (0.79, 1.96)	< 0.001

Note: RM ANOVA between group analysis was applied; MD = mean difference.

Table 4 presents the comparison of mean cognitive scores between the intervention and control groups over time, reflecting the time-by-intervention interaction effect, as illustrated in Figure 2. At pre-test, the mean cognitive score for the intervention group was 3.76, which did not overlap with the 95% confidence interval (CI) of the control group (2.60–3.54). Similarly, at post-test, the intervention group had a higher mean cognitive score of 7.18, which also fell outside the 95% CI of the control group (4.63–5.61). The confidence intervals indicated differences between groups at both time points, consistent with the statistically significant interaction effects, further supporting the association between e-RAP use and higher cognitive scores over time. Assumptions of normality, homogeneity of variances, and compound symmetry were checked and fulfilled.

Table 4: Comparison of cognitive scores between intervention and control groups based on time (time-intervention interaction)

Comparison	Treatment group	Mean cognitive scores	95% CI
Pre-test	Intervention	3.76	3.22, 4.30
	Control	3.07	2.60, 3.54
Post-test	Intervention	7.18	6.61, 7.74
	Control	5.12	4.63, 5.61

Notes: RM ANOVA between-group analysis with regard to time was applied.
F-statistic (degree of freedom) = 201.39 (1).

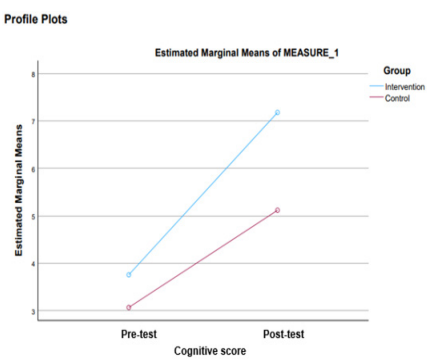


Figure 2: Profile plot of estimated marginal means of cognitive scores for the intervention and control groups at pre-test and post-test.

Effect on Engagement

Our results demonstrated statistically significant differences between the intervention and control groups in three engagement domains as measured by the BESS (Table 5). Notably, the intervention group reported significantly higher mean scores for emotional engagement, in-class cognitive engagement, and out-of-class cognitive engagement than the control group. These findings suggest that the e-RAP tool was associated with higher emotional and cognitive engagement among students, both during and outside of class time. In the physical engagement domain, there was no statistically significant difference between the intervention and control groups, although the intervention group showed a trend towards higher engagement.

Table 5: Comparison of mean scores for engagement between intervention and control groups

Variable	Mean (SD)		MD [95% CI]	*p*-value
	Intervention group	Control group		
Emotional engagement	4.55 (0.41)	4.27 (0.71)	0.28 (0.06, 0.50)	0.013
Physical engagement	4.37 (0.59)	4.10 (0.78)	0.27 (−0.01, 0.54)	0.057
Cognitive engagement: In class	4.33 (0.57)	4.03 (0.86)	0.30 (0.01, 0.59)	0.044
Cognitive engagement: Out of class	4.46 (0.60)	4.16 (0.70)	0.30 (0.04, 0.56)	0.022

Notes: *Independent *t*-test; MD = Mean difference. Level of significance set at $p < 0.05$.

Effect on Motivation

The MSLQ was utilised to assess different aspects of students' motivational beliefs and their self-regulated learning. Our results revealed significant differences between the intervention and control groups in all sub-domains except self-efficacy (Table 6). Notably, the intervention group consistently showed significantly higher mean scores in three sub-domains of intrinsic value, cognitive strategy use, and self-regulation, suggesting that e-RAP use was associated with higher scores in these domains. Moreover, the intervention group also exhibited significantly lower levels of test anxiety than the control group, indicating that e-RAP use was associated with lower reported test anxiety. However, no statistically significant difference was found for the self-efficacy sub-domain between the intervention and control groups. By and large, the use of the e-RAP learning tool was associated with higher scores across most motivational and self-regulated learning domains.

Table 6: Comparison of mean scores for motivation between intervention and control groups

Variable	Mean (SD)		MD [95% CI]	*p*-value
	Intervention group	Control group		
Intrinsic value	6.23 (0.49)	5.84 (0.78)	0.40 (0.15, 0.65)	0.002
Self-efficacy	5.10 (1.10)	5.01 (0.96)	0.09 (−0.31, 0.50)	0.642
Test anxiety	4.25 (1.45)	4.95 (1.37)	−0.70 (−1.26, −0.15)	0.013
Cognitive strategy use	5.80 (0.62)	5.41 (0.80)	0.39 (0.11, 0.66)	0.006
Self-regulation	5.16 (0.77)	4.77 (0.70)	0.39 (0.10, 0.68)	0.008

Notes: *Independent *t*-test; MD = Mean difference. Level of significance set at $p < 0.05$.

DISCUSSION

This pilot study evaluated the association between the use of the e-RAP tool and preclinical medical students' learning, focusing on cognitive performance, engagement, and motivation. Both the intervention and control groups demonstrated significant improvements in cognitive performance from pre-test to post-test. However, the intervention group, which used the e-RAP tool, showed a significantly greater cognitive gain, suggesting that e-RAP use was associated with greater cognitive improvement compared to conventional didactic lectures. This preliminary finding suggests the potential value of incorporating e-RAP into instructional strategies to further support students' cognitive development. The observed improvement in cognitive scores in the intervention group aligns with the existing literature reporting a positive association between instructional approaches and student learning outcomes. A systematic scoping review of 56 studies performed by Abaei et al. (36) reported that among several teaching methods being employed in pharmacology education worldwide, e-learning appears to be effective in strengthening self-directed learning, providing ease of access to educational materials and yielding greater student satisfaction, in comparison with traditional lectures. Furthermore, a prospective, single-group, pre-post intervention study conducted by Patel et al. (37) revealed a significantly higher post-test score than the pre-test score after students had completed the e-learning module on pharmacovigilance, indicating an association between the e-learning module and higher scores. Therefore, our work might add the e-RAP learning tool to existing strategies such as team-based learning, problem-based learning combined with case-based learning, and the flipped classroom (38) as a complementary strategy, particularly for enhancing cognitive ability. It may function as a structured supplementary scaffold that complements existing instructional strategies by facilitating integration of foundational concepts within a guided self-directed framework.

Our results from the BESS questionnaire indicated that the e-RAP tool was associated with improvements across several engagement domains, particularly the emotional and cognitive domains. Emotional engagement was significantly higher in the intervention group than that in the control group, highlighting the association between the e-RAP use and higher emotional engagement. This finding is crucial as previous research has also identified a positive relationship between emotional engagement and students' academic performance (39). Cognitive engagement, defined as the time and energy that students devote to cognitive processes (40), was also significantly higher in both in-class and out-of-class contexts for the intervention group. It was discovered that students using e-RAP demonstrated higher engagement during class and also sustained cognitive engagement outside of class. The observed increase in cognitive engagement might be explained by the self-paced nature of the e-RAP tool, which allowed students to revisit QR-linked educational content at their convenience, affording them greater control over their learning process, irrespective of time and location. This is consistent with the established benefits of e-learning, particularly its capacity to support learner-driven education (5). As a result, it is plausible that higher cognitive engagement may be related to the higher mean cognitive scores observed among the students in the intervention group compared to those who followed the conventional teaching method.

Our findings parallel those of Ramli et al. (34), who conducted a randomised controlled trial involving 58 first-year medical students to investigate the impact of two types of supplementary e-learning courses on "Anatomy of the Thigh" on students' engagement. While their quantitative analysis did not reveal significant differences in engagement between the intervention group (i.e., those receiving radiological images in their e-learning course) and the control group (i.e., those receiving non-radiological diagrams in their

e-learning course), the qualitative findings highlighted a positive impact of e-learning in promoting students' emotional and cognitive engagement in the intervention group (34). Similarly, in our study, the use of the e-RAP tool was associated with higher reported scores in these engagement domains.

However, in terms of physical engagement, our analysis did not show a statistically significant difference between the intervention and control groups, indicating that using the e-RAP tool was not superior to the conventional teaching method in improving students' physical engagement. This result is not surprising, as an earlier study also found that supplementary e-learning in learning anatomy has no substantial effect on fostering students' physical engagement (34). Moreover, another study by Dumford and Miller (41) found that students who enrolled in more online courses were less likely to engage in collaborative learning activities than their peers in traditional classroom settings. The authors attributed this observation to feelings of isolation that may be associated with online, self-directed learning, which can be mitigated by assigning group projects or encouraging classmate interactions via chats and discussion boards (41). To address this issue, future extensions of the e-RAP tool could incorporate collaborative features, such as group projects or peer discussions, to reinforce students' physical engagement and foster a sense of community among learners. In addition, incorporating gamified quizzes can provide an engaging, interactive way to encourage active participation further. Despite the preliminary results of our present study revealing a noteworthy positive association between e-RAP use and certain aspects of students' engagement, further refinements are required to enhance physical engagement and promote collaborative learning.

Regarding students' motivation, our preliminary results indicated that e-RAP use was associated with higher scores across several domains of motivational beliefs and self-regulated learning strategies. The intervention group showed a significantly higher intrinsic value compared to the control group. This suggests that e-RAP use was associated with higher intrinsic motivation, indicating that students were intrinsically motivated to learn and that this, in turn, led them to perceive the learning materials as important and interesting. Students in the intervention group also exhibited significantly higher cognitive strategy use and higher self-regulation than those in the control group. This may reflect stronger use of learning strategies among those in the intervention group, which may also be associated with higher academic performance. Moreover, they reported significantly lower test anxiety compared to those in the control group. This finding is important because it suggests that e-RAP use may be associated with lower reported test anxiety, which, in turn, may positively influence students' performance and well-being.

Regarding the self-efficacy sub-domain, there was no statistically significant difference between the intervention and control groups. This indicates that while e-RAP use was associated with higher scores across several aspects of motivation and learning strategies, it did not substantially affect students' self-efficacy, which refers to their perceived competence and confidence in performing the learning tasks (32). We postulated that the lack of a significant difference in self-efficacy between the groups could imply that the students may not possess well-developed self-confidence, since items in this sub-domain require them to make self-judgements and comparisons with peers. For example, students were asked to evaluate the extent of their knowledge relative to others in the class or to reflect on the quality of their study skills compared with classmates (32). Such comparative self-assessment may be particularly challenging for preclinical medical students, which could partly explain the observed results. Moreover, findings from a recent study have suggested a relationship between self-confidence and self-efficacy, in which both can lead to more self-

determined forms of motivation and motivated learning behaviour (42). Taken together, our preliminary results suggest that e-RAP use was associated with certain aspects of motivation and learning strategies. However, future research could refine the current version of the e-RAP tool to improve students' self-efficacy in learning the functional microanatomy of the nephron and the pharmacology of diuretics.

It is also important to note that the control and intervention groups were drawn from different academic years (Year 1 and Year 2, respectively), which may have introduced some variability in academic maturity, prior learning experiences, and learning readiness. Although baseline knowledge scores and demographic characteristics were comparable across groups, the potential confounding influence of academic year cannot be fully excluded. This is a recognised limitation in quasi-experimental designs where randomisation is not feasible (43). Future studies employing randomisation or stratified sampling across year levels would help strengthen causal inferences and minimise this potential bias.

Limitations and Future Recommendations

While the results of this pilot study are encouraging, several limitations should be considered. First, the small and unequal sample sizes, although reflective of the eligible student population within the study context, may limit the generalisability of the study findings (44). This study was conducted within a Scholarship of Teaching and Learning context, where implementation within a formal course precluded randomisation, and findings should therefore be interpreted with caution.

Second, the study's short duration focused solely on immediate knowledge acquisition and did not assess long-term retention. This limits our ability to ascertain whether the observed cognitive gains were sustained over time. Future studies should therefore prioritise delayed post-test designs or longitudinal follow-up to assess the sustainability of cognitive gains and the long-term impact of the e-RAP tool.

Third, students' engagement and motivation data were based on self-reported surveys, which may be influenced by social desirability bias. Engagement and motivation were measured using self-reported instruments administered immediately after the intervention in a supervised setting. Accordingly, the findings reflect students' perceptions rather than objectively observed behaviour or sustained outcomes, and may be influenced by short-term affective responses (45). Immediate post-session measurement may capture transient enthusiasm rather than sustained changes in engagement or self-regulated learning. Future research could incorporate additional data sources (e.g., structured interviews) (32) and qualitative assessments to provide deeper insights into students' learning experiences with the e-RAP tool.

Fourth, the anatomy content in the current version of the e-RAP tool was intentionally limited to microanatomical context to support pharmacological understanding. We acknowledge this as a limitation, and future iterations should expand the anatomical scope, such as incorporating gross renal anatomy and more anatomy-aligned assessments, to provide students with a more comprehensive learning experience.

Fifth, while the e-RAP tool demonstrated benefits for cognitive and emotional engagement, physical engagement remained limited. Future extensions could address this by incorporating collaborative elements, such as group discussions or gamified quizzes, to foster peer interaction and more active participation.

Finally, the control and intervention groups consisted of Year 1 and Year 2 students, respectively, which represents a potential confounding factor inherent to the study design due to differences in academic maturity, experience, or learning readiness. Although baseline comparability was demonstrated, differences in academic maturity across year groups may still confound. Future multi-centre studies employing larger, stratified samples and, where possible, randomisation are recommended to minimise such confounding and strengthen causal inference.

CONCLUSION

In conclusion, this pilot quasi-experimental study found that e-RAP use was associated with higher cognitive performance, emotional and cognitive engagement, and selected motivational domains, compared to conventional teaching in a preclinical context. While promising, these findings should be interpreted cautiously given the study's limitations and short-term outcome assessment. Further randomised controlled trials are required to determine causality and sustainability of knowledge acquisition. Future studies incorporating delayed post-tests or longitudinal follow-up are needed to evaluate the long-term impact of the e-RAP tool. Nevertheless, our findings suggest that e-RAP may represent a promising supplementary approach for undergraduate medical teaching, with potential to inform the development of technology-enhanced learning strategies within similar preclinical settings.

ACKNOWLEDGEMENTS

This study was financially supported by the UniSZA Scholarship of Teaching and Learning (SoTL) Grant 2023 (UniSZA/2023/SoTL/011) with a project number of RK046. We would like to thank the students who participated in this study for their full commitment throughout the study. We would also like to thank Dr. Sharifah Nany Rahayu Karmilla Syed Hassan and Dr. Che Mohd Nasril Che Mohd Nassir for their assistance in arranging the relevant slots in the students' timetables and during the post-test assessment of the study. We also thank Dr. Myat Moe Thwe Aung for her expertise and consultation on statistical analyses.

ETHICAL APPROVAL

Ethical approval for conducting the study was obtained from UniSZA Human Research Ethics Committee (UHREC) (Study Protocol Code: UniSZA/UHREC/2023/607). All participants in this study were informed about the details of the study. Participation in this study was entirely voluntary and the study participants could withdraw from the study without any consequences. Written informed consent was obtained from all study participants before being enrolled in this study. The anonymity and confidentiality of study participants were guaranteed. Only research team members had access to the data.

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