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ORIGINAL ARTICLE

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Is online-only learning as effective as blended learning? A longitudinal study comparing undergraduate students' performance in oral radiology

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Abstract

Introduction: Blended learning seems to be an effective teaching concept in oral radiology. During the COVID-19 pandemic, blended learning shifted towards online-only learning. The aim of the present study was to compare the effectiveness of pandemic online-only and pre-pandemic blended learning in three consecutive oral radiology courses (C1, C2 and C3) and to examine whether additional video-based e-learning modules (VBLMs) had a positive impact on undergraduate students' performance during pandemic semesters.

Materials and Methods: Data from 205 undergraduate dental students participating either in a blended learning or an online-only learning concept were analysed. Pre-pandemic blended learning comprised face-to-face seminars and access to an oral radiology platform (ORP). Pandemic online-only learning comprised online seminars, access to the ORP and additional VBLMs (two VBLMs for C1, four VBLMs for C2 and six VBLMs for C3). Through standardised e-exams at the beginning and end of each semester, performance in final exams and knowledge gain were compared between the two groups.

Results: No significant differences in scores in final exams ($p = .11$) and knowledge gain ($p = .18$) were found when comparing the pre-pandemic and pandemic groups. On course level, however, students receiving a lower number of VBLMs performed significantly worse in final exams (C1: $p < .01$, C2: $p = .02$) and showed inferior knowledge gain (C2: $p < .01$) during the pandemic.

Conclusions: Within the limitations of the study, the present investigation confirmed that pandemic online-only learning involving VBLMs might be as effective as pre-pandemic blended learning.

KEYWORDS
blended learning, online-only learning, oral radiology, undergraduate students' performance, video-based e-learning modules

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1 | INTRODUCTION

Blended learning concepts are generally thought to be the gold standard for effective content delivery in medical education.[1-7] It combines synchronous (i.e. time-fixed live lessons, online or on campus) face-to-face (F2F) learning and asynchronous (i.e. time independent, on-demand) e-learning. F2F learning has a long tradition in higher education and is expected to promote reflection on a high cognitive level by stimulating social interaction and discussions.[8] E-learning, on the other hand, is thought to be particularly effective in conveying theoretical knowledge.[3] In addition, it allows educators to develop student-centred content (e.g. asynchronous interactive and adaptive online learning content).[9] Through rapidly evolving interactivity and associated transfer of theoretical knowledge to a higher cognitive level, e-learning might also facilitate the acquisition of complex competencies.[10,11] Moreover, high-quality learning content can be provided modularly, allowing teachers to regulate students' cognitive load. The high extent of flexibility in e-learning (e.g. time and place independence and the possibility for repetition) may encourage students to develop their own pace of learning and is considered to lead to effective memory consolidation eventually.[8,10,12,13]

According to the Miller pyramid,[14] the acquisition of medical competencies involves three consecutive competence levels. Level 1 comprises descriptive, factual knowledge; level 2 describes the ability to explain facts and relationships and place them in a scientific-clinical context; and level 3 encompasses the ability to apply what has been learned. Developing diagnostic skills in oral radiology, which is defined as the ability to interpret radiographic images accurately,[15] primarily corresponds to level 3 of the Miller pyramid. Therefore, it depends on acquiring theoretical knowledge (of not only anatomy but also prevalence, aetiology, clinical symptoms of underlying pathologies and possible differential diagnoses) as well as clinical experience (through case-based training).[16,17] Acquiring these skills may be achieved by means of different learning concepts. The subject of oral radiology may be particularly suitable for implementation in online-only concepts since it includes a variety of digital images that can be conveniently accessed and viewed online.[18,19] Interestingly, the only previous study the authors are aware of that compared blended and online-only learning (and also F2F and problem-based learning) in oral radiology did not find any significant differences in students' performance between these learning concepts.[20]

Even though online-only learning, that is, the combination of synchronous and asynchronous e-learning, was broadly employed during the COVID-19 pandemic, there is virtually no indication of its impact on students' learning effectiveness measured by standardised, validated assessment methods. Until now, studies only gave an overview of how universities adapted their teaching concepts to the crisis,[21] discussed the advantages and disadvantages of e-learning in dental education,[22] surveyed students to rate asynchronous and synchronous online teaching compared to F2F teaching[23] and assessed students' satisfaction with online-only teaching[24-27] and assessment.[28] However, to our best knowledge, there is no study that investigated differences in diagnostic skill development in oral radiology between pre-pandemic blended learning and pandemic online-only learning, although it has been emphasised by multiple authors.[27,29,30,31]

At Heinrich Heine University Düsseldorf (HHU), oral radiology in undergraduate dental education is taught using a blended learning concept in three consecutive courses (C1, C2 and C3) since 2015. It comprises case-based F2F seminars four times a week and access to a digital oral radiology platform (ORP) with annotated radiographs. In April 2020, due to the COVID-19 pandemic, universities were obliged to minimise F2F contact and to use online formats for higher education. As a consequence, F2F seminars in oral radiology at HHU were held online (same frequency and duration as in pre-pandemic semesters), students received continuous access to the ORP and six additional video-based e-learning modules (VBLMs) were introduced and integrated into the pre-existing blended learning concept (two VBLMs for C1, four VBLMs for C2 and six VBLMs for C3). This provided the unique opportunity to compare the online-only to the previous blended learning concept.

Aim of the present study was to compare the effectiveness of these two learning concepts in three consecutive oral radiology courses (C1, C2 and C3) by means of comparing students' performance in final exams and the associated knowledge gain (i.e. the difference in scores between final and baseline exams). Moreover, we aimed to assess whether the number of VBLMs provided to the students positively impacted students' performance in final exams. Finally, we examined the relationship between students' knowledge gain and usage statistics from the ORP.

2 | MATERIALS AND METHODS

2.1 | Study design

2.1.1 | Participants

The study was conducted at the Departments of Oral Surgery and Orthodontics at HHU. A total of 205 undergraduate dental students (62 males and 143 females) participated in this study during their oral radiology courses. Students participated in two groups according to the time point of participation. Eighty-three students in the pre-pandemic group were enrolled in the regular teaching programme (October 2018 until February 2020, mandatory case-based lectures four times a week and voluntary access to the ORP). Seventy-five students in the pandemic group were enrolled in a video-enhanced online-only teaching programme (April 2020 until July 2021, mandatory synchronous online seminars, voluntary access to the ORP and a variable number of VBLMs). A total of 47 students participated in the radiology courses both in pre-pandemic and pandemic semesters, thus experiencing both teaching concepts. Figure 1 depicts the timeline of the study including the course distribution over the pre-pandemic and pandemic semesters. During pre-pandemic semesters, 86 students participated in C1 final exams, 76 students in C2 final exams and 83 students in C3 final exams. During pandemic

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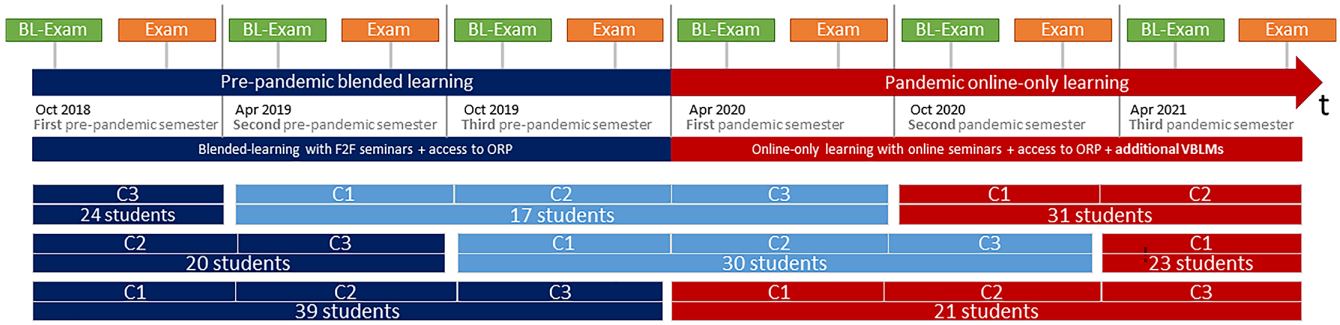

FIGURE 1 Timeline of the study. The study period was from October 2018 until July 2021. Each semester started with a baseline exam (BL-Exam) and ended with a final exam (Exam). From October 2018 to February 2020, the pre-pandemic blended learning concept (dark blue) was implemented comprising face-to-face (F2F) seminars and access to the oral radiology platform (ORP). From April 2020 to July 2021, the pandemic online-only learning concept (red) with online seminars and access to the ORP and additional video-based e-learning modules (VBLMs) was implemented. Students participated in three consecutive oral radiology courses (C1, C2 and C3) at different time points (dark blue = blended learning; red = online-only learning; light blue = both blended and online-only learning).

semesters, 75 students participated in C1 final exams, 82 students in C2 final exams and 68 students in C3 final exams. Since this study was conducted during the COVID-19 pandemic, no a priori sample size calculation was performed. It was therefore aimed to calculate the post hoc power.

2.1.2 | Course outline and procedure

Oral radiology was taught throughout three subsequent courses as part of the clinical teaching programme at the HHU to acquire diagnostic skills.

- Course 1 (C1): students of seventh semester. Students were supposed to have no or just basic knowledge of clinical oral radiology.
- Course 2 (C2): students of eighth semester. Students already have basic knowledge. A prerequisite for participation is passing C1.
- Course 3 (C3): students of ninth semester. Students already have advanced knowledge. A prerequisite for participation is passing C1 and C2.

Figure 2 shows the timeline and course of the study for a pre-pandemic and a pandemic semester including information about the specific time points, at which students were allowed to access the different VBLMs during pandemic semesters and at which exams had to be completed.

2.2 | Online platforms

2.2.1 | Oral radiology platform

The oral radiology platform is operated by a commercial software provider (SmartZoom®, Smart In Media AG, Germany). As it is implemented as a web application, it is accessible from PCs, tablets and smartphones. At the time of the study, it contained a total of 481 images, including mainly not only dental radiographs but also histopathological and clinical images (Table 1). The radiographs were further organised into different categories (prosthodontics, endodontics, orthodontics and oral surgery) and subcategories. Access was given to all students attending one of the above-mentioned courses (C1, C2 and C3) for both pre-pandemic and pandemic semesters. Students were also informed which topics were relevant to their course.

After selecting a radiograph (Figure 3), students could choose between different interactive learning options. (1) Annotation pins, linked to short information texts, were located on the radiographs to mark specific anatomical structures or pathologies. (2) In a submenu, all annotation texts, additional information and related images could be accessed. (3) Various interactive tools allowed students to personalise their learning experience. For example, students could write their own annotations, place additional pins, share images through creation of QR codes, measure areas of interest or utilise a presentation cursor during online sessions. (4) Students could also direct questions to the academic staff with the option of making these questions visible to fellow students as an annotation afterwards.

2.2.2 | Video-based e-learning modules (VBLMs)

At the onset of the pandemic, additional VBLMs were created. Each module comprised pre-recorded educational video lectures (length: 20–39 min) and videos not the module were enhanced with Power Point presentations. These videos were embedded in learning modules (Figure 4) on ILIAS (*integrated learning, information and work cooperation system*, ILIAS open-source e-Learning e.V., Cologne, Germany), an open-source learning management system provided by the HHU. Among the topics of the ORP, six topics of different difficulty were selected to be covered in the VBLMs. Depending on the assumed difficulty of VBLMs and students' pre-existing knowledge level, the VBLMs were assigned to the three different courses

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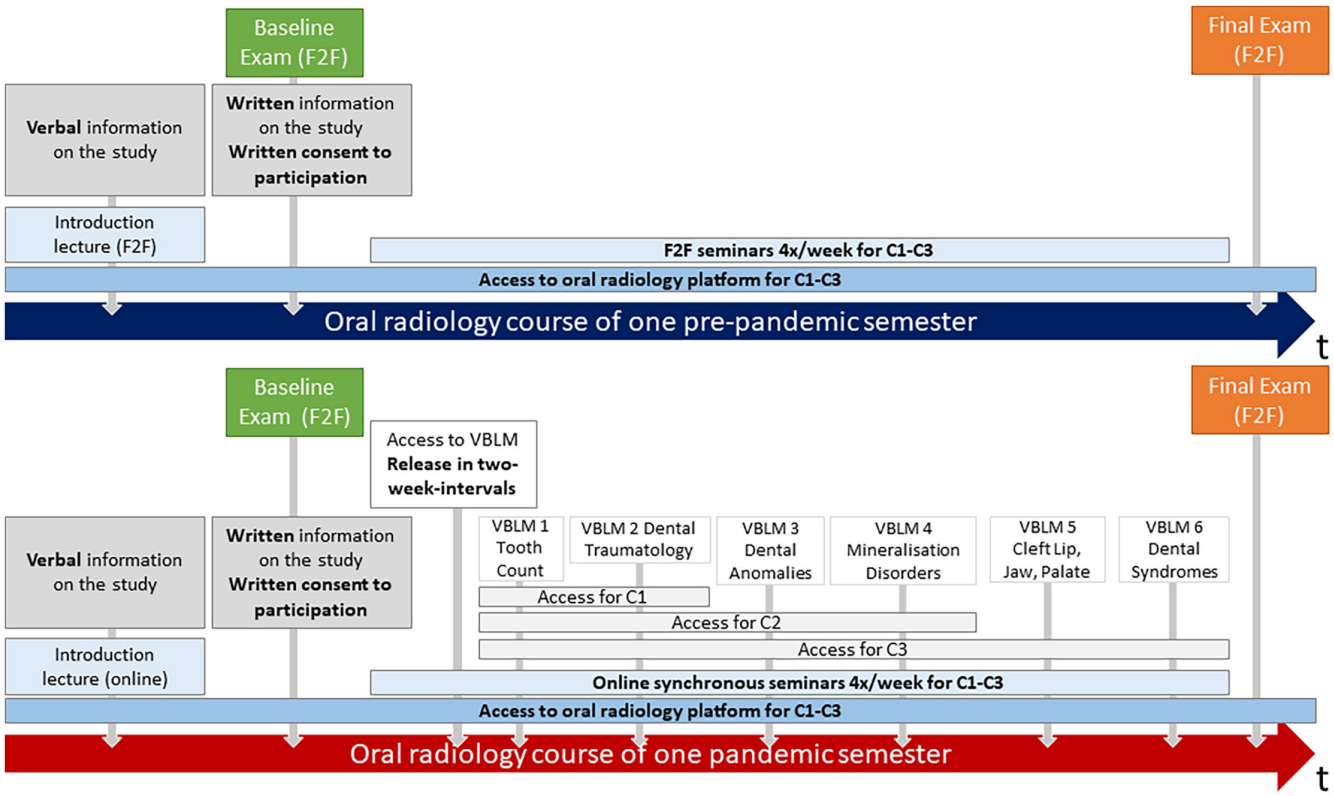

FIGURE 2 Timeline of oral radiology course during pre- (blue) and pandemic (red) semesters and the accompanying study elements. Oral information regarding the study was given at the beginning of each semester in a face-to-face (F2F) or during the online introduction lecture. After the baseline exam, F2F or online synchronous seminars were held four times a week. In pandemic courses, the video-based e-learning modules (VBLMs) were released in 2-week intervals. Course 1 (C1) had access to two VBLMs, course 2 (C2) had access to four VBLMs and course 3 (C3) had access to six VBLMs. During the entire semester (pre-pandemic and pandemic), all students (C1, C2 and C3) had access to the oral radiology platform.

TABLE 1 Types of images on oral radiology platform.

Type of image	Quantity
Panoramic X-ray	252
Periapical X-ray (Dental film)	84
Histopathological slide	36
Lateral cephalogram	33
Clinical image	22
Partial panoramic X-ray	19
Bite-wing X-ray	11
Three-dimensional imaging (i.e. digital volume tomography)	7
Frontal cephalogram	4
Occlusal X-ray	4
Mandible overview radiograph	3
Lateral temporal mandibular joint radiograph	2
Periodontal radiographic status	1
PA (posterior–anterior) radiograph	1

Note: Ordered by frequency of occurrence.

(Figure 2). First, the VBLMs with the lowest level of difficulty covered the topics 'Tooth Count' and 'Dental Traumatology', which were grouped as the 'Beginners' set and were provided to all three courses. Second, the VBLMs with intermediate difficulty covered the topics 'Dental Anomalies' and 'Mineralisation Disorders', which were grouped as the 'Advanced' set, and were provided to C2 and C3. Third, VBLMs with the highest level of difficulty covered the topics 'Cleft Lip, Jaw, Palate' and 'Dental Syndromes', which were grouped as the 'Experts' set and were given only to C3.

The access to the material was limited to time intervals specified below. The estimated completion time per VBLMs was 60–90 min. The structure of each VBLMs comprised (1) an introduction consisting of patient examples, learning objectives and background information (image–text combination and textbook style); (2) a video lecture; (3) a quiz consisting of 7–10 questions for self-evaluation; and (4) a summary and conclusion (Figure 4).

The VBLMs were released online at 1-week (first pandemic semester) or 2-week intervals (remaining pandemic semesters). Weekly notifications and reminders were emailed to the students. Upon completion of a set of VBLMs ('Beginners', 'Advanced' and

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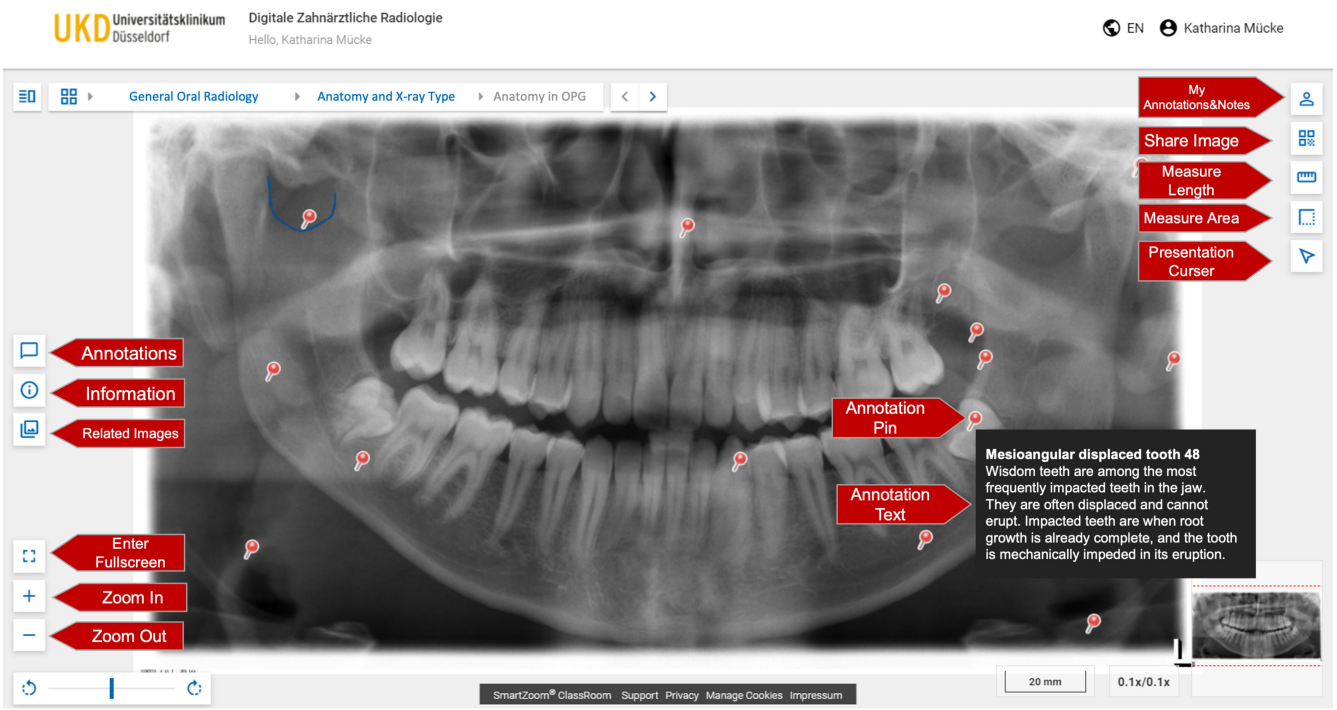

FIGURE 3 Example of an annotated panoramic X-ray on the oral radiology platform. The oral radiology platform provided annotated images, explanatory texts and several interactive tools such as user annotations and notes, measurement tools, presentation cursor as well as a communication system to contact the teachers.

'Experts'), quiz questions with direct feedback were unlocked for self-evaluation. As a prerequisite, both VBLMs of this set had to be completed.

2.3 | Analysis of platform usage

User access data of the ORP were tracked using Matomo Version 4.14.1 (open-source web analytics programme). The number of access per internet protocol number per day was analysed, which corresponded to the number of students utilising the ORP per day. These data were also summarised to obtain the cumulated number of platform accessors per month and semester respectively. For the VBLMs, usage statistics were extracted from the learning management system (ILIAS).

2.4 | Additional learning opportunities

To further support the students during the first month of the COVID-19 pandemic, we offered 1 h of online consultation per week. Additionally, we introduced another synchronous format to the curriculum: the 'digital radiology lunch'. It entailed an online lunchtime lecture on Microsoft Teams that was conducted two times (14th May 2020 and 28th May 2020) per semester, covering the topics 'caries diagnostics' and 'cysts'. In the two following semesters, we offered a repetition lecture for all courses at the end of the semester lasting around 2 h per lecture. The lecture was a synchronous PowerPoint-based presentation with interactive options to ask open questions.

2.5 | Exams

We assessed students' knowledge and diagnostic skills in oral radiology by conducting standardised exams at the beginning and the end of each semester (Figures 1 and 2). Questions validated with respect to item difficulty, selectivity and reliability were used (Table 2). Item difficulty and selectivity were calculated for each question based on the respective exams' results from previous years using the R package *psych* (Revelle, 2023; Item Response Theory based on factor analysis).[32] Eventually, we computed the *selectivity* a priori and only utilised questions having a *selectivity* above 0.3. Table 2 summarises the percentages of item difficulties. Additionally, a reliability analysis (Cronbach's alpha) was performed for the entire set of questions (Table A1). The number of questions and scores per question was standardised and amounted to 50 questions (2 points each) per exam. Students were given 90 s per question, resulting in a total completion time of 75 min. The following types of questions were used: (1) multiple-choice questions (single answer), (2) multiple-select questions (multiple answers), (3) kprim questions, (4) hotspot/imagemap questions, (5) gap-fill questions, (6) mark errors in text questions and (7) questions on professional terms.

The content was based on 29 different dental categories (Table A2). From each category, the same number of questions were utilised in each exam comprising 50% orthodontic as well as 50% non-orthodontic questions related to oral radiology. In the pandemic semesters, the VBLMs covered 18%–20% of the respective exam questions in C1, 30%–46% in C2 and 24%–32% in C3. The exams were conducted under supervision of the centre of information

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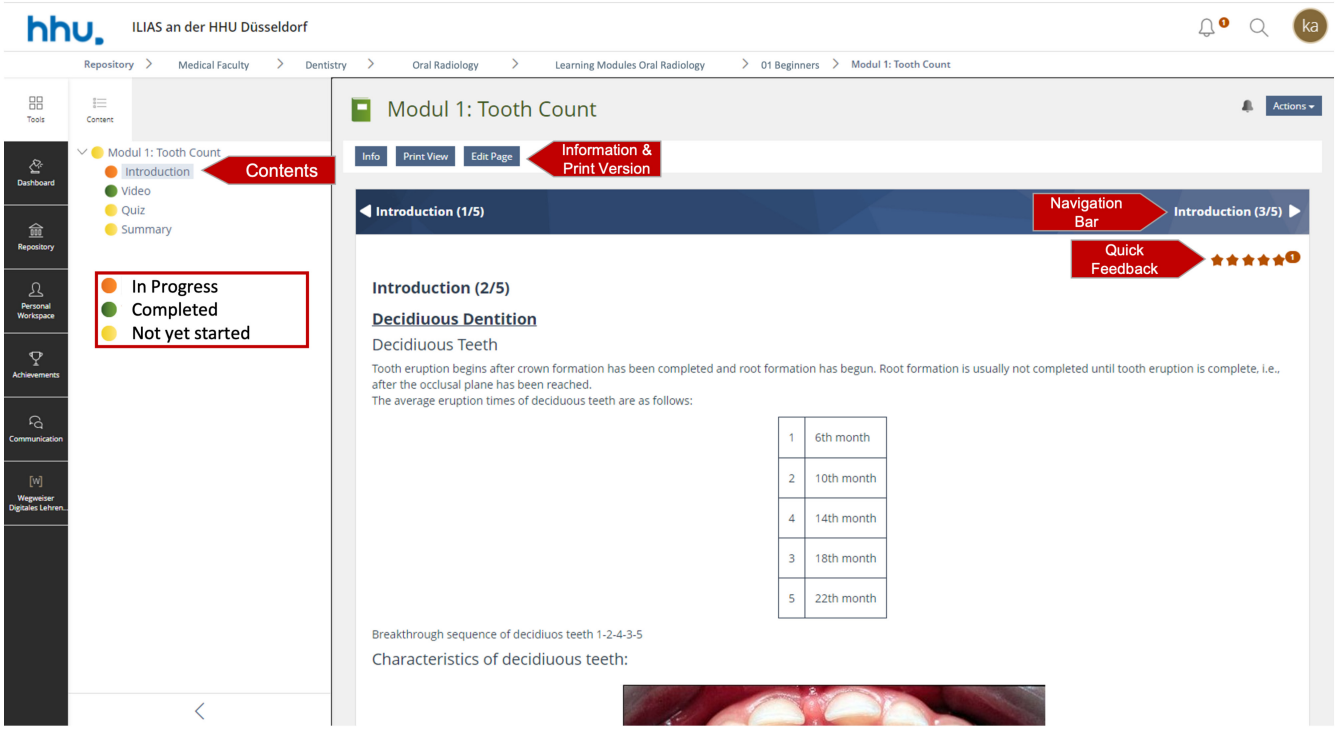

FIGURE 4 Video-based learning module 1 'Tooth Identification' on ILIAS (learning management system provided by the Heinrich Heine University of Düsseldorf). The learning progress was colour coded (left), navigation through the module was achieved by means of the white arrows on the blue navigation bar (right) and it was also possible to create a print version.

TABLE 2 Level of difficulty and item difficulty.

Level of difficulty	The proportion of standardised e-exam (%)	Item difficulty
1 Easy	10	0.85–1
2 Moderate	55	0.65–0.849
3 Moderately difficult	20	0.45–0.649
4 Difficult	10	0.25–0.449
5 Very difficult	5	0–0.249

Note: Percentage of questions in each standardised exam depending on the level of difficulty and the equivalent definition of item difficulty. Colour shades indicate the process of quesion categorization.

and media technology (German: *Zentrum für Informations- und Medientechnologie*) of the HHU. Students completed the exams on computers operating in a 'kiosk' mode, thus preventing any access to external information. To pass the exams, students had to answer 60% of the questions correctly.

2.6 | Statistical analysis

The statistical analysis was performed using R (R Core Team, 2021).[33] For each variable and group, the respective mean, standard deviation, median, quartiles and minimum and maximum values were computed. The R package *ggplot2* (Wickham, 2016) was used to create the boxplots. Normal distribution was assessed using boxplots.[34] Intra-semester comparisons were performed using a paired *t*-test for partially dependent data (Derrick, 2017), as few students did not attend both exams.[35] Comparisons between pre- and pandemic semesters were performed using unpaired *t*-tests.

From April 2020 to February 2021, some students had attended C1 or C2 before the pandemic but were enrolled in the remaining course(s) during the pandemic. In contrast, all students enrolled in radiology courses during the third pandemic semester had no prior experience with blended learning (Figure 1). To assess if the previous experience with blended learning had an impact on final exam scores, pandemic subgroups were built for each course and semester, and Kruskal–Wallis tests were utilised for comparison among subsequent semesters. In addition, a Nemenyi post hoc test was used in the case of significance. Results were found significant at $p < .05$.

3 | RESULTS

A total of 83 students were enrolled during the pre-pandemic blended learning programme, whereas 75 students were enrolled in the pandemic online-only format. The 47 remaining students participated in the radiology courses both in pre-pandemic and pandemic semesters, thus experiencing both teaching concepts at different, consecutive semesters.

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3.1 | Performance in final exams

Final exams were conducted at the end of each semester. Students failed to pass the final exams on the first attempt in 2.86% of the cases in the pre-pandemic group and 2.67% of the cases in the pandemic group (scores <60%). These students were given the opportunity to retake the final exam a few weeks later. The results of the second attempt were not included in our analysis. When comparing the scores from final exams between pre-pandemic and pandemic semesters, no significant difference was found (78% vs. 77%, $p = .11$). On course level, students in the pandemic semesters showed significantly lower scores in C1 (86% vs. 82%, $p < .01$) and in C2 (77% vs. 74%, $p = .02$), whereas no such difference was found in C3 (73% vs. 75%, $p = .11$; Figure 5). Regarding the 47 students who participated in the radiology courses both in the pre-pandemic and pandemic group, the Kruskal–Wallis tests revealed no significant differences in the pandemic semesters among all pandemic C1 courses ($p = .115$) and all pandemic C2 courses ($p = .358$). Among pandemic C3 courses, however, a significant difference was found ($p = .007$), and the Nemenyi post hoc test showed that results from the second pandemic semester were significantly better than the remaining pandemic semesters (all $p < .05$).

3.2 | Knowledge gain

In all semesters, the scores at the end were significantly higher than those at the beginning of the semesters (all $p < .05$). These comparisons include the pre-pandemic and the pandemic phases. Comparing the overall knowledge gain, which was calculated by subtracting the baseline scores from the final exam scores, no significant difference was seen between pre-pandemic (gain MD 25.83% ± 14.27) and pandemic (gain MD 23.78% ± 17.73) semesters ($p = .18$). On course level, no significant difference in knowledge gain between pre-pandemic and pandemic semesters was found in C1 ($p = .09$) and C3 ($p = .30$). In C2, the scores in the pandemic semesters were inferior compared to the pre-pandemic semesters ($p < .01$; Table 3).

3.3 | Impact of the number of the VBLMs

Different numbers of VBLMs were assigned to the three different courses. C1 received two VBLMs ('Beginners'), C2 a total of four VBLMs ('Beginners' and 'Advanced') and C3 a total of six VBLMs ('Beginners', 'Advanced' and 'Experts'). When splitting the scores in final exams into questions regarding the topics covered by VBLMs and those that were not covered, the following findings were retrieved: In C1, scores in questions covered by VBLMs at final exams were significantly worse in pandemic (85%) compared to pre-pandemic (89%) semesters ($p < .01$). In C2 and C3, no significant difference was found (C2: 70% vs. 70%, $p = .70$; C3: 79% vs. 81%; $p = .43$; Figure 6).

3.4 | Platform usage

Analysis of usage statistics revealed that the oral radiology platform was accessed constantly throughout the semesters. The highest number of accesses was seen a day before the final exam (Figure 7) in all semesters before and during the pandemic. In the pandemic semesters, access numbers prior to the final exams were twice as high as in the pre-pandemic semesters. The utilisation rate of the VBLMs was high according to the analysis of usage statistics on the learning management system (ILIAS); 97.7% of the students used this optional tool. The average usage time was 78, 76 and 66 min for C1, C2 and C3 respectively.

3.5 | Impact of the radiology lunch

Significantly higher scores were found in questions based on topics covered by the radiology lunch (i.e. 'caries diagnostics' and 'cysts') compared to the rest of the questions in C1 at the end of the semester ($p < .01$), whereas no differences were found in the baseline exams ($p > .05$). In C2 and C3, no significant differences were found in baseline and final exams ($p = .07$ and $p = .20$; Figure A1).

3.6 | Post hoc sample size

The post hoc sample size calculation was performed with G*Power Version 3.1.9.6. (Franz Fraul, University Kiel, Germany) for the comparison between pre- and post-pandemic courses and revealed a power of 27.51%. To obtain a significant effect with a power of 80%, a sample size of 987 students would have been required.

4 | DISCUSSION

Online-only learning concepts rapidly evolved over the past three decades with advancing technologies in mobile devices and online platforms. Due to the COVID-19 pandemic, the question resurfaced whether online-only learning is as effective as traditional blended learning. The results of the present study show that performance in final exams as well as the associated knowledge gain from baseline

FIGURE 5 (A) Comparison of scores in final exams (%) pre-pandemic (blue) with pandemic (red) in course 1. In course 1, students showed lower scores (pre-pandemic 86% vs. pandemic 82%, $p < .01$). (B) Comparison of scores in final exams (%) pre-pandemic (blue) with pandemic (red) in course 2. In course 2, students showed lower scores (pre-pandemic 77% vs. pandemic 74%, $p = .02$). (C) Comparison of scores in final exams (%) pre-pandemic (blue) with pandemic (red) in course 3. No significant difference in performance in final exams during pandemic semesters was found (pre-pandemic 73% vs. pandemic 75%, $p = .11$). * indicates Significance level was set at $p < .05$.

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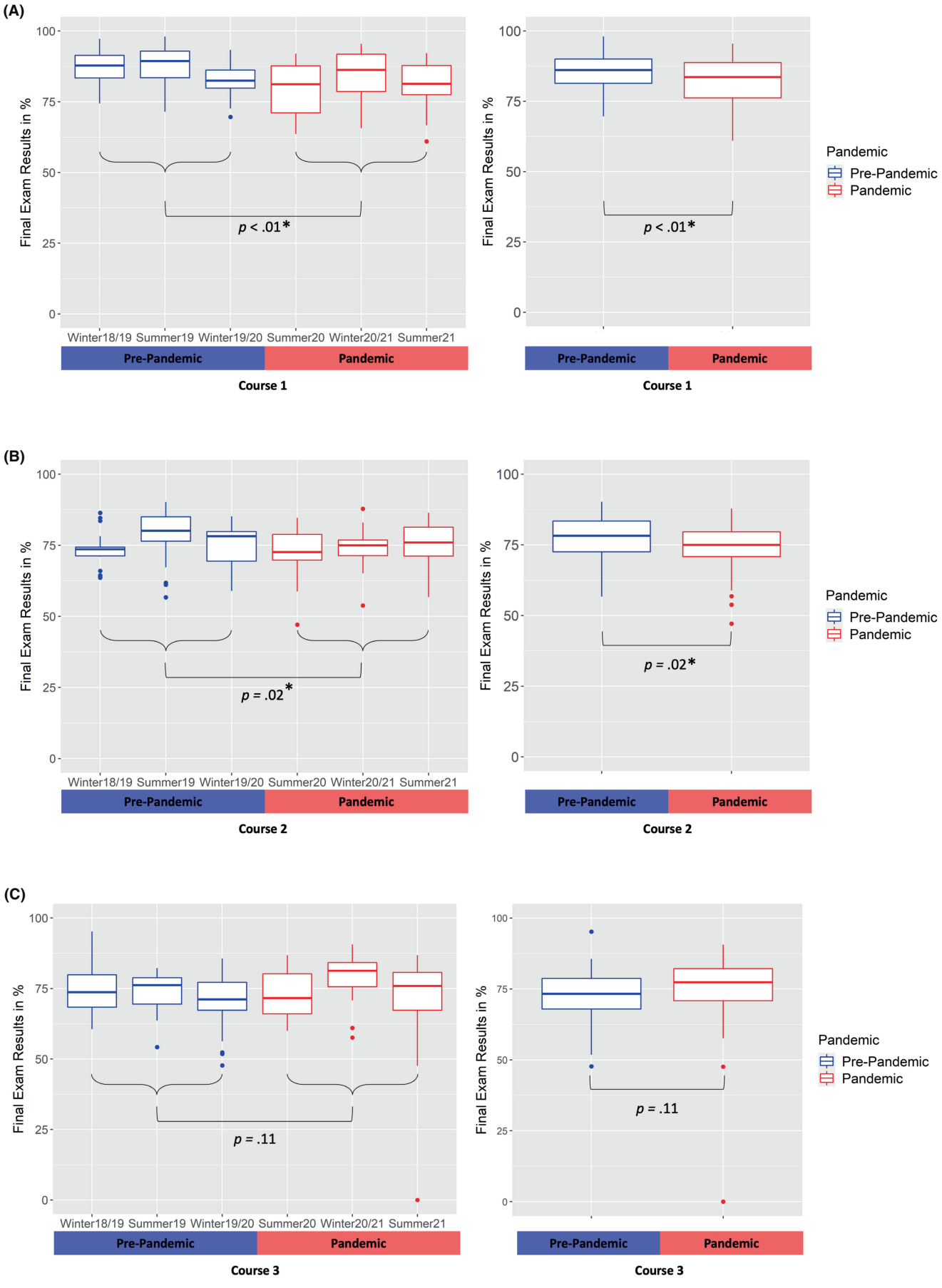

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Course	Pre-pandemic – blended learning	Pandemic – online-only learning	*p*-Value
1	27.30% ± 12.20	31.42% ± 16.52	.09
2	26.86% ± 12.73	20.10% ± 17.03	<.01
3	23.42% ± 17.10	20.37% ± 17.53	.30

TABLE 3 Knowledge gain (mean, SD) of all semesters.

Note: Comparing the pre-pandemic blended learning concept with the pandemic online-only learning concept. For courses 1 and 3, no significant difference in knowledge gain was found. In course 2, knowledge gain was inferior during pandemic semesters.

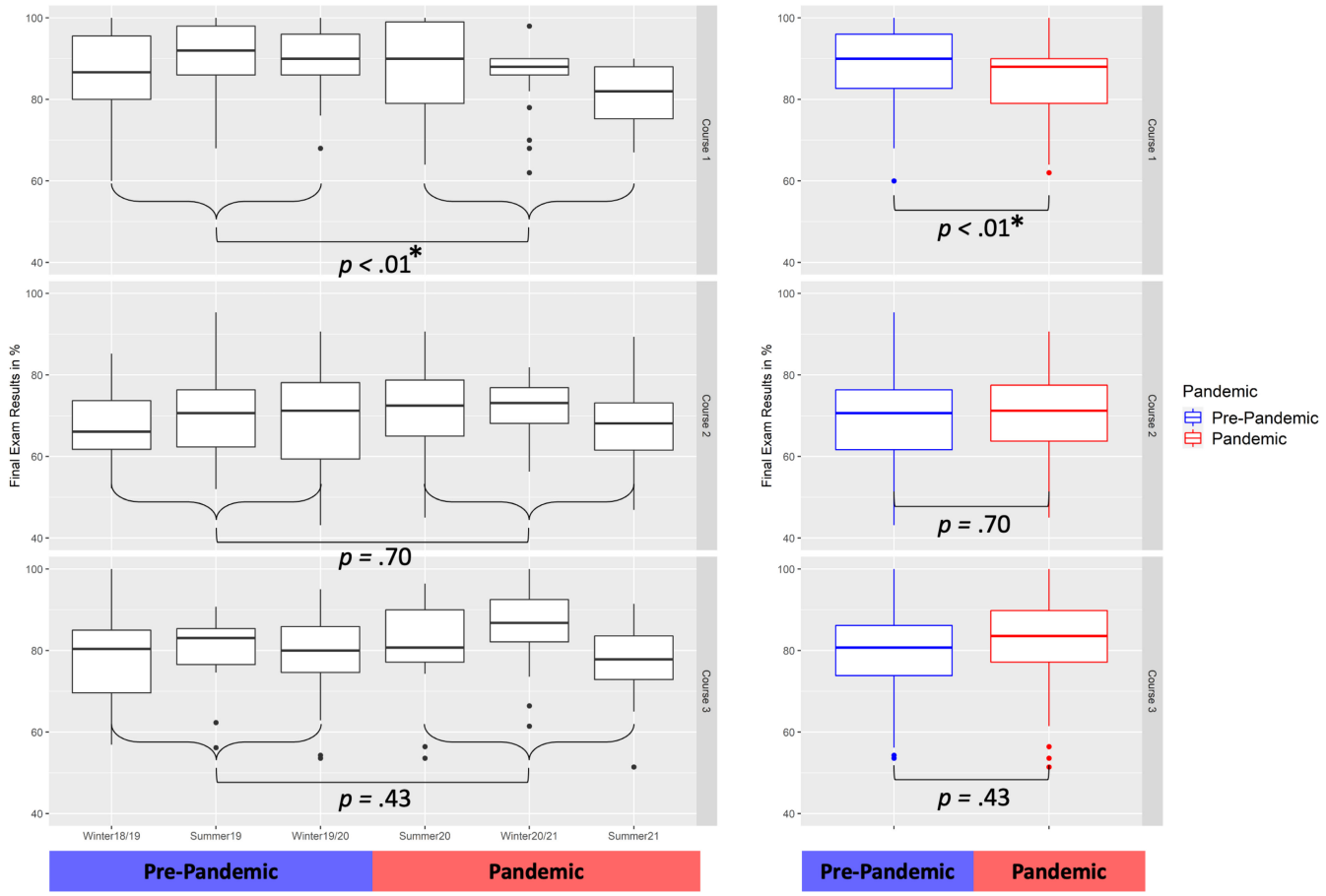

FIGURE 6 Scores in questions covered by the video-based e-learning modules (VBLMs) in final exams in %. Differentiating between the three different courses. Course 1 received 2, course 2 a total of 4 and course 3 a total of six VBLMs. In course 1, scores in questions covered by VBLMs at final exams were significantly worse in pandemic compared to pre-pandemic semesters. In course 2, no significant difference was found. * indicates Significance level was set at p < .05.

to final exams was consistently high in both the pre-pandemic (conventional blended learning) and pandemic (online-only learning) group, confirming the overall high effectiveness of both educational concepts. No significant differences in final exam scores and knowledge gain between these two groups were found. Furthermore, the number of VBLMs that students received had a positive impact on final exam scores; Students receiving few VBLMs (C1 and C2) had significantly lower scores in final exams and a lower knowledge gain (only C2) during pandemic semesters compared to students who received a high number of VBLMs (C3).

The results of the present study are in line with the general notion that blended learning is a highly effective learning concept in medical education.[7] Specifically in dental education, blended learning concepts were reported to be more effective than F2F learning.[5,6] Importantly, these studies did not include online-only learning concepts, and consequently, comparability to our results is limited. Only a few studies included a direct comparison between traditional blended learning and online-only learning. In an orthodontic cephalometric analysis course, Bains et al.[1] found no differences in students' performance between these concepts in 60%

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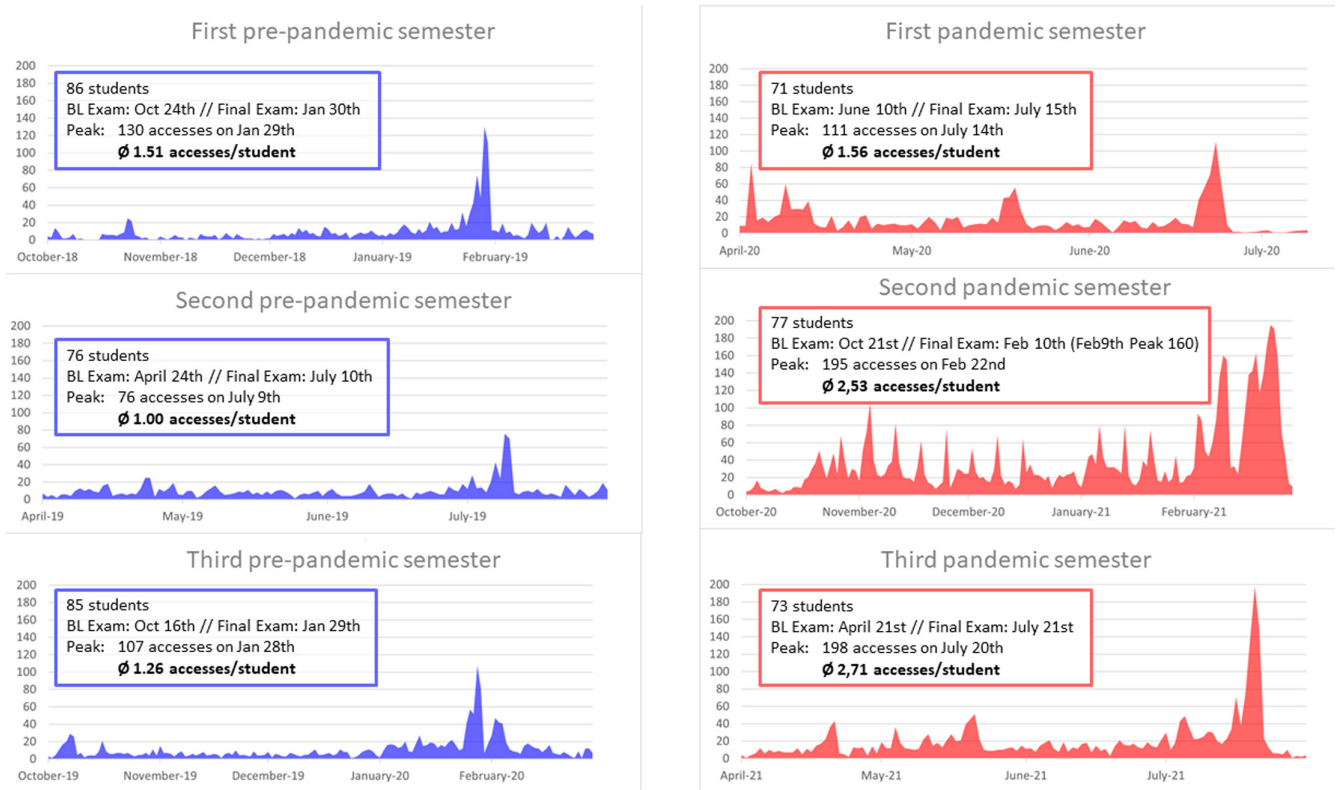

FIGURE 7 Usage protocols of the oral radiology platform. Usage protocols of the oral radiology platform during pre-pandemic semesters (blue) from October 2018 until February 2020 and pandemic semesters (red) from April 2020 until July 2021, with additional information about the number of students who attended one of the radiology courses during the respective semester, dates of the baseline (BL Exam) and final exams (Final Exam) and the highest peak of platform accesses with an average access per student.

of exam questions. In the remaining 40% of questions, students who received e-learning performed worse compared to students who received blended or traditional learning. Bock et al.[3] suggest that, compared to e-learning and F2F learning, traditional blended learning is most effective in acquiring theoretical knowledge of local anaesthetics. Interestingly, they did not find any differences in skill development (i.e. hands-on application of local anaesthetics) among the different learning concepts. The results of these studies must be interpreted with caution, however. For example, outcome assessments only comprised 10 multiple-choice questions,[1] and students' performance was tested immediately after the learning intervention,[1,3] resulting in low internal validity as well as reliability coefficients. Since short-term recall is not necessarily predictive of long-term recall, our results extend these earlier findings by including longer retention intervals as outcome variables, which, by definition, increases the validity. Another reason for differing results may be the fact that most other studies assessed competencies in different dental fields (e.g. dental anatomy,[5,6] conservative dentistry[5,6] or local anaesthetics[3]), assessed different competencies (e.g. theoretical knowledge gain, practical skills or theoretical skills) or varied in the amount of e-learning in blended learning concepts.

So far, only one other study has examined how different learning concepts (including online-only learning) affect undergraduate student performance in oral radiology. Rocha et al.[20] compared the effectiveness of F2F, problem-based, blended and e-learning in identifying radiographic carious lesions and reported no differences in students' performance in baseline and final exams among these concepts. This result is partially in line with our finding of consistently high performance in both pre-pandemic (blended learning) and pandemic (online-only) groups. Contrary to Rocha et al.,[20] however, our results suggest a positive effect of additional VBLMs in online-only blended learning.

When focusing on C1 and C2, the performance in final exams was worse in the pandemic group compared to the pre-pandemic group. This effect may derive from pooling the scores in final exams across all pre-pandemic and pandemic semesters respectively. The performance in final exams during the first pandemic semester was the lowest of all semesters. Possibly, pandemic-related factors might have negatively influenced these results. First, there was a massive delay at the start of the first pandemic semester in April 2020. Consequently, exams at the beginning and end of the semester were just 5 weeks apart. All VBLMs had to be completed within this period, whereas 12 weeks were available in the consecutive semesters. This may have contributed to the already increased COVID-19-related stress levels with a further negative impact on knowledge retention (stress–performance relationship).[36] Second, as in a pilot phase,[8] several new processes had to be developed and established during this period (e.g. installation of, introduction to and interaction with Microsoft Teams, implementation of VBLMs on learning management system, etc.) and teachers as well as students had to familiarise themselves with these processes.[23] Consequently, students may have performed worse because they still had to get

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used to the new learning concept. Moreover, when interpreting the significantly lower scores in C1 during the pandemic, it has to be mentioned that students from C1 had no prior experience with the oral radiology course structure and the ORP before the pandemic. To what extent this lack of experience constituted the lower scores remains unclear. Nonetheless, final exam scores were highest in C1 and C3 during the second pandemic semester compared to the remaining two pandemic semesters, and the respective students had utilised merely online-only content. Hence, pre-existing e-learning options (i.e. ORP) and weekly email reminders implemented in a pre-existing learning management system might have encouraged this shift towards online-only learning, as has also been described elsewhere.[37]

As already pointed out by numerous other authors,[1,38,39] not only the modality but also the quality and quantity of e-learning content might play a crucial role in the effectiveness of learning. To test the influence of the quantity of e-learning content, we provided a varying number of VBLMs to the students of the different courses. Results show that compared to pre-pandemic semesters, pandemic students in C1 (two VBLMs) performed significantly worse on questions covered by the VBLMs during the pandemic. No significant difference was found in C2 (four VBLMs) and C3 (six VBLMs) between pandemic and pre-pandemic courses. However, students in the pandemic group who received the highest amount of VBLMs (C3) showed a trend to perform better on questions covered by the VBLMs compared to students in the pre-pandemic group. In other words, with an increasing number of VBLMs, performance on questions covered by these VBLMs improved, demonstrating the direct benefit of VBLMs. Further studies are needed to define the precise relationship between the number of VBLMs and learning effectiveness.

For the pandemic group, the usage statistics analysis revealed continuous frequent access to the ORP. In addition, 97.7% of the students accessed the VBLMs, which demonstrates high motivation and eagerness to utilise additional e-learning formats. Our results seem to support the idea that students tend to prefer asynchronous over synchronous concepts.[23] With an asynchronous format, it was possible to provide stable, focused and well-captioned online content. For the faculty staff, this offered the advantage of reviewing and updating content quickly. For the students, on the other hand, it allowed remote learning with flexibility in time and place at their comfort.[23,24,37] Finally, repeated study of the content contributes to optimal exam preparation.[40] These key features have been shown to enhance learning effectiveness.[41]

Regarding the limitations of this study, the generalisability of our results may be limited as we only examined data from one university with a relatively small sample size. Previous research almost exclusively focused on comparing learning concepts implemented prior to the pandemic. Attitude towards digital media might have changed during the pandemic and comparison between our results, and results of pre-pandemic studies therefore may be limited. In addition, potential psychological effects such as frustration, depression and anxiety associated with social isolation have been reported during pandemic times,[42] possibly further affecting learning outcomes. Finally, it should be mentioned that we did not differentiate between knowledge and diagnostic skill development in our outcome measures. From a theoretical standpoint, knowledge and skill development are two different concepts, which may also depend on different competence levels[14] and even on different neural representations.[43] Therefore, it may be interesting to examine these two different processes with separate assessment methods in future studies, since it may also be the case that effects of e-learning differ between these two processes.

Within the limitations of this study, the present investigation confirmed that an online-only learning concept might be as effective as a conventional blended learning concept. Additional VBLMs may further increase students' performance, specifically when implemented on a pre-existing learning management system. In the present study, the combination of synchronous online lectures and asynchronous learning opportunities (ORP and VBLMs) may have contributed to an overall high performance even under detrimental conditions during the pandemic.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest related to this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL APPROVAL

The study was approved by the ethics committee of the University Hospital Düsseldorf (IRB no: 5596). At the beginning of each semester, verbal and written information about the study was provided. Students voluntarily gave informed consent to participate in the study. Students also signed a declaration of anonymity and

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confidentiality prior to data collection. Thus, they were informed that no personal information and only anonymised data would be published. Participation was neither mandatory nor relevant for passing the oral radiology courses, which are, however, part of the undergraduate dental curriculum and therefore compulsory.

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APPENDIX

TABLE A1 Cronbach's alpha for each exam.

Semester	Exam	Course	Cronbach's alpha
Winter 18/19	BL Exam	1	.67
		2	.32
		3	.83
	Final Exam	1	.62
		2	.48
		3	.69
Summer 2019	BL Exam	1	.94
		2	.82
		3	.89
	Final Exam	1	.81
		2	.70
		3	.53
Winter 19/20	BL Exam	1	.85
		2	.85
		3	.83
	Final Exam	1	.46
		2	.66
		3	.72
Summer 2020	BL Exam	1	.91
		2	.80
		3	.91
	Final Exam	1	.77
		2	.66
		3	.60
Winter 20/21	BL Exam	1	.86
		2	.88
		3	.85
	Final Exam	1	.81
		2	.61
		3	.64
Summer 2021	BL Exam	1	.90
		2	.95
		3	.90
	Final Exam	1	.71
		2	.58
		3	.94

Note: Reliability (Cronbach's alpha) for each baseline (BL) and final exam (Final) was calculated using the R package *psych* (Revelle, 2023).[32] All Cronbach's αs <.60 are highlighted in dark grey.

TABLE A2 Question categories for standardised exams.

ID	Categories
1	Anatomy in panoramic X-rays
2	Artefacts in panoramic X-rays (film based/digital)
3	Setting errors in panoramic X-rays
4	Descriptive recording of pathological findings (single/multi-chambered, translucent/opaque, displacing, infiltrating, etc.)
5	Recording of number of teeth (number of teeth in excess, number of teeth in shortfall and no deviation)
6	Determine patient age (alternate dentition phases I-III, age in years)
7	Caries diagnosis (Bitewing diagnostic)
8	Root canal filling assessment in the tooth film
9	Silver pin exposure in the tooth film
10	Periodontitis diagnostics in the OPTG/ZF
11	Anatomy/points/angles in the cephalometric lateral image
12	Adjustment errors in the cephalometric lateral image (no questions in ILIAS)
13	Artefacts in Cephalometric lateral images, also parallax errors (adjustment errors?) (1 question in ILIAS)
14	Classification of pathological findings (cyst, tumour, etc.)
15	Diseases of the maxillary sinus
16	Fracture diagnostics (dental/jaw)
17	Root anomalies Tooth shape anomalies (taurodontism, gemination, etc.)
18	Dental traumatology (ankylosis, infraposition, re-inclusion, etc.)
19	Syndromes
20	TMJ (temporomandibular joint)
21	Cleft lip
22	Differential diagnosis neoplasia
23	Differential diagnosis fibro-osseous lesions
24	Differential diagnosis cysts
25	Mineralisation disorders
26	Cephalometric front image (anatomy, indication, interpretation)
27	Justifying indication
28	Which X-ray image do we need, when and why? Further diagnostics
29	Adjustment errors, artefacts and beam path in tooth film

Note: The content of the exam questions was based on 29 different dental categories (ID), comprising 50% orthodontic (highlighted in dark grey) as well as 50% non-orthodontic questions (highlighted in light grey) related to oral radiology.

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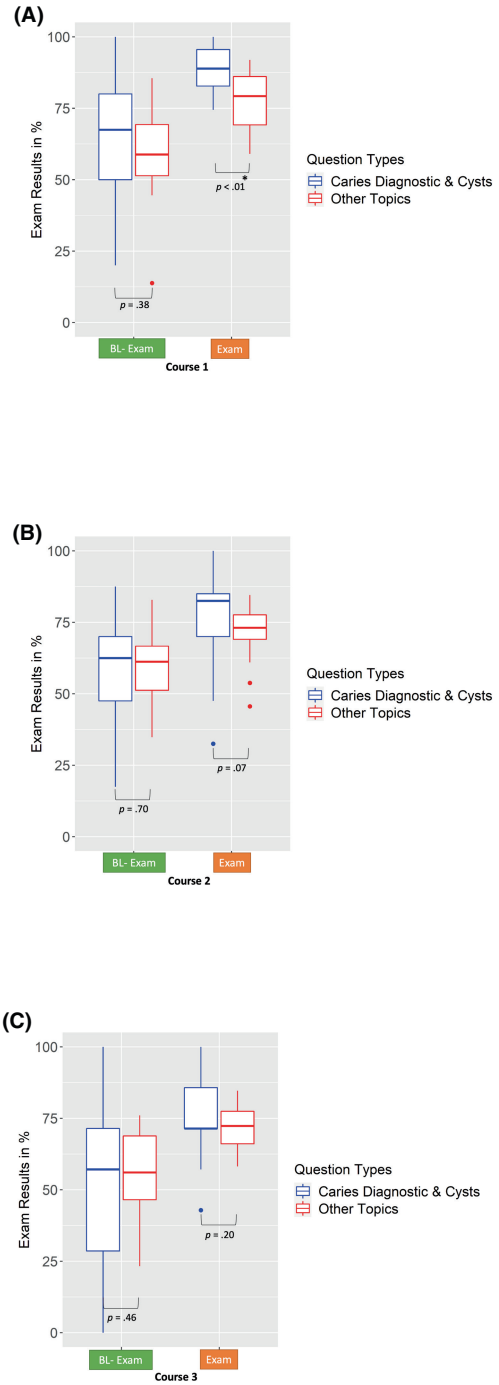

FIGURE A1 Comparison of exam results of questions based on the radiology lunch topics (Caries Diagnostic & Cysts) between baseline exam (BL-Exam) and final exam (Exam) of the summer semester 2020 in (A) course 1 (B) course 2 (C) course 3.

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