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Augmented Vision for Dental Students' Education in Detecting Proximal Carious Lesions on Bitewing Radiographs: A Randomized Controlled Trial

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Keywords

Augmented reality · Radiographic image interpretation · Computer-assisted tools · Dental caries · Dental students' education

Abstract

This two-arm, parallel, randomized controlled trial aimed to assess the effect of augmented vision (AV, using interactive color overlays) on the education of dental students in detecting proximal carious lesions on bitewing radiographs compared to black-and-white textbook-like illustrations. Forty-eight preclinical third-year dental students were randomized using a random number generator into two learning groups: test (AV, allowing interaction with color-highlighted carious lesions, $n = 24$) and control (showing the native radiograph and a black-and-white illustration displaying the carious lesion, $n = 24$). First, students had 2 weeks to assess 50 bitewings (lesion prevalence on the tooth level: 54.5%) in the test or control. Due to the nature of the intervention, participants could not be blinded toward the intervention. After that, they were asked to detect lesions on 10 independent bitewings and to assess lesion extent (outer/inner enamel; outer/middle/inner dentin). The reference test was constituted by two experienced dentists. No significant differences in accuracy (test 0.84 [95% CI: 0.79, 0.88]; control 0.83 [0.78, 0.87]), AUC (test 0.82 [0.81, 0.84]; control 0.81 [0.80, 0.83]) and F1 score (test 0.79 [0.75, 0.82]; control 0.77 [0.72, 0.81]) were observed between groups. Students of both groups showed difficulties in differentiating enamel from dentin carious lesions. While AV was reported to be motivating by students, it did not increase their accuracy.

Introduction

One of the most recurrent challenge in dentistry is the recording of dental status and the detection and diagnosis of caries, resulting in individual recommendations for preventive and operative management [Schwendicke et al., 2019; Kühnisch et al., 2022]. Therefore, the search for more accurate methods for early caries detection has grown in the last years to reduce the number of false-positive decisions and to avoid unnecessary invasive treatment.

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The presence of proximal contact makes the visual detection of initial carious lesions on the proximal surfaces of teeth difficult. Radiographic examination has been widely used and has been the standard for supporting contemporary visual-tactile methods by increasing its sensitivity, especially for detecting proximal dentinal caries lesions [Wenzel, 2000; Lussi et al., 2006]. For detecting initial lesions, more sensitive methods could be considered in populations with high caries risk and prevalence [Schwendicke et al., 2015]. Also, the role of radiographic examination can be different depending on which visual-tactile method is used and from which diagnostic threshold caries is detected [Machiulskiene et al., 1999; Mendes et al., 2012]. Besides, the accuracy of radiographic examination depends on examiners' training and calibration, background knowledge, quality of images as well as examiners' experience, gained during education and practice [Rocha et al., 2020].

Effective education is believed to be the most fundamental factor in prosperity and knowledge of students. Learning must be independent and self-directed in order to be effective [Soltanimehr et al., 2019]. Traditional classroom education can be somehow tiresome, and the force to learn at a certain predetermined time might limit the learning process [Thiele, 2003]. In contrast, learners who have access to educational content at any time via virtual instructions may show increased learning performance.

For educating dental students in radiology, various strategies have been employed, with mixed results [Wenzel, 2000; Kay et al., 2001], for example theoretical lectures [Wrbas et al., 2000], e-learning [Luz et al., 2015; Alves et al., 2018], as well as computer-assisted tools involving traditional and virtual education [Soltanimehr et al., 2019]. Soltanimehr et al. [2019] assessed an online education system (focusing on the detection of bony lesions), which included a combination of learning path options, quizzes, weekly homework, links, articles, and interactions between students and mentors, and found it superior to traditional lecture-based learning [Soltanimehr et al., 2019]. A blended course combining face-to-face and online instructions of undergraduate students on oral radiology was developed and implemented previously, containing presentations, quizzes, and links to relevant websites, as well as the option for e-mail exchange, all ensuring near-unlimited access to learning material and instructors, again with positive findings [Kavadella et al., 2012].

Even more recent learning strategies involve augmented reality or, specifically, augmented vision (AV), i.e., a real-time three-dimensional digital content overlay of the physical space [Azuma, 1997; Liao et al., 2020], which allows the user to interact with both the physical and digital object. AV has been lately employed in medical educational process, being considered a new approach in executing detailed surgical operations [Shuhaiber, 2004] and a valid tool for objectively assessing laparoscopic suturing skills [Botden et al., 2009]. In dentistry, its use was so far limited to enhance teaching of operative dentistry that enabled the development of a learning object with a high index of acceptance for all users [Espejo-Trung et al., 2015] and anatomy, demonstrating criterion validity of the augmented reality virtual assessment tool for tooth identification [Kim-Berman et al., 2019]. The efficacy of AV for education on dental radiology has so far not been explored.

We hypothesized that the use of AV (interactive color overlays) during learning would increase dental students' accuracy in caries detection but also their motivation toward learning. The aim of this randomized controlled trial was to assess the effect of AV on the education of dental students in detecting proximal carious lesions on bitewing radiographs.

Material and Methods

This two-arm, parallel, randomized controlled trial was approved by the Local Research Ethics Committee (#EA4/237/20). All participating students were volunteers and signed an informed consent form before commencement. All study methods were carried out as per relevant guidelines and the study is reported according to the CONSORT statement criteria (online suppl. material; for all online suppl. material, see www.karger.com/doi/10.1159/000525777).

Sample Size Estimation

Our primary outcome, accuracy, was used for sample size calculation, which was performed assuming a comparison between the test and control group using a paired two-sided *t* test in a clustered design model, since multiple teeth were assessed per radiograph. The design effect (DE) was calculated via DE = 1 + (m – 1) × ICC, with m being the cluster size and ICC being the intraclass correlation coefficient. The ICC reflects on the clustering of teeth in each radiograph and has been estimated to be approximately 0.2 in this population [Meinhold et al., 2020]. As we expected moderate differences in accuracy between the test group (mean accuracy: 0.75) and the control group (in mean 0.70), and conservatively assuming a standard deviation of 0.4, a study with a power of 1-beta = 0.80 and alpha = 0.05 requires a total of 442 teeth to be assessed (442 assessments). Considering a cluster size of 8 permanent teeth per assessed radiograph, the DE was 1 + (8 – 1) × 0.2 = 2.4. Hence, the overall number of required assessments increased to 442 × 2.4 = 1,061 teeth (assessments). Hence, the minimum sample size was 10 bitewing images being assessed by minimum 14 students (10 × 14 × 8 teeth). As we eventually decided to enroll the whole cohort of third-year dental students (see below), the sample size exceeded this number considerably.

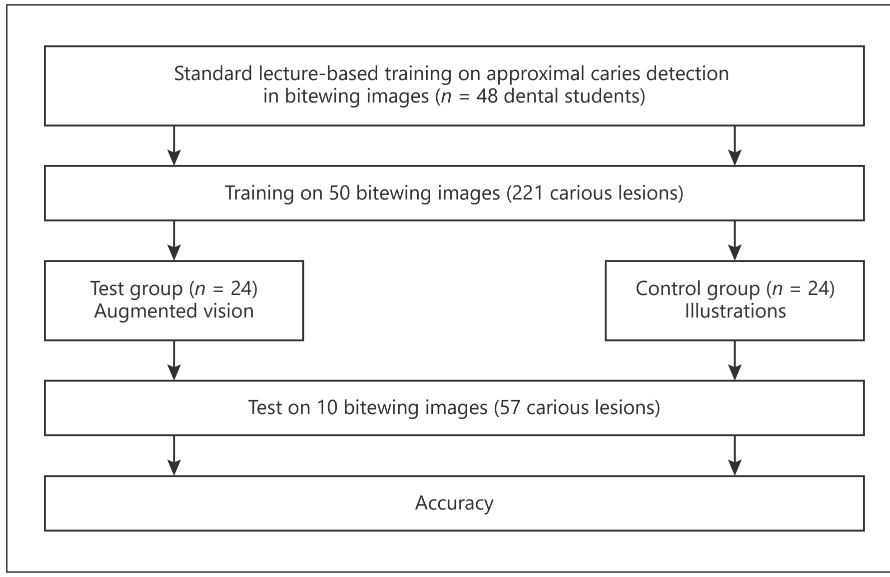

Fig. 1. Flow diagram of the study.

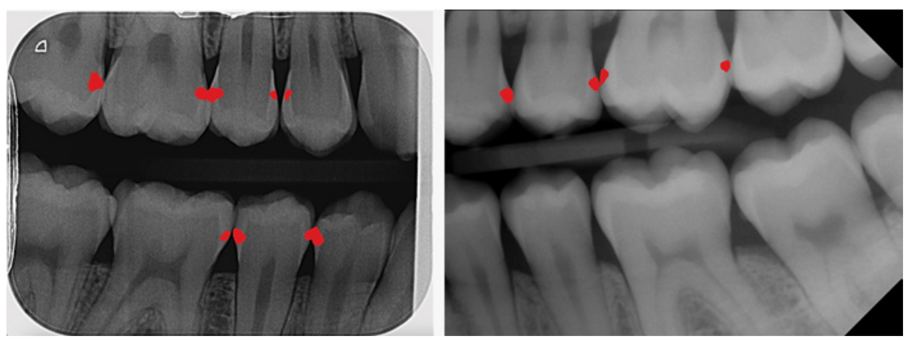

Fig. 2. Test group: AV allowed to assess carious lesions using pixel overlays (in red). The opacity of the pixel overlays could be modified, and overlays could also be fully removed to show the native image.

Color version available online

Study Participants

Forty-eight preclinical third-year dental students enrolled in the 2020/2021 course of radiology were invited and agreed to participate in this study. Based on their regular curricular schedule, students were allotted numbers from 1 to 48 and randomly assigned into the two intervention groups using a random number generator (www.random.org), with 24 participants in the test group (learning using AV) and 24 in the control group (learning using conventional illustrations). The allocation was concealed up to the point when the students of each group received the instructions on how to handle the images for the learning sessions. Due to the nature of the intervention, participants could not be blinded. The study flow is summarized in Figure 1.

Interventions – Education on Caries Detection

After 2 h of basic theoretical lecture on caries detection in bitewing radiographs, each student received 50 digital bitewing images showing proximal carious lesions in different stages of enamel and outer/middle third of dentin (total of 221 lesions, lesion prevalence on tooth level: 54.5%), according to the previously described randomization scheme for training. Bitewing images were generated using radiographic machines from Orthophos XG (Dentsply Sirona, Bensheim, Germany) and Dürr Dental machines (Bietigheim-Bissingen, Germany). They had 2 weeks to train on these images according to their group assignment: students from the test group trained by using an online AV tool, originally developed for image labeling [Ekert et al., 2018]. The tool allowed to display the native images as well as colored pixel overlays of carious lesions; via interaction, the overlays could be modified in their opacity or fully removed or added (Fig. 2). Students from the control group received the same 50 bitewing images along with an illustration showing the lesion, its location, and extent (Fig. 3). Both groups were additionally provided with information as to the lesion stage classified as enamel caries (E), caries in the outer third of dentin (D1), and caries in the middle/inner third of dentin (D2).

Both pixel overlays in AV as well as the illustrations in the control group were generated using pixel-wise labeled imagery from a previous study [Cantu et al., 2020]. In that study, carious lesions had been independently pixel-wise labeled by three expert dentists and in triplicate, using an in-house custom-built annotation tool [Ekert et al., 2018]. All the labels were revised by a fourth expert dentist. All experts were employed at specialist clinics for oral diagnostics or operative and preventive dentistry, mainly cariology, with a minimum clinical experience of 3 years. The examiners had been instructed in person and calibrated using a handbook (de-

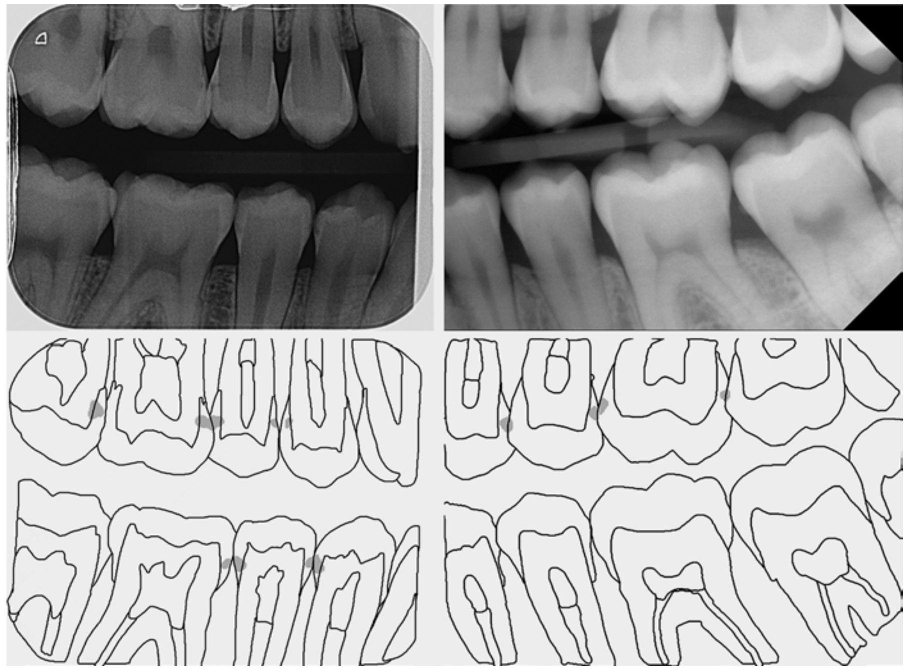

Fig. 3. Control group: native images and illustrations showing proximal carious lesions (in gray) on bitewing radiographs.

scribing how to use the annotation tool and how to annotate caries lesions but also how to discriminate them from other entities) before the labeling tasks.

For the control group of the present study, illustrations for the 50 training images have been prepared. These illustrations aimed to resemble textbook-like drawings of tooth structures such as the enamel, dentin, pulp chamber, and the root canal. These drawings were generated by dental students in the 6th semester, using the custom-built annotation tool as referenced above and were reviewed and approved by a second independent dentist. The annotated caries lesions as described above were superimposed on those illustrations so that both arms, the control group and the test group, were exposed to illustrations and bitewing radiographs, respectively, but with caries lesions of the exact same position and shape.

Students' Assessment

After a period of 2 weeks of learning period, students from both groups were invited for a test session. During this test session, each participant was comfortably seated on a chair in front of a diagnostic screen in a dimly lit room, following the instructions to assess the bitewing images.

They received 10 bitewing images independent from those included in the training. They were asked to identify lesions and grade them according to the outlined scheme. A total of 58 proximal carious lesions (35 E, 17 D1, 5 D2) and 139 caries-free proximal surfaces were assessed. Participant's assessments were verbally communicated to the principal investigator, who recorded them on a spreadsheet for further analysis. No time limit was imposed on the participant to assess the images.

The reference for the test phase was established by two experienced dentists (J.A.R. and S.M.M.) who independently assessed all bitewing images and classified them as described. In case of disagreement, a third experienced dentist (F.S.) was consulted, and the classification which matched to that chosen by one of the previous examiners was considered as the reference. Disagreement occurred in 3 cases.

Additionally, students of both groups were asked to report the approximated time during the past 2 weeks that they spent using the learning methods (in days and hours per day). Moreover, a questionnaire on students' satisfaction with their learning experience using a Likert scale [Zafar et al., 2014] was applied, with scores varying from 1 to 5 (1 = strongly agree; 2 = partially agree; 3 = indifferent; 4 = partially disagree; 5 = strongly disagree). The statements were the following: the student felt motivated during learning; the student found the learning method easy to use; the student felt stimulated to continue to learn using the method.

Table 1. Performance metrics (AUC, sensitivity, specificity, accuracy, F1 score, PPV, and NPV) of students according to groups (mean [95% CI]) considering all carious lesions depth

	Control (illustrations) (*n* = 24)	Test (AV) (*n* = 24)	*p* value
AUC	0.82 (0.81, 0.84)	0.81 (0.80, 0.83)	0.21
Sensitivity	0.74 (0.65, 0.82)	0.70 (0.61, 0.78)	0.18
Specificity	0.91 (0.85, 0.95)	0.93 (0.88, 0.96)	0.58
Accuracy	0.85 (0.83, 0.87)	0.83 (0.80, 0.86)	0.34
F1 score	0.79 (0.75 0.82)	0.77 (0.72, 0.81)	0.49
PPV	0.85 (0.76, 0.91)	0.87 (0.79, 0.93)	0.86
NPV	0.83 (0.77, 0.88)	0.81 (0.75, 0.87)	0.12

PPV, positive predictive value; NPV, negative predictive value.

Table 2. Performance metrics (AUC, sensitivity, specificity, accuracy, F1 score, PPV, and NPV) of students according to groups (mean [95% CI]) considering carious lesions stratified by depth; enamel versus dentin lesions

	Enamel caries		Dentin caries	
	control (illustrations) (n = 24)	test (AV) (n = 24)	control (illustrations) (n = 24)	test (AV) (n = 24)
AUC	0.80 (0.78, 0.81)	0.77 (0.76, 0.79)	0.87 (0.85, 0.89)	0.87 (0.86, 0.89)
Sensitivity	0.69 (0.56, 0.79)	0.62 (0.50, 0.74)	0.84 (0.70, 0.93)	0.82 (0.68, 0.92)
Specificity	0.91 (0.85, 0.95)	0.93 (0.88, 0.96)	0.91 (0.85, 0.95)	0.93 (0.88, 0.96)
Accuracy	0.85 (0.83, 0.88)	0.83 (0.81, 0.86)	0.92 (0.89, 0.94)	0.92 (0.89, 0.95)
F1 score	0.72 (0.68, 0.75)	0.68 (0.63, 0.74)	0.77 (0.72, 0.81)	0.78 (0.74, 0.83)
PPV	0.76 (0.64, 0.86)	0.79 (0.66, 0.89)	0.71 (0.57, 0.83)	0.76 (0.61, 0.87)
NPV	0.87 (0.81, 0.92)	0.85 (0.79, 0.90)	0.95 (0.91, 0.98)	0.95 (0.91, 0.98)

PPV, positive predictive value; NPV, negative predictive value.

Table 3. Cross-tabulation of the presence and absence of carious lesions (%)

	Reference standard	Students' assessments	
		carious lesion present	carious lesion absent
Control (Illustrations)	Carious lesion present	85	17
	Carious lesion absent	15	83
	Total	100	100
Test (AV)	Carious lesion present	87	19
	Carious lesion absent	13	81
	Total	100	100

Statistical Analysis

For our cluster-randomized trial design, we first estimated the DE as previously described. This DE was applied to all analyses, as relevant, to account for clustering and the associated deflation of uncertainty.

Performance metrics, such as receiver operating curve's area under the curve, sensitivity, specificity, accuracy, F1 score, positive predictive value, and negative predictive value, were estimated for both students' groups. For each performance metric, the mean and corresponding 95% confidence intervals were estimated, along with formal tests for differences between the control and test groups (DeLong's test for receiver operating curve's area under the curve and Welch two-sample t test for the other metrics). Additionally, we computed these performance metrics separately for the surfaces with enamel and dentin carious lesions. Next, we have shown the confusion matrices of the classification of the carious lesions by the students as compared to the reference test. For this, the number of surfaces classified by the students (i.e., caries present vs. absent) in each group were cross-tabulated with the reference test. Similarly, for lesion depths, the number of surfaces assigned by the students to each category (i.e., no caries vs. E1 vs. D1 vs. D2) was cross-tabulated with the reference test, in each group. Differences in diagnosing lesion depths between the two groups were tested by the adjusted χ^2 test [Donner, 1989]. Lastly, students' perceptions on the learning experience were summarized. Differences between the two groups were tested by the Kruskal-Wallis rank sum test for continuous variables and χ^2 test for categorical variables.

For all tests, $p < 0.05$ was considered as statistically significant. No deviation from the intended to the provided intervention occurred. All statistical analyses and data management were performed using R (Version 4.0.3, www.r-project.org).

Results

All 48 invited students (37 female and 11 male) accepted to participate and accomplished the test. Table 1 shows the performance metrics of both groups of students in the detection of proximal carious lesion. No significant differences were found between groups. Lower values of sensitivity, AUC, accuracy, F1 score, and negative predictive value were observed in the enamel caries group compared to the dentin caries group (Table 2).

Cross-tabulations of assessments are shown in Tables 3 and 4. Students from the control group agreed on 85% of the cases where carious lesions were present and on 83% where they were absent. Students from the test group agreed on 87% and 81%, respectively. Considering cross-tabulation of lesion depth (Table 4), no difference was observed between groups, showing carious lesions in dentin the lowest percentage of agreement between students' findings and the reference standard.

The analysis of the questionnaire on the duration of time spent for learning and their satisfaction with the learning method is shown in Table 5. There were no sig-

Table 4. Cross-tabulation of lesion depth

Groups	Reference standard	Students' findings				
		no caries	E	D1	D2	Total
Control (illustrations)	Overall	2,082 (64)	895 (27)	220 (7)	57 (2)	3,254 (100)
	No carious lesion	**1,735 (91)**	137 (7)	29 (1)	9 (<1)	1,910 (100)
	E	262 (32)	**535 (65)**	23 (3)	6 (1)	826 (100)
	D1	78 (19)	180 (45)	**127 (32)**	17 (4)	402 (100)
	D2	7 (6)	43 (37)	41 (35)	**25 (22)**	116 (100)
Test (AV)	Overall	2,216 (67)	834 (25)	196 (6)	65 (2)	3,311 (100)
	No carious lesion	**1,802 (93)**	101 (5)	25 (1)	17 (<1)	1,945 (100)
	E	320 (38)	**497 (59)**	25 (3)	1 (<1)	843 (100)
	D1	87 (21)	199 (49)	**106 (26)**	13 (3)	405 (100)
	D2	7 (6)	37 (31)	40 (34)	**34 (29)**	118 (100)

N (%). No significant differences between groups, overall and stratified into subgroups (with the "no caries" category as the reference group) were found.

Table 5. Students' report on the satisfaction and learning according to groups

Students' report	Control (illustrations) (*n* = 24)	Test (AV) (*n* = 24)	*p* value
Duration of learning (median [IQR])			
Days	3.00 [2.00, 4.00]	3.00 [2.00, 4.00]	0.957
Hours per day	1.00 [0.92, 1.00]	0.83 [0.38, 1.00]	0.083
Levels			
Felt motivated, *n* (%)			
1	6 (25.0)	5 (20.8)	
2	7 (29.2)	16 (66.7)	
3	11 (45.8)	3 (12.5)	0.017*
4	0 (0.0)	0 (0.0)	
5	0 (0.0)	0 (0.0)	
Found easy to use, *n* (%)			
1	4 (16.7)	11 (45.8)	
2	9 (37.5)	8 (33.3)	
3	8 (33.3)	5 (20.8)	0.071
4	3 (12.5)	0 (0.0)	
5	0 (0.0)	0 (0.0)	
Felt stimulated to learn, *n* (%)			
1	9 (37.5)	19 (79.2)	
2	12 (50.0)	5 (20.8)	
3	2 (8.3)	0 (0.0)	0.024*
4	0 (0.0)	0 (0.0)	
5	1 (4.2)	0 (0.0)	

1 = strongly agree; 2 = partially agree; 3 = indifferent; 4 = partially disagree; 5 = strongly disagree IQR, interquartile range. IQR; χ^2 test, $p < 0.05$. Significant differences between groups are indicated with an asterisk.

nificant differences in learning duration. Most of students of the test group agreed to the statement that they felt motivated during learning using AV and would like to use this tool to continue to learn.

Discussion

This study was undertaken to assess whether AV using an in-house custom-built tool [Ekert et al., 2018] would have a learning impact on the performance of preclinical third-year dental students from a German dental school in the detection of proximal carious lesions in bitewing radiographs. To the best of our knowledge, this study is the first to test AV as an active educational strategy to teach dental students with regards to radiographic detection of caries. The main finding was that the educational effect (considering accuracy) of AV was as good as the conventional method using illustrations.

Our sample comprised unexperienced dental students who had their first contact with radiographic images and interpretation right before the commencement of this study, through a theoretical lecture of approximately 2 h, which was conducted to minimize knowledge bias in the study. Therefore, it can be assumed that all students had similar knowledge before randomization. Thus, they had their first training experience on radiographic proximal caries detection during the exercises of the present investigation.

The ability to radiographically detect proximal carious lesions is an important cognitive task, being this method alone not enough for making caries management decisions. Together with the detection of cavitation and the assessment of lesions activity status, radiographic examination allows the establishment of a diagnosis and to come to a treatment decision. Both learning methods tested in this study did not differ statistically in relation to the students' diagnostic performance. Notably, some previous studies [Vuchkova et al., 2012; Santos et al., 2016; Rocha et al., 2020] also found different learning methods to yield similar results in learning results in this field, while others found certain approaches (e.g., involving interactive learning) to be beneficial [Shuhaiber, 2004; Meckfessel et al., 2011].

Overall, the accuracy of students in detecting the presence or absence of proximal carious lesions was relatively high, independent of the allocated group. Notably, students were less apt in discriminating enamel from early dentin carious lesions, oftentimes classifying lesions extending into the outer third of dentine as enamel ones, underestimating the lesion extent. Such underestimation has been reported to occur more often in dental students than dentists [Mileman and Van Den Hout, 2002].

Students from both groups were instructed to learn using the allocated methodology during a 2-week period; they could organize themselves and choose the best time to fit in their daily routine at home to learn. Although more students who used AV reported to feel motivated to learn and satisfied after learning, the time spent for learning during the training method was not significantly different between groups. If assuming that the time spent for learning is an important pillar in reaching learning success, then the absence of a difference in learning effect between the groups may be ascribed to the similar learning time. In this case, further efforts to improve learning motivation may be needed, or alternative learning forms (e.g., mandatory learning on a defined set of images) may be sought.

Methodologies involving interaction between the educational material and the student as well as technical elements during learning have been found to improve the attention of the students. Kunin et al. [2014] qualitatively compared the preferences and perceptions of postgraduate dental residents for face-to-face, synchronous, and asynchronous learning methods and confirmed the relevance of technology for learning process and students' satisfaction. The authors also suggest that the asynchronous format can be an effective way to teach dental students since it allows for collaborative teaching and learning and provides residents with access to online lectures, articles, and discussion forums 24 h a day, 7 days a week, allowing to steer and self-engage in learning and relearning as needed [Kunin et al., 2014].

Subjective factors involving users' preferences, such as easiness of accessibility, interaction, and connectivity of any learning tool may affect its usefulness and performance. For example, easy accessibility and applicability, the freedom of navigation, the high quality of images, and the possibility of repeating learning units have been identified as supportive for learning using electronic platforms [Potomkova et al., 2006].

Our study results should be interpreted in the light of the following limitations. First, since the participants were students and the study was conducted in their university, there may be the presence of social desirability bias: students may have responded in a manner that they believed would be acceptable in the specific setting. We tried to overcome this by anonymizing the questionnaires and informing the students that their answers could not be linked to them. Second, since the test session was pre-scheduled, the students new exactly the day of the test and may have learned more intensively directly before the test phase. This may have biased the accuracy in both groups. Further studies on radiographic detection of carious lesions could blend AV to other synchronous strategies, such as tutoring students during laboratory training, online quizzes, and not pre-scheduled intermediate tests during the period of learning. Besides, students' perceptions about the use of AV must be further studied.

It can be concluded that educating third-year dental students on caries detection using AV was as good as the traditional learning method using illustrations. Students who learned with AV reported to be motivated and found the tool easy to use.

Acknowledgments

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Statement of Ethics

This study was approved by the Charité's Ethics Committee (#EA4/237/20). A written informed consent was obtained from all participants.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

All the authors have made substantive contribution to this study and manuscript, and all reviewed the final paper prior to its submission. Jonas Almeida Rodrigues and Falk Schwendicke designed the study; Jonas Almeida Rodrigues conducted the students' instruction and tests; Lubaina T. Arsiwala and Joachim Krois performed statistical analysis; Jonas Almeida Rodrigues, Lubaina T. Arsiwala, Joachim Krois, and Falk Schwendicke drafted manuscript. All the authors contributed to data analysis and interpretation, critically revised manuscript, and gave final approval.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

References

Alves LS, de Oliveira RS, Nora ÂD, Cuozzo Lemos LF, Rodrigues JA, Zenkner JEA, et al. Dental students' performance in detecting in vitro occlusal carious lesions using ICDAS with E-learning and digital learning strategies. J Dent Educ. 2018;82(10):1077–83.

Azuma RT. A survey of augmented reality [Internet]. In: Presence teleoperators virtual environ. 1997 [cited 2021 Jul 27];6:355–85.

Botden SMBI, De Hingh IHJT, Jakimowicz JJ. Meaningful assessment method for laparoscopic suturing training in augmented reality. Surg Endosc. 2009;23(10):2221–8.

Cantu AG, Gehrung S, Krois J, Chaurasia A, Rossi JG, Gaudin R, et al. Detecting caries lesions of different radiographic extension on bitewings using deep learning. J Dent. 2020;100:103425.

Donner A. Statistical methods in ophthalmology: an adjusted chi-square approach. Biometrics. 1989;45(2):605.

Ekert T, Krois J, Schwendicke F. Building a mass online annotation tool for dental radiographic imagery; 2018.

Espejo-Trung LC, Elian SN, De Cerqueira Luz MAA. Development and application of a new learning object for teaching operative dentistry using augmented reality. J Dent Educ. 2015;79(11):1356–62.

Kavadella A, Tsiklakis K, Vougiouklakis G, Lionarakis A. Evaluation of a blended learning course for teaching oral radiology to undergraduate dental students. Eur J Dent Educ. 2012;16(1):e88–95.

Kay EJ, Silkstone B, Worthington HV. Evaluation of computer aided learning in developing clinical decision-making skills. Br Dent J. 2001;190(10):554–7.

Kim-Berman H, Karl E, Sherbel J, Sytek L, Ramaswamy V. Validity and user experience in an augmented reality virtual tooth identification test. J Dent Educ. 2019;83(11):1345–52.

Kühnisch J, Meyer O, Hesenius M, Hickel R, Gruhn V. Caries detection on intraoral images using artificial intelligence. J Dent Res. 2022;101(2):158–65.

Kunin M, Julliard KN, Rodriguez TE. Comparing face-to-face, synchronous, and asynchronous learning: postgraduate dental resident preferences. J Dent Educ. 2014;78(6):856–66.

Liao T, Chang PF, Lee S. Augmented reality in health and medicine: a review of augmented reality application for health professionals, procedures, and behavioral interventions. Technol Heal. 2020:109–28.

Lussi A, Hack A, Hug I, Heckenberger H, Megert B, Stich H, et al. Detection of approximal caries with a new laser fluorescence device. Caries Res. 2006;40(2):97–103.

Luz PB, Stringhini CH, Otto BR, Port ALF, Zaleski V, Oliveira RS, et al. Performance of undergraduate dental students on ICDAS clinical caries detection after different learning strategies. Eur J Dent Educ. 2015;19(4):235–41.

Machiulskiene V, Nyvad B, Baelum V. A comparison of clinical and radiographic caries diagnoses in posterior teeth of 12-year-old Lithuanian children. Caries Res. 1999;33(5):340–8.

Meckfessel S, Stühmer C, Bormann KH, Kupka T, Behrends M, Matthies H, et al. Introduction of e-learning in dental radiology reveals significantly improved results in final examination. J Craniomaxillofac Surg. 2011;39(1):40–8.

Meinhold L, Krois J, Jordan R, Nestler N, Schwendicke F. Clustering effects of oral conditions based on clinical and radiographic examinations. Clin Oral Investig. 2020;24(9):3001–8.

Mendes FM, Novaes TF, Matos R, Bittar DG, Piovesan C, Gimenez T, et al. Radiographic and laser fluorescence methods have no benefits for detecting caries in primary teeth. Caries Res. 2012;46(6):536–43.

Mileman PA, Van Den Hout WB. Comparing the accuracy of Dutch dentists and dental students in the radiographic diagnosis of dentinal caries. Dentomaxillofacial Radiol. 2002;31(1):7–14.

Potomkova J, Mihal V, Cihalik C. Web-based instruction and its impact on the learning activity of medical students: a review [Internet]. Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub. 2006;150(2):357–61.
Rocha BC, Rosa BSP, Cerqueira TS, de-Azevedo-Vaz SL, Barbosa GLR, Ferreira LM, et al. Evaluation of different teaching methods in the radiographic diagnosis of proximal carious lesions. Dentomaxillofacial Radiol. 2021;50(4):20200295.
Santos GNM, Leite AF, Figueiredo PT, Pimentel NM, Flores-Mir C, de Melo NS, et al. Effectiveness of E-learning in oral radiology education: a systematic review. J Dent Educ. 2016;80(9):1126–39.
Schwendicke F, Splieth C, Breschi L, Banerjee A, Fontana M, Paris S, et al. When to intervene in the caries process? An expert Delphi consensus statement. Clin Oral Investig. 2019;23(10):3691–703.
Schwendicke F, Tzschoppe M, Paris S. Radiographic caries detection: a systematic review and meta-analysis. J Dent. 2015;43(8):924–33.
Shuhaiber JH. Augmented reality in surgery. Arch Surg. 2004;139(2):170.
Soltanimehr E, Bahrampour E, Imani MM, Rahimi F, Almasi B, Moattari M, et al. Effect of virtual versus traditional education on theoretical knowledge and reporting skills of dental students in radiographic interpretation of bony lesions of the jaw. BMC Med Educ. 2019;19(1):233.
Thiele JE. Learning patterns of online students. J Nurs Educ. 2003;42(8):364–6.
Vuchkova J, Maybury T, Farah CS. Digital interactive learning of oral radiographic anatomy. Eur J Dent Educ. 2012;16(1):e79–87.
Wenzel A. Digital imaging for dental caries [Internet]. Dent Clin North Am. 2000 [cited 2021 Apr 26];44(2):319–38. Available from:
Wrbas KT, Kielbassa AM, Schulte-Mönting J, Hellwig E. Effects of additional teaching of final-year dental students on their radiographic diagnosis of caries. Eur J Dent Educ. 2000;4(3):138–42.
Zafar S, Safdar S, Zafar AN. Evaluation of use of e-Learning in undergraduate radiology education: a review. Eur J Radiol. 2014;83(12):2277–87.