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Diagnostic Accuracy, Satisfaction and Self-Confidence of Dental Students When Classifying Dental Caries Lesions Using Simulation-Based Experience and Photographs: A Randomised Crossover Study of Intervention Sequence

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ABSTRACT

Aim: To evaluate the diagnostic accuracy, satisfaction and self-confidence of dental students when classifying dental caries lesions using simulation-based experience and photographs, and to examine whether the sequence of these interventions influences diagnostic performance.

Method: A randomised crossover study was conducted with 37 second-year undergraduate dental students. Participants were assigned to one of two intervention sequences: Photograph–Simulation-based Experience (P–SBE) or Simulation-based Experience–Photograph (SBE–P). Each student completed four diagnostic attempts, two with photographs and two with simulation-based experience, using the Nyvad criteria. Diagnostic accuracy was assessed using the area under the receiver operating characteristic curve (AUC) and pairwise discriminative accuracy (pAUC). Satisfaction and self-confidence in learning were measured using the National League for Nursing Satisfaction and Self-Confidence in Learning Questionnaire.

Results: Simulation-based experience demonstrated higher diagnostic accuracy than photographs in both sequences. In the P–SBE sequence, AUC increased from 79.7 (95% CI: 77.2–82.3) in the first photograph-based attempt to 93.2 (95% CI: 91.6–94.9) in the second simulation-based attempt. In the SBE–P sequence, AUC was also higher in the second simulation-based attempt, reaching 89.9 (95% CI: 88.1–91.7). Students also reported greater satisfaction, higher self-confidence and a more positive overall perception of simulation-based experience ($p < 0.05$).

Conclusion: Simulation-based experience yielded higher diagnostic accuracy than photographs in this Nyvad-based educational context. The highest overall performance was observed when photographs preceded simulation-based experience, supporting the progressive and complementary use of both approaches in undergraduate cariology teaching. Simulation-based experience was also perceived as enhancing satisfaction and self-confidence in learning.

1 | Introduction

Dental caries is a dynamic, multifactorial, non-communicable disease, mediated by the dental biofilm and modulated by diet, which results in the demineralisation of the tooth's hard tissues [1]. This disease is determined by biological, behavioural, psychosocial and environmental factors [1]. The World Health Organisation's Global Oral Health Status Report 2022 estimates that two billion people suffer from dental caries in their permanent teeth, and 514 million children suffer from caries in their primary teeth [2].

A dental caries lesion is the clinical sign of the disease and may be categorised according to its anatomical location, severity, depth and activity [1]. Caries lesion detection refers to the identification of the signs of the disease and can be performed through visual–tactile examination, radiographic methods or fluorescence-based techniques [3]. More recently, digital and artificial intelligence-assisted methods have also been integrated into dental caries detection and clinical decision-making [4, 5]. Despite this expansion, visual–tactile examination remains the most used method in clinical practice due to its simplicity and practicality; however, it is characterised by high specificity but low sensitivity and reproducibility [6, 7]. Diagnostic accuracy refers to a method's ability to distinguish between individuals who have and those who do not have a condition [3]. In this regard, the systematic review by Gimenez et al. [7] demonstrated that visual–tactile examination is more accurate than radiographic or fluorescence-based methods for detecting dental caries lesions. The use of visual–tactile scoring criteria, systems or indices for classifying caries lesions, such as the Nyvad criteria [8], aims to enhance sensitivity and minimise subjectivity in examiners' interpretations, thereby improving the reproducibility of the visual–tactile method [9].

A global consensus on caries teaching agrees that one of the core competencies of the general dentist is the ability to collect data on the signs and symptoms of dental caries, identify past caries experience, and record lesions according to their severity and activity [10–12]. To enable students to attain and demonstrate this competence, practical training methods have included the use of clinical photographs and extracted human teeth. In this regard, the systematic review and meta-analysis conducted by Ku et al. [13] showed that dental caries detection based on visual assessment of clinical photographs presents clinically acceptable accuracy when compared with visual intraoral clinical examination. Although photographs have also proven to be an accurate training method for classifying dental caries lesions according to the Nyvad criteria [14], they do not allow assessment of tactile features associated with lesion activity, such as surface texture. While the use of extracted teeth is ideal for the development and evaluation of diagnostic competence, obtaining an adequate number of teeth that represent all stages of the caries process has become increasingly difficult. In addition, natural teeth deteriorate over time and through repeated use by students. Moreover, in some countries, ethical considerations prohibit the use of extracted human teeth for educational purposes.

In this context, simulation—defined as an educational strategy in which specific conditions are created or replicated to resemble authentic situations, enabling individuals to experience representations of real events for practice, learning and assessment—emerges as a method of training and evaluation that can overcome the limitations of using photographs or extracted teeth in caries diagnosis teaching. Although simulation-based experiences have demonstrated benefits in other areas of the health sciences [15], the evidence in dentistry and particularly in cariology, remains limited. The present study aimed to compare the diagnostic accuracy, satisfaction and self-confidence of undergraduate dental students when classifying dental caries lesions according to the Nyvad criteria using simulation-based experience (SBE) and photographs (P), and to examine whether the sequence of these interventions influenced diagnostic performance.

2 | Materials and Methods

This study is reported in accordance with the Simulation-Based Research Extensions for the CONSORT Statement [16], the STAndard Reporting of CAries Detection and Diagnostic Studies (STARCARDDS) [17] and the Guideline for Reporting Evidence-based Practice Educational Interventions and Teaching (GREET) [18].

2.1 | Study Design and Participants

This was an experimental, randomised, crossover, analytical and longitudinal study, approved by the Human Research Ethics Committee of CES University (Ae-1249; 2024). The study population comprised all 37 second-year undergraduate students enrolled in the course *Diagnosis of Hard Tissue Lesions of the Tooth* at the Faculty of Dentistry, CES University (Medellín, Colombia), during the period from January to July 2025. The course is based on the international consensus on domains, learning objectives and content in cariology for undergraduate dental students [11], with the learning outcome that students should be able to classify caries lesions by severity and activity. The crossover design ensured that all participants received both educational interventions (SBE and P) in a different order, depending on the sequence to which they were allocated.

2.2 | Randomisation and Blinding

The randomisation sequence was generated in Microsoft Excel (version 2024; Microsoft Corporation, Redmond, WA, USA) by assigning a random number to each of the 37 enrolled students. Based on this sequence, participants were allocated to one of the following intervention orders: Photograph–Simulation-based Experience (P–SBE) or Simulation-based Experience–Photograph (SBE–P). Allocation remained concealed until the start of each session, ensuring that students were blinded to their order of participation. Implementation was carried out by an external researcher who was not involved in delivering the interventions or in the statistical analysis. Similarly, the investigators conducting the analysis were blinded to each student's assigned sequence.

2.3 | Interventions

Two educational interventions were applied in this study: simulation-based experience (SBE) and clinical photographs (P). All students participated in both, following the assigned sequence (P–SBE or SBE–P). Each intervention was conducted in two attempts separated by a one-week interval, so that every student completed a total of four assessments: two with photographs and two with simulation-based experience. Altogether, this represented approximately 4 h of training with simulation and 4 h with photographs, ensuring balanced exposure to both teaching methods.

The Nyvad criteria were used for classifying caries lesions [8]. This visual–tactile method is based on the characteristics of enamel and dentine surfaces, which change in response to biofilm activity [8]. Lesion activity is determined by surface texture, while severity is established by the presence or absence of a microcavity or cavity [8]. The Nyvad criteria use 10 codes to classify surfaces as sound, carious lesions (active or inactive; with intact surface, microcavity or cavity) or restored [8]. This system has been validated and has demonstrated high reliability, as well as construct and predictive validity [19, 20]. The use of the Nyvad criteria was intentional because lesion activity assessment requires interpreting surface characteristics along with lesion severity, making this system particularly useful for comparing a visual-only method (photographs) with a visual–tactile educational intervention (simulation-based experience).

The educational interventions were structured around the five-step model of evidence-based practice [21]. The clinical question addressed related to the diagnosis and detection of caries lesions; therefore, bibliographic material on the classification of caries lesions according to the Nyvad criteria [8, 20] was selected and provided. Educational materials were sent to all students via their institutional email accounts.

The interventions were facilitated by two faculty members in paediatric dentistry, both with more than 5 years of experience in university teaching, cariology and simulation (A.L.F. and M.R.), supported by a final-year postgraduate student in paediatric dentistry and a master's student in dental sciences (S.C.-M.). All activities were delivered face-to-face at the Faculty of Dentistry, CES University. They took place in a computer laboratory equipped with a notebook with WUXGA IPS anti-glare screen, 33.8 cm (13.3″) diagonal, 300 nits, 45% NTSC (1920 × 1200), and internet connection; and in a simulation room equipped with a computer with internet access, dental simulators (A-dec 41pro Simulator, A-dec, Oregon, USA), multipurpose dental typodonts (TOM, Medical Shapes, Colombia), artificial permanent teeth (Medical Shapes, Colombia), blue–white examination light, and all instruments and supplies recommended by the World Health Organization (WHO) for clinical examination [2]. Dental caries lesion recording was carried out through the institutional virtual platform (CES Virtual; Moodle version 4.5) using the questionnaire resource.

A total of seven face-to-face sessions of 2 h each were conducted, distributed as follows: (a) during the first two sessions, a lecture was delivered to explain and discuss terminology related to dental caries, clinical features, epidemiology, visual–tactile diagnosis of caries lesions and the Nyvad criteria; (b) in the third session, students engaged in training exercises to familiarise themselves with the educational interventions (simulation-based experience and photographs) and the virtual platform; and (c) between the fourth and seventh sessions, students performed lesion classification using simulation-based experience and photographs, and subsequently completed the satisfaction and self-efficacy in learning questionnaire [22, 23] (Figure 1).

The educational interventions formed part of the course's summative assessment, and therefore attendance was required of all students. Attendance was monitored manually by the course instructor and via access logs on the virtual platform, which required individual usernames and passwords.

2.3.1 | Simulation-Based Experience

For this educational intervention, 56 artificial permanent teeth were mounted in two pairs of multipurpose typodonts (TOM, Medical Shapes, Colombia), each coupled to a dental simulator. The artificial teeth included both sound surfaces and carious lesions, designed to represent the different categories of severity and activity defined by the Nyvad criteria [6]. Two clinical scenarios were developed in consultation with a cariology lecturer, a paediatric dentist, a restorative dentist, a general dentist and a facilitator, all of whom are independent and not involved in this research. The scenarios were constructed according to the 11 criteria of the Healthcare Simulation Standards of Best Practice: Simulation Design [24]. Each scenario included 16 dental surfaces with dental caries lesions and 16 sound surfaces, allowing each student to evaluate a total of 72 surfaces. Before implementation, two pilot tests of the simulation-based experiences were conducted, involving 10 postgraduate paediatric dentistry students. These pilot tests allowed validation by consensus of the dental caries lesions (inter-examiner Kappa = 0.87), the level of difficulty, the feasibility and the clarity of the instructions. No adjustments were made to the scenarios after piloting [24].

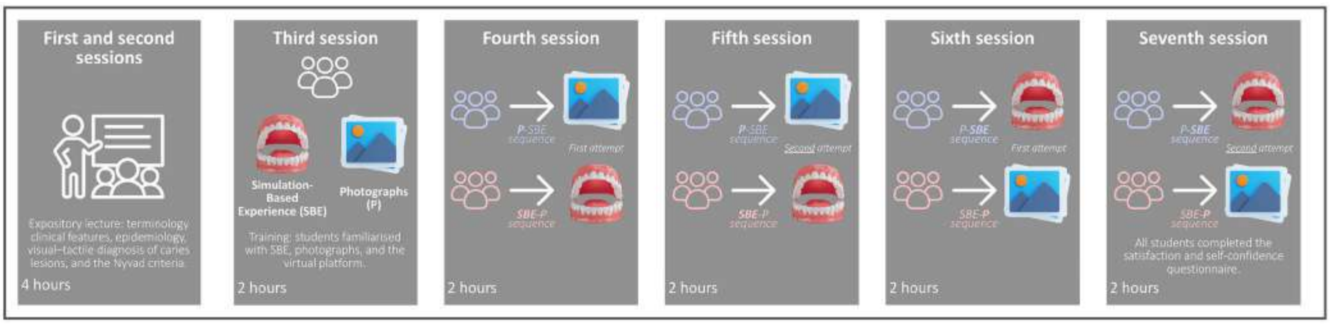

FIGURE 1 | Graphical representation of the methodological design of this study. Learning outcome: Students should be able to classify dental caries lesions according to their severity and activity. The interval between each session was one week. Between the fourth and seventh sessions, each began with a prebriefing [22] and ended with a debriefing [24].

The simulation employed in this study was classified as medium- to high-fidelity. In the physical domain, the typodonts and artificial teeth accurately represented the anatomy and surface features of enamel and dentine. Environmental fidelity was ensured by using a dental simulation room equipped with examination light, standardised instruments and conditions resembling a real clinical setting. Psychological fidelity was promoted through the incorporation of contextualised clinical cases, defined roles and clear expectations for students, which supported immersion and diagnostic decision-making analogous to professional practice [2].

The educational intervention was conducted in a dental simulation room and began with a 30-min structured prebriefing, designed to prepare students cognitively, psychologically and logistically [25]. This was led by the faculty facilitator (A.L.F.). During prebriefing, the facilitator addressed creating a safe learning environment, confidentiality, the educational relevance of the intervention, session flow and available support resources. The clinical scenarios were also described, including patient details (age, chief complaint, current condition and medical/dental history), along with guidance on using resources and requesting support during the intervention. Finally, the expected learning outcomes were explained, specifying the clinical context, role allocation and definition of expectations [25].

Subsequently, students examined the clinical scenarios in accordance with WHO recommendations [26], with a maximum of 1 h to complete both. The classification of each surface was recorded in the virtual platform, where each item specified the tooth number and surface to be assessed. As additional support, each student received a printed cognitive aid containing the Nyvad criteria scores, categories and descriptions [8]. Once all responses were submitted, the virtual platform automatically reported the number of correct answers and, in cases of error, provided immediate feedback explaining the proper response.

At the end of the scenarios, the facilitator and co-facilitator (A.L.F. and M.R.) conducted a structured debriefing following the PEARLS model (Promoting Excellence and Reflective Learning in Simulation) for 30 min [27]. This strategy guided students through a reflective and analytical process focused on diagnostic performance [27]. The debriefing began with students' initial reactions to the educational intervention, followed by an objective description of the steps taken and the classifications obtained. Subsequently, a facilitated analysis was conducted, in which the instructor promoted critical reflection through open-ended questions, guided feedback and inquiry into the application of the Nyvad criteria, highlighting both strengths and areas for improvement in diagnostic interpretation. Finally, key learning points and their transfer to real clinical practice were discussed, reinforcing the importance of diagnostic accuracy in the detection and classification of dental caries lesions (Figure 1).

2.3.2 | Photographs

For this educational intervention, 72 clinical photographs of permanent teeth were used, including both sound surfaces and surfaces with dental caries lesions. The images had been previously validated through visual–tactile examination by an independent examiner (inter-examiner Kappa = 0.90). To ensure complete representation of the Nyvad criteria, four surfaces were selected for each of codes 1–9, while 36 surfaces were included for code 0 (sound surface). In total, each student evaluated 72 dental surfaces. Photographs showing surfaces with uncertain diagnosis, dentoalveolar trauma, dentinogenesis imperfecta, complete, partial or removable prostheses, fixed orthodontic appliances (brackets) or developmental enamel defects—including hypoplasia, amelogenesis imperfecta, dental fluorosis and demarcated hypomineralisation—were excluded. Before implementation, two pilot tests of the simulation-based experiences were conducted, involving 10 postgraduate students in paediatric dentistry. These pilot tests verified the feasibility and the clarity of the instructions. No adjustments were made to the scenarios after they were piloted.

The educational intervention was conducted in a semi-darkened computer room and commenced with a structured prebriefing, led by the facilitator and co-facilitator, as previously described. The photographs were presented on the virtual platform in random order; for each one, the tooth and surface were specified for classification according to the Nyvad criteria [8], with a maximum allotted time of 1 h. As in the simulation-based experience, students were provided with a printed cognitive aid containing the description of the Nyvad criteria [8]. Once the evaluation was completed, the platform generated immediate feedback. Subsequently, the facilitator (A.L.F.) conducted a structured debriefing following the PEARLS model [27], aimed at fostering reflection on the application of the Nyvad criteria in surface classification and strengthening diagnostic reasoning in a visual environment (Figure 1).

2.4 | Satisfaction and Self-Confidence in Learning

At the end of the seventh session, all students completed the Satisfaction and Self-Confidence in Learning Questionnaire on the virtual platform [22, 23]. The *National League for Nursing developed this instrument*, which consists of a 13-item scale designed to measure students' satisfaction with the activity (5 items) and their self-confidence in learning (8 items) [22, 23]. Responses were rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

2.5 | Outcomes

The primary outcome was the diagnostic accuracy of students in classifying dental caries lesions according to the Nyvad criteria, assessed using the area under the receiver operating characteristic curve (AUC) and pairwise discriminative accuracy (pAUC), with both the educational intervention and the intervention sequence considered.

Secondary outcomes included students' perceptions of both training methods, measured with the Satisfaction and Self-Confidence in Learning Questionnaire across three dimensions (satisfaction, self-confidence and overall perception), and the detailed analysis of pairwise classification performance in the best-performing experimental condition.

2.6 | Analysis and Sample Size

Diagnostic accuracy was analysed using the Obuchowski method to estimate and compare the area under the receiver operating characteristic curve (AUC) when the reference standard is not binary [28]. This approach allowed the calculation of both overall diagnostic accuracy (AUC) and pairwise discriminative accuracy (pAUC) between each pair of Nyvad categories [8].

AUC values with their corresponding 95% confidence intervals (95% CI) were estimated for each diagnostic attempt within each intervention sequence. This analytical approach allowed the study to examine not only differences between photographs and simulation-based experience, but also the possible influence of the order in which these interventions were delivered within the crossover design. To further explore classification performance, pairwise discriminative accuracy was analysed in the best-performing experimental condition, namely the second attempt using simulation-based experience in the P–SBE sequence, and a confusion matrix was constructed to represent the distribution of students' responses according to the reference category.

Differences in students' perceptions between photographs and simulation-based experience were analysed using quantile regression. Results are presented as median differences with 95% CIs across three dimensions: satisfaction with the evaluation method, self-confidence in learning and overall perception.

No missing data were recorded. The sample size allowed AUC estimates with an error range of ±0.8 to ±1.3 for students' attempts. A significance level of $p<0.05$ was adopted. All analyses were conducted using R (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria) and Microsoft Excel (version 2024; Microsoft Corporation, Redmond, WA, USA).

3 | Results

3.1 | Effect of Intervention and Sequence on Overall Diagnostic Accuracy

Overall diagnostic accuracy was higher when students classified dental caries lesions using simulation-based experience than when using photographs in both intervention sequences. In the P–SBE sequence (Figure 2, left panel), students showed an increase in AUC from 79.7 (95% CI: 77.2–82.3) in the first attempt with photographs to 93.2 (95% CI: 91.6–94.9) in the second attempt with simulation-based experience. In the SBE–P sequence (Figure 2, right panel), AUC was also higher in the second attempt with simulation-based experience, reaching 89.9 (95% CI: 88.1–91.7), whereas both attempts with photographs showed lower AUC values.

3.2 | Confusion Matrix

Table 1 presents the confusion matrix for the second attempt using simulation-based experience in the P–SBE sequence, which showed the highest AUC value. Despite a high overall AUC of 93.2 (95% CI: 91.6–94.9), frequent misclassifications were observed, particularly in teeth with intact surfaces (Sc 1 and Sc 4) and with microcavities (Sc 2 and Sc 5). For teeth with active caries and an intact surface (Sc 1), classification was correct in 47.2% of cases; however, 36.1% were incorrectly classified as sound (Sc 0) and 13.9% as inactive caries with intact surface (Sc 4). In the case of inactive caries with intact surface (Sc 4), 58.3% of responses were correct, whereas 27.8% were misclassified as active caries with intact surface (Sc 1) and 8.3% as sound (Sc 0).

For teeth with microcavities, false negatives were more frequent in inactive lesions (Sc 5), with 25.0% misclassified as sound, compared with 8.3% for active lesions (Sc 2). Notably, responses for lesions categorised as Sc 2 were distributed almost evenly across Sc 0–Sc 4, indicating the absence of a clear error pattern. Finally, in the case of restorations with active caries (Sc 8), 8.3% were misclassified as restorations with sound surface (Sc 7). For all other categories, correct classification rates exceeded 90%.

3.3 | Pairwise Accuracy

Table 2 presents the pairwise classification accuracies of the Nyvad categories obtained in the second attempt using simulation-based experience in the P–SBE sequence, which showed the highest AUC value. It was observed that discrimination between inactive lesions with intact surfaces (Sc 4) and those with microcavities (Sc 5), as well as between inactive

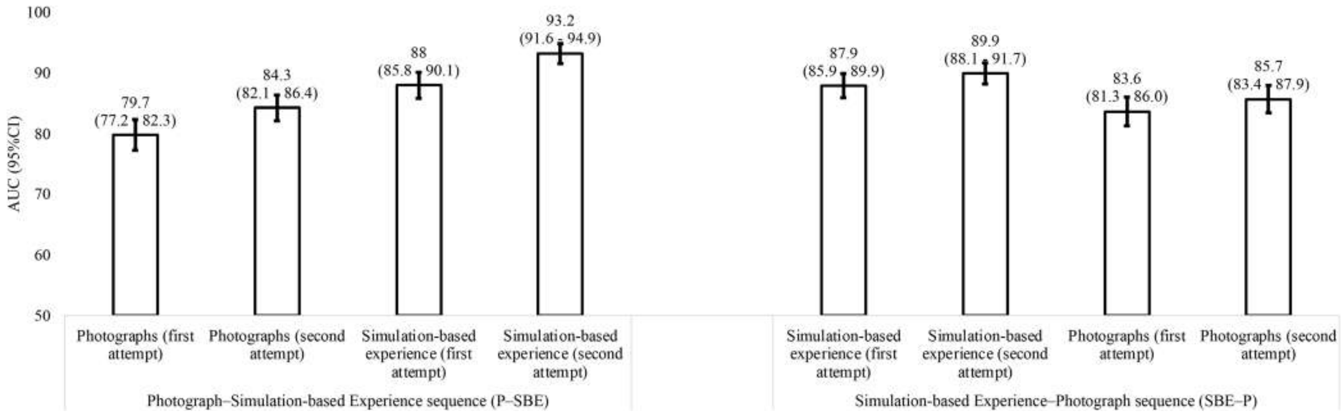

FIGURE 2 | Diagnostic accuracy (AUC with 95% CI) of attempts with simulation-based experience and photographs, according to sequence.

TABLE 1 | Confusion matrix for the second attempt in the Photograph–Simulation-based Experience (P–SBE) sequence.

	Student responses									
Reference standard	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0. Sound	**96.5**	2.0	0.5		1.0					
1. Active caries (intact surface)	36.1	**47.2**	2.8		13.9					
2. Active caries (surface discontinuity)	8.3	8.3	**63.9**	8.3	8.3	2.8				
3. Active caries (cavity)			2.8	**97.2**						
4. Inactive caries (intact surface)	8.3	27.8			**58.3**	2.8		2.8		
5. Inactive caries (surface discontinuity)	25.0					**69.4**	5.6			
6. Inactive caries (cavity)				5.6		2.8	**91.7**			
7. Restoration (sound surface)								**100**		
8. Restoration + active caries	2.8		2.8	2.8				8.3	**80.6**	2.8
9. Restoration + inactive caries	2.2							2.2	2.2	**93.3**

Note: The values represent the percentage of student responses for each score and category of the Nyvad criteria in comparison with the reference standard. The main diagonal (values in bold) corresponds to the percentage of surfaces classified correctly.

TABLE 2 | Pairwise classification accuracy of the Nyvad criteria categories among undergraduate students.

	Students[a]									
Score. Category (Nyvad)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0. Sound		**80.0**	94.5	99.0	94.7	87.1	99.9	100	98.5	98.8
1. Active caries (intact surface)			**78.3**	86.1	**77.9**	**79.5**	99.2	100	96.9	98.2
2. Active caries (surface discontinuity)				83.7	**63.6**	**75.1**	99.1	100	95.5	97.9
3. Active caries (cavity)					**63.9**	**75.0**	97.3	100	93.1	97.8
4. Inactive caries (intact surface)						**73.0**	93.8	98.6	93.7	97.8
5. Inactive caries (surface discontinuity)							92.2	100	93.4	98.1
6. Inactive caries (cavity)								100	91.7	97.8
7. Restoration (sound surface)									87.5	96.7
8. Restoration + active caries										93.6
9. Restoration + inactive caries										

Note: The values represent the pairwise estimated area under the curve (pAUC). Discriminations with pAUC $\leq$80 are highlighted in bold.
[a]Corresponds to the second attempt with simulation-based experience in the Photograph–Simulation-based Experience (P–SBE) sequence.

lesions and active lesions (Sc 1, Sc 2 and Sc 3), consistently demonstrated low diagnostic accuracy.

3.4 | Satisfaction and Self-Confidence in Learning

Simulation-based experience was rated significantly higher than photographs across all evaluated dimensions (Table 3). Students reported greater satisfaction with the educational interventions (median difference: 1.3; 95% CI: 0.6–1.9) and greater self-confidence in learning (median difference: 1.0; 95% CI: 0.4–1.6). Moreover, the overall perception of simulation-based experience was more positive than that of photographs, with a median difference of 1.5 (95% CI: 0.7–2.3).

4 | Discussion

This study showed that undergraduate dental students achieved higher diagnostic accuracy when classifying dental caries lesions using simulation-based experience than when using photographs. The highest overall performance was observed among students who were first exposed to photographs and subsequently to simulation-based experience (P-SBE). In addition, simulation-based experience was associated with greater satisfaction, higher self-confidence in learning and a more positive overall perception. Taken together, these findings suggest that the educational roles of the two approaches may be better understood as complementary rather than competing. Furthermore, the crossover design

TABLE 3 | Comparison of students' perceptions of the interventions (photographs and simulation-based experience).

Dimension[a]	Median (IQR)		Median difference	95% Confidence interval	*p*
	Photographs	Simulation-based experience			
Satisfaction with the evaluation method	2.4 (1.5–2.8)	3.8 (3.0–4.0)	1.3	(0.6–1.9)	0.001
Self-confidence in learning	2.3 (2.0–3.0)	3.5 (3.0–4.0)	1.0	(0.4–1.6)	0.003
Overall perception	2.0 (1.5–3.0)	4.0 (3.5–4.0)	1.5	(0.7–2.3)	< 0.001

[a]Median scores (with interquartile ranges–IQR) are presented for satisfaction with the evaluation method, self-confidence in learning and overall perception. Scale range: 0–4.

allowed performance to be examined according to both the educational approach and the order of intervention delivery; although, as in other learning-based crossover studies, some carryover effect cannot be fully excluded because no complete washout of prior learning is possible.

The classification of dental caries lesions by activity and severity is a fundamental competence that dental students must acquire and demonstrate during their professional training [10–12]. In this regard, the Nyvad criteria were adopted because, in addition to describing the severity of dental caries lesions, they also allow the assessment of lesion activity, thereby providing relevant information for clinical decision-making [8, 19, 20]. One of their main strengths is their predictive validity, as demonstrated in longitudinal studies [19, 20]. This ability to estimate the probability of progression or stability of dental caries lesions reinforces an evidence-based approach to dental practice and supports the use of these criteria in both teaching and clinical contexts [14, 19, 20]. The choice of diagnostic criteria in this study was guided by the specific educational aims of the intervention. Since students were asked to classify lesions according to both severity and activity, the Nyvad criteria were considered appropriate for the present research context. This should not be interpreted as a hierarchical preference over other established systems, such as ICDAS/ICCMS [29, 30], but rather as a criterion selection aligned with the objectives of the study and the intended learning outcomes of the course.

This study arose from the need to address the limitations of photograph-based training, particularly its restriction to visual information alone. Although photographs may support the development of early diagnostic skills, they do not allow students to engage with the three-dimensional, visuo-tactile and contextual features that are relevant to clinical reasoning in cariology [14]. In this context, simulation-based education was proposed as an active teaching and assessment methodology aimed at recreating reality in a safe and constructive environment. In this study, this educational intervention integrated visual features of dental caries lesions with information on volume, contour, texture, spatial relationships and tactile surface characteristics, providing students with a more thorough diagnostic scenario. This richer environment may be especially relevant when using the Nyvad criteria, which require interpreting lesion activity and severity [8]. Scientific evidence strongly supports the use of simulation-based education in various areas of the health sciences [15], demonstrating its effectiveness in promoting the acquisition of new skills, both technical and non-technical, training responses to specific clinical situations, familiarising students with unfamiliar environments and assessing professional competences [31]. In addition, the meta-analysis conducted by Kim et al. [32] showed that simulation-based interventions yield significant educational effects, particularly in the psychomotor domain, including the development of practical skills, physical dexterity and the execution of clinical procedures.

In line with this rationale, undergraduate students achieved higher diagnostic accuracy with simulation-based experience than with photographs. This result is consistent with the richer diagnostic environment provided by simulation, which combines visual, three-dimensional, visuo-tactile, environmental and contextual cues that more closely resemble clinical reasoning. These findings also align with evidence from other health disciplines, where medium- to high-fidelity simulation has been associated with greater clinical accuracy than image-based or case-based educational approaches [33, 34]. In addition, the use of cognitive aids, immediate feedback and structured debriefing through the PEARLS model may have reinforced learning and improved diagnostic performance.

This crossover study showed that the P–SBE sequence was associated with higher diagnostic performance than the SBE–P sequence. This finding can be interpreted considering cognitive load theory, the pre-training principle and cognitive predisposition, which suggest that beginning with activities in a less complex environment facilitates information processing and reduces mental overload, thereby optimising performance in more demanding scenarios [35, 36]. Models of fidelity progression in health simulation emphasise that gradually moving from lower- to higher-fidelity experiences enhances the acquisition and transfer of competences [37]. Similar results have been reported in areas such as dermatology and radiology, where initial exposure to clinical images improved diagnostic sensitivity in subsequent, more realistic contexts [38, 39]. Likewise, the superiority of the P–SBE sequence can be explained by a memory consolidation effect, a process through which learning acquired in an initial, simpler practice is stabilised and reinforced in long-term memory, allowing diagnostic schemas to become more resistant to forgetting and more transferable to clinical practice [40]. From this perspective, photograph-based training may support the early development of visual diagnostic skills, whereas simulation-based experience may represent a subsequent stage in competence development by incorporating three-dimensional, contextual and visuo-tactile elements.

Although overall diagnostic accuracy was high in this study, it is essential to analyse the errors in the classification of dental caries lesions. Students experienced greater difficulty classifying lesions with intact or microcavitated surfaces and tended to underestimate activity—findings consistent with those reported by Escobar et al. [14]. In such lesions, discrimination depends on subtle clinical differences—such as changes in opacity and roughness—that may be difficult to identify, particularly in the early stages of professional training. Moreover, at the time of taking the course *Diagnosis of Hard Tissue Lesions of the Tooth*, students' clinical experience had focused mainly on laboratory practice with cavitated lesions or teeth with extensive coronal destruction, which could limit their ability to recognise incipient signs. By contrast, active and inactive cavitated dental caries lesions were classified with greater accuracy in both this study and that of Escobar et al. [14], suggesting that greater clinical severity facilitates detection and classification. These findings highlight the need to strengthen the practical teaching of dental caries lesions with intact (Sc 1 and Sc 4) and microcavitated surfaces (Sc 2 and Sc 5) through a wider variety of cases and progressive exposure that reduce diagnostic variability in these categories.

In restored surfaces, diagnostic accuracy exceeded 90%. This high level of accuracy can be explained by the fact that restorations constitute a clear and easily recognisable visual reference for students, which reduces the complexity of the diagnostic decision compared with natural surfaces that present more subtle changes. Moreover, the task is mainly limited to determining the presence or absence of signs of activity of dental caries lesions at the margins, which narrows the range of diagnostic alternatives and favours more accurate responses.

Although simulation-based experience involved a more complex diagnostic environment than photographs, students evaluated this educational intervention more positively. This may be explained by their perception of simulation as a bridge between theory and practice, providing a safe environment in which to apply knowledge, make mistakes without consequences and reflect upon them [41–43]. In addition, the level of fidelity may influence students' perceptions, as more realistic experiences are often associated with greater satisfaction and engagement with learning [44–46].

From an educational perspective, photographs should not be regarded as an inadequate method, but rather as a valuable visual educational resource with specific advantages and limitations. They may be particularly useful in contexts where simulation facilities or three-dimensional models are not available, as they offer a feasible, standardised and less resource-intensive approach to early diagnostic training. Their standardisation may facilitate pattern recognition and support structured learning, particularly in the initial stages of competence development. However, because photographic assessment relies solely on visual information, its educational contribution should be interpreted within the limits of a visual-based approach to caries diagnosis, especially when diagnostic tasks require three-dimensional or visuo-tactile judgement.

This study has several limitations that should be considered when interpreting the results. Firstly, the sample size was restricted to a single cohort of students from a single institution, limiting the generalisability of the findings to other academic contexts or levels of training. Secondly, the study assessed diagnostic performance only in the short term; neither competence retention nor transfer to real clinical settings with patients was evaluated. Future research should therefore include multicentre studies with larger and more heterogeneous samples, as well as longitudinal follow-up, to determine the persistence of acquired competences and their transfer to real clinical practice. Additionally, further research could explore whether similar educational effects occur when training and assessment are based on other established frameworks, such as ICDAS/ICCMS [29, 30], particularly regarding lesion detection and clinical decision-making.

5 | Conclusion

Undergraduate students showed greater diagnostic accuracy when classifying dental caries lesions with simulation-based experience than with photographs in this Nyvad-based educational context. They also reported higher levels of satisfaction and self-confidence in learning. The best overall performance occurred when photographs preceded simulation-based experience. These findings support the progressive and complementary use of both methods in undergraduate cariology education.

Author Contributions

S.C.-M.: conceptualisation, methodology, data collection, drafting of the initial manuscript. D.F.R.-G.: methodology, data analysis, data management, drafting of the initial manuscript and visualisation. L.I.A.-G.: conceptualisation, methodology, drafting of the initial manuscript. L.F.V.: conceptualisation, project administration. A.L.F. and M.R.: contributed equally to conceptualisation, methodology, formal analysis, data collection and management, as well as to the review and editing of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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