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# Virtual simulation and practice time across increasing tooth complexity in dental wax pattern training: an exploratory secondary analysis of a crossover study

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## Abstract

# Objective

To exploratorily evaluate whether virtual simulation training is associated with different practice-time trajectories during dental wax pattern fabrication compared with traditional physical model training.

# Methods

This exploratory secondary analysis used data from a randomized crossover study. Fourteen dental students were randomly assigned to a physical-first group (n = 7) or a virtual-first group (n = 7). Only first-stage data were analyzed to minimize carryover effects. Practice time across four tooth positions with progressively increasing anatomical complexity was recorded. Linear mixed-effects models were initially specified with random intercepts and random slopes. Because of the small number of participants per group, the random-slope model showed a singular fit; therefore, random-effects variance estimates and asymptotic Wald p-values were not used for definitive inference. Fixed-effect estimates are reported as exploratory findings.

# Results

The virtual-first group showed a smaller increase in practice time across complexity levels than the physical-first group. The estimated slope was 6.40 minutes per complexity level in the physical-first group and 2.32 minutes per level in the virtual-first group. The group-by-complexity interaction estimate was − 4.08. However, because of the small sample size and singular random-slope fit, this estimate should be interpreted as exploratory and hypothesis-generating. No reliable

## Introduction

Skill acquisition in dental education is commonly characterized by learning curve trajectories, in which performance improves progressively with practice and may be influenced by the training modality employed[1]. Dental wax pattern fabrication is a foundational preclinical exercise that requires the sequential acquisition of psychomotor coordination, spatial perception, and anatomical carving skills across tooth positions of progressively increasing complexity[2]. As procedural complexity increases, novice learners often experience greater cognitive and technical demands, particularly when performing anatomically detailed tasks such as occlusal morphology carving.

Conventional physical model training has long been the standard approach for teaching dental wax pattern fabrication. However, traditional training methods may rely heavily on instructor supervision and repeated trial-and-error practice, which can contribute to variability in learning efficiency among students. In contrast, virtual simulation platforms provide standardized demonstrations, repeatable

practice opportunities, and immediate feedback, potentially facilitating early procedural skill acquisition and reducing unnecessary cognitive load[3]. Previous studies have suggested that virtual simulation may improve preclinical dental training outcomes and learner confidence[3, 4]. Nevertheless, quantitative evidence regarding how virtual simulation influences learning curve trajectories during dental wax pattern training remains limited.

Learning curves in procedural education are commonly evaluated by examining changes in task performance across repeated or progressively complex training tasks[1]. In the context of dental wax pattern fabrication, tooth positions with increasing anatomical complexity may provide a practical framework for assessing how learners adapt to progressively more demanding procedural tasks. Understanding whether virtual simulation alters the rate at which practice time increases across these complexity levels may provide additional insight into its educational value beyond conventional outcome comparisons.

Therefore, we conducted an exploratory secondary analysis of a randomized crossover study to examine whether virtual simulation training was associated with a shallower increase in practice time across progressively complex tooth positions compared with traditional physical model training. Because the original study included only seven participants per group, the present analysis should be regarded as hypothesis-generating, and no definitive conclusions were drawn regarding inter-individual variability or statistical significance.

## Methods

## 2.1 Study design and participants

This study was a secondary analysis of data derived from a previously conducted randomized crossover study investigating virtual simulation and traditional physical model training in dental wax pattern fabrication. Fourteen dental technology students (5 males and 9 females) from Binzhou Medical University were enrolled and randomly assigned to either a physical-first group (n = 7) or a virtual-first group (n = 7). Randomization was performed using a computer-generated random allocation sequence.

To minimize potential carryover effects inherent to crossover designs, only data obtained during the first training stage were included in the present analysis. During this stage, participants completed wax pattern fabrication tasks involving four tooth positions presented in order of progressively increasing anatomical complexity: central incisor (level 1), canine (level 2), first premolar (level 3), and first molar (level 4). Practice time required to complete each tooth task was recorded in minutes.

Students in the physical-first group received conventional training using gypsum models and dental wax materials under instructor guidance. Students in the virtual-first group were trained using a custom-developed virtual simulation platform that provided standardized procedural demonstrations and real-time feedback during tooth morphology carving exercises.

The original crossover study was approved by the Ethics Committee of Yantai Stomatological Hospital of Binzhou Medical University (Approval No. 202509101). Written informed consent was obtained from all participants prior to study enrollment.

## 2.2 Outcome measures

The primary outcome was practice time (minutes) required to complete wax pattern fabrication tasks at each tooth complexity level. In the present study, increasing tooth complexity levels were used as a surrogate framework for evaluating changes in procedural performance across progressively more demanding training tasks.

## 2.3 Statistical analysis

Statistical analyses were performed using R software (version 4.6.0; R Foundation for Statistical Computing, Vienna, Austria) with the lme4 package. Continuous variables are presented as mean ± standard deviation (SD).

Linear mixed-effects models were initially constructed to examine the association between training modality and changes in practice time across tooth complexity levels. Fixed effects included training group (physical-first vs. virtual-first), tooth complexity level (1–4), and the group-by-complexity interaction. Random intercepts and random slopes for complexity level were specified for individual students.

However, because only seven participants were included in each group, the random-slope model produced a singular fit, indicating that the random-slope variance and intercept–slope correlation were not reliably identifiable. Therefore, random-effects variance estimates were not interpreted as evidence for group differences in individual variability. Asymptotic Wald-based p-values from lme4 were also not used for definitive inference because the number of clusters was very small and such inference is not well justified under these conditions. Fixed-effect estimates are reported descriptively as exploratory results[7].

A sensitivity analysis treating tooth complexity level as a categorical variable was performed. For future confirmatory studies, permutation tests, parametric bootstrap, or Bayesian multilevel models with substantially larger samples should be prespecified.

# Results

## 3.1 Descriptive results

Practice time increased progressively across tooth positions with greater anatomical complexity in both training groups (Table 1). Students in the virtual-first group had lower practice times than those in the physical-first group at all complexity levels.

In the physical-first group, mean practice time increased from 23.5 ± 8.2 minutes for the central incisor task to 44.2 ± 12.8 minutes for the first molar task. In the virtual-first group, practice times ranged from 5.8 ± 0.9 minutes at the central incisor level to 13.2 ± 3.6 minutes at the first molar level.

Table 1
Practice time (minutes) by tooth position and group (mean ± SD)

| Tooth position | Difficulty level | Physical-first (n = 7) | Virtual-first (n = 7) |
|---|---|---|---|
| Central incisor | 1 | 23.5 ± 8.2 | 5.8 ± 0.9 |
| Canine | 2 | 25.7 ± 6.2 | 8.1 ± 1.3 |
| First premolar | 3 | 27.6 ± 7.3 | 8.9 ± 1.8 |
| First molar | 4 | 44.2 ± 12.8 | 13.2 ± 3.6 |

# 3.2 Mixed-effects model analysis

The exploratory mixed-effects model estimated a group-by-complexity interaction of -4.08. The estimated slope of practice time increase was 6.40 minutes per complexity level in the physical-first group and 2.32 minutes per level in the virtual-first group. These estimates suggest that students receiving virtual simulation training may have had a shallower increase in practice time as procedural complexity increased(Fig. 1).

However, the random-slope model showed a singular fit. Because of the small sample size and unstable random-effects structure, this interaction estimate is reported as exploratory only. No asymptotic p-value was used for definitive inference, and the result should not be regarded as confirmatory evidence.

# 3.3 Inter-individual variability in learning trajectories

The initially specified random-slope model showed a singular fit, likely reflecting the very small number of participants per group and the complexity of the random-effects structure. Consequently, variance components for individual slopes were unstable and were not interpreted. Although descriptive plots of individual slopes were inspected, no reliable conclusion could be drawn regarding group differences in inter-individual variability(Fig. 2).

# 3.4 Sensitivity analysis

Sensitivity analysis treating tooth complexity level as a categorical variable yielded directionally consistent findings, with the virtual-first group showing smaller increases in practice time at higher-complexity tooth tasks. However, because of the small sample size and model instability, these findings remain exploratory.

# 3.5 Model diagnostics

Residual plots were visually inspected. No severe violations of normality or homoscedasticity were identified. The random-slope structure produced a singular fit and was therefore not used for definitive inference. The results should be interpreted as hypothesis-generating.

## Discussion

This exploratory secondary analysis suggested that virtual simulation training may be associated with a shallower increase in practice time across tooth tasks of progressively increasing anatomical complexity compared with conventional physical model training. However, because only seven participants were included per group and the random-slope model showed a singular fit, these findings are preliminary and cannot support definitive conclusions.

Learning curves in procedural education reflect how learners adapt to increasing technical demands over time or across progressively complex tasks[7, 8]. In the present study, increasing tooth complexity levels were used as a practical framework to evaluate changes in procedural performance during dental wax pattern fabrication training. Compared with students receiving conventional physical model training, students exposed to virtual simulation showed smaller increases in practice time as task complexity increased. These findings may suggest that virtual simulation could facilitate earlier acquisition of foundational procedural strategies, but this interpretation requires confirmation in larger studies.

Several mechanisms may explain these exploratory findings. Virtual simulation platforms provide standardized demonstrations, repeatable practice opportunities, and immediate corrective feedback, which may help novice learners establish more accurate mental representations of tooth anatomy and procedural workflows. Traditional physical model training often depends more heavily on instructor availability and repeated trial-and-error practice. The ability to repeatedly visualize and rehearse procedural steps within a controlled virtual environment may reduce unnecessary cognitive load and improve procedural consistency when learners encounter increasingly complex carving tasks. This finding is broadly consistent with cognitive load theory, which posits that well-structured simulation environments reduce extraneous cognitive load and free mental resources for schema construction[9].

Previous studies have generally reported positive effects of virtual simulation on preclinical dental training outcomes and learner confidence[8]. However, most previous investigations focused on final performance scores or subjective learner perceptions. The current study extends the literature by examining practice-time trajectories using mixed-effects modeling, but the small sample size limits the strength of any conclusion.

Importantly, we did not confirm that virtual simulation reduced inter-individual variability. The random-effects variance estimates were unstable because of the small number of participants per group and the singular fit of the random-slope model. Therefore, the earlier observation of lower variability in the virtual-first group should not be interpreted as a reliable finding. Future studies with substantially larger samples are needed to examine whether virtual simulation standardizes learning trajectories.

Several limitations should be acknowledged. First, the sample size was very small, which limits statistical power, generalizability, and the reliability of random-effects variance estimates. The singular fit observed in the mixed-effects model reflects this limitation. Second, only first-stage data from the crossover study were analyzed to minimize carryover effects; therefore, the findings primarily reflect short-term training adaptation rather than long-term retention or transfer.[10] Third, procedural performance was evaluated using practice time rather than objective morphology quality scores. Fourth, asymptotic Wald-based inference was not considered appropriate with so few clusters; the reported estimates are exploratory and should not be used to claim statistical significance.

Overall, the present findings suggest that virtual simulation may support more efficient early-stage procedural skill acquisition during dental wax pattern training, but this remains a hypothesis. Integrating simulation-based training into preclinical dental curricula should be evaluated in adequately powered, multicenter studies with prespecified statistical analysis plans.

## Conclusion

In this exploratory secondary analysis of a randomized crossover study, virtual simulation training was associated with a shallower increase in practice time across tooth tasks of progressively increasing anatomical complexity compared with conventional physical model training. However, because of the very small sample size and unstable random-effects estimates, no reliable conclusion can be drawn regarding inter-individual variability.

These findings should be considered hypothesis-generating. Larger, adequately powered studies with prespecified multilevel or permutation-based statistical methods are needed before integrating virtual simulation into early-stage dental wax pattern curricula.

## Declarations

# Ethics approval and consent to participate:

**Clinical trial number**: Not applicable. This study was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. The study protocol was reviewed and approved by the Ethics Committee of Yantai Stomatological Hospital of Binzhou Medical University (Approval No. 202509101). All participants were informed about the purpose and procedures of the study, and written informed consent was obtained from all individual participants prior to the commencement of the training.

**Consent for publication:**

Not applicable. This manuscript does not contain any individual persons data, images, or other identifiable information.

**Informed Consent**

**Statement**:All participants were informed about the purpose and procedures of the study, and written informed consent was obtained from all individual participants included in the study prior to the commencement of the training.

# Conflicts of Interest:

The authors declare no conflicts of interest.

# Funding:

This research received no external funding.

# Author Contribution

Conceptualization: Guanghui Ren, Qilong SuMethodology: Guanghui Ren, Jing Zhang, Xiaojing AnSoftware: Kaixuan DiaoValidation: Qilong Su, Kaixuan DiaoFormal analysis: Qilong Su, Kaixuan DiaoInvestigation: Qilong Su, Kaixuan DiaoData curation: Jing Zhang, Xiaojing AnWriting – original draft: Qilong SuWriting – review & editing: Guanghui RenProject administration: Guanghui RenFunding acquisition: None.

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# Data Availability Statement:

The data presented in this study are available on request from the corresponding author. The data are not publicly available because of institutional and national data policy restrictions imposed by the ethics committee since the data contain information that could potentially identify study participants. Data are available upon request (contact via rgh@bzmc.edu.cn) for researchers who meet the criteria for access to confidential data (please provide the manuscript title with your inquiry).

## References

1. PUSIC M V, BOUTIS K, HATALA R, et al. Learning curves in health professions education[J]. Acad Med. 2015;90(11):1460–5.

2. FONSECA A, GUIMARÃES V B D S, JUNIOR S A R, et al. Effect of Dental Course Cycle on Anatomical Knowledge and Dental Carving Ability of Dental Students[J]. Anat Sci Educ. 2021;15(2):352–9.
3. REN J, LI R, ZHANG W, et al. Effect of digital virtual reality simulator on pre–clinical dental surgical skill training: a retrospective study[J]. BMC Med Educ. 2025;25(1):1189.
4. CONTE D B, ZANCANARO M. Educational Interventions to Improve Dental Anatomy Carving Ability of Dental Students: A Systematic Review[J]. Anat Sci Educ. 2020;14(1):99–109.
5. R CORE TEAM. R: A language and environment for statistical computing[M]. Vienna, Austria: R Foundation for Statistical Computing; 2026.
6. BATES D, MÄCHLER M. Fitting Linear Mixed-Effects Models Using lme4[J]. J Stat Softw. 2015;67(1):1–48.
7. RAMSAY C R, GRANT A M, WALLACE S A, et al. Statistical assessment of the learning curves of health technologies[J]. Health Technol Assess. 2001;5(12):1–79.
8. ALGARNI Y A, SAINI R S, VADDAMANU S K, et al. The impact of virtual reality simulation on dental education: A systematic review of learning outcomes and student engagement[J]. J Dent Educ. 2024;88(6):1–10.
9. VAN MERRIËNBOER J J G, SWELLER J. Cognitive load theory in health professional education: design principles and strategies[J]. Med Educ. 2010;44(1):85–93.
10. MATUSCHEK H, KLIEGL R, VASISHTH S, et al. Balancing Type I error and power in linear mixed models[J]. J Mem Lang. 2017;94:305–15.

# Figures

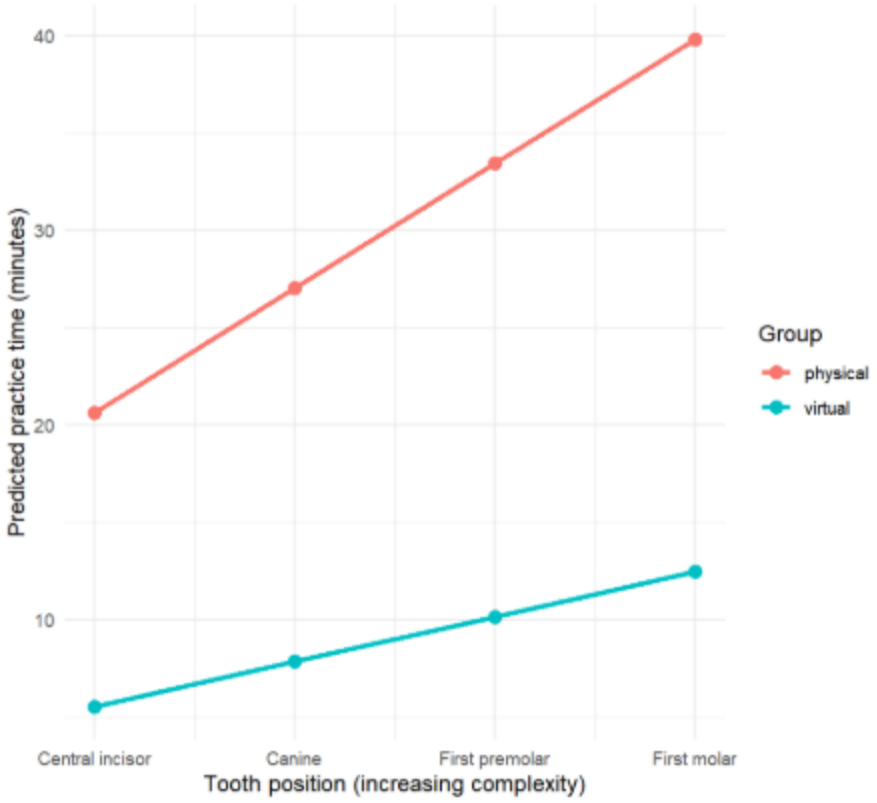



**Figure 1**

Predicted learning curves from the mixed-effects model

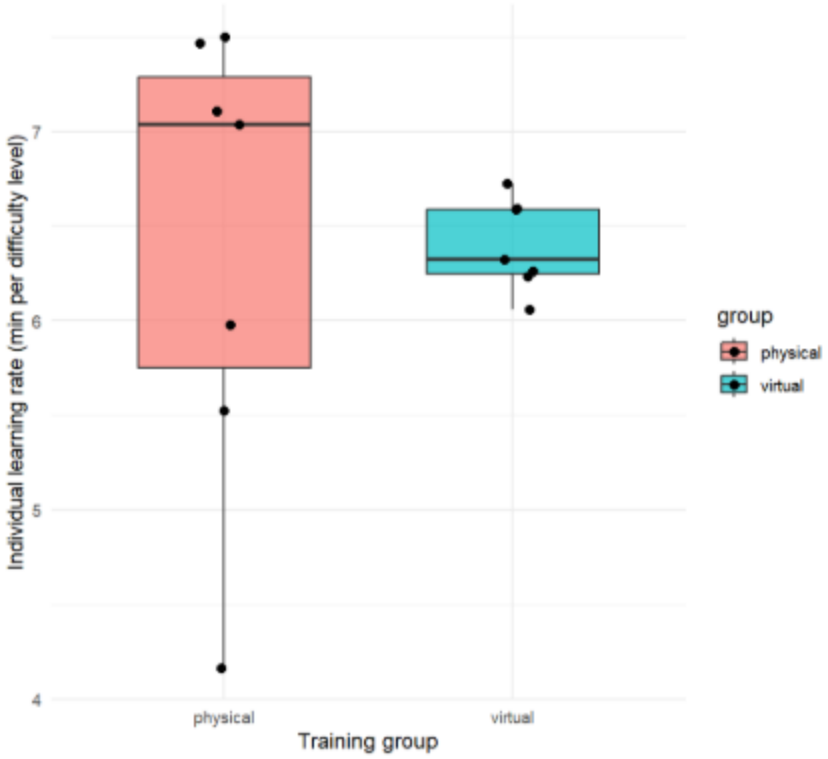



**Figure 2**

Boxplot of individual learning rates by training group