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Integrating 3D digital anatomy applications into Team-Based Learning (TBL): Effects on nursing students' self-directed learning and TBL experiences

Pelin Ismailoglu[1], Aylin Akca Sumengen[2]

[1]*Recep Tayyip Erdoğan University, Faculty of Medicine, Department of Anatomy, Rize, Türkiye*
[2]*The University of Alabama, Capstone College of Nursing, Tuscaloosa, AL, USA*

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Abstract

The purpose of this study is to examine the effect of supporting the Team-Based Learning (TBL) approach with three-dimensional (3D) digital anatomy applications on nursing students' knowledge level, self-directed learning, and team-based learning experiences. This study was conducted using a prospective, two-group, comparative post-test–only study design. The research sample consisted of 81 nursing students, divided into two groups: a control group (n = 42) that used only TBL and an experimental group (n = 39) that used TBL+3D digital anatomy applications. Data collection tools included a demographic information form, a post-test knowledge exam, the Self-Directed Learning Scale (SDLS), and the Turkish version of the Team-Based Learning Student Assessment Inventory (TBL-SAI-TR). The experimental group demonstrated significantly higher post-test knowledge scores and self-directed learning levels compared with the control group (U = 444.50, p < .001; and U = 1039.0, p = .037, respectively). Similarly, TBL-SAI-TR responsibility subscale scores showed a significant difference in favor of the experimental group (U = 1039.0, p = .036). Correlation analyses revealed moderate positive relationships between self-directed learning and TBL responsibility (r = .386, p < .001) and total TBL experience (r = .303, p = .006). Post-test knowledge scores showed weak-moderate negative correlations with TBL preference (r = -.297, p = .007) and total TBL score (r = -.319, p = .004). The findings indicate that supporting the TBL approach with 3D digital anatomy applications strengthens self-directed learning and the sense of responsibility in nursing students and has a positive effect on their learning experiences. These results reveal that integrating digital learning tools with active learning-based approaches has significant potential in nursing education, though the post-test only design requires findings to be interpreted with caution.

Keywords: Team-based learning, anatomy education, nursing education, self-directed learning, three-dimensional digital anatomy, active learning

Introduction

Anatomy education is fundamental to nursing students' clinical decision-making, acting as a key factor in patient safety through professional competence and correct practice [1,2]. However, anatomy is typically considered a challenging subject by nursing students because of its dense content, complex terminology, and the requirement to understand spatial relationships between anatomical structures and clinical practice [1,3]. Successful learning of this complex subject necessitates advanced spatial visualization skills. These skills require students to mentally convert two-dimensional text and visual information into three-dimensional models [4].

Two-dimensional images and text-based explanations are the mainstays of traditional anatomy education, but they create significant cognitive difficulties for students in understanding the spatial relationships of anatomical structures. The use of three-dimensional digital anatomy models as an effective pedagogical tool is therefore recommended to overcome this limitation [3]. However, traditional passive teaching methods do not sufficiently support this transformation, leading students to superficial memorization rather than deep understanding [1,3]. The literature frequently reports that such approaches may be insufficient in supporting knowledge retention and its integration into clinical reasoning processes [5,6]. Increasingly, student-

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Corresponding Author: Pelin Ismailoglu, Recep Tayyip Erdoğan University, Faculty of Medicine, Department of Anatomy, Rize, Türkiye
Email: pelinismailoglu@yahoo.com

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centered, active learning strategies such as Team-Based Learning (TBL) are being incorporated into nursing curricula to address these challenges [7,8]. The TBL method is defined as an approach that not only improves students' academic performance but also develops self-directed learning skills and a sense of individual responsibility [4,9]. Despite these strengths, evidence suggests that in content-heavy and spatially complex disciplines such as anatomy, the effectiveness of TBL may depend on whether the approach is supported by instructional tools that facilitate visualization and knowledge consolidation [1,3,10,11].

In digital learning environments, 3D digital anatomy applications offer valuable cognitive support for visualizing complex anatomical structures [3,10]. The three-dimensional presentation of organs and tissues facilitates students' mental structuring of anatomical structures in a holistic manner; in this respect, 3D anatomy models are reported to be more effective than traditional two-dimensional teaching methods in terms of comprehension level and class participation [3]. Integrating the TBL technique with 3D digital tools can make students' pre-class preparation processes more visible and structured, thereby increasing the level of responsibility they feel towards their teams [3,11]. Previous research has demonstrated moderate positive associations between self-directed learning and perceived responsibility within TBL environments [12]. In addition, technology-supported active learning settings have been shown to facilitate students' access to learning resources and support their ability to construct knowledge independently [10,13]. Crucially, the successful integration of these tools also depends heavily on the nursing students' technology readiness. Recent studies highlight that a high level of digital readiness, defined as the motivation and competence to use technology, is a significant predictor of academic achievement and successful adaptation to digital learning environments [14,15]. Students with higher technology readiness can engage more effectively with these platforms, whereas a lack of readiness can create a cognitive barrier, limiting the potential benefits of the technology [14].

This study aimed to examine whether integrating 3D digital anatomy applications into TBL enhances nursing students' knowledge acquisition, self-directed learning, and perceptions of the TBL experience. This study addressed the following research questions:

1. Whether post-test anatomy knowledge differed between students receiving TBL supported by 3D digital anatomy applications and those receiving TBL alone;
2. Whether self-directed learning levels differed between groups;
3. Whether perceptions of team-based learning experiences differed between groups; and
4. How self-directed learning, team-based learning dimensions, and post-test knowledge scores were related.

Material and Methods

This study was conducted as a single-center, prospective, two-group comparative study based solely on post-test measurements. For the purposes of the study, nursing students were divided into two groups. The experimental group received support from computer-assisted, 3D digital anatomy applications as part of the TBL approach, while the control group received anatomy education solely using the TBL method. This study was conducted and reported in accordance with the Transparent Reporting of Evaluations with Nonrandomized Designs (TREND) statement for nonrandomized and quasi-experimental study designs [16].

Eligibility Criteria: Eligible participants were first-year nursing students enrolled in the Anatomy course during the Fall semester of the 2025–2026 academic year. Students were required to agree to install and use a 3D digital anatomy application on their personal computer or tablet, actively participate in TBL sessions, and complete all study-related assessments. Participation was voluntary, and written informed consent was obtained from all participants prior to data collection. Students were excluded if they were absent on the day of the intervention, declined or were unable to use the 3D digital anatomy application due to technical reasons, did not actively participate in TBL sessions, or did not provide informed consent.

Study Setting and Participants: The study population consisted of all first-year nursing students enrolled in the Anatomy course (HEM117) at the Faculty of Health Sciences, Recep Tayyip Erdoğan University, during the Fall semester of the 2025–2026 academic year. The study sample included students who voluntarily agreed to participate and met the eligibility criteria. All eligible students registered for the course during the study period were invited to participate, and no additional sampling strategy was applied in order to maximize representativeness. This study was conducted in accordance with the Declaration of Helsinki and received ethical approval from the Recep Tayyip Erdoğan University Social and Human Sciences Ethics Committee (Date: 08.10.2025, Decision No: 2025/606).

Sample Size and Power Analysis: The required sample size was determined based on effect size estimates reported in a previous randomized controlled study comparing Team-Based Learning (TBL) with Interactive Lecture methods in health professions education [17]. In that study, mean knowledge scores were reported as 85.40 ± 13.06 in the intervention condition and 76.48 ± 16.19 in the comparison condition, with a statistically significant difference between groups ($p = .02$). Based on these values, the effect size was calculated as Cohen's $d = 0.892$. An a priori power analysis was conducted using G*Power version 3.1, assuming a two-tailed test, an alpha level of .05, and a statistical power of 95% ($1-\beta$). The analysis indicated that a minimum of 34 participants per group (total $N = 68$) would be required. To account for potential attrition (approximately 5–10%), the target sample size was increased, and the study aimed to include at least 36 students per group. Ultimately, a

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total of 81 students participated in the study (experimental n=39, control n=42), exceeding the minimum required sample size and ensuring adequate statistical power. Post-hoc power analysis was conducted using G*Power 3.1 based on the post-test knowledge scores of the experimental and control groups. The analysis was performed for the comparison of two independent groups using the observed effect size derived from group means and standard deviations (Cohen's d = 0.79), with a significance level of α = .05 and sample sizes of 39 and 42 students, respectively. The results indicated a high achieved statistical power ($1 - \beta$ = .97), demonstrating that the sample size was sufficient to detect group differences in post-test knowledge scores.

3D Digital Anatomy Application: A three-dimensional (3D) digital anatomy application was used as an instructional support tool in the experimental group. The application was freely accessible and could be installed on students' personal smartphones or tablets. It provided interactive, high-resolution, three-dimensional representations of human anatomical structures. Users were able to rotate, zoom, isolate, and layer anatomical components to examine structural relationships from multiple perspectives. It enables interactive, three-dimensional exploration of anatomical structures, with particular emphasis on detailed visualization of the musculoskeletal system [18]. In this study, the application was used specifically for the visualization of the musculoskeletal system, particularly the bones, joints, and muscles of the upper and lower extremities. Within the TBL sessions, the application was integrated to support students' examination of anatomical structures, facilitate discussion within teams, and reinforce course learning objectives through visual representation and peer interaction. The use of the 3D digital anatomy application was intended to support students' understanding of spatial relationships and to complement the active learning processes inherent to the TBL approach.

Data Collection Tools

Multiple data collection instruments were used to assess the study variables. These instruments were designed to comprehensively evaluate participants' sociodemographic and academic characteristics, self-directed learning levels, perceptions of team-based learning, and anatomy knowledge. Data were collected at the post-test stage following the educational intervention.

Sociodemographic Information Form: The sociodemographic information form was developed by the researchers based on relevant literature to collect data on students' demographic and academic characteristics. The form included an initial section addressing voluntary participation, in which students indicated their willingness to participate in the study using a Yes/No response format. The demographic section collected information on student identification number, age, and gender. In addition, students were asked to report their study-related behaviors using Yes/No responses, including whether they studied anatomy before class, after class, regularly, whether they took notes during class, and whether they reviewed course materials after class.

Team-Based Learning Student Assessment Instrument (TBL-SAI-TR): The Team-Based Learning Student Assessment Instrument (TBL-SAI) was originally developed by to evaluate students' perceptions of the team-based learning (TBL) approach [19]. The Turkish validity and reliability study of the instrument was conducted by [12] . As a result of psychometric analyses, the original 33-item scale was reduced to a 23-item version with a three-factor structure, which was confirmed through confirmatory factor analysis. The TBL-SAI-TR is rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), with higher scores indicating more positive perceptions and experiences related to team-based learning. The scale comprises three subscales: Accountability (5 items), Preference for Lecture or Team-Based Learning (9 items), and Student Satisfaction (9 items). Subscale scores are calculated by summing item responses, yielding possible score ranges of 5–25 for Accountability, 9–45 for Preference, and 9–45 for Student Satisfaction. The total scale score ranges from 23 to 115, with scores above 69 indicating a positive TBL experience. In the Turkish version, negatively worded items reflecting unfavorable perceptions of team-based learning are reverse-scored to ensure that higher scores consistently represent more positive evaluations. Specifically, items 7, 8, and 13 in the Preference for Lecture or Team-Based Learning subscale, and items 18 and 20 in the Student Satisfaction subscale are reverse-coded prior to analysis. In the Turkish validation study, the overall internal consistency of the TBL-SAI-TR was reported as Cronbach's α = .90, with subscale reliability coefficients of .78 for Accountability, .76 for Preference for Lecture or Team-Based Learning, and .88 for Student Satisfaction. Internal consistency in the current sample (n = 81) was acceptable, with Cronbach's alpha coefficients of .786 for Accountability, .710 for Preference, .784 for Student Satisfaction, and .745 for the total scale score. In the present study, the TBL-SAI-TR was administered only at the post-test stage.

Self-Directed Learning Scale (SDLS): The Self-Directed Learning Scale (SDLS) was used to assess students' levels of self-directed learning. The scale was developed by [20] and consists of 10 items with a unidimensional structure. Responses are rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Total scores range from 10 to 50, with higher scores indicating higher levels of self-directed learning. The Turkish validity and reliability study of the scale was conducted by [21], who reported a Cronbach's alpha coefficient of .85 for the Turkish version. In the present study, the SDLS was administered at the post-test stage only, and the internal consistency of the scale was found to be acceptable in the current sample (Cronbach's α = .753).

Anatomy Knowledge Test: To assess students' knowledge levels at the end of the course, an anatomy knowledge test developed by the researchers in line with the relevant literature was used as a post-test [22]. The test consists of 25 questions based on three-dimensional visual materials covering the relevant course content. The instrument was designed to evaluate students' cognitive learning outcomes and their ability to recognize and interpret anatomical structures through visual representations.

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Intervention Procedures: The data collection process was carried out as part of a single training session and in accordance with the research design. The application was carried out in the fifth week of the term, after the relevant theoretical topics of the anatomy lesson had been completed. The entire process was initiated after ethical committee approval and institutional permission were obtained, and written informed consent was obtained from the students. To ensure the standardisation of the application, the training sessions for the experimental and control groups were conducted in two adjacent classrooms, simultaneously and under similar physical conditions. On the day of the application, all students were given oral and written information about the purpose, scope and application process of the study; students who signed the informed consent form were included in the study. Participants were divided into two groups according to a pre-determined group allocation plan: the experimental group, which was supported by TBL + 3D digital anatomy applications; and the control group, which received anatomy education using only the TBL method. Students who did not participate in the study or did not meet the inclusion criteria were offered the same course content on a different day and at a different time using traditional teaching methods to ensure that they did not miss out on any learning outcomes. The students in the experimental group were organised into small teams and, during the TBL-based training session, worked on the relevant anatomy topics using three-dimensional digital anatomy applications on their personal computers or tablets. The teams examined the anatomical structures' positions, relationships and functions on 3D visuals, in line with the learning objectives set by the course instructor. They had the opportunity to apply their knowledge of information structuring and self-regulation by using digital materials in discussion and analysis processes. Meanwhile, the control group students were organised into small teams and worked through the same educational content using the TBL method, without the use of three-dimensional digital materials, under the guidance of the teaching staff and with printed and two-dimensional visual materials. The training sessions for both groups were conducted simultaneously and lasted approximately 60 minutes. After the educational sessions had finished, both groups were given the TBL-SAI-TR, SDLS and anatomy knowledge evaluation form; approximately 60 minutes were allocated for the final test. After the data collection process was completed, access to the three-dimensional digital anatomy application was provided to the control group students in accordance with ethical principles, and an applied evaluation session was conducted with the participation of both groups on the same content at the end of the lesson. This additional session was not included in the research data and was organised solely for educational purposes. Additionally, after the application, both the experimental and control groups were given access to three-dimensional digital anatomy materials for approximately one week, to allow for individual study and revision.

Statistical Analysis: Study data were collected online using Google Forms. Following completion of data collection, all responses were exported to Microsoft Excel, personal identifiers were removed to ensure anonymity, and the dataset was imported into IBM SPSS Statistics version 27.0 for analysis. After data coding and cleaning procedures were completed, statistical analyses were conducted. Descriptive statistics were calculated to summarize participants' sociodemographic characteristics, study-related learning behaviors, and outcome measures, including frequencies, percentages, means, and standard deviations. Baseline equivalence between the experimental (TBL + 3D digital anatomy) and control (TBL only) groups was assessed by comparing demographic variables and study-related behaviors with the Mann-Whitney U test. Data distribution was examined using the Shapiro–Wilk test, along with assessments of skewness and kurtosis. As the assumption of normality was violated, nonparametric statistical methods were employed. Baseline group comparisons and between-group differences in post-test outcomes were analyzed using two-tailed Mann–Whitney U tests. Between-group differences in self-directed learning, assessed using the SDLS, and team-based learning perceptions, assessed using the TBL-SAI-TR and its subscales, as well as post-test knowledge scores, were evaluated using Mann–Whitney U tests. For group comparisons, median values and mean rank statistics were reported. Associations among SDLS, TBL-SAI-TR subscales and total score, and post-test knowledge scores were examined using Spearman's rank-order correlation analyses. In addition, associations between students' study-related learning behaviors (studying before class, studying after class, regular studying, note-taking during class, and reviewing course materials after class) and self-directed learning levels were evaluated using Mann–Whitney U tests. All statistical analyses were conducted using a two-tailed significance level of $p < .05$.

Results

Descriptive statistics were computed to summarize participants' demographic characteristics, study-related behaviors, and outcome variables. The majority of participants were female (n = 64, 79.01%). Most students reported studying anatomy before class (n = 56, 69.14%) and after class (n = 72, 88.89%). Slightly more than half of the participants indicated that they did not study anatomy regularly (n = 43, 53.09%). A large proportion of students reported taking notes during class (n = 75, 92.59%) and reviewing course-related materials after class (n = 71, 87.65%). Participants' mean age was 19.10 years (SD = 1.47). Examination of distributional properties indicated that age was positively skewed (skewness = 2.22) with high kurtosis (7.70), suggesting a deviation from normality. The mean post-test total score was 20.64 (SD = 4.43). The distribution of post-test scores demonstrated negative skewness (skewness = −2.32) and elevated kurtosis (6.10), indicating a non-normal distribution characterized by potential outliers. Baseline group comparisons were conducted to assess the equivalence of the experimental and control groups. Given the non-normal distribution of several variables, baseline differences in demographic characteristics and study-related behaviors were evaluated using Mann–Whitney U tests. The results indicated that the groups did not differ significantly with respect to pre-class studying, post-class studying, regular studying habits, note-taking during class, or reviewing course materials after class (all $p > .05$). However, a significant difference was observed in gender distribution between groups ($U = 528.0$, $p < .001$) Descriptive statistics were also calculated for the primary outcome measures. The mean self-directed learning score (SDLS) was 38.19 (SD = 4.86), with skewness (0.27) and kurtosis (0.81) values indicating an approximately symmetric distribution. For the TBL-SAI-TR, the mean scores were 18.95 (SD = 3.09) for Accountability, 33.91 (SD = 3.86) for Preference for Lecture or Team-Based Learning, 35.52 (SD = 6.17) for Student Satisfaction, and 88.38 (SD = 10.94) for the total TBL-SAI-TR score. As the mean total score exceeded the established cut-off value of 69, these findings indicate that students overall reported a positive experience with team-based learning. Skewness and kurtosis values for these scales ranged between −1.06 and 1.00 for skewness and between −0.19 and 2.18 for kurtosis, suggesting no extreme deviations from normality at the descriptive level. Detailed descriptive statistics are presented in Table 1.

Table 1. Participant characteristics and baseline comparisons

Variable	Category	n	%	Mann–Whitney U	p
Gender	Female	64	79.01	528.0	**<.001**
	Male	17	20.99		
Study anatomy before class	Yes	56	69.14	736.5	.330
	No	25	30.86		
Study anatomy after class	Yes	72	88.89	724.5	.101
	No	9	11.11		
Study anatomy regularly	Yes	38	46.91	628.5	.137
	No	43	53.09		
Take notes during class	Yes	75	92.59	742.5	.111
	No	6	7.41		
Review course materials after class	Yes	71	87.65	811.5	.901
	No	10	12.35		
Variable	**Mean ± SD**	**Skewness (S)**	**Kurtosis (K)**	**Mann–Whitney U**	**p**
Age (years)	19.10 ± 1.47	2.22	7.70	655.0	.100
Post-test total score	20.64 ± 4.43	-2.32	6.10	-	-
SDLS	38.19 ± 4.86	0.27	0.81	-	-
TBL-SAI-TR accountability	18.95 ± 3.09	-0.48	-0.19	-	-
TBL-SAI-TR preference	33.91 ± 3.86	0.01	1.00	-	-
TBL-SAI-TR satisfaction	35.52 ± 6.17	-1.06	1.81	-	-
TBL-SAI-TR total	88.38 ± 10.94	-0.80	2.18	-	-

SD: Standard Deviation, SDLS: Self-Directed Learning, TBL-SAI-TR: Team-Based Learning Student Assessment Instrument Turkish Version; Note*:* Baseline group comparisons were conducted using Mann–Whitney U tests

To assess the normality of the data, Shapiro–Wilk tests were conducted to evaluate whether the distributions of the study variables deviated from a normal distribution. The results indicated that the data were not normally distributed, as significant departures from normality were observed across all examined variables ($p < .05$). Specifically, significant departures from normality were observed for age ($W = 0.76$, $p < .001$) and post-test total score ($W = 0.75$, $p < .001$). Similarly, the Self-Directed Learning Scale total score showed a significant deviation from normality ($W = 0.95$, $p = .005$). For the TBL-SAI-TR, significant non-normal distributions were identified for the Accountability ($W = 0.96$, $p = .012$), Preference for Lecture or Team-Based Learning ($W = 0.95$, $p = .005$), Student Satisfaction ($W = 0.89$, $p < .001$), and the total TBL-SAI-TR score ($W = 0.94$, $p = .001$). As the assumption of normality was violated across variables, nonparametric statistical tests were used for subsequent inferential and comparative analyses.

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Group differences between the experimental (TBL + 3D) and control (TBL only) conditions were examined using two-tailed Mann–Whitney U tests (experimental n = 39; control n = 42). A statistically significant difference was observed for self-directed learning, indicating that students who received TBL supported by 3D digital anatomy applications demonstrated higher self-directed learning levels than those who received TBL alone (U = 1039, z = −2.09, p = .037). A similar pattern was found for the Accountability subscale of the TBL-SAI-TR, indicating greater perceived accountability among students in the experimental group (U = 1039, z = −2.09, p = .036). In contrast, no statistically significant differences were found for Preference for Lecture or Team-Based Learning, Student Satisfaction, or the total TBL-SAI-TR score, indicating that the addition of 3D digital anatomy applications did not lead to differential outcomes in these dimensions of the TBL experience (all p > .05). In addition, post-test knowledge scores were significantly higher in the experimental group than in the control group, indicating superior knowledge acquisition when TBL was supported by 3D digital anatomy applications (U = 444.50, z = −3.57, p < .001). Overall, these findings suggest that integrating 3D digital anatomy applications into TBL primarily enhances students' self-directed learning and accountability, rather than their overall satisfaction or learning preferences (Table 2).

Table 2. Differences in learning and team-based learning outcomes by study group

Variable	Experimental MR (n = 39)	Control MR (n = 42)	U	z	p
SDLS	46.64	35.76	1039.00	−2.09	**.037***
TBL-SAI-TR total	39.73	42.18	769.50	−0.47	.639
TBL-SAI-TR accountability	46.64	35.76	1039.00	−2.09	**.036***
TBL-SAI-TR preference	37.17	44.56	669.50	−1.42	.154
TBL-SAI-TR satisfaction	38.60	43.23	725.50	−0.90	.368
Post-test knowledge score	50.60	32.08	444.50	−3.57	**< .001****

SDLS: Self-Directed Learning, TBL-SAI-TR: Team-Based Learning Student Assessment Instrument Turkish Version, MR: Mean Rank; *p < .05; **p<.001

Spearman correlation analyses were conducted to examine associations among self-directed learning, team-based learning dimensions, and post-test knowledge scores. Self-directed learning was moderately and positively correlated with TBL Accountability (ρ = .386, p < .001) and with the overall TBL-SAI score (ρ = .303, p = .006), indicating that higher self-directed learning was associated with stronger perceptions of responsibility and overall engagement within the TBL environment. Smaller but significant associations were also observed between self-directed learning and TBL Preference (ρ = .234, p = .036), whereas the association with TBL Satisfaction was not statistically significant (ρ = .162, p = .149). Strong positive correlations were observed among TBL dimensions, particularly between TBL Total and TBL Satisfaction (ρ = .900, p < .001), and between TBL Total and TBL Preference (ρ = .807, p < .001), reflecting substantial overlap among TBL experience components. In contrast, post-test knowledge scores were not significantly correlated with self-directed learning (ρ = .022, p = .842) or accountability (ρ = −.013, p = .906), but showed small-to-moderate negative correlations with TBL Preference (ρ = −.297, p = .007), TBL Satisfaction (ρ = −.306, p = .005), and TBL Total (ρ = −.319, p = .004). These findings suggest that higher post-test performance was not directly associated with greater perceived enjoyment or preference for TBL, highlighting a distinction between cognitive performance and learning experience perceptions (Table 3).

Table 3. Spearman correlations among SDLS, TBL-SAI-TR, and post-test knowledge scores

Variable	1	2	3	4	5	6
1. SDLS	—	**.386****	**.234***	.162	**.303****	.022
2. TBL-SAI-TR accountability		—	**.278***	**.356****	**.584****	−.013
3. TBL-SAI-TR preference			—	**.686****	**.807****	**−.297****
4. TBL-SAI-TR satisfaction				—	**.900****	**−.306****
5. TBL-SAI-TR total					—	**−.319****
6. Post-test knowledge score						—

Values are Spearman's rho (ρ); SDLS: Self-Directed Learning; n = 81; *p < .05; **p<.001

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To better understand individual differences in self-directed learning, associations between students' study-related behaviors and self-directed learning were examined. Students who reported studying anatomy before class, studying after class, studying regularly, and reviewing course materials after class demonstrated significantly higher self-directed learning scores compared with those who did not engage in these behaviors (all $p < .01$). In contrast, note-taking during class was not significantly associated with self-directed learning levels ($p = .103$). Overall, these findings suggest that out-of-class study behaviors and regular engagement with course materials are more strongly associated with self-directed learning than in-class note-taking alone (Table 4).

Table 4. Associations between study behaviors and self-directed learning (SDLS)

Study behavior	Yes MR	No MR	U	z	p
Study anatomy before class	45.77	30.32	433.00	−2.75	**.006***
Study anatomy after class	43.78	18.72	123.50	−3.03	**.002***
Study anatomy regularly	49.20	33.76	505.50	−2.96	**.003***
Take notes during class	42.20	26.00	135.00	−1.63	.103
Review course material after class	43.78	21.25	157.50	−2.85	**.004***

MR: mean rank; *p < .05

Discussion

This study examined the effects of integrating a three-dimensional (3D) digital anatomy application into team-based learning (TBL) on nursing students' anatomy knowledge, self-directed learning, and perceptions of the TBL experience. The findings indicate that supporting TBL with a 3D digital anatomy tool was associated with higher post-test knowledge scores, greater self-directed learning, and increased perceived accountability. In contrast, students' preferences for TBL and their satisfaction with the learning experience did not differ between groups, although both groups reported generally positive perceptions of TBL. These results suggest that the added value of 3D digital tools within TBL may be more pronounced for cognitive and learning-process outcomes than for affective evaluations of the learning experience.

Students in the experimental group (TBL + 3D) achieved significantly higher post-test knowledge scores than those in the control group, indicating that the integration of three-dimensional visual supports may enhance the cognitive impact of TBL in anatomy education. Anatomy learning requires the integration of visual memory and spatial intelligence, both of which have been shown to be strongly associated with academic achievement in anatomy-related courses [23]. Three-dimensional models facilitate learners' ability to construct and manipulate mental representations of anatomical structures, thereby supporting deeper conceptual understanding. Recent evidence also suggests that immersive and interactive 3D visualization environments improve learning efficiency in anatomy by reducing the cognitive burden associated with translating two-dimensional information into spatial knowledge [3]. In addition, the use of visual learning materials, such as visual worksheets, has been shown to improve study behaviors and academic performance in anatomy education by promoting active engagement with visual content [24]. From a cognitive perspective, visually enriched learning environments may support more effective cognitive strategies by guiding learners' attention and facilitating efficient information processing, which is particularly relevant in complex and visually demanding subjects such as anatomy [25]. Taken together, these findings support the notion that combining active learning approaches such as TBL with visualization-based digital tools can strengthen students' cognitive learning outcomes in anatomy. Similarly, recent research has shown that visualization-based instructional materials can positively influence both learning outcomes and study behaviors in anatomy education [24]. For example, the use of structured visual worksheets in dental anatomy education has been reported to significantly improve students' short-term academic performance and promote more conscious and regular study habits [24]. These findings suggest that visually supported instructional strategies can enhance students' engagement with anatomical content and facilitate more effective learning processes. In this context, integrating visualization-based digital tools, such as 3D digital anatomy applications, within active learning environments like TBL may provide additional cognitive support for students learning complex anatomical structures.

Students in the experimental group demonstrated significantly higher levels of self-directed learning than those in the TBL-only group. This suggests that integrating three-dimensional digital tools into TBL may help students take ownership of their learning and regulate their processes more effectively. Technology-enhanced learning environments provide learners with continuous and flexible access to educational resources, enabling independent exploration of content and engagement in learning activities outside of scheduled class time [26]. In anatomy education, for example, interactive 3D models allow students to actively manipulate and examine anatomical

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structures, encouraging exploratory learning behaviours and fostering greater learner autonomy [3]. From this perspective, technology-supported TBL environments appear to contribute to both content acquisition and the development of learning skills such as self-regulation, responsibility and active engagement. The present findings support the idea that digital innovations, when meaningfully integrated into active learning approaches, can help students transition from passive recipients of information to self-directed, strategic learners. However, it is important to recognize that students' successful adaptation to digital learning environments and their subsequent educational outcomes are multifaceted phenomena. Evidence suggests that these outcomes can be significantly influenced by a variety of individual attributes and demographic factors, including gender differences [15]. The sociodemographic characteristics of the sample, particularly gender distribution, may offer additional context for these findings. In the present study, a significant difference in gender distribution between groups was observed, with a predominantly female sample. While this reflects the traditional demographic profile of nursing programs, it is worth noting that gender can play a role in digital learning contexts. Recent investigations have highlighted a heightened inclination, motivation, and readiness towards e-learning and digital educational tools among female nursing students [15,27]. Additionally, gender disparities in online comfort and motivation have been identified as key factors influencing e-learning preparedness [28]. Therefore, rather than being merely a confounding variable, the predominantly female demographic in this study might synergize with the digital nature of the intervention. The higher self-directed learning and knowledge scores observed in the experimental group could be partially facilitated by this underlying technological readiness and positive attitude towards digital tools frequently reported among female nursing students.

A significant difference was observed in favor of the experimental group on the accountability subscale of the TBL-SAI-TR, suggesting that the integration of three-dimensional digital anatomy applications within TBL may strengthen students' sense of individual responsibility toward their teams. Technology-enhanced learning environments have been shown to support learner engagement by making learning tasks more concrete and increasing students' awareness of their contributions to collaborative work [26]. In the context of anatomy education, interactive 3D visualisation tools allow learners to actively explore and explain anatomical relationships, which may encourage them to prepare adequately and participate meaningfully in team discussions. Evidence from a meta-analysis indicates that 3D visualisation technologies contribute to improved engagement in learning and more active involvement in anatomy learning processes, particularly when learners are required to interact with visual content rather than observe it passively [29]. Similarly, pilot studies evaluating the use of 3D anatomy applications as supplementary learning tools have reported that such applications encourage students to take greater responsibility for their own learning by supporting self-paced exploration and preparation outside formal classes [30]. Taken together, these findings suggest that integrating 3D digital anatomy tools into TBL may enhance accountability by promoting preparatory behaviours and reinforcing students' perceptions of responsibility towards their teams. However, these positive findings must be interpreted in light of the study's post-test-only design. Because pre-training measurements of anatomy knowledge and self-directed learning skills were not conducted, the initial equivalence of the groups remains unknown. This introduces a potential selection bias; it is possible that the higher knowledge and self-directed learning scores observed in the experimental group were partially influenced by pre-existing differences in academic ability, baseline self-directed learning capacity, or inherent motivation, rather than solely the 3D digital anatomy intervention. While the groups were similar in their reported study behaviors, this unmeasured baseline variance requires a transparent and cautious interpretation of the intervention's precise impact.

Despite both groups reporting positive TBL experiences, as reflected by total scores exceeding the established cut-off value, no significant differences were observed between the experimental and control groups with respect to TBL preference, student satisfaction, or total TBL-SAI-TR scores. This finding is consistent with prior research indicating that TBL is generally well received by nursing students as a pedagogical approach and tends to yield favourable perceptions regardless of specific instructional enhancements [31]. Evidence from a systematic review and meta-analysis further suggests that, while TBL is effective in improving educational quality and learning outcomes, its impact on student satisfaction and preference is not always proportional to gains in cognitive or behavioural outcomes [32]. In this context, the absence of group differences may reflect a ceiling effect, whereby students' baseline perceptions of TBL were already high, limiting the potential for additional tools to enhance satisfaction further. Furthermore, evaluations of the early stages of TBL implementation have shown that improvements in accountability and engagement may emerge before changes in students' evaluations of the affective aspects of the learning experience [11]. Taken together, these findings suggest that integrating three-dimensional digital tools into TBL primarily influences how students learn and engage with content rather than how much they enjoy or prefer the instructional approach — particularly when TBL itself is already perceived positively.

Correlation analyses revealed moderate positive relationships between self-directed learning and both the accountability subscale and the total team-based learning (TBL) experience. This suggests that students with stronger self-directed learning abilities perceive greater responsibility and engagement within TBL environments. This finding aligns with evidence indicating that self-directed learning in nursing students is closely associated with proactive learning behaviours, taking responsibility for one's own learning, and actively participating,

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particularly towards the end of their undergraduate education [33]. In TBL contexts, structured team activities require learners to prepare independently and contribute meaningfully to group processes, creating conditions that naturally align with self-directed learning skills. Studies examining the implementation of TBL in anatomy education have also emphasised that team-based structures encourage students to take responsibility for their own preparation and participation, thereby reinforcing accountability for learning rather than passive involvement [34]. Furthermore, comparative research has demonstrated that active learning approaches, such as TBL, promote greater engagement and learning-related behaviours than interactive lecture formats, despite inconsistent gains in affective outcomes, such as enjoyment or preference [17]. Taken together, these findings suggest that self-directed learning is more strongly linked to taking responsibility and active engagement within TBL than to students' subjective satisfaction. This underscores the distinction between learning competencies and affective perceptions of the learning experience.

Correlation analyses revealed weak-to-moderate negative relationships between post-test knowledge scores and students' perceptions of TBL preference, satisfaction, and overall TBL experience. This finding suggests that higher academic achievement within a TBL environment may not necessarily coincide with more favorable affective evaluations of the learning process. Similar patterns have been reported in studies examining the effects of TBL on learning behaviors, where increased cognitive engagement and responsibility were associated with greater learning demands rather than heightened enjoyment [9]. In team-based learning contexts, students are required to engage in pre-class preparation, active problem-solving, and peer discussion, all of which may increase cognitive effort during the learning process. From the perspective of educational psychology, this inverse relationship between knowledge acquisition and student satisfaction can be explained through the concepts of cognitive load and productive failure. According to Cognitive Load Theory, active learning environments, such as TBL, require learners to process, synthesize, and immediately apply new information, resulting in a higher intrinsic and meaningful cognitive load compared to passive lectures [35]. While this intense cognitive effort is highly effective for deep learning, it is often perceived by students as a learning pain or struggle, leading to temporary dissatisfaction, a phenomenon Kapur (2016) conceptualizes as productive failure [36]. Furthermore, recent literature supports this psychological paradigm. Traditional lecture formats place students in a passive comfort zone; thus, shifting to TBL requires a disruptive transition in the knowledge-transfer paradigm, increasing student accountability and occasionally generating resistance [37]. Notably, these findings closely parallel a 2021 study by Whillier et al., which introduced TBL to an undergraduate neuroanatomy course with 204 students [38]. Similar to our study, they observed that the intensive cognitive demands and the shift towards an active, practice-based paradigm did not improve overall satisfaction and even generated student resistance. Experiential learning theories also acknowledge that encountering discomfort and cognitive struggle is often a necessary phase when transforming learners' foundational skills and competencies [39]. Therefore, while more challenging and cognitively demanding learning experiences are effective in promoting knowledge acquisition, they may be perceived as less enjoyable by some students. This underscores the importance of interpreting student satisfaction alongside learning effectiveness rather than using it as a proxy for learning effectiveness. Analysis of study-related behaviours revealed that students who engaged in pre- and post-class studying, maintained regular study routines and reviewed course materials demonstrated significantly higher levels of self-directed learning. In contrast, in-class note-taking was not associated with self-directed learning. This pattern is consistent with prior research indicating that team-based learning primarily influences behaviours relating to preparation, review and sustained engagement with learning materials outside the classroom, rather than passive in-class activities [9]. In TBL environments, responsibility for learning shifts towards the learner, meaning that participation in team activities depends on students' willingness to prepare and manage their learning outside of scheduled class time. Furthermore, the use of structured visual learning tools has been shown to promote effective study behaviours and academic performance by encouraging active interaction with learning content and facilitating planned review processes [24]. Taken together, these findings suggest that self-directed learning is more closely linked to intentional, active and planned behaviours outside the classroom than to routine or passive behaviours during class. This highlights the importance of designing learning environments that explicitly support and reinforce such behaviours.

Overall, the findings of this study suggest that incorporating three-dimensional digital anatomy applications into team-based learning adds value, particularly in areas related to learning quality rather than enjoyment. Using 3D digital tools in TBL was associated with improvements in knowledge acquisition, self-directed learning and perceptions of individual responsibility, demonstrating their positive impact on cognitive and learning outcomes. However, these benefits did not extend to higher levels of student satisfaction or a greater preference for TBL; satisfaction and preference remained high across both groups. This suggests that, when students already have positive perceptions of active learning, integrating additional digital resources can enhance their learning and engagement without necessarily altering their perception of the learning experience as enjoyable or preferable.

Conclusion

This study demonstrates that supporting TBL with 3D digital anatomy applications has a meaningful impact on the learning outcomes of nursing students. The findings show that TBL supported by 3D digital anatomy applications strengthens students' knowledge levels and self-directed learning skills; however, satisfaction with and learning preferences for TBL were

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high in both groups and did not result in a statistically significant difference between the groups. The fact that the experimental group obtained higher information scores suggests that 3D digital anatomy applications facilitate the learning of anatomy topics and support cognitive learning in the TBL process. Furthermore, the positive relationship between self-regulated learning and the TBL responsibility sub-dimension suggests that technology-supported TBL environments can increase students' sense of individual responsibility and active participation in the learning process. Conversely, the weak–moderate negative relationships between information level and TBL satisfaction and learning preference suggest that academic success and perceptions of the learning experience do not always progress in parallel. This finding suggests that TBL and technology integration may increase cognitive gains in learning outcomes while not necessarily affecting students' subjective learning experiences to the same extent. Overall, the findings of this study suggest that integrating active learning approaches based on TBL with digital learning tools in nursing education has significant potential, particularly with regard to key educational objectives such as self-directed learning and knowledge acquisition. Future studies incorporating pre-test–post-test designs, long-term follow-up measurements, and interventions in different subject areas will contribute to a more comprehensive evaluation of the effectiveness of these integrated learning approaches. While these findings are highly promising, the post-test-only nature of the study suggests they should be interpreted with caution. Therefore, future studies incorporating pre-test–post-test designs, long-term follow-up measurements, and interventions in different subject areas will contribute to a more comprehensive evaluation of the effectiveness of these integrated learning approaches.

Limitations

Several limitations should be considered when interpreting these findings. First, this study used a single-center, two-group comparative post-test–only design, which limits causal inference and prevents evaluation of within-person change over time. Without baseline (pre-test) measures for anatomy knowledge, SDLS (Self-Directed Learning), and TBL-SAI-TR (Team-Based Learning Student Assessment Instrument Turkish Version) outcomes, it is not possible to determine whether observed between-group differences reflect intervention effects or pre-existing differences between groups. Second, group allocation was not randomized, raising the possibility of selection bias and unmeasured confounding. Although baseline equivalence was assessed for demographic and study-related behaviors and groups appeared similar on these observed variables, a significant imbalance in gender distribution was detected, and other potentially relevant characteristics (e.g., prior anatomy achievement, prior exposure to digital anatomy tools, general academic performance, technology readiness, learning styles, or baseline motivation) were not measured and therefore could not be controlled statistically. Third, outcomes were assessed immediately following the intervention and focused on short-term post-test performance and perceptions. The lack of follow-up measurement limits conclusions about the durability of knowledge gains and whether any improvements in self-directed learning or accountability are sustained over time or translate into longer-term educational outcomes (e.g., course grades, retention, or clinical application). Fourth, the intervention was implemented as a single standardized session within the course timeline. This dosage may not reflect typical curricular integration of 3D digital anatomy applications across multiple weeks. Similarly, variability in how students engaged with the 3D application (e.g., intensity, time-on-task, depth of exploration) was not objectively tracked; therefore, dose–response relationships could not be examined, and fidelity to the intended use of the application could not be verified. Finally, the overall sample size, while adequately powered for detecting group differences in post-test knowledge scores, may have been limited for detecting smaller effects on broader TBL experience dimensions (e.g., satisfaction or preference). The use of nonparametric analyses due to non-normal distributions also reduces efficiency relative to parametric alternatives.

Ethical Approval

This study was conducted in accordance with the Declaration of Helsinki and received ethical approval from the Recep Tayyip Erdoğan University Social and Human Sciences Ethics Committee (Date: 08.10.2025, Decision No: 2025/606)

Patient Consent

Written informed consent was obtained from all participants after they were fully informed about the procedures involved in the study. Participation was voluntary, and all participants were nursing students.

Conflict of Interest

The authors confirm the absence of any conflicts associated with this work.

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