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► To cite this version:

Yassine Yachou, Olivier Samson, Olivier Lasvergnas. Prospective comparative study on enhancing geometrical mental representation and anatomical learning in medical students through modeling clay as an assessment tool. *Anatomical Sciences Education*, 2024, 10.1002/ase.2404 . hal-04531757

HAL Id: hal-04531757

<https://hal.science/hal-04531757v1>

Submitted on 4 Apr 2024

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Prospective comparative study on enhancing geometrical mental representation and anatomical learning in medical students through modeling clay as an assessment tool

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Abstract

While traditional anatomy education often emphasizes passive learning and rote memorization, it seldom employs constructivist theories that focus on active, hands-on experiences for effective learning. This study tests the hypothesis that tactile experiences with modeling clay enhance geometric mental representation more effectively than verbal descriptions. We examine the potential of clay modeling to reflect and evaluate students' mental representation of anatomical structures. Utilizing a prospective randomized, open, blind endpoint (PROBE) design, we engaged 36 participants divided into three groups: blind, visually impaired, and a control group. The primary outcome measure was the difference between post-touch score and pre-touch score, which gauged the efficacy of tactile intervention in enhancing the participants' capacity to mentally reconstruct a well-designed anatomical fiction structure. Scoring was executed using a double-blind double-evaluation methodology, positioning clay model reconstruction as both an objective reliable assessment and a pedagogical tool. The analysis demonstrated a pronounced improvement in mental representation of anatomical structures, particularly in spatial comprehension and detailed textural discernment, with the mean score soaring from 47.81 pre-touch to 85.09 post-touch. Distinct cognitive processing adaptations were evident across groups, with the blind group excelling in tactile acuity and the visually impaired group showing the most significant gains in spatial understanding post-intervention (Cohen's $d=2.74$). The application of modeling clay as a tactile intervention tool can significantly improve the learning of anatomy among medical students. The study underscores the value of active, multisensory engagement and customized teaching strategies for effective anatomy education among this demographic.

KEYWORDS

assessment, mental representation, clay-based modeling, experiential learning, tactile engagement, multi-sensory engagement, visual impairments

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INTRODUCTION

Anatomy, a cornerstone of medical and paramedical education, poses significant challenges for students due to its complexity and extensive terminology, often leading to intimidation and reduced motivation.¹⁻³ A notable difficulty is bridging the gap between anatomical knowledge and its clinical application, crucial for appreciating the discipline's relevance in medical practice.⁴

Recent advances in medical education, such as problem-based learning (PBL), case-based learning (CBL), team-based learning (TBL), and direct patient contact, have transformed anatomy education. These methods emphasize active, engaging learning, enhancing critical thinking and problem-solving skills.⁵⁻⁸ Conversely, traditional teaching methods, mainly focusing on memorization, often lead to superficial understanding and fail to foster deep engagement.⁹⁻¹¹

However, the adoption of these modern educational methodologies faces significant barriers in developing countries, such as high professor-to-student ratios, limited infrastructure, and technological costs¹² (Sugand et al., 2010).¹³ These challenges call for a blended approach that combines traditional and modern techniques.⁴

Despite the known effectiveness of educational theories like Piaget's cognitive development¹⁴, Mayer's multimodal learning¹⁵, Ausubel's meaningful learning¹⁶, Bruner's discovery learning¹⁷, and Flavell's metacognition and socioconstructivism¹⁴, they are underutilized in anatomy teaching. Their integration could diversify teaching strategies, catering to different learning styles and enhancing comprehension. This gap is particularly significant in settings where innovative, feasible pedagogical approaches are needed to improve educational quality and accessibility, especially for visually impaired students.

Current anatomy assessment methods, such as oral exams and multiple-choice questions (MCQs), predominantly test memorization rather than understanding of anatomical structures. This highlights the need for assessment tools that evaluate spatial comprehension and mental representation, particularly for blind and visually impaired students.

Clay modeling has been identified as an effective active learning tool in anatomy education, though its impact varies. Studies have shown its benefits in enhancing understanding and engaging students, but its effectiveness depends on the implementation and student preferences¹⁸⁻²⁰ (Kooloos et al., 2014; Curlewis et al., 2020).^{21,22}

To investigate this, we will conduct a comparative study examining the differences in students' geometrical mental representations formed through verbal descriptions alone and those enhanced after a tactile interaction. This comparison will enable us to objectively observe the development and accuracy of mental representations, thereby evaluating the reliability of clay modeling as an assessment tool. If our study finds that verbal descriptions are insufficient for students to form accurate geometrical mental representations, it will validate clay modeling as a reliable assessment tool and also will strongly advocate for the necessity of experiential learning methods since verbal descriptions are insufficient. This could have

profound implications for teaching strategies, emphasizing the importance of tactile and interactive learning experiences in achieving a comprehensive understanding of geometrical and anatomical concepts.

By conducting this experiment, we aim to validate the assessment potential of clay modeling not only from an individual perspective but also by identifying patterns in mental representations across different groups. We hypothesize that by comparing these patterns between groups, as well as individually, we can uncover and address specific learning challenges characteristic of groups with unique cognitive processing styles. This approach underscores the potential utility of clay modeling as more than just an evaluation tool; it serves as a means to diagnose and understand distinct learning needs among groups. This is especially relevant for populations that may process information differently. Ultimately, such insights could lead to the development of more personalized and effective educational strategies, tailored to meet the varied cognitive needs of diverse learner groups, especially in resource-limited settings where implementing advanced teaching methodologies is challenging. Our focus is on creating cost-effective, accessible educational methods that maintain high educational quality, regardless of resource constraints.

METHODS

Our research utilizes a prospective randomized, open, blind endpoint (PROBE) design with three comparative groups. The primary outcome is to investigate the differences between groups, mainly through variations in clay model assessment scores before and after tactile interaction.

The experimental design of our study involves a four-step process, aimed at assessing the role of sensory inputs in anatomical understanding by analyzing the mental representation via the clay modeling reconstructions. Initially, participants, blindfolded for the whole steps to ensure reliance on non-visual cues, listen to an audio description of a fictitious anatomical structure. They then use clay to construct this structure based on the auditory information alone (pre-touch reconstruction). This is followed by a tactile interaction with an actual model of the structure, after which participants reconstruct the model in clay (post-touch reconstruction).

Our primary objective is to determine if there is a substantial difference between verbal description and tactile experience in refining the geometric mental representations of anatomical structures. If proven, it will substantiate clay modeling's role in accurately mirroring students' mental images of anatomy, hence advocating its use as an evaluation tool.

We hypothesize that mere verbal descriptions are insufficient for accurate mental representation of complex anatomical structures. We posit that tactile experience, specifically through clay modeling, will significantly enhance the precision of these mental reconstructions. Furthermore, we hypothesize that there will be no significant difference between the groups (blind, visually impaired, and control)

in terms of their ability to accurately reconstruct these structures post-tactile intervention.

Our study incorporates distinct methodological and statistical features to ensure scientific rigor and objectivity of the obtained results. First, we implement a double-blind design, where both participants and evaluators are unaware of the assigned groups, minimizing potential bias. Additionally, two independent evaluators assess participants' anatomical model reconstructions, ensuring reliability and eliminating individual assessment biases. Furthermore, our study includes a representative sample of visually impaired medical students, divided into visually impaired and blind groups, along with a control group, allowing for generalization of results to the target population. These features enhance the validity and applicability of our findings.

Study structure and participant selection

Selection and grouping

We include two distinct groups of visually impaired participants, either totally blind students or visually impaired with some visual capacity, permitting examination of differential impacts of pedagogical strategies. Moreover, a control group of non-medically trained, visually unimpaired individuals enables comparative effectiveness assessment of teaching methods.

The study included a total of 36 participants, categorized into three groups based on their visual abilities: visually impaired individuals ($n=21$), blind individuals ($n=7$), and a control group ($n=8$). The varying sample sizes within these groups should be acknowledged, as it may impact the generalizability of the findings (Figure 1).

In our study, the term "visually impaired" is used in line with the World Health Organization's categorization and specifically refers to students who have been legally recognized as having a disability. This classification is not just a medical condition but also a legal status in France that acknowledges their requirement for special educational needs. According to WHO, the boundary between low vision and blindness is set at a visual acuity of less than 1/20. Visual impairment is categorized into five levels. Categories I and II are typically referred to as low vision, which also encompasses terms like amblyopia or reduced vision. Categories III, IV, and V fall under the definition of blindness. A person is considered legally blind when their visual field is narrowed to less than 20 degrees in both eyes.

Inclusion criteria

To ensure the suitability of participants for this study, several inclusion criteria were established. First, participants needed to be at least 18 years old, ensuring their ability to provide informed consent. Additionally, participants were required to be physiotherapy students, as this would ensure they had a foundational understanding of anatomy and spatial concepts, which are relevant to the study

objectives. Adequate language comprehension was also necessary to ensure participants could understand the instructions and questionnaires used in the study. Furthermore, participants needed to demonstrate proficiency in manipulating modeling clay, as this skill was central to the study tasks. Lastly, participants were required to possess sufficient cognitive ability to comprehend the study instructions accurately and provide appropriate responses on the questionnaires.

Exclusion criteria

To maintain the integrity and validity of the study, certain exclusion criteria were applied. Participants with prior professional or artistic experience in sculpture or 3D geometry were excluded to minimize potential bias that could arise from their previous exposure to similar tasks. Individuals with intellectual and learning disabilities were also excluded, as these conditions could impact their ability to fully engage with and comprehend the study tasks. Additionally, participants with mental health issues or substance abuse problems were not included, as these factors could potentially affect their focus and performance. Individuals with neurological diseases or motor disorders that could impact their motor skills or sensory perception were also excluded. Furthermore, individuals with health problems that could hinder their full participation in the study activities were not included. Lastly, participants who had previously been involved in a similar experiment were excluded to ensure a fresh and unbiased experience for all participants.

The experimental procedure

AVH medical students with visual impairments were invited via email to participate, choosing from three possible dates. On arrival, the investigator provided an overview of the study objectives and protocol, excluding the mention of the second reconstruction.

The experimental procedure ensured that students participated individually to prevent any interaction or exchange of information. Each participant completed their session separately and was not allowed to communicate with other students who had not yet participated. This measure minimized potential bias, ensuring that each student's performance was independent and not influenced by others' experiences or insights.

Each participant received a unique code to maintain anonymity and signed a consent form. They were then given equal amounts of modeling clay, and all wore an eye mask to standardize conditions.

An audio description of a fictitious anatomical structure was played, which participants could replay as needed. They constructed the shape while listening or after playback completion. The time and quality of the reconstructions were noted for baselining and identifying participant differences (Figure 2).

Following the first reconstruction, participants tactically interacted with the model and then made a second attempt. Time taken

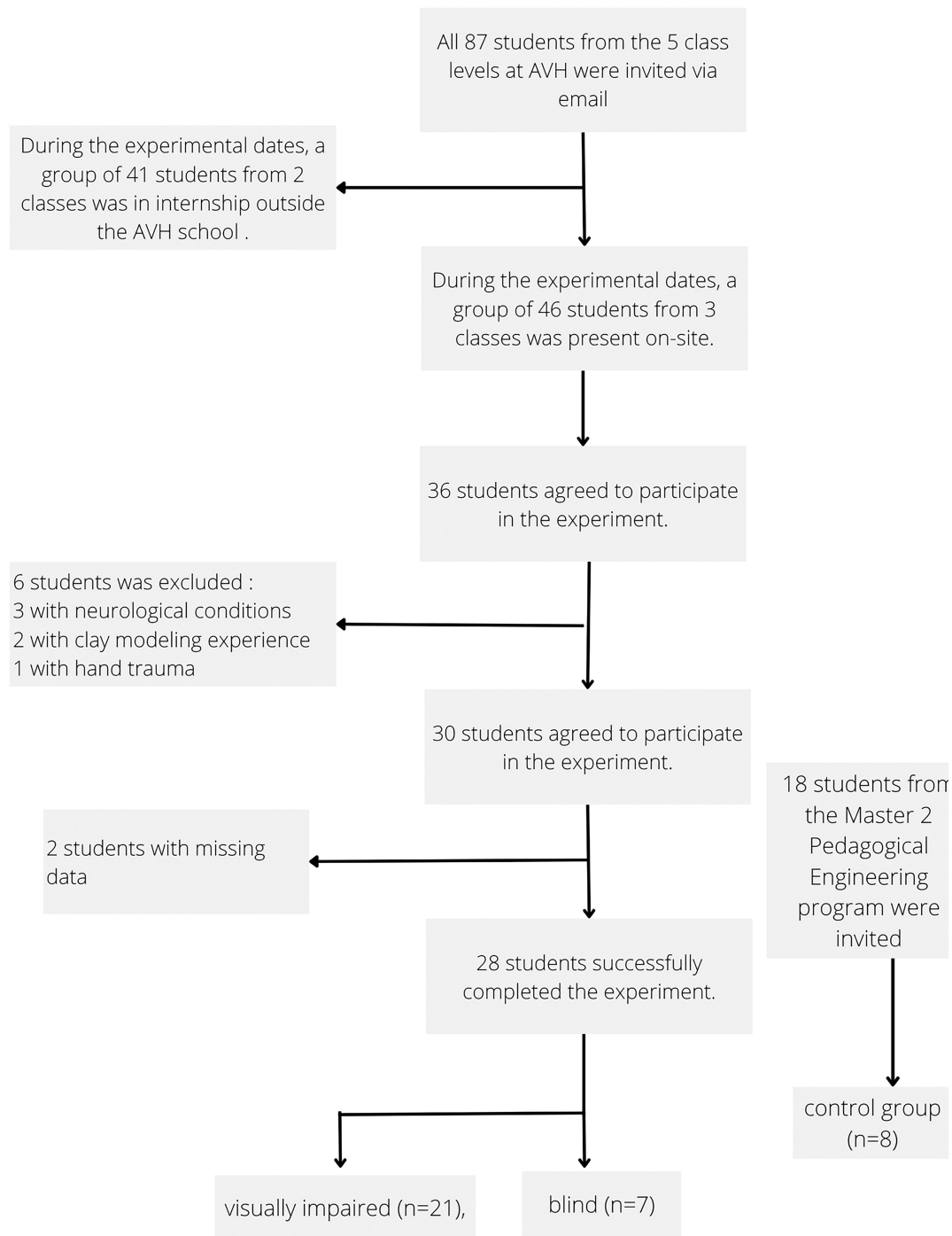


FIGURE 1 Participant flow and group distribution in the study. This flowchart depicts the flow of participants through the study, beginning with initial inclusion, followed by group distribution, and detailing any exclusions. It provides a clear, visual representation of the participant screening process, allocation to different groups (visually impaired, blind, and control), and the final participant count included in the study's data analysis.

was recorded, and photographs of both reconstructions were taken for comparative analysis.

Anonymity was maintained by marking photos with participants' codes, ensuring participants' comfort and confidentiality.

Throughout the entirety of the experimental procedure, all participants, regardless of their level of visual impairment, wore eye masks. This constant condition was maintained to standardize

the experience across all students and eliminate any potential visual cues or assistance. From the initial introduction, through both modeling attempts, and even during the tactile interaction phase with the anatomical model, the eye masks remained on. This assured a fair and uniform testing environment, focused solely on tactile and auditory information for the reconstruction task.

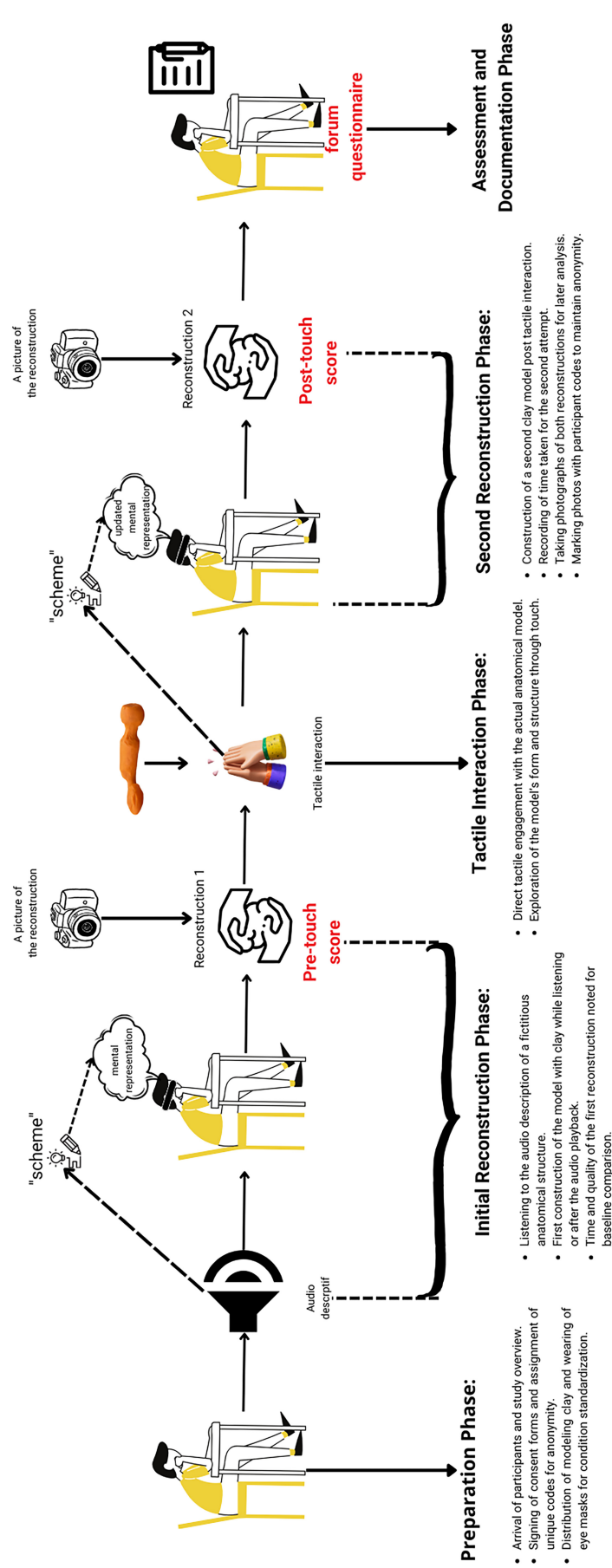


FIGURE 2 The experimental procedure flowchart: Auditory instruction, first clay construction, tactile engagement, and second clay construction. The figure illustrates the four key steps in the experimental procedure: audio description, first construction, tactile engagement, and second construction. First, participants listened to an audio description of a fictitious anatomical structure while blindfolded. Then, based on this description, they constructed a model using clay (first construction). After this, the participants tactically interacted with the actual anatomical model, exploring its form and structure. Finally, the participants constructed a second model post-tactile interaction. These steps were conducted individually to prevent information exchange, and participants remained blindfolded throughout the entire process to ensure reliance on tactile and auditory cues.

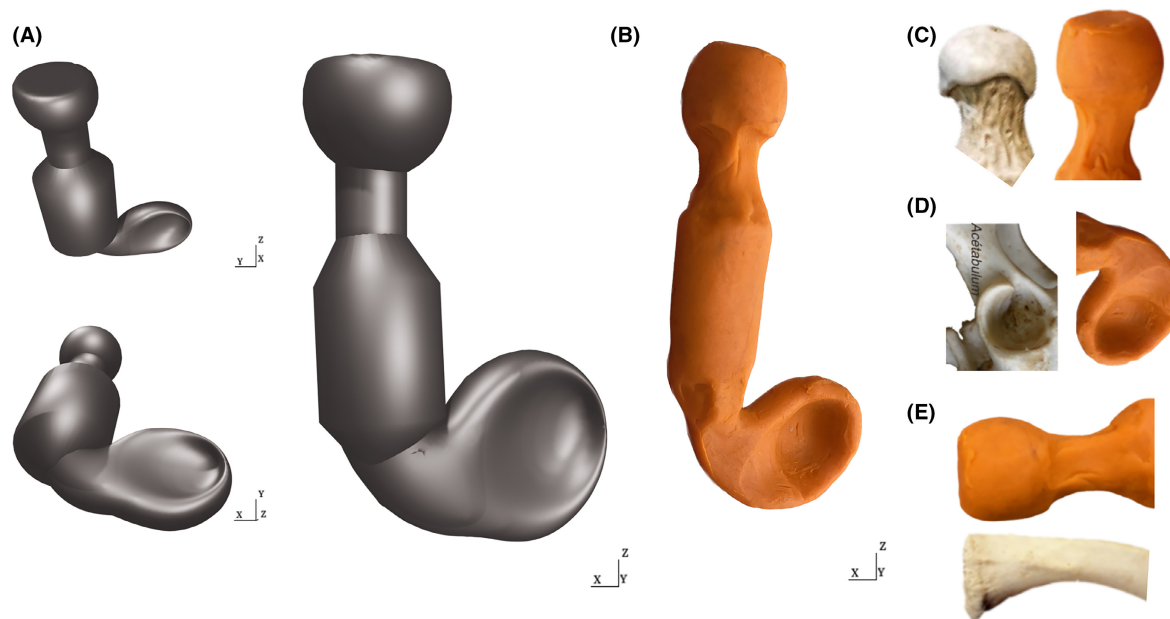


FIGURE 3 Comparative analysis of the fictitious anatomical structure with real anatomical entities. (A) 3D Virtual Reconstruction: This panel presents a computer-generated 3D model of the fictitious anatomical structure. The model is shown from different angles to highlight its three-dimensional features and to provide a comprehensive view of its geometry. (B) Clay reference model: Here, a hand-crafted clay model of the fictitious anatomical structure is displayed. The model serves as a tangible reference, providing a realistic interpretation of the structure's texture and volume. (C) Neck of femur comparison: This image compares a real human femur's neck (left) with the narrowed neck and oval head of the fictitious anatomical structure (right). The comparison illustrates the structural similarities between the two, emphasizing the anatomical plausibility of the fictitious design. (D) Acetabulum of Os coxal bone comparison: The image displays a real human acetabulum (left) alongside the corresponding excavation found in the fictitious anatomical structure (right). It highlights the concavity and depth of the structures, drawing parallels in their form and function. (E) Extremity of clavicle comparison: This panel shows the extremity of a real clavicle (left) next to the flattened head of the fictitious anatomical structure (right). The comparison underscores the likeness in shape and curvature, suggesting a potential functional resemblance.

Fictitious anatomical structure

In designing the fictitious anatomical structure for our study, methodological rigor was paramount to ensure its effectiveness in assessing cognitive processes related to anatomical understanding. The structure was meticulously crafted to incorporate three key categories that we believe are critical in anatomical cognition: general geometric shapes, dimensional ratios and proportions, and detailed transitional shaping.

- 1. General geometrical shapes:** The overall shape of the structure mimics the long cylindrical form of the femur, the flatness of the sternum, and the irregular contours of the sacrum. This category tests the ability to recognize and understand basic geometric forms as they apply to human anatomy.
- 2. Dimensional ratios and proportions:** We incorporated aspects such as the length-to-width ratio akin to the femur, the proportionality seen in the sternum relative to its rib attachments, and the scale of the sacrum in relation to its articulation with the pelvic bones. These ratios and proportions are vital for understanding the spatial relationships and functional mechanics in human anatomy.
- 3. Small details in transitional shaping:** The structure includes finer details, such as variations in angles, narrowings, and subtle

shifts in contours. The structure includes features like the femoral neck's angle, which is crucial in understanding hip mechanics, the subtle curvature changes found in the sternum, impacting rib articulation, and the nuanced surface topography of the sacrum, which is important for understanding sacroiliac joint articulation. These details are often the most challenging for students to grasp but are essential for a comprehensive understanding of human anatomy.






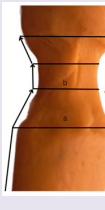


By including these specific anatomical parallels, our fictitious structure provides a wide-ranging assessment tool that challenges and evaluates a student's ability to integrate various aspects of anatomical understanding, from basic geometry to complex structural details.

A comparative analysis (Figure 3 and Table 1) illustrates similarities between the fictitious structure and real ones, such as the femur and clavicle, emphasizing the equal opportunity for participants and the study's focus on evaluating the efficacy of different learning methods.

Primary outcome

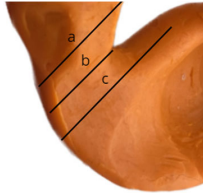

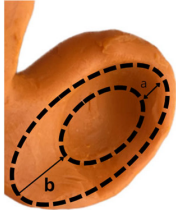

The primary outcome of this study is the difference between the pre-touch and post-touch scores. These scores are attributed to

TABLE 1 Comparative analysis of fictitious anatomical structure: Scoring, anatomical correlations, and pedagogical implications.

Component	Characteristic	Score	Real anatomical similarity	Pedagogical importance	Visual illustration
General geometric shapes	Forme L (L Shape)	10	Femur (overall shape)	Tests understanding of basic bone structure and alignment	
General geometric shapes	Cylindre (Cylinder)	10	Humerus shaft	Assesses recognition of long bone characteristics (diaphyse)	
Dimensional ratios and proportions	Tête ovale (Oval Head)	10	Femoral head	Evaluates perception of joint surfaces and articulations	
Dimensional ratios and proportions	Tête aplatie (Flattened head)	5	Scapula	Focuses on flat bone characteristics and spatial orientation	
Dimensional ratios and proportions	Rapport tête/cou (Head/Neck Ratio)	2.5	Femur head-to-neck ratio	Tests understanding of proportionality in bone structures	 a=b
Dimensional ratios and proportions	Cou rétréci (Narrowed neck)	10	Cervical vertebrae (narrowing)	Assesses ability to recognize and interpret structural narrowing	 a>b
Detailed transitional shaping	Angle de 90 (90 Degree angle)	10	Knee joint angles	Important for understanding joint mechanics and movement	 90
Detailed transitional shaping	Angle arrondi (Rounded angle)	2.5	Acetabulum curvature	Focuses on curvatures and their role in joint function	

(Continues)

TABLE 1 (Continued)

Component	Characteristic	Score	Real anatomical similarity	Pedagogical importance	Visual illustration
Detailed transitional shaping	Angle se rétréci (Narrowed angle)	2.5	Elbow joint narrowing	Evaluates perception of joint space and motion constraints	 <p>a>b and c>b</p>
Detailed transitional shaping	Excavation (Excavation)	10	Pelvic bone indentations	Assesses understanding of bone depressions and their significance	
Detailed transitional shaping	Excavation plus profonde à l'extrémité droite (Deeper excavation...)	2.5	Spinal cord canal depth variation	Tests perception of internal bone structures and variations	
Detailed transitional shaping	Excavation plat (Flat excavation)	2.5	Sternum surface flatness	Focuses on recognizing flat areas and their implications in bone structure	

Note: This table categorizes the key categories of the fictitious anatomical structure used in our study, aligning them with their respective scores, real anatomical similarities, and pedagogical significance. The three main categories are general geometric shapes, dimensional ratios and proportions, and detailed transitional shaping. Each characteristic under these categories is scored based on its complexity and relevance to the structure. The “real anatomical similarity” column provides a direct comparison to actual anatomical structures, enhancing the contextual understanding of each characteristic. The “pedagogical importance” column explains why each characteristic is essential for assessing anatomical cognition, highlighting the specific anatomical concepts and skills that the study aims to test and develop in participants, especially those with visual impairments. This structured approach ensures a comprehensive and detailed evaluation of the participants' ability to perceive, interpret, and reconstruct complex anatomical forms.

participants' anatomical reconstructions before and after their tactile interaction with the model of the anatomical structure, respectively. This difference serves as a quantifiable measure of how tactile engagement influences the participants' ability to accurately recreate an anatomical structure, essentially assessing the impact of touch in learning anatomy. A higher difference between the post-touch and pre-touch scores signifies a greater improvement in anatomical reconstruction ability following tactile interaction, indicating successful integration of tactile information into their understanding of anatomical structures, particularly among the visually impaired.

Secondary outcome

In our research, the secondary outcome focuses on identifying the specific geometric difficulties encountered by each group, a crucial aspect of understanding how different populations process anatomical information. To achieve this, we meticulously analyze the

subscores attributed to each specific anatomical feature, both before (pre-touch) and after (post-touch) tactile intervention. These subscores are divided into three key categories (general geometric shapes, dimensional ratios and proportions, and detailed transitional shaping) each representing a fundamental aspect of anatomical cognition.

By examining the subscores across these three categories, we aim to uncover patterns in how different groups, including those with unique cognitive processing styles, interpret and reconstruct anatomical structures. We hypothesize that a comparative analysis of these patterns, both within and between groups, will reveal specific learning challenges characteristic of each group.

Evaluation process

Our systematic evaluation process assesses participants' proficiency in reconstructing a fictitious anatomical structure, ensuring comprehensive, objective examinations.

Trained assessors use a guide with a listing of anatomical features and corresponding sub-scores, supported by multiple images of the reference object from different angles.

A scoring system gauges the presence of each feature in the reconstruction, ranging from 10 for primary features to 2.5 for less crucial ones, as shown in Table 1.

Sub-scores are assigned to each distinct part of the reconstruction based on its significance to the overall shape and its relevance to tactile skills development in anatomy.

Pre-touch and post-touch scores are determined by two separate teachers, assessing the participants' ability to reconstruct the structure before and after a tactile experience.

This thorough approach ensures an exhaustive and precise evaluation, accounting for all crucial aspects of the anatomical structure and the participants' ability to recreate it.

Data analysis

Our analysis employed appropriate statistical methods to evaluate the data. The main focus was on comparing pre-touch and post-touch scores to gauge the impact of tactile interaction on the quality and accuracy of anatomical reconstructions. Participant demographics and study characteristics were presented using descriptive statistics.

We used an independent *t*-test to compare mean pre-touch and post-touch scores, determining the extent of improvement after tactile engagement. A paired *t*-test evaluated the statistical significance of the difference in scores before and after touch for each participant.

We controlled potential confounding factors like age, gender, and prior anatomy or clay modeling experience through a multivariate analysis, ensuring the observed score differences were primarily attributable to tactile engagement.

A sensitivity analysis checked the robustness of our findings, providing additional result validation and identifying potential biases.

All analyses were conducted using statistical software with an alpha level of 0.05 for statistical significance. The results, including tables and graphs, were presented clearly and concisely.

Mitigating potential biases

To ensure the scientific rigor, objectivity, and integrity of our study while mitigating potential biases, we employed several strategies. First, participant biases were addressed through random selection, diverse skill levels, and the analysis of confounding variables. A double-blind assessment method with trained evaluators and standardized instructions minimized bias. Second, design biases were mitigated by including a control group outside the medical field and using standardized measurement methods. Consistent conditions and a diverse sample reduced confounding variables. Third, rigorous statistical analysis techniques were employed, including a detailed analysis plan, handling of missing data and outliers, and sensitivity analyses. An experienced statistician conducted all analyses using appropriate software. Finally, strategies were implemented to minimize valuation and interpretation biases, such as validated assessment tools, blinded teachers, participant anonymity, accurate audio

TABLE 2 Participant demographics and characteristics by group.

Characteristic	Visually impaired	Blind	Control
Number of participants—no.	21	7	8
Female sex—no. (%)	6 (26.08%)	4 (57.14%)	6 (75.0%)
Age—yr	29.78	26	30.12
Academical experience—no. (%)			
Bachelor's degree	15 (65.21%)	4 (57.14%)	0 (0.0%)
Master's degree	5 (21.73%)	3 (42.85%)	5 (62.5%)
Doctoral or postgraduate students	0 (0.0%)	0 (0.0%)	3 (37.5%)
Professional experience—no. (%)			
No experience	10 (43.47%)	1 (14.28%)	2 (25.0%)
Unqualified	1 (4.34%)	2 (28.57%)	0 (0.0%)
Skilled workers	3 (13.04%)	3 (42.85%)	2 (25.0%)
Technicians and intermediate professions	3 (13.04%)	0 (0.0%)	2 (25.0%)
Executives and higher intellectual professions	6 (26.08%)	1 (14.28%)	2 (25.0%)
Average time of the construction	7.09	8.11	6.83

Note: The table provides an overview of participant demographics and characteristics across three groups: visually impaired, blind, and a control group. Key data include the number and gender ratio of participants, their average age, and educational and professional backgrounds. Notably, Bachelor's degree holders form the majority in visually impaired (65.22%) and blind (57.14%) groups. Furthermore, the table includes the average time taken by each group for the construction task, with the control group being the fastest (6.83 min), followed by the visually impaired (7.10 min), and blind participants (8.11 min).

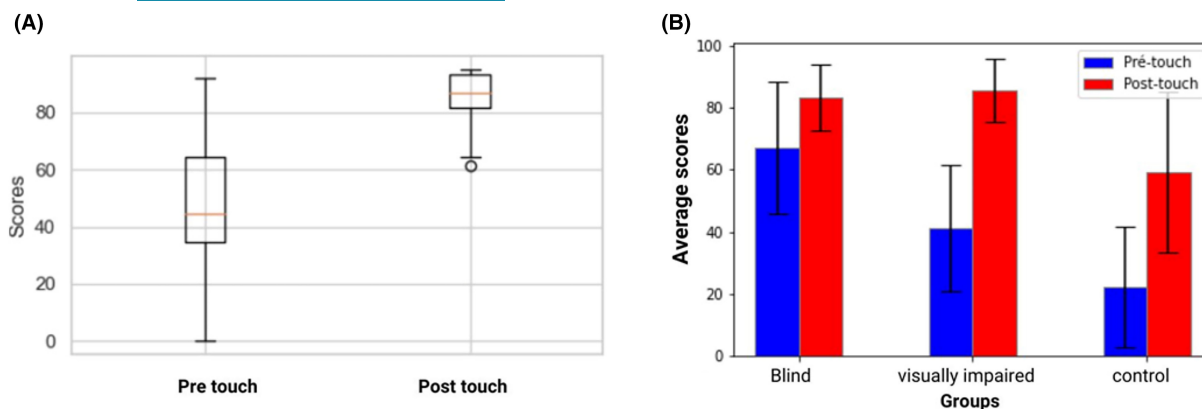


FIGURE 4 “Boxplot and bar chart analysis of pre-touch and post-touch scores across participant groups”. (A) This boxplot visually depicts the distribution and dispersion of scores before and after tactile intervention. The general trend of higher median scores post-intervention suggests an overall enhancement in participants' performance. (B) The bar chart compares average pre-tactile (depicted in red) and post-tactile (shown in blue) scores for each group. A visible shift upwards in the blue bars signals an improvement in understanding post-intervention.

TABLE 3 Primary outcome: Pre-touch and post-touch score statistics across participant groups.

Group	Blind	Visually impaired	Control	Total
Sample size	7	21	8	36
Average pre-touch score	67,28	41,32	22,18	47,81
Pre-touch median (SD)	75,81 (21,37)	40,32 (20,39)	25,81 (19,62)	44,35 (44,35)
Average post-touch score	83,41	85,65	59,27	85,09
Post-touch median (SD)	87,10 (10,60)	88,71 (10,34)	66,13 (26,09)	87,10 (10,07)
T-statistic	-3.069	-9.703	-3.2334	-8,63
p-value	0.0022	5,24e-09	0.01438	-8,63
Effect size (Cohen's d)	1,51	2.74	1.606	1,63

Note: This table displays the statistical analysis of pre and post-tactile engagement scores across blind, visually impaired, and control groups. It highlights the average and median scores for both stages, along with the standard deviation (SD). The table also includes *t*-statistics and *p*-values from paired *t*-tests assessing the score changes within groups, and Cohen's *d* values as a measure of effect size. Key findings show that all groups significantly improved post-tactile engagement, with visually impaired participants exhibiting the highest effect size (Cohen's *d*=2.74).

descriptions, and a commitment to transparency. By implementing these strategies, we aimed to ensure the validity, reliability, and integrity of our study's results.

Ethical considerations

This study was conducted in alignment with the established pedagogical teaching strategies of the Institut de formation en masso-kinésithérapie Valentin Haüy. An attestation from the Director, Cécile FUMERON, confirms that the research did not require specific ethical approval based on the institution's guidelines, as clay modeling was a pre-established teaching method at the school. All participants gave informed consent, with measures taken to ensure their anonymity and uphold ethical standards throughout the study. Ethical approval exemption was granted since subject IDs were not collected beyond experimental and demographic factors.

RESULTS

The study involved 36 participants, mostly aged in their 20s (50%) and 30s (25%), with a gender ratio of 1.25 (M/F). The participants were categorized into three groups based on visual abilities: The visually impaired group, with an average age of 29.48 years, showed substantial age variation due to the larger standard deviation of 11.50 years. The blind group had a lower mean age of 25.57 years and a minor standard deviation of 5.80 years, implying a less varied age distribution, although the small group size might limit its representativeness. The control group's average age was 29.62 years, with a standard deviation of 12.24 years (Table 2).

Primary outcome

Our primary outcome showed broad variability in students' abilities, with a mean pre-touch score of 47.81, median of 44.35,

standard deviation of 22.83, and a wide range of 91.94. However, post-intervention scores reflected significant improvement and reduced variability, yielding a mean of 85.09, median of 87.10, standard deviation of 10.07, and a narrower range of 33.87 (Figure 4). Statistical analysis using the *t*-test (-8.63 , $p < 0.001$) and Wilcoxon signed-rank test ($p < 0.001$) confirmed the meaningful positive effect of tactile intervention on students' capabilities in anatomical structure reconstruction (Supplemental Digital Appendix 1, Supplemental Digital Appendix 2).

For the visually impaired group ($n=21$), the pre-touch mean and median scores were 41.32 and 40.32, respectively, with a standard deviation of 20.39 showing a high degree of variability. The range of pre-touch scores was broad at 77.42. After the tactile intervention, both mean and median scores increased substantially to 85.65 and 88.71, respectively. The decreased post-touch standard deviation of 10.34 and range of 33.87 suggest a significant reduction in variability and a general improvement in scores following the intervention.

For the blind group ($n=7$), the pre-touch mean score was 67.28 ($std=21.37$), increasing to 83.41 ($std=10.60$) post-touch. For visually impaired students ($n=21$), the pre-touch mean score was 41.32 ($std=20.39$), rising to 85.65 ($std=10.34$) post-touch. In both cases, a decrease in standard deviation post-touch suggests less variability in student scores.

The control group ($n=8$) experienced a less marked improvement, from a pre-touch mean score of 22.18 ($std=19.62$) to a post-touch mean score of 59.27 ($std=26.09$). Despite improvement, the increased post-touch score standard deviation suggests high variability in scores.

In the visually impaired group, the paired *t*-test and Wilcoxon's signed rank test resulted in p -values < 0.001 , suggesting a notable improvement in performance due to the tactile intervention (Table 3).

In the blind group, paired *t*-test and Wilcoxon's signed rank test also indicated statistical significance with p -values of 0.022 and 0.015, respectively, affirming that the intervention positively influenced their performance (Table 2).

Effect sizes for the visually impaired group, as measured by Cohen's *d* and Eta-squared, were 2.74 and 4.78, respectively, indicating a substantial intervention effect. The confidence interval for the mean difference in scores was 34.55 to 54.11, highlighting the significant improvement due to the intervention (Table 2).

Secondary outcome

The post-touch subscores were generally higher than the pre-touch subscores for all assessed anatomical features. "angle" had the highest pre-touch mean, while "flat excavation" had the highest post-touch mean. Participants struggled most with the "head/neck ratio" and "narrowing angle" in the pre-touch phase, indicated by the lowest mean subscores (Figure 5A).

The visually impaired group had relatively low average pre-touch scores for the tasks "head/neck ratio" (3.57), "narrowing angle"

(3.57), "deeper excavation at right end" (3.57), "excavation" (3.57), and "flat excavation" (7.14), indicating that these tasks were difficult to understand through verbal description alone. In contrast, the visually impaired group had better mean pre-touch scores for the tasks "angle" (67.86), "L-shape" (53.57), "flattened head" (50), "cylinder" (39.29), "shrunken neck" (32.14), "oval head" (14.29), and "rounded angle" (10.71), suggesting that these tasks were more easily understood with verbalization (Figure 5A).

Similarly, the blind group struggled to understand tasks like "head/neck ratio" (28.57), "narrowing angle" (28.57), "flat excavation" (28.57), and "deeper right excavation" (14.29) through verbal description alone. However, the visually impaired group performed even worse on these tasks, with scores of 3.57, 3.57, and 7.14, respectively, for "head-to-neck ratio," "narrowing angle," and "flat excavation" (Figure 5A).

Conversely, the blind group demonstrated better understanding for tasks like "L-shape" (85.71), "cylinder" (85.71), "angle" (71.43), "oval head" (57.14), "flat head" (57.14), "shrunken neck" (57.14), "rounded angle" (42.86), and "excavation" (42.86) through verbalization alone. The higher pre-touch scores for these tasks suggest that the blind group was able to understand them more effectively using only verbal descriptions, while the visually impaired group showed lower scores in some of these tasks, such as "oval head" (14.29) and "rounded angle" (10.71) (Figure 5A).

Analyzing the pre-touch scores across different groups provides insightful comparisons regarding their initial mastery of various pedagogical categories. In the "detailed transitional shaping" category, the blind group exhibited the highest initial understanding with an average pre-touch score of 33.33, indicating a relatively stronger baseline ability in perceiving and understanding intricate details, likely due to their enhanced tactile and spatial awareness. The visually impaired group followed with a score of 27.38, suggesting a somewhat lower yet notable grasp of detailed shaping. The control group scored the lowest in this category, with an average of 16.67, indicating initial difficulties in comprehending these complex shapes (Figure 5B).

For the "dimensional ratios and proportions" category, the blind group again led with the highest pre-touch score of 60.71. This score demonstrates their strong capacity to understand spatial relationships and proportions, potentially due to heightened non-visual senses. The visually impaired group, scoring 47.32, also showed considerable understanding, possibly leveraging their residual vision alongside other sensory inputs. The control group had a lower average score of 31.25, reflecting a more moderate initial understanding of these concepts (Figure 5B).

In the "general geometric shapes" category, the blind group had the highest pre-touch score with 71.43, showcasing their proficiency in identifying basic shapes through non-visual senses. The visually impaired group's score of 55.36 indicates a good understanding, although slightly lesser compared to the blind group. The control group's lowest score of 33.93 suggests more initial challenges in this category (Figure 5B).

Our findings reveal significant improvements in tactile interventions across all groups and categories, corroborated by substantial effect sizes (Cohen's d) and statistical test results.

In the category of "general geometric shapes," we observed positive effects with effect sizes of $d=1.15$ for the visually impaired group, $d=1.00$ for the blind group, and $d=1.32$ for the control group. The paired t -test yielded a t -statistic of -2.000 (non-significant p -val), while the Wilcoxon test resulted in a W -statistic of 0.0 (non-significant p -val).

For "dimensional ratios and proportions," the improvements were even more pronounced, with effect sizes of $d=1.65$ for the visually impaired group, $d=1.44$ for the blind group, and $d=1.62$ for the control group. The paired t -tests resulted in t -statistics of -8.521 (p -val= 0.003), -4.899 (p -val= 0.016), and -9.728 (p -val= 0.002), respectively. The Wilcoxon test yielded W -statistics of 0.0 for all groups (non-significant p -val= 0.125), indicating statistical significance.

In the "detailed transitional shaping" category, we observed varying effect sizes. The visually impaired group showed a notable effect size of $d=2.06$, while the blind group had a slightly lower effect size of $d=1.58$, and the control group had a significant effect size of $d=2.22$. The paired t -tests resulted in t -statistics of -2.834 (p -val= 0.037), -2.484 (p -val= 0.056), and -5.222 (p -val= 0.003), respectively. The Wilcoxon test yielded a W -statistic of 1.0 for the visually impaired group (p -val= 0.063) and 0.0 for the blind group (non-significant p -val= 0.500), while the control group's Wilcoxon test resulted in a significant p -val= 0.031 .

Given the substantial effect sizes observed in the "detailed transitional shaping" category across all groups, a complementary analysis was conducted to delve deeper into the specific anatomical characteristics within this category to determine which showed the most significant improvements. While "Excavation plus profonde à l'extrémité droite (deeper excavation...)" showed substantial improvement, particularly for the Blind Group with an impressive effect size of 6.71 , other characteristics had less pronounced improvements. Notably, "Angle de 90 (90 degree angle)" had a negligible effect size for the blind group and only a modest improvement for the control group. For detailed data on the range of improvements across all characteristics within this category, Figure 5C provides an extensive breakdown.

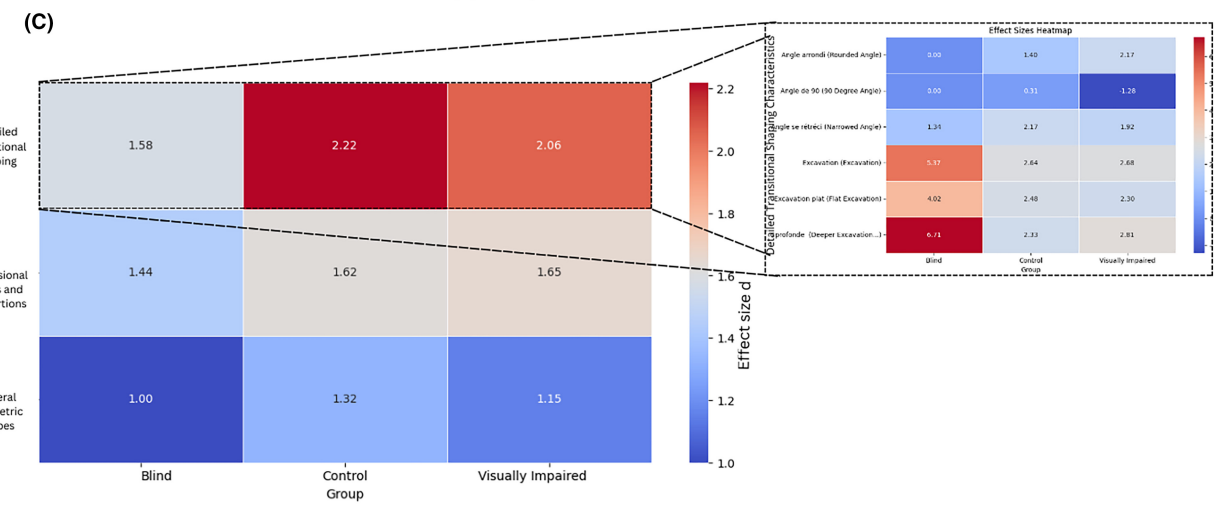
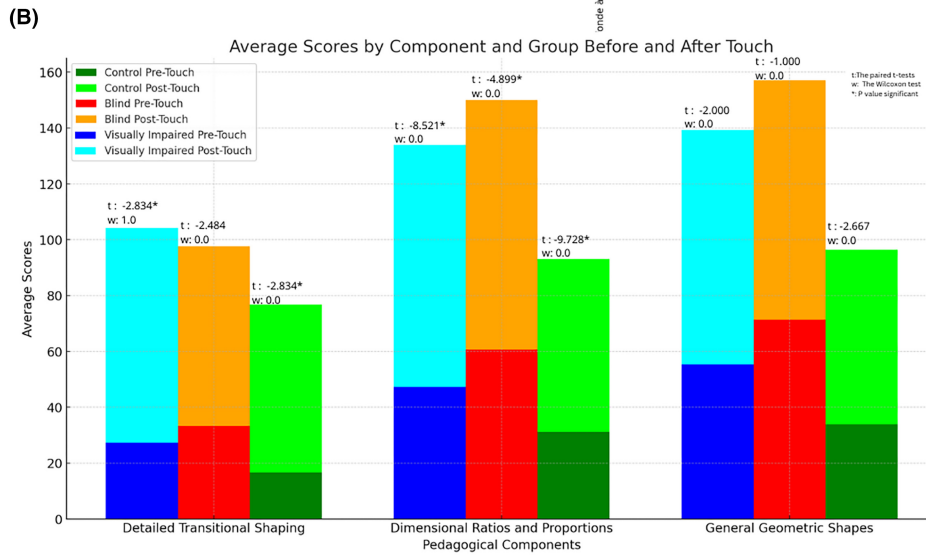
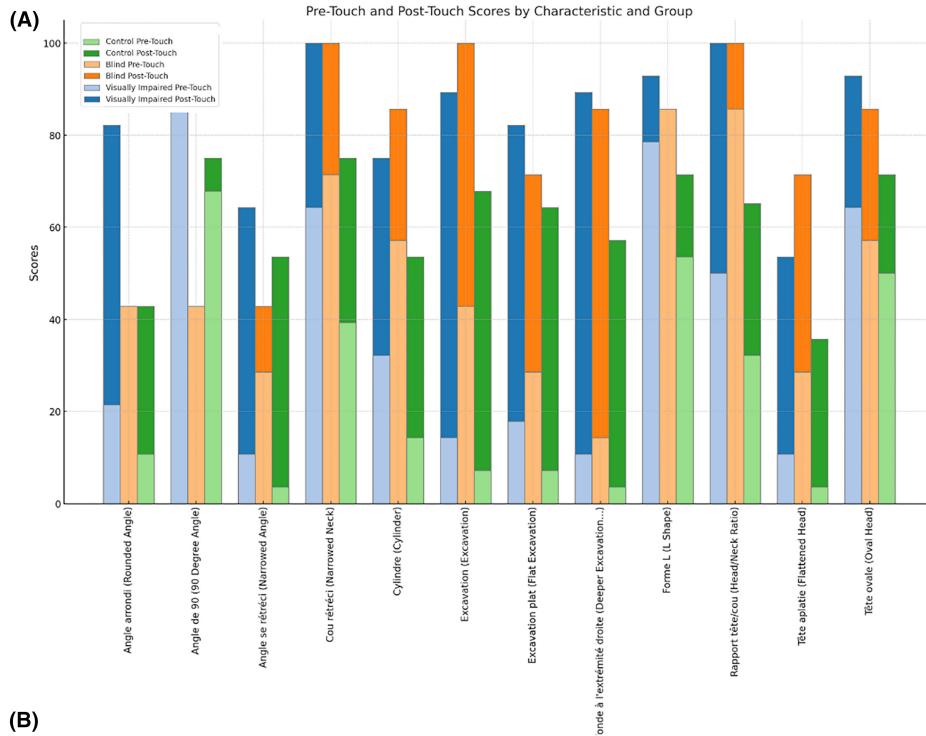
DISCUSSION

Our study seeks to explore the feasibility and accuracy of utilizing clay modeling as an assessment tool to visualize mental representations across three groups, by assessing the insufficiency of verbal descriptions alone and the effect of tactile intervention in providing accurate mental imagery. The study found significant variability in pre-touch scores, indicating differences in abilities before the intervention. However, the tactile intervention led to significant improvements in post-touch scores, reducing variability and resulting in more consistent performance. Factors such as gender, age, and job skill did not significantly influence student performance. Comparing blind and visually impaired groups, the blind group had higher pre-touch scores, with both groups showing significant improvement after the intervention. Statistical analyses, including the paired t -test and the Wilcoxon signed rank test, confirmed the statistically significant differences in performance before and after the intervention for all groups. The visually impaired group showed a larger effect, the blind group also experienced improvement with a smaller Cohen's d .

The observed differences between the groups could be attributed to various factors. Visually impaired participants may benefit more from tactile contact as they rely on their residual vision to perceive their surroundings. Blind individuals, on the other hand, may have developed enhanced skills in processing non-visual information and creating accurate mental representations based on verbal descriptions alone. The analysis of pre-touch subscores revealed that the visually impaired group struggled with subtle details conveyed through verbal description, while the blind group faced challenges related to proportion and size. This could be due to their experiences and reliance on different sensory modalities.

Hötting and Röder²³ have shown that blind individuals often excel in perceptual auditory tasks and auditory language and memory tasks, a manifestation of neural plasticity at different levels of the auditory processing stream due to compensatory behavior. Furthermore, Arnaud et al.²⁴ found that congenitally blind adults exhibit enhanced auditory processing capabilities, such as perceiving accelerated speech and superior pitch discrimination in speech and music. Gori et al.²⁵ noted that blind individuals demonstrate exceptional abilities in auditory spatial tasks, which can be attributed

FIGURE 5 Comparative analysis of pre-touch and post-touch scores for different anatomical parameters across all groups. (A) This panel shows a bar graph with the pre-touch and post-touch scores for each characteristic within different groups. Each characteristic is listed on the x-axis, and the scores are plotted on the y-axis. The graph uses color coding to differentiate between the groups and whether the score is pre- or post-touch. This allows for a direct visual comparison of performance improvements within each characteristic and across the groups. (B) This stacked bar graph represents the average scores by component and group before and after touch. The x-axis lists the pedagogical components, while the y-axis indicates the average scores. The colors represent different groups and whether the score is pre- or post-intervention. The paired t -test statistics are displayed above each group of bars, with significant p -values highlighted, indicating the statistical significance of the improvements after the tactile intervention. (C) This panel contains a heatmap that shows the effect sizes (Cohen's d) of the tactile intervention for each pedagogical component across the different groups. The effect size values are color-coded, with darker shades representing higher magnitudes of effect. The x-axis lists the groups, and the y-axis lists the pedagogical components. The right side of the heatmap provides a key for interpreting the effect size magnitudes, with values ranging from 1.00 to 2.22 . Given the substantial effect sizes observed in the "detailed transitional shaping" category across all groups, a complementary analysis was conducted to delve deeper into the specific anatomical characteristics within this category to determine which showed the most significant effect size.



to cerebral reorganization and a heightened reliance on auditory cues. Additionally, Klinge et al.²⁶ identified stronger corticocortical connections from the primary auditory cortex to the primary visual cortex in blind individuals, suggesting that plastic changes in connectivity enable auditory information to evoke responses in the primary visual cortex.

We can suggest that students with low vision often continue to rely on their residual visual capabilities, a reliance that, in our observations, appears to diminish their engagement with and attention to full verbal inputs. This reliance on their remaining visual sense diverts a significant portion of their cognitive resources toward maximizing the utility of their limited vision. As a consequence, these students may not fully process or prioritize detailed verbal descriptions, as their mental efforts are predominantly channeled toward interpreting whatever visual information they can perceive. In contrast, students with blindness, devoid of visual input, tend to focus more intensively on verbal information. This heightened focus on auditory inputs not only compensates for the lack of visual cues but also stimulates their neuroplasticity, leading to a highly adaptive brain. This adaptiveness, fostered by a reliance on non-visual senses, enables blind students to develop a more nuanced and sensitive response to verbal descriptions. Their cognitive processing is less about “seeing what is left” and more about “hearing and understanding fully,” making them potentially more receptive to verbal nuances and complexities. This divergence in cognitive engagement underscores the varying impacts of sensory experiences on the mental representation and information processing strategies of individuals with different visual abilities.

The differential cognitive processing observed in students with blindness compared to those with low vision is substantiated by several studies. D'Angiulli and Waraich²⁷ found that early-blind people demonstrate superior tactile skills and higher memory recognition due to cortical reorganization, suggesting enhanced perceptual encoding and recognition of memory as cognitive correlates of cross-modal plasticity in congenital blindness. This enhanced perceptual ability indicates a profound adaptation in the brain's processing capabilities. Cattaneo et al.²⁸ also noted that blind individuals often employ different cognitive mechanisms than sighted subjects, which implies that compensatory mechanisms can significantly offset the limitations of sight loss. This finding highlights the impact of perceptual input on the organization of mental processes. Vecchi et al.²⁹ discussed how blind individuals face challenges in simultaneously maintaining different spatial information, shedding light on the unique spatial processing challenges posed by congenital blindness. Furthermore, Adhitama and Afifah³⁰ emphasized that while low vision students still primarily rely on their sense of vision, totally blind students predominantly depend on their sense of touch, indicating a distinct approach to understanding environmental conditions. Finally, the work of Röder et al.³¹ on language processing in blindness revealed that blind people process auditory language stimuli faster than sighted people, demonstrating distinct neural mechanisms in language processing.

The pre-touch subscores analysis reveals that the visually impaired group struggled with small details, which were not effectively conveyed through verbal descriptions. Tasks such as narrowing angle (3.57), deeper excavation at right end (3.57), and flat excavation (7.14) specifically reflect their difficulty in comprehending intricate details through verbal means alone. Conversely, the blind group encountered challenges related to proportion and size, as evidenced by their scores in tasks like head-to-neck ratio (28.57) and angle shrinks (28.57). It appears that blind students, due to their experience with braille writing, tend to focus on fine details and take a more “microscopic” approach to tactile tasks.

The comprehensive analysis of pre- and post-touch scores in various pedagogical categories unveils a remarkable narrative about the efficacy of tactile interventions and their differential impact across diverse groups. The study's unexpected results, crucial for discussing cognitive processing differences among the groups, are primarily observed in the “dimensional ratios and proportions” and “detailed transitional shaping” categories. In “dimensional ratios and proportions,” despite the blind group having the highest initial understanding (pre-touch score of 60.71), the visually impaired group exhibited the most substantial improvement post-intervention (effect size $d=1.65$), which was higher than the blind group ($d=1.44$). This suggests that while the blind group had a better baseline, the visually impaired group's potential for improvement in understanding spatial relationships was greater.

In the “detailed transitional shaping” category, the control group showed the most significant improvement (effect size $d=2.22$, t -statistic -5.222 , p -value $=0.003$), despite starting with the lowest pre-touch score (16.67). This indicates that the control group, while initially struggling with complex shapes, made the most substantial cognitive leaps post-intervention, possibly due to their lesser reliance on non-visual senses compared to the other groups.

These findings suggest specific anatomical category sensitivities for each group. The visually impaired group demonstrated a particular responsiveness to “dimensional ratios and proportions.” The blind group, with their heightened tactile and spatial awareness, initially excelled in all categories but showed less pronounced improvement, suggesting a ceiling effect in their learning curve. The control group's significant improvement in “detailed transitional shaping” suggests a potential initially untapped cognitive processing capability, unlocked through tactile interventions.

The results emphasize significant differences in how blind and visually impaired students perceive and understand object details and proportions through verbal descriptions. Blind students' reliance on braille writing may contribute to their inclination to focus on fine details, while the visually impaired group faced difficulties in accurately perceiving subtle details solely through verbal descriptions. The tactile intervention significantly improved the subscores of the visually impaired group, indicating that tactile experience was instrumental in enhancing their understanding in this population.

This finding aligns with the study by Atchley et al. (1997), which demonstrated that attentional selection in spatial contexts, such as

in-depth perception, can be “depth-aware,” a concept potentially applicable to the spatial detail perception in blind individuals.³² Moreover, the experiment by Williams et al. (1969), involving identical twins where one was blind from birth, revealed that the blind twin excelled in tasks requiring fine manipulative movements of the hands or fingers.³³ This indicates an enhanced perceptual-motor skill set in the absence of vision, further supporting the idea that blind students' focus on fine details.

The role of tactile perception in discerning textures and fine details is significant, both for sighted and blind individuals.³⁴ research elucidates that touch can be particularly advantageous for detecting the smoothness of surfaces and very fine textures, indicating that visual imagery is not a prerequisite for texture perception. This finding is crucial, as it underscores the innate ability of touch to convey detailed information about textures, which can be particularly beneficial for those who rely on tactile senses due to visual impairment. Further supporting this notion, Goldreich and Kanics³⁵ conducted a study on tactile acuity in blindness and discovered that blind individuals exhibit significantly enhanced tactile acuity. Intriguingly, this heightened sensitivity was found to be independent of factors such as the degree of childhood vision, light perception level, or proficiency in Braille reading. This enhancement in tactile acuity points toward crossmodal plasticity as a potential underlying mechanism. Together, these studies affirm the vital role of tactile experiences in providing detailed sensory information, particularly in the context of those with visual impairments, where such information is crucial for understanding and interacting with their environment.

In our study, an intriguing tendency emerged regarding the physical reconstructions created by the blind group compared to those by the visually impaired and control groups. Despite all groups being provided with an equal amount of clay for modeling, we observed that the reconstructions by the blind participants consistently tended to be smaller in size. This difference in the representation of size may be attributed to their unique spatial and tactile processing abilities. Without visual cues to guide their perception of scale, blind individuals might rely more on tactile feedback, which could lead to a more conservative estimation of size in their models. This tendency, while subtle, offers valuable insights into how the absence of visual information influences spatial understanding and physical representation in blind individuals. It underscores the variations in sensory processing and cognitive interpretation of spatial information across different sensory abilities.

The insights garnered from our study, revealing the cognitive processing changes in students, strongly advocate for the reliability of clay modeling as a technique to unveil mental representations. The inadequacy of verbal descriptions alone in forming what Piaget terms as “schema”—the mental framework for understanding or representing some aspect of the world—is highlighted in our findings. Verbal descriptions often fall short in providing the comprehensive details necessary for creating accurate mental representations. Clay modeling, on the other

hand, serves as a tangible and interactive medium that allows students to manifest their mental representations physically. This hands-on approach not only illuminates the intricacies and nuances of their cognitive processing but also exposes the errors in mental representation that verbal discussions alone fail to reveal. Consequently, the use of clay models in our study has proven to be an effective method for visualizing and understanding the cognitive processes underlying mental representation, thereby validating our approach and showcasing the significant role of tactile experiences in cognitive development and understanding.

Clay modeling proved to be an excellent assessment tool for gauging students' geometric understanding. Educators can visualize students' comprehension and identify areas of difficulty or conceptual errors by examining their recreated anatomical structures. Furthermore, it provides students with immediate feedback, promoting continuous improvement and skill acquisition.

LIMITATIONS

Our findings offer valuable insights into the effectiveness of tactile interventions across different groups. However, there are several limitations that should be acknowledged:

Sample size and diversity: With a total of 36 participants divided into three groups, the study's sample size is modest, which poses challenges to the generalizability of the results. The rarity of the population in focus—individuals with visual impairments and blindness—compared to the general population makes recruiting a large and diverse sample challenging.

Group variability: The uneven distribution of participants among the groups—more visually impaired individuals than blind individuals—mirrors the actual prevalence in the population but introduces variability that can affect the comparative analysis. The fact that visually impaired students are three times more represented than blind students is reflective of their relative proportions in the general population, but it may still limit the strength of conclusions drawn about comparative improvements across groups.

Statistical analysis challenges: Small sample sizes can constrain the power and sensitivity of statistical analyses, including the *t*-tests and multivariate approaches employed in the study. These constraints may lead to a higher risk of Type II errors (failing to detect an effect that is present) or overestimating the effect sizes, thus affecting the reliability and interpretation of the study's findings.

Long-term efficacy and retention: The study's scope is limited to immediate post-intervention outcomes, lacking longitudinal data to assess long-term knowledge retention and the enduring impact of the tactile educational interventions. Without this information, the sustainability of the cognitive benefits observed cannot be confirmed, and the long-term educational implications remain uncertain.

CONCLUSION

In conclusion, our investigation supports the use of modeling clay as a valuable instructional resource, reinforcing its role in facilitating mental representation—a cornerstone for grasping anatomical concepts. Although beneficial in reducing cognitive load and aiding experiential learning, particularly for visually impaired students, it is imperative to consider individual learning needs. Our findings, while promising, suggest a humble reflection on the complexities of learning and the necessity for adaptable teaching methodologies. We recommend further studies to explore the long-term effects of such tactile learning tools, ensuring a comprehensive understanding of their impact on anatomical education.

ACKNOWLEDGMENTS

The authors extend their gratitude to Lauriane, Reda Bakkar, and Cécile Fumeron. Lauriane assisted significantly in the design and evaluation of the study, while Reda Bakkar and Cécile Fumeron provided indispensable administrative support at the IFMK, Centre de formation et de rééducation professionnelle Valentin Haüy, Paris, France.

FUNDING INFORMATION

None. The study was conducted without any external financial assistance.

CONFLICT OF INTEREST STATEMENT

None. The authors report no potential conflicts of interest that would infringe on Academic Medicine's Authorial Conflict of Interest Policy.

DATA AVAILABILITY STATEMENT

All data used and analyzed in this study were collected by the authors specifically for this research, maintaining full respect for the rights and confidentiality of the participants.

ETHICAL STATEMENT

Not applicable. Nevertheless, the study was conducted with the informed consent of all participants, ensuring anonymity and strict adherence to ethical standards. It should be noted that clay modeling was already a well-established pedagogical teaching strategy prior to the commencement of the study. Furthermore, we have provided the editors with an attestation from Cécile Fumeron, Director of the Institut de formation en masso-kinésithérapie Valentin Haüy. In the document, she certifies that Dr. Yachou's study on modeling clay as a tool aligns with the school's standard teaching practices and does not require special ethical approval as per the institution's guidelines. This attestation was issued in Paris on 09/10/2023.

DISCLAIMERS

None. The authors have no disclaimers to declare regarding the content and findings of this study.

PREVIOUS PRESENTATIONS

None. The materials of this research have not been presented in any other form or at any conference prior to this publication.

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Yassine Yachou, a medical doctor and Ph.D. candidate in neuroscience, serves as a professor of neuroanatomy at the CFRP Valentin Haüy, Paris, and is an active researcher within both the INSERM U955 transitional neuropsychiatric team and the PsyBrain Team at the French Alternative Energies and Atomic Energy Commission. His research interests include neuroanatomy, ethical neurosurgery, and neuromodulation. Beyond his academic and clinical research pursuits, Dr. Yachou is deeply committed to transforming anatomical education for general students by understanding and addressing the adaptive needs of disabled students, he aims to develop innovative low-cost teaching techniques that can enhance learning for the broader student population by using adaptive teaching tools and cognitive processing seeing with disabled students via an innovative approach to pedagogy that seeks to benefit all learners through the insights gained from adapting to the needs of disabled students.

Olivier Samson, serves as the pedagogical manager of the third-year class and lectures in anatomy at the Valentin Haüy Vocational Training and Rehabilitation Center. Currently, a Ph.D. student in adult education at the Conservatoire National des Arts et Métiers in Paris, France, Samson is dedicated to improving educational tools and frameworks for the visually impaired. His work focuses on enhancing the accessibility and inclusivity of anatomical education, aiming to ensure that visually impaired students have effective and equitable learning opportunities.

Olivier Lasvergnas has made significant contributions in the fields of education and training, particularly in developing and leading projects that bridge scientific animation, professional integration, health, and popular education. Since September 1, 2014, he has served as a full professor of sciences of education and training at the University of Lille and, from 2020, at Paris-Nanterre University, where he leads the "Learning, Training, and Digital" team within the CREF laboratory (UR 1589). His research focuses on the effects of academic categorization as "scientific" or not, and its transgression, especially in collaborations between laypeople and academic researchers, including amateur scientists, patients as co-researchers in health, and in situations of popular epidemiology. Lasvergnas has also been deeply involved in the exploration of school scientific categorization as a practitioner–researcher in scientific mediation and collaborative sciences. His work aims to foster new reflexive corporations in health, informal e-learning situations, and the institutionalization of scientific and technical culture in France.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Yachou Y, Samson O, Lasvergnas O. Prospective comparative study on enhancing geometrical mental representation and anatomical learning in medical students through modeling clay as an assessment tool. *Anat Sci Educ*. 2024;00:1–17. <https://doi.org/10.1002/ase.2404>