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To cite this version:

Nour Al-Badri, Sandrine Roumazeille, Alexandra Nuytten, Joel Ferri, Marie - Laure Charkaluk, et al.. Three-dimensional printing models improves long-term retention in medical education of pathoanatomy: A randomized controlled study. Clinical Anatomy, 2022, Clinical Anatomy, 35 (5), pp.609-615. 10.1002/ca.23878 . hal-03999981

HAL Id: hal-03999981
https://hal.univ-lille.fr/hal-03999981v1

Title & Abstract:

Three-dimensional printing models improves long-term retention in medical education of pathoanatomy: A randomized controlled study

Nour Al-Badri, Sandrine Touzet-Roumazeille, Alexandra Nuytten, Joël Ferri, Marie-Laure Charkaluk, Romain Nicot

Introduction

Craniosynostosis is a rare and complex pathology, and visuospatial skills are necessary for a good understanding of the condition. While the use of three-dimensional (3D) models has improved the understanding of complex craniofacial anatomy, no study has evaluated the impact of this teaching support on long-term retention.

Materials and Methods

Our randomized controlled trial was designed to compare the long-term retention of information with 3D-printed models of four types of craniosynostosis versus classic 3D reconstructions displayed in two-dimensional (2D) among undergraduate students. All students benefited from the same standardized course followed by the manipulation of the learning tool associated with the group for 15 minutes. Long-term retention was assessed by the capability to properly recognize different types of craniosynostosis 3 weeks after the course.

Results

Eighty-five students were enrolled. Previous educational achievements and baseline visuospatial skills were similar between the groups. The bivariate analysis showed the mean score in the 3D and 2D groups were 11.32 (2.89) and 8.08 (2.81), respectively ($p < 0.0001$).

Conclusions

3D-printed models of structures with spatial complexity such as various craniosynostosis patterns improve significantly medical students’ long-term retention, indicating their educational efficacy.

Keywords : **Education, Medical** ; **Anatomy** ; **Printing**, Three-Dimensional ; **Craniosynostoses**

Text

Introduction

Craniosynostosis is the premature fusion of cranial sutures. It could be present at birth or develop gradually in the first few months of a child’s life. If surgical treatment is needed, it has to be performed at an early age when the corrective procedures required are less extensive and yield better results (Hudgins, 1993). Identifying skull shape abnormalities is therefore essential for all future practitioners. However, it can be difficult because normal craniofacial anatomy is already complex and unfamiliar. Moreover, this abnormal bone growth can occur in various directions, which can be difficult to visualize spatially during two-dimensional (2D) static learning. In 1851, Virchow described that growth in the plane perpendicular to a fused suture is restricted (Regnault, 1911), and in 1989, Delashow added that sutures adjacent to prematurely fused sutures compensate in growth more than do the sutures that are not contiguous (Delashaw, 1989). Therefore, understanding this complex condition, which can also involve orbital and facial deformities, requires specific learning and training skills such as visuospatial ability. However, because of the rarity of the condition, there is low exposure to these patients during medical studies, which increases the difficulty in acquiring this competency.

Various learning technologies have been developed in the field of craniofacial diseases, and most of them are aimed at neurosurgery residents because the related treatment procedures are associated with a high risk of complications (Grall, 2021a,b). Thereby the concept of simulation, which allows for the recreation of a desired scenario without the actual accompanying risk and the training and improvement of all the necessary skills, has become very popular and essential (Rehder, 2016). Numerous simulation tools have been proposed for neurosurgery training, from animal models to computer-based virtual reality models (Bernardo, 2017). Regarding craniosynostosis, few simulation models are available, and the existing models are associated with some drawbacks, such as the high cost associated with the first anatomic pediatric model proposed by Coelho et al. (Coelho, 2020) or unsuitable animal cadaveric models. Ghizoni et al. (Ghizoni, 2018) developed the first refined simulation model based on a three-dimensional (3D) printed polyamide in 2018. This model facilitated major surgical procedures (osteotomy) with realistic tactile feedback. Despite the emergence of 3D-printed models, few studies have evaluated the benefits of these new tools for pediatric malformations in the education of undergraduate students (Lane, 2020).

The interest in 3D learning support compared to images displayed in 2D for medical students has been shown in several prior randomized studies on improvements in the comprehension of complex anatomical structures, assessment scores, and learner satisfaction in different fields: orthopedics and traumatology (Chen, 2017 ;AlAli, 2018), cardiovascular diseases (Knoedler, 2015 ; Kong, 2016 ; Lim, 2016 ; Garas, 2018 ; Langridge, 2018 ; Nicot, 2019 ; Nicot, 2022), digestive anatomy (Li, 2015 ; Lim, 2018 ; Smerling, 2019), and craniofacial surgery (Chen, 2017 ; AlAli, 2018 ; Lane, 2020). A recent randomized controlled study on a large sample showed the interest in 3D-printed models of craniofacial trauma among undergraduate students (Nicot, 2019 ;

Nicot, 2022). This study highlighted the role of 3D-printed models of craniofacial fractures compared to 2D visualization in facilitating the understanding of complex anatomical structures. Nevertheless, no study has evaluated the impact of these 3D-printed models on long-term retention in undergraduate students. Therefore, the primary aim of this randomized controlled trial was to evaluate long-term retention among undergraduate students who were taught about craniosynostosis by using 3D-printed models. We focused on 3D-printed, low-cost accurate models of the four most common and non-syndromic types of craniosynostosis, namely scaphocephaly, anterior plagiocephaly, brachycephaly, and trigonocephaly. The secondary objective was to evaluate students' feedback and satisfaction about learning with the models.

Materials & methods:

This randomized controlled trial was conducted in adherence to the CONSORT guidelines.

Participants and ethical approval

All 6th-year undergraduate medical students from the Faculty of Medicine & Midwifery at Lille Catholic University were given the opportunity to participate in the study. Students from this level of graduation are not specialized and received the same standardized lectures on craniofacial anatomy, physiology, and pediatrics since their first year. A total of 112 students were eligible for inclusion in this trial, and 97 of them voluntarily accepted to participate in the study. All included students received the same information about the trial process, which was provided by the same tutor. Students who could not take the entirety of the dedicated course or attend both planned sessions were excluded (12 students). Ethical exemption was obtained from the institutional review board of Lille Catholic University (09-Dec-2019). The trial was strictly performed in accordance with the approved conditions.

Trial design

This randomized controlled trial was designed to compare the long-term retention of information about various craniosynostosis patterns by using 3D-printed models versus classic 3D reconstructions displayed in 2D as part of the undergraduate educational medical program. The students were randomized into two groups in the same amphitheater: 3D group (comprising 37 students) and 2D group (comprising 48 students).

All the students benefited from the same standardized course at the beginning of the first session. This course lasted 15 minutes and focused on the definition of craniosynostosis, the Virshow law, and the description of the major signs for recognizing the most common types of craniosynostosis: scaphocephaly, anterior plagiocephaly, brachycephaly, and trigonocephaly. The course was followed by the manipulation of the learning tool associated with the group: a set of four 3D-printed models of craniosynostosis was manipulated by the 3D group (Figure 1) and 2D images of standardized views of 3D reconstructions were proposed for the 2D group (three views for each type of craniosynostosis: one facial view, one profile, and one view from the top). The observation/manipulation time was 15 minutes for all students.

Primary endpoint evaluation

The primary endpoint evaluated the long-term retention of learning information. These evaluations were performed three weeks after the standardized course with manipulation of the randomized learning tool by using a multiple-choice question

(MCQ) form. The test was designed to assess the capability of students to properly recognize different types of craniosynostoses displayed in different non-standardized views in 2D. The assessment was composed of 15 true/false MCQs illustrated by an unusual view of the craniosynostosis described above and by a pre-test to record baseline data about the students' interest in video games, their previous exposure to 3D-printing models, and their spatial representation skills, which were evaluated using a mental rotation test.

After performing the trial assessment, all students of the 3D and 2D control groups (2D group) were offered a lesson on correction using respectively classic 3D reconstructions displayed in 2D and 3D-printed models to avoid any inequity.

Secondary endpoint evaluation

The students' feedback on the 3D-printed models and their satisfaction levels were assessed and evaluated by 5 MCQs and an open-ended question at the end of the teaching experience (Supplementary data, 1). The open-ended question required the students to enumerate three words related to their interest in this learning tool.

Description of 3D-printed models

To obtain data for the manufacturing of our 3D models, we collected computed tomography images of patients aged 18 months with one of these four types of craniosynostosis (single suture): scaphocephaly, anterior plagiocephaly, brachycephaly, and trigonocephaly.

Digital Imaging and Communications in Medicine (DICOM) files were transferred to an automatized segmentation program (Mimics® inPrint 3.0; Materialize NV, USA), which allowed segmentation of these data to obtain a 3D standard tessellation language

(STL) files. A 350-HU threshold was used to select only the bone structures. Models were printed in Plastic ABS by the low-cost 3D UPplus2® printer (Beijing TierTime Technology Co. Ltd) using the following settings: 70% scale, finest quality, 2-layer support, and 0.15-mm-thick layers. Models were printed from the maxilla to the vertex.

Statistical analysis

Descriptive statistics were calculated for the variables of interest. Continuous variables are presented as means and standard deviations (SD). Discrete variables are expressed as frequencies and percentages.

All the available variables were used to evaluate the comparability of the two groups. The principal objective was evaluated by comparing the total score (over 15) between both groups. The chi-squared test was performed to compare categorical variables. The Student two-sample T-test was used to compare means. Tests were 2-sided, and p values less than 0.05 were considered significant. The analysis was performed using Xlstat® software.

Results

Eighty-five sixth-year undergraduate medical students were enrolled in this study. Thirty-seven students were allocated to the 3D group, whereas 48 were allocated to the 2D group. Twelve participants were excluded from the trial. Eighty-five students were thus included in the statistical analysis. The trial flowchart is presented (Supplementary data, 2). Participants in both groups had similar educational achievements and visualspatial skills (appetence for video games, success in the cube-building test, or previous exposure to 3D-printed models). Participant characteristics are shown in Table 1.

The 3D-printed model was considered to be a better teaching material than the two-dimensional support by significantly improving long-term retention. The bivariate analysis estimated the mean score to be 11.32 (2.89) in the 3D group versus 8.08 (2.81) in the 2D group ($p < 0.0001$) (Figure 2).

In the qualitative analysis, the positive feedback (strongly agree and agree) rate exceeded 97% for every satisfaction- and relevance-related question. Almost all students (99%) recommended systematic use of the models in the teaching curriculum. Keywords related to the interest in the learning tool were listed in a word cloud (Figure 3). The three most represented words chosen were as follows: playful (15.6%), visualization (14.6%), and pedagogic (9.6%).

Discussion

This prospective randomized controlled educational trial showed that 3D-printed models of structures with spatial complexity, such as various craniosynostosis patterns, can improve medical students' long-term retention.

Generalizability

3D printing has been extensively used worldwide over the past 30 years, and its use in medicine has rapidly expanded in areas ranging from education to surgical practice. Within the past 5 years, more than 80 papers related to 3D printing and medical education have been published, and many studies have already demonstrated its usage in addition to or instead of traditional educational methods in anatomy (Knoedler 2015 ; Li, 2015 ; Kong, 2016 ; Lim, 2016 ; Chen, 2017 ; Garas, 2018 ; Langridge, 2018). However, assessment of 3D models varies significantly, and well-established education tools representing patho-anatomy remain rare (Knoedler , 2015 ; Li, 2015 ; AlAli, 2017 ; Loke, 2017 ; Lim, 2018 ; Smerling, 2019 ; Lane, 2020).

In the field of craniofacial education, only four randomized controlled trials were published to evaluate the learning efficiency of 3D-printed models in education on undergraduate students (AlAli, 2017 ; Lane, 2020, Nicot, 2022). Chen et al. considered 3D-printed colored skull models to be superior to cadaveric skulls and atlases by facilitating basicranial education in assisting structure recognition (Chen, 2017). In the field of patho-anatomy, Ali et al. showed that the addition of a cleft lip/palate 3D-printed model resulted in a significant improvement in the mean percentage of knowledge gained (AlAli, 2017). Another large randomized controlled study evidenced the interest in 3D-printed models of craniofacial trauma among undergraduate students by pointing out the improved understanding as a result of this learning tool (Nicot, 2019 ; Nicot, 2022). In addition to these craniofacial results, Lane et al. investigated the educational value of 3D-printed models of different craniosynostosis patterns, including scaphocephaly, trigonocephaly, and brachycephaly (Lane, 2020). Their study, which was conducted on undergraduate students, focused on the education of craniofacial pathology and its surgical repair. This study found no statistical difference in post-module quiz scores between groups (PowerPoint® presentation Vs PowerPoint® + 3D-printed models) even though the score improvement was greater in the 3D group. Nevertheless, a qualitative evaluation showed that all students in the 3D group would recommend the use of these models as a teaching aid (Lane, 2020).

Our study showed that the 3D-printed model offered better teaching support than two-dimensional models by significantly improving long-term retention. Literature reviews classically contrast immediate or short-term retention with long-term retention of information. Nevertheless, educational studies are rarely designed to assess long-term retention. As a result, there is no clear definition of long-term retention in the literature review. Kong et al. found that 3D hepatic printed models significantly improved students' understanding of hepatic segmentation and facilitated retention of acquired knowledge 5 days after the teaching module in comparison with a traditional anatomy atlas (Kong, 2016). They suggested that evaluations over more time points would make the comparisons more convincing, especially in relation to the long-term effects. Our study was designed with a more long-term education examination pattern and is the only study highlighting the significant benefit of 3D-printed models in pathologic anatomy on long-term retention in undergraduate students. Another study *focusing* on 3D silicone-based prosthetic mimics of common serious lesions and eruptions previously showed immediate and long-term improvement in lesion recognition (Garg, 2010). In their systematic review focusing on educational games, Blakely et al. found multiple timings for assessing long-term retention, ranging from 1 day to 1 semester (Blakely, 2009). The majority of reported studies performed the post-test survey between 2 weeks and 8 weeks. Therefore, our assessment time of 3 weeks seems consistent with previous studies published in the literature. Moreover, our qualitative analysis was consistent with the results reported by Lane et al. (Lane, 2020), clarifying the primary qualitative advantages of the teaching support.

Interpretation

Trainees learning of craniofacial anatomy are generally limited to picture representation, traditional 2D teaching from imaging, or cadaveric dissection. Moreover, craniofacial pathologies are rare, which limit exposure to the complex patho-anatomies at the hospital and make them challenging to teach. In 2016, Yammine et al. reviewed eight studies comparing 3D physical models with 2D digital images or 3D virtual textbooks or 3D virtual simulators displayed on a computer screen (Yammine, 2016). Their review suggested that physical anatomical models offer significant advantages in terms of the overall knowledge outcome and spatial knowledge acquisition. The mechanisms contributing to this superiority have been explored by Wainman et al., who highlighted that physical models have a large and consistent advantage over images projected on a computer as a consequence of binocular, stereoscopic vision (Wainman, 2018). Moreover, the mental images of the anatomy arising from cadaveric dissection have been shown to be enhanced by touching specimens (Reid, 2019). Thus, haptic models could complement visual sources of information to form a more detailed and understandable 3D mental images. The presentation of congruent multisensory information (visuo-haptic) has been associated with enhanced task performance and learning and memory processes. This phenomenon, known as intersensory facilitation, has been demonstrated in humans (Shams, 2008) and also primates (Carducci, 2020). For example, auditory-visual synesthesia has been suggested to provide a superior memory capacity (Lurija and Solotaroff, 1968). Such results are consistent with the psychological notion of “redintegration” which refers to the fact that an overall state of mind is restored from an element of the whole (Nyberg, 2000). Neuroimaging studies of memory suggest that multisensory exposure enables stimuli to be encoded into multisensory representations and will later activate a larger network of brain areas that underlie this behavioral facilitation (Murray, 2004). Finally, by employing physical interaction, stereoscopic vision, and multisensory facilitation, 3D-printed models seem to bridge the gap between theoretical learning and actual patho-anatomy, enhancing memorization processes. Previous studies on unisensory assessment of haptic system through evaluations in persons with visual impairments showed that 3D-printed models provided specific information related to the tactile perception of the 3D-printed support (Nicot, 2020, Nicot, 2021). Such information support can also be applied in clinical practice to inform expectant parents to apprehend a complex craniofacial malformation (Schlund, 2020). Therefore, a pathological physical model may allow them to better understand the disease process and participate more directly in shared medical decision-making, leading to increased patient satisfaction (Hong, 2020 ; Schlund, 2020).

Limitations

Emerging novel educational interventions require strong experimental evidence to support their use (Torgerson, 2002). The major strengths of our study include the stringent experimental conditions and the high number of participants. Students were randomly separated into two groups and statistical analysis showed the absence of intergroup differences in all the possible biases tested: sex, frequency of video-game playing, previous exposure to 3D printing, and success in the cube building test, which represented previous visuospatial ability.

Studies comparing educational interventions frequently differ in the quality and amount of teaching received. In this study, no other teaching format on this topic was permitted and all the students received the same standardized course and the same teaching time by one single speaker. Plus, participant exchange of key study details are important confounders, and this study minimized the influence of this factor by administering the teaching exposure to the groups simultaneously. Both objective and subjective assessments were adopted. Subjective evaluation allowed us to collect student feedback concerning the trial and their interest in 3D printing for educational purposes by an open-ended question and a post-test survey.

Major limitations mainly include the absence of a pre-module test to precisely evaluate the baseline knowledge between the two groups. However, all the students received theoretically the same course since the beginning of their medical studies. Moreover, knowledge of the grouping and interventions could affect student's performance partially.

Our findings not only provide robust evidence to support the educational efficacy of 3D-printed models but also emphasize their major role in understanding and memorizing spatial structures practically by reproducing the unique complex bone abnormalities present in different craniosynostosis patterns. Nevertheless, additional studies are mandatory to assess the more long-term retention.

References:

AlAli, A.B., Griffin, M.F., Calonge, W.M., Butler, P.E. (2018) Evaluating the Use of Cleft Lip and Palate 3D-Printed Models as a Teaching Aid. *J Surg Educ*, *75*(1),200-208.

Bernardo, A. (2017) Virtual Reality and Simulation in Neurosurgical Training. *World Neurosurg, 106*,1015-1029.

Blakely, G., Skirton, H., Cooper, S., Allum, P., Nelmes, P. (2009) Educational gaming in the health sciences: systematic review. *J Adv Nurs*, *65*(2), 259-269.

Carducci, P., Squillace, V., Manzi, G., Truppa, V. (2020) Touch improves visual discrimination of object features in capuchin monkeys (Sapajus spp.). *Behav Processes, 172*,104044.

Chen, S., Pan, Z., Wu, Y., Gu, Z., Li, M., Liang, Z., Zhu H., Yao Y., Shui W., Shen Z., Zhao J., Pan H. (2017) The role of three-dimensional printed models of skull in anatomy education: a randomized controlled trail. *Sci Rep, 7*(1)*,* 575–11.

Coelho, G., Figueiredo, E.G., Rabelo, N.N., Rodrigues de Souza, M., Fagundes, C.F., Teixeira, M.J., Zanon, N. (2020) Development and Evaluation of Pediatric Mixed-Reality Model for Neuroendoscopic Surgical Training. *World Neurosurg, 139*, e189-e202.

Delashaw, J.B., Persing, J.A., Broaddus, W.C., Jane, J.A. (1989) Cranial vault growth in craniosynostosis. *J Neurosurg, 70*(2), 159-165.

Garas, M., Vaccarezza, M., Newland, G., McVay-Doornbusch, K., Hasani, J. (2018) 3D-Printed specimens as a valuable tool in anatomy education: A pilot study. *Ann Anat, 219, 57-64.*

Garg, A., Haley, H-L., Hatem, D. (2010) Modern moulage: evaluating the use of 3-dimensional prosthetic mimics in a dermatology teaching program for second-year medical students. *Arch Dermatol, 146*(2)*,* 143-146.

Ghizoni, E., de Souza, J.P.S.A.S., Raposo-Amaral, C.E., Denadai, R., de Aquino, H.B., Raposo-Amaral, C.A., Joaquim, A.F., Tedeschi, H., Bernardes, L.F., Jardini, A.L. (2018) 3D-Printed Craniosynostosis Model: New Simulation Surgical Tool. *World Neurosurg, 109,* 356-361.

Grall, P., Ferri, J., Nicot, R. (2021a) Surgical training 2.0: A systematic approach reviewing the literature focusing on oral maxillofacial surgery - Part I. *J Stomatol Oral Maxillofac Surg, 122*(4), 411-422.

Grall, P., Ferri, J., Nicot, R. (2021b) Surgical Training 2.0: A systematic approach reviewing the literature focusing on oral maxillofacial surgery - Part II. *J Stomatol Oral Maxillofac Surg, 122*(4), 423-433.

Hong, D., Lee, S., Kim, T., Baek, J.H., Kim, W.W., Chung, K-W., Kim, N, Sung, T-Y. (2020) Usefulness of a 3D-Printed Thyroid Cancer Phantom for Clinician to Patient Communication. *World J Surg, 44*(3)*,* 788-794.

Hudgins, R.J., Burstein, F.D., Boydston, W.R. (1993) Total calvarial reconstruction for sagittal synostosis in older infants and children. *J Neurosurg, 78*(2), 199-204.

Knoedler, M., Feibus, A.H., Lange, A., Maddox, M.M., Ledet, E., Thomas, R., Silberstein, J.L. (2015) Individualized Physical 3-dimensional Kidney Tumor Models Constructed From 3-dimensional Printers Result in Improved Trainee Anatomic Understanding. *Urology, 85*(6), 1257-1261.

Kong, X., Nie, L., Zhang, H., Wang, Z., Ye, Q., Tang. L, Huang, W. Li, J. (2016) Do 3D Printing Models Improve Anatomical Teaching About Hepatic Segments to Medical Students? A Randomized Controlled Study. *World J Surg, 40*(8), 1969-1976.

Lane, J.C., Black, J.S. (2020) Modeling Medical Education: The Impact of Three-Dimensional Printed Models on Medical Student Education in Plastic Surgery. *J Craniofac Surg, 31*(4), 1018-1021.

Langridge, B., Momin, S., Coumbe, B., Woin, E., Griffin, M., Butler, P. (2018) Systematic Review of the Use of 3-Dimensional Printing in Surgical Teaching and Assessment. *J Surg Educ, 75*(1), 209-221.

Li, Z., Li, Z., Xu, R., Li, M., Li, J., Liu, Y., Sui, D., Zhang, W., Chen, Z. (2015) Three-dimensional printing models improve understanding of spinal fracture--A randomized controlled study in China. *Sci Rep, 5,* 11570-11579.

Lim, K.H.A., Loo, Z.Y. Goldie, S.J., Adams, J.W., McMenamin, P.G. (2016) Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy. *Anat Sci Educ, 9*(3), 213-221.

Lim, P.K., Stephenson, G.S., Keown, T.W., Byrne, C., Lin, C.C., Marecek, G.S., Scolaro, J.A. (2018) Use of 3D Printed Models in Resident Education for the Classification of Acetabulum Fractures. *J Surg Educ, 75*(6), 1679-1684.

Loke, Y-H., Harahsheh, A.S., Krieger, A., Olivieri, L.J. (2017) Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease. *BMC Med Educ, 17*(1), 54-58.

Lurija, A.R., Solotaroff, L. (1968) *The Mind of a Mnemonist: a Little Book About a Vast Memory.* Harvard University Press.

Murray, M.M., Michel, C.M., Grave de Peralta, R., Ortigue, S., Brunet, D., Andino, S.G., Schnider, A. (2004) Rapid discrimination of visual and multisensory memories revealed by electrical neuroimaging. *Neuroimage, 21(*1), 125-135.

Nicot, R., Druelle, C., Schlund, M., Roland-Billecart, T., Gwénaël, R., Ferri, J., Gosset, D. (2019) Use of 3D printed models in student education of craniofacial traumas. *Dent Traumatol, 35*(4-5), 296-299.

Nicot, R., Joachim, S., Levaillant, J-M. (2020) Prenatal tactile three-dimensional ultrasonography for visually impaired women. *Acta Obstet Gynecol Scand, 99*(4), 555-556.

Nicot, R., Hurteloup, E., Joachim, S., Druelle, C., Levaillant, J-M. (2021) Using low-cost 3D-printed models of prenatal ultrasonography for visually-impaired expectant persons. *Patient Educ Couns, 104*(9), 2146-2151.

Nicot, R., Druelle, C., Chazard, E., Roland-Billecart, T., Nuytten, A., Richard, F., Dupré, A., Raoul, G., Ferri, J., Lacroix, D., Gosset, D., Schlund, M., Truffert, P. (2022) Three-dimensional printing model enhances craniofacial trauma teaching by improving morphological and biomechanical understanding: A randomized controlled study. *Plast Reconstr Surg, 149*(3), 475e-484e.

Nyberg, L., Habib, R., McIntosh, A.R., Tulving, E. (2000) Reactivation of encoding-related brain activity during memory retrieval. *Proc Natl Acad Sci USA, 97*(20), 11120-11124.

Regnault, F. (1911). Mécanisme des déformations crâniennes consécutives à la synostose prématurée. *Bulletins et Mémoires de la Société d'Anthropologie de Paris, 2*(1), 181-184.

Rehder, R., Abd-El-Barr, M., Hooten, K., Weinstock, P., Madsen, J.R., Cohen, A.R. (2016) The role of simulation in neurosurgery. *Childs Nerv Syst, 32*(1):43-54.

Reid, S., Shapiro, L., Louw, G. (2019) How Haptics and Drawing Enhance the Learning of Anatomy. *Anat Sci Educ, 12*(2), 164-172.

Schlund, M., Levaillant, J-M., Nicot, R. (2020) Three-Dimensional Printing of Prenatal Ultrasonographic Diagnosis of Cleft Lip and Palate: Presenting the Needed “Know-How” and Discussing Its Use in Parental Education. *Cleft Palate Craniofac J, 57*(8), 1041-1044.

Shams, L., Seitz, A.R. (2008) Benefits of multisensory learning. *Trends Cogn Sci, 12*(11), 411-417.

Smerling, J., Marboe, C.C., Lefkowitch, J.H., Pavlicova, M., Bacha, E., Einstein, A.J., Naka, Y., Glickstein, J., Farooqi, K.N. (2019) Utility of 3D Printed Cardiac Models for Medical Student Education in Congenital Heart Disease: Across a Spectrum of Disease Severity. *Pediatr Cardiol, 40*(6), 1258-1265.

Torgerson, C.J. (2002) Educational research and randomised trials. *Med Educ, 36*(11),1002-1003.

Wainman, B., Wolak, L., Pukas, G., Zheng, E., Norman, G.R. (2018) The superiority of three-dimensional physical models to two-dimensional computer presentations in anatomy learning. *Med Educ, 52*(11), 1138-1146.

Yammine, K., Violato, C. (2016) The effectiveness of physical models in teaching anatomy: a meta-analysis of comparative studies. *Adv Health Sci Educ Theory Pract, 21*(4), 883-895.

Footnotes:

Acknowledgements:

We thank Mr. Louis Béal, Dr. Tony Bagnarossa, Prof. Gwénaël Raoul and Prof. Patrick Truffert for their contribution to this manuscript.

Ethics:

According to French law (Jardé Law) educational research is free of hospital IRB reviewing. Ethical approval was obtained from the institutional review board of Lille Catholic University.

Declarations of interest:

The authors declare no conflicts of interest.

Funding:

Authors declare no funding sources.

Tables and Illustrations:

Table 1: Demographic characteristics and evaluation of previous visuospatial skills of undergraduate medical students.

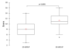
Figure 1. Set of 3D-printed models representing four types of craniosynostosis: scaphocephaly, brachycephaly, trigonocephaly, and plagiocephaly.

Figure 2. Box plot comparing the results of the evaluation for the 2D and 3D groups.

Figure 3. Word cloud representing the keywords chosen by the students related to the interest of 3D-printed models as an educational tool.

Supplementary data, 1: Post-test survey

Supplementary data, 2: CONSORT diagram of enrollment and follow up.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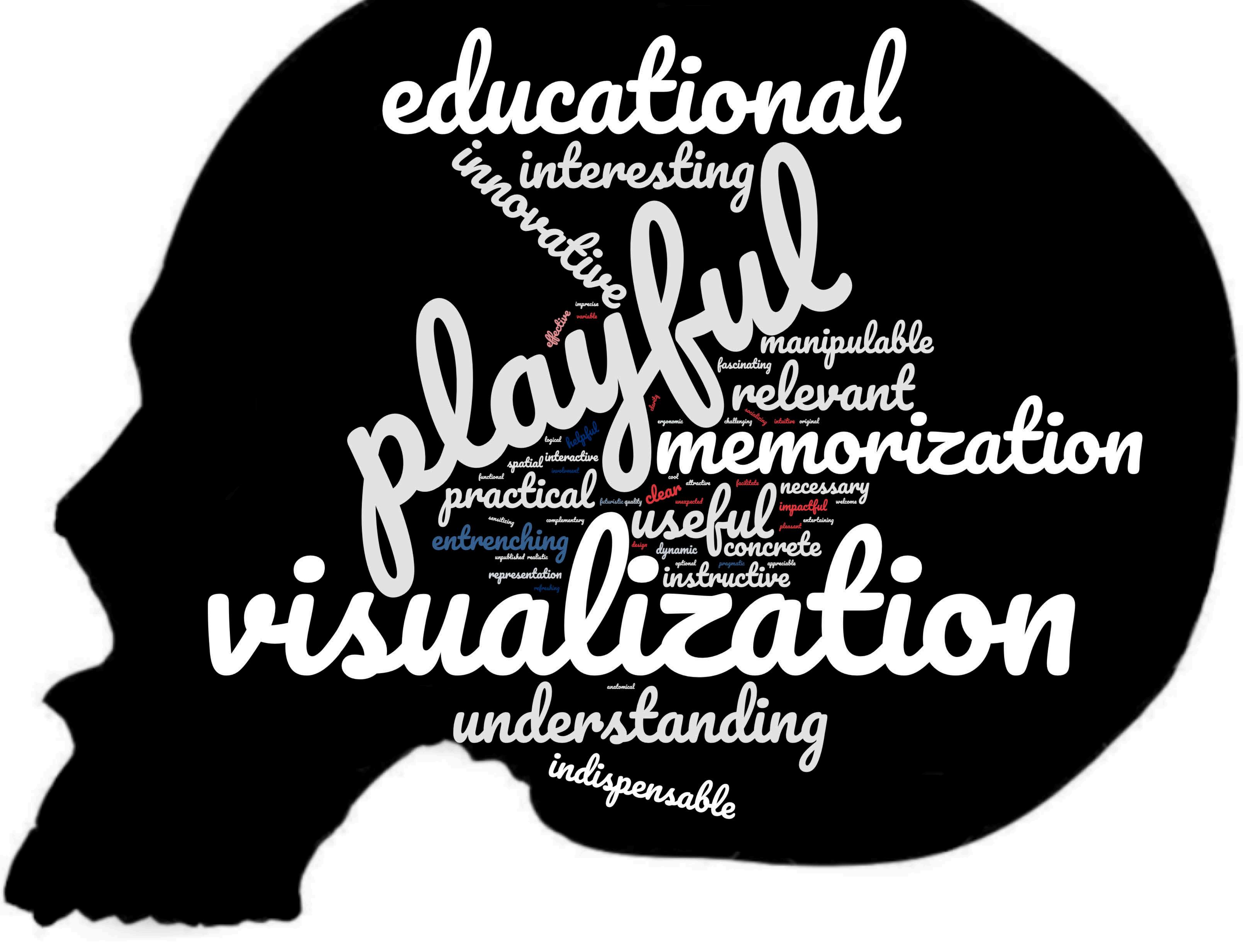

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