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

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1 **Title & Abstract:**

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

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

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10 Introduction

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

16 Materials and Methods

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

24 Results

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

29 Conclusions

30 3D-printed models of structures with spatial complexity such as various
31 craniosynostosis patterns improve significantly medical students' long-term retention,
32 indicating their educational efficacy.

33

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

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58 **Text**

59

60 **Introduction**

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

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

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

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

113

114 **Materials & methods:**

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

117

118 *Participants and ethical approval*

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

128 review board of Lille Catholic University (09-Dec-2019). The trial was strictly performed
129 in accordance with the approved conditions.

130

131 Trial design

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

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

148

149 Primary endpoint evaluation

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

153 (MCQ) form. The test was designed to assess the capability of students to properly
154 recognize different types of craniosynostoses displayed in different non-standardized
155 views in 2D. The assessment was composed of 15 true/false MCQs illustrated by an
156 unusual view of the craniosynostosis described above and by a pre-test to record
157 baseline data about the students' interest in video games, their previous exposure to
158 3D-printing models, and their spatial representation skills, which were evaluated using
159 a mental rotation test.

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

163

164 Secondary endpoint evaluation

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

169

170 Description of 3D-printed models

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

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

178 (STL) files. A 350-HU threshold was used to select only the bone structures. Models
179 were printed in Plastic ABS by the low-cost 3D UPplus2® printer (Beijing TierTime
180 Technology Co. Ltd) using the following settings: 70% scale, finest quality, 2-layer
181 support, and 0.15-mm-thick layers. Models were printed from the maxilla to the vertex.
182

183 Statistical analysis

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

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

193

194 **Results**

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

203 The 3D-printed model was considered to be a better teaching material than the two-
204 dimensional support by significantly improving long-term retention. The bivariate
205 analysis estimated the mean score to be 11.32 (2.89) in the 3D group versus 8.08
206 (2.81) in the 2D group ($p < 0.0001$) (Figure 2).

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

213

214 **Discussion**

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

218

219 *Generalizability*

220 3D printing has been extensively used worldwide over the past 30 years, and its use
221 in medicine has rapidly expanded in areas ranging from education to surgical practice.
222 Within the past 5 years, more than 80 papers related to 3D printing and medical
223 education have been published, and many studies have already demonstrated its
224 usage in addition to or instead of traditional educational methods in anatomy (Knoedler
225 2015 ; Li, 2015 ; Kong, 2016 ; Lim, 2016 ; Chen, 2017 ; Garas, 2018 ; Langridge, 2018).
226 However, assessment of 3D models varies significantly, and well-established

227 education tools representing patho-anatomy remain rare (Knoedler , 2015 ; Li, 2015 ;
228 AlAli, 2017 ; Loke, 2017 ; Lim, 2018 ; Smerling, 2019 ; Lane, 2020).

229 In the field of craniofacial education, only four randomized controlled trials were
230 published to evaluate the learning efficiency of 3D-printed models in education on
231 undergraduate students (AlAli, 2017 ; Lane, 2020, Nicot, 2022). Chen et al. considered
232 3D-printed colored skull models to be superior to cadaveric skulls and atlases by
233 facilitating basicranial education in assisting structure recognition (Chen, 2017). In the
234 field of patho-anatomy, Ali et al. showed that the addition of a cleft lip/palate 3D-printed
235 model resulted in a significant improvement in the mean percentage of knowledge
236 gained (AlAli, 2017). Another large randomized controlled study evidenced the interest
237 in 3D-printed models of craniofacial trauma among undergraduate students by pointing
238 out the improved understanding as a result of this learning tool (Nicot, 2019 ; Nicot,
239 2022). In addition to these craniofacial results, Lane et al. investigated the educational
240 value of 3D-printed models of different craniosynostosis patterns, including
241 scaphocephaly, trigonocephaly, and brachycephaly (Lane, 2020). Their study, which
242 was conducted on undergraduate students, focused on the education of craniofacial
243 pathology and its surgical repair. This study found no statistical difference in post-
244 module quiz scores between groups (PowerPoint® presentation Vs PowerPoint® +
245 3D-printed models) even though the score improvement was greater in the 3D group.
246 Nevertheless, a qualitative evaluation showed that all students in the 3D group would
247 recommend the use of these models as a teaching aid (Lane, 2020).

248 Our study showed that the 3D-printed model offered better teaching support than two-
249 dimensional models by significantly improving long-term retention. Literature reviews
250 classically contrast immediate or short-term retention with long-term retention of
251 information. Nevertheless, educational studies are rarely designed to assess long-term

252 retention. As a result, there is no clear definition of long-term retention in the literature
253 review. Kong et al. found that 3D hepatic printed models significantly improved
254 students' understanding of hepatic segmentation and facilitated retention of acquired
255 knowledge 5 days after the teaching module in comparison with a traditional anatomy
256 atlas (Kong, 2016). They suggested that evaluations over more time points would
257 make the comparisons more convincing, especially in relation to the long-term effects.
258 Our study was designed with a more long-term education examination pattern and is
259 the only study highlighting the significant benefit of 3D-printed models in pathologic
260 anatomy on long-term retention in undergraduate students. Another study *focusing* on
261 3D silicone-based prosthetic mimics of common serious lesions and eruptions
262 previously showed immediate and long-term improvement in lesion recognition (Garg,
263 2010). In their systematic review focusing on educational games, Blakely et al. found
264 multiple timings for assessing long-term retention, ranging from 1 day to 1 semester
265 (Blakely, 2009). The majority of reported studies performed the post-test survey
266 between 2 weeks and 8 weeks. Therefore, our assessment time of 3 weeks seems
267 consistent with previous studies published in the literature. Moreover, our qualitative
268 analysis was consistent with the results reported by Lane et al. (Lane, 2020), clarifying
269 the primary qualitative advantages of the teaching support.

270

271 *Interpretation*

272 Trainees learning of craniofacial anatomy are generally limited to picture
273 representation, traditional 2D teaching from imaging, or cadaveric dissection.
274 Moreover, craniofacial pathologies are rare, which limit exposure to the complex patho-
275 anatomies at the hospital and make them challenging to teach. In 2016, Yamine et
276 al. reviewed eight studies comparing 3D physical models with 2D digital images or 3D

277 virtual textbooks or 3D virtual simulators displayed on a computer screen (Yammine,
278 2016). Their review suggested that physical anatomical models offer significant
279 advantages in terms of the overall knowledge outcome and spatial knowledge
280 acquisition. The mechanisms contributing to this superiority have been explored by
281 Wainman et al., who highlighted that physical models have a large and consistent
282 advantage over images projected on a computer as a consequence of binocular,
283 stereoscopic vision (Wainman, 2018). Moreover, the mental images of the anatomy
284 arising from cadaveric dissection have been shown to be enhanced by touching
285 specimens (Reid, 2019). Thus, haptic models could complement visual sources of
286 information to form a more detailed and understandable 3D mental images. The
287 presentation of congruent multisensory information (visuo-haptic) has been associated
288 with enhanced task performance and learning and memory processes. This
289 phenomenon, known as intersensory facilitation, has been demonstrated in humans
290 (Shams, 2008) and also primates (Carducci, 2020). For example, auditory-visual
291 synesthesia has been suggested to provide a superior memory capacity (Lurija and
292 Solotaroff, 1968). Such results are consistent with the psychological notion of
293 “redintegration” which refers to the fact that an overall state of mind is restored from
294 an element of the whole (Nyberg, 2000). Neuroimaging studies of memory suggest
295 that multisensory exposure enables stimuli to be encoded into multisensory
296 representations and will later activate a larger network of brain areas that underlie this
297 behavioral facilitation (Murray, 2004). Finally, by employing physical interaction,
298 stereoscopic vision, and multisensory facilitation, 3D-printed models seem to bridge
299 the gap between theoretical learning and actual patho-anatomy, enhancing
300 memorization processes. Previous studies on unisensory assessment of haptic system
301 through evaluations in persons with visual impairments showed that 3D-printed models

302 provided specific information related to the tactile perception of the 3D-printed support
303 (Nicot, 2020, Nicot, 2021). Such information support can also be applied in clinical
304 practice to inform expectant parents to apprehend a complex craniofacial malformation
305 (Schlund, 2020). Therefore, a pathological physical model may allow them to better
306 understand the disease process and participate more directly in shared medical
307 decision-making, leading to increased patient satisfaction (Hong, 2020 ; Schlund,
308 2020).

309

310 *Limitations*

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

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

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

332 Our findings not only provide robust evidence to support the educational efficacy of
333 3D-printed models but also emphasize their major role in understanding and
334 memorizing spatial structures practically by reproducing the unique complex bone
335 abnormalities present in different craniosynostosis patterns. Nevertheless, additional
336 studies are mandatory to assess the more long-term retention.

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476 **Tables and Illustrations:**

477

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

480

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

483

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

485

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

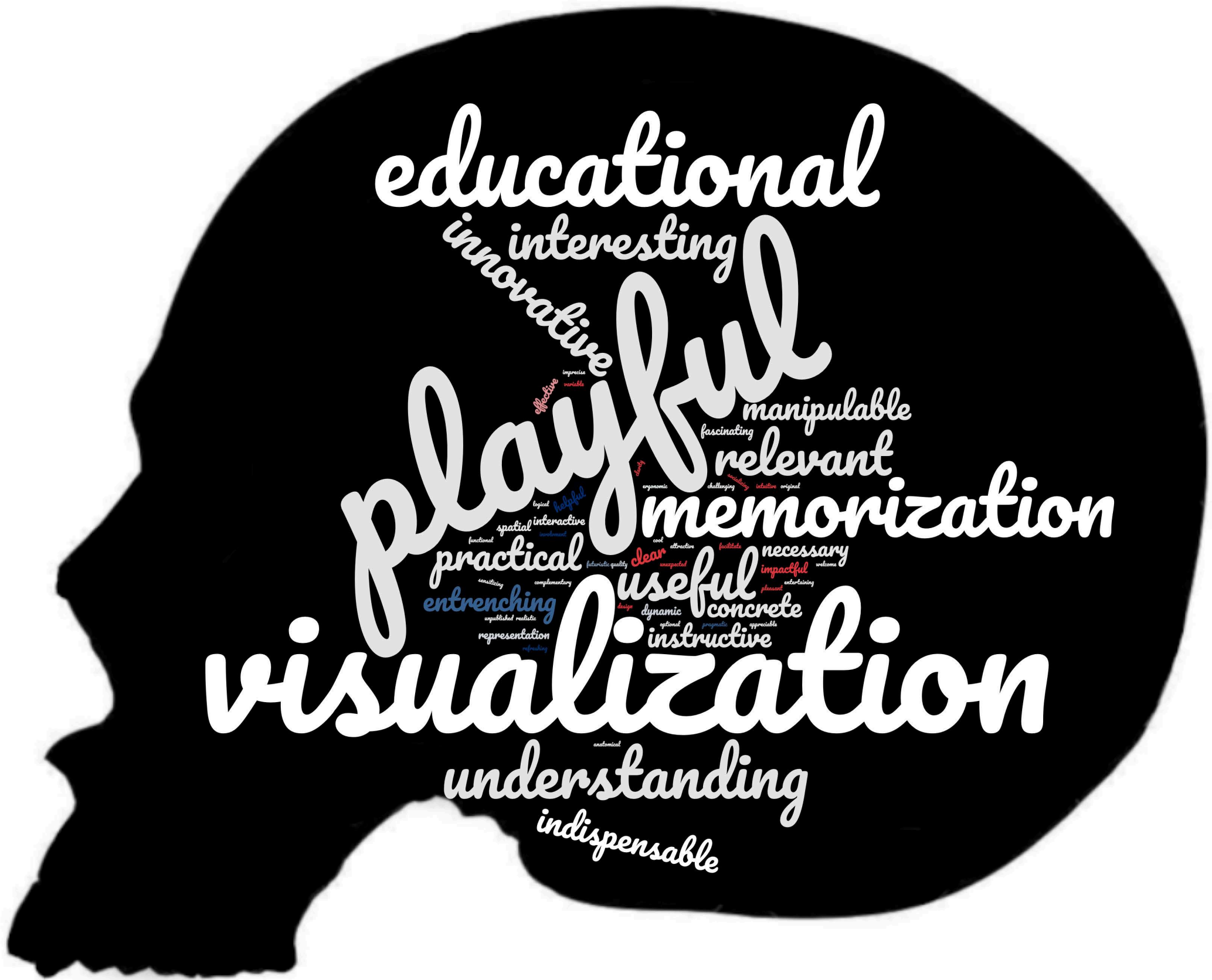
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489 Supplementary data, 1: Post-test survey
490

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







educational

interesting

innovative

playful

manipulable

fascinating

relevant

memorization

practical

useful

necessary

entrenching

concrete

visualization

instructive

understanding

indispensable