Title Page:

Three-dimensional (3D) printing model enhances craniofacial trauma teaching by improving morphological and biomechanical understanding: A randomized controlled study

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Abstract:

Teaching about craniofacial traumas is challenging given the complexity of the craniofacial anatomy, the necessity of good spatial representation skills. To solve these problems, three-dimensional (3D) printing seems to be an appropriate educative material. In this study, we conducted a randomized controlled trial. Our main objective was to compare the performance of the undergraduate medical students in an examination based on the teaching support: 3D printed models versus two-dimensional (2D) pictures. All participants were randomly assigned to one of two groups using a random number table: 3D printed support group (3D-group) and 2D displayed support group (2D-group). All participants completed an MCQ evaluation questionnaire on facial traumatology (first a zygomatic bone fracture, then a double mandible fracture). Sex and potential confounding factors have been evaluated. 432 fifth-year undergraduate medical students were enrolled in this study. 206 students were allocated to the 3D-group, whereas 226 were allocated to the 2D-group. The 3D printed model was considered to be a better teaching material compared with two-dimensional support. The global mean score was 2.36 in the 3D-group versus 1.99 in the 2D-group (p=0.008). Regarding teaching of biomechanical aspects, 3D printed models provide better understanding (p=0.015). Participants in both groups exhibited similar previous student educational achievements and visual-spatial skills. This prospective randomized controlled educational trial demonstrated that incorporation of 3D printed models improves medical students' understanding. This trial reinforces previous studies highlighting academic benefits in using 3D printed models mostly in the field of understanding complex structures.

Keywords: Medical Education, 3D printing, Craniofacial Trauma, Mandibular Fracture

Text:

Introduction:

Learning about craniofacial traumas is fundamental to all undergraduate and graduate students given the impact of head and neck injuries encountered by general practitioners every day in emergency practice [1]. Undergraduate students must be knowledgeable about the anatomy of head and neck bones, the spatial organization of theses bones, their anatomical relationship with sensory organs, the main mechanisms and biomechanical concepts, and the clinical aspects of craniofacial fractures. Teaching about craniofacial traumas is, however, challenging given the complexity of the craniofacial anatomy, the necessity of good spatial representation skills and the implication of some specific biomechanical concepts. To solve these problems, numerous teachers have resorted to three-dimensional (3D) visualization technologies, displaying 3D representations of the craniofacial fractures on a two-dimensional monitor. While these 3D visualization technologies are gaining in popularity due to their reliable realism, studies investigating 3D printed models as a teaching support remain a subject of considerable interest [2,3].

Three-dimensional printing or rapid prototyping is a technology that uses 3D computed-aided design data sets to produce 3D haptic physical models. Its primary advantage is its ability to create almost any complex shape or geometric feature [4]. The cost and size of 3D printers have rapidly decreased over the past decade and it has become ease to access of digital data used to build 3D printed models, democratizing its use in education and medical practice [4–6].

Numerous initiatives in the field of medical education have been particularly undertaken to improve the understanding of anatomy and for surgical simulation [7]. Several randomized controlled trials were published in the literature regarding learning human anatomy and skeletal traumatology [8–11]. Chen *et al.* compared the learning efficiency of 3D printed skulls with cadaveric skulls and atlases. They reported that the 3D printed skull model was an inexpensive, precise and rapidly produced teaching material with many advantages especially in structure recognition compared with traditional education materials [10]. Three-dimensional printing was also evaluated in the context of skeletal trauma, especially spinal [8,11], pelvic and limb fractures [8,9]. The authors noted that 3D printed models may improve medical students understanding of bone spatial anatomy and fractures in some anatomically complex sites [8,11]. Furthermore, Li *et al.* compared 3D printing to conventional educative materials, such as physical models and virtual reality, highlighting that 3D printed models were the most valuable material in complex spinal fracture anatomy education [11].

Given the complexity of craniofacial anatomy and the difficulties for medical students to have a good spatial representation of facial bone pieces and fractures, 3D printing seems to be an appropriate educative material in the field of craniofacial traumas. Although these educative developments have impacted teaching clinically relevant anatomy, evidence-based assessments of this emerging technology in traumatic pedagogy have been limited to spinal or limb fractures. Moreover, all previous studies focused on static 3D printed models, allowing only structure recognition. Facial fractures however include an important biomechanical dimension due to their impact on dental occlusion and the possibility of obstacles on jaw mobility. In this study, we conducted a randomized controlled trial comparing 3D printed models versus classic virtual 3D reconstruction displayed in two dimensions in the education of undergraduate medical students on facial fractures. Our main objective was to compare the performance of the students in an examination based on the teaching support: 3D printed models versus two-dimensional pictures. The secondary objectives involved comparing their performance on questions related to biomechanics and diagnosis.

Material and Methods:

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

Participants and ethical approval:

All 487 fifth year medical undergraduate students at Lille Medical School were eligible for the trial. Eligible participants included all students enrolled in the fifth year program in our medical school.

55 participants were excluded from the study because they did not show up or arrived late for the session. In practice, the test was standardized and timed and any participant arriving late therefore could not be included. Regarding absent students, we have no information on the reason for the absence. Theoretically, all of these students are expected to attend the class sessions. However, the courses are not usually attended by 100% of the students and the rate of absenteeism is consistent with that usually encountered.

In total, 432 students attended the oral and maxillofacial surgery course and were enrolled in this study. All participants entered the trial voluntarily and completed it without loss to follow-up. Ethical approval was obtained from the Institutional Review Board of the Lille

Medical School. Study methods were strictly performed in accordance with the approved guidelines.

About French medical curriculum:

In French medical curriculum, the diagnosis of a craniofacial trauma, including the diagnosis of mandibular fracture, is part of the standard undergraduate curriculum. On the other hand, more specific elements of the diagnosis, such as differentiating stable or unstable fractures or diagnose complex fractures are part of the postgraduate curriculum. The trial focuses herein on the basis diagnosis assessment.

Study design:

This randomized controlled trial was designed to compare understanding of facial fractures with 3D printed models versus classic virtual 3D reconstructions displayed in two-dimensions in the oral and maxillofacial surgery educational program.

At Lille Medical School, fifth years medical undergraduate students are typically taught within 13 teaching groups of 29 to 36 students. All participants were randomly assigned to one of two groups within their usual teaching group using a random number table: 206 participants were assigned to the 3D printed support group (3D-group) and 226 were assigned to the two-dimensional displayed support group (2D-group).

After an introductory lecture explaining the trial, both groups were assigned to two separate classrooms for a one-hour self-directed assessment session using 3D printed (Figure 1a, 1b & 1c) and two-dimensionally displayed models. Exam proctors were assigned to each room to prevent student communication.

All participants completed pre-tests to record baseline data about their interest in video games, previous contact with 3D printing models and spatial representation skills. They then performed the same context-based multiple choice question (MCQ) examination with randomized teaching support.

Context-based multiple choice questions form:

The context-based true/false multiple choice questionnaire with clinical vignettes was specifically designed to distinguish the two teaching materials based on questions related to biomechanical, anatomical, and clinical aspects and through the supposed difference in spatial representation between these two teaching modalities.

The clinical context dealt with a patient first presenting a fracture of the zygomatic bone that occurred in a sport accident followed by a second trauma with a double mandible fracture.

The MCQ questionnaire included 10 questions: 6 questions related to the biomechanical dimension, 3 anatomical questions and 1 diagnostic question (Table 1). The questions were timed, and the student had one minute to answer question.

All participants completed the MCQ evaluation questionnaire. This MCQ evaluation was corrected computationally through automatized MCQ forms. Finally, student academic standing was obtained by obtaining the average score on recent school exams.

Participant demographics and confounding factors:

Sex and potential confounding factors have been evaluated. As mentioned below potential confounding factors included appetence for video games, previous contact with 3D printing models, spatial representation skills, and educational achievements of the students. Appetence for video games was evaluated by asking about playing frequency and the type of video games played, differentiating 3D-based video games, such as first person shooter (FPS) or massively multiplayer online role-playing game (MMO-RPG), from others (video games on smartphone). Previous contact with 3D printing models differentiated students who had previously manipulated 3D printed objects or who owned a 3D printer from students who did not have any significant previous contact with this technology. Spatial representation skills were evaluated using a mental rotation test that involved mentally building a cube from shredded models in two dimensions (Figure 2). Finally, previous educational achievements of the students were obtained by recovering the general average score on recent school exams.

Steps to build the 3D printed models:

The steps used to build the 3D printed haptic model were previously described [12]. A set of three models was printed, including a model of the midface with the zygomatic fracture and two mandible models (normal and fractured mandibles) (Figure 1a, b & c). Each complete set was printed at the 65% scale with 0.2-mm layer thickness for a total duration of 16 hours and 32 minutes and a total weight of 137 g. 3D models were printed in 65% scale because all the printing was performed in our own department with low-cost 3D printers, which only allows to print pieces up to 13x13cm. The set of three models was exactly the same for each student.

Statistical analysis:

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

All the available variables were used to evaluate the comparability of both groups. The principal objective was evaluated by comparing the total score (over 10) between both groups. Secondary objectives were evaluated by comparing the biomechanical score (over 6) between both groups and the diagnostic question (over 1) between both groups. The chi-square test was performed to compare categorical variables. The Welch two-samples 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 R statistical software [13].

Results:

Four hundred thirty-two fifth year undergraduate medical students were enrolled in this study. Two hundred six students were allocated to the 3D-group, whereas 226 were allocated to the 2D-group. Only one participant was excluded from the 3D-group during the trial after randomization because he did not correctly complete the questionnaire, which was rejected during the automatized correction. Four hundred thirty-one students were thereby included in statistical analysis. The trial flowchart is presented in Figure 3.

Participants in both groups exhibited similar previous student educational achievements and visual-spatial skills (appetence for video games or success in cube building test). More students reported at least one previous contact with 3D printed models in the 3D-group. Nevertheless, only one student had prior regular contacts with a 3D printer. Sex-related differences were not observed between the randomized groups. Participant characteristics are shown in Table 2.

Regarding the global score, the 3D printed model was considered to be a better teaching material compared with two-dimensional support (Figure 2). Bivariate analysis estimated the global mean score at 2.36 (1.47) in the 3D-group versus at 1.99 (1.34) in the 2D-group (p=0.008) (Figure 4). Regarding teaching of biomechanical aspects, 3D printed models provide better understanding. The mean score (over 6) of the biomechanical questions set was 1.87 (1.27) in the 3D-group versus 1.59 (1.10) in the 2D-group (p=0.015). Focusing exclusively on the diagnostic question, the success rate was 49,8% in the 3D-group versus 38,5% in the 2D-group (p=0.024).

Discussion:

This prospective randomized controlled educational trial demonstrated that incorporation of 3D printed models of structures with spatial complexity, such as craniofacial fractures, improves medical students' understanding.

Generalizability:

3D printed models have a broad range of potential applications within surgical education and training [7]. Several medical education randomized studies have been performed in the field of cardiovascular surgery [14–19], digestive surgery [20–23], orthopedics and traumatology [9,11,24,25], and craniofacial surgery [8,10,26,27]. These prior studies reported that 3D models globally enhance spatial learning, understanding, and recognition of anatomic structures compared with traditional methods, including images displayed in two-dimensions such as textbook and computer-based learning [8,9,11,15–18,21–27]. Moreover, it has been shown that memory for real objects is significantly better than their two-dimensional representations [28]. On another hand, spatial abilities are relevant predictors for anatomy outcomes, highlighting the influence of presentation formats when spatial abilities are involved as well as the differentiated influence of spatial abilities on anatomical tasks [29]. All the previous studies reported improved medical teaching as measured by increased assessment scores [11,17,22–27] or improved learner satisfaction [10,11,15], highlighting interest in this teaching support for complex anatomy. White *et al.* showed no added benefit for understanding ventricular septal defects but an enhanced comprehension in tetralogy of Fallot due to the increased complexity of this condition and the difficulty of visualizing spatial relationships in congenital heart diseases with multiple components [17]. These results supported the outcomes of Loke *et al.* who noted the complexity and elaborate anatomy of this disease [15]. This observation has also been made in the field of complex bone fractures [8,9,11,14]. Our study confirms these previous results with a highly relevant methodology using a large sample and managing potential confounding factors.

In general trauma teaching, the main advantage of this learning support is the ability to visualize abnormal anatomy. Many undergraduate students have thereby taken anatomy courses with cadaveric dissection. However, most cadaveric specimens have normal anatomy and are not useful for fracture learning [14]. The use of 3D-printed model offers the possibility to contextualize the course by choosing the desired fracture. A 3D printed model can be generated from a stored STL file from an interesting trauma case encountered in the clinical practice or from modification of an existing STL file [12].

A particularity of our study involved the biomechanical aspects of this teaching support given the multipart of the printed models used. In the first part of the presented course, the progressive clinical case focused on a patient with a zygomatic fracture with an important displacement. This type of fracture can induce a mouth opening limitation due to a conflict between the zygomatic arch and the coronoid process of the mandible. On the other hand, in the second part of the case, the patient presented a displaced double mandibular fracture, leading to an altered bite, including contralateral premature occlusal contact and homolateral anterolateral open bite. Both biomechanical abnormalities are very difficult to teach and to understand without the use of dynamic support [30]. Our study is the first to show a significant enhancement of the ability to optimize spatial representation understanding of complex mobile anatomical structures through 3D printed models.

Interpretation:

The literature reports that cadaveric-based teaching, medical imaging and clinical case-based scenarios are the key elements of a musculoskeletal anatomy curriculum, noting that educational performances are not only influenced by the method of cadaveric instruction within undergraduate medical programs [31]. Our study reinforces this assertion by integrating these three educational dimensions into the same teaching support. Three-dimensional printed models include a visual-spatial and haptic dimension that can be manipulated and correctly oriented by the students. It has been suggested that mental images and memorization of the anatomy arising from cadaveric dissection could be enhanced by touching specimens [32]. Haptic models could thereby complement visual sources of information to form a more detailed and understandable 3D mental picture. Rincon-Gonzalez *et al.* suggested that tactile sensation is encoded in a two-dimensional map that undergoes continual dynamic modification by an underlying proprioceptive map [33]. Hansson *et al.* supported this outcome by functional magnetic resonance imaging study showing that sight and touch are linked in a cross-modal arrangement in the somatosensory cortices, suggesting that they are mutually enhancing [34]. Moreover, including these haptics models into a progressive clinical case likely increases understanding by contextualizing hapticovisual data and facilitating precise exploration of specific competences to be acquired by the students, such as biomechanical concepts.

On the other hand, the somatosensory cortex may be dispensable for active detection of objects in the environment [35]. Miller *et al.* highlighted that sensorimotor internal models could anticipate the structural dynamics of an object in motion by mechanically transducing impact location into vibratory motifs that are decoded by the somatosensory system [36]. In our study, the biomechanical score was significantly improved in the 3D-group, suggesting that this group better understands biomechanical concepts, such as the mouth limited opening induced by the coronozygomatic conflict and the occlusal trouble due to both mandibular fractures. These results are concordant with neurophysiological data, suggesting the role of the somatosensory cortex and its coordination with other brain-related structures [35].

In addition to being a large study population, the main strength of our study is its prospective, randomized and controlled methodology, incorporating several potential visual-spatial confounding factors, such as appetence for video games, previous contact with 3D printing models, and spatial representation skills.

On the other hand, individuals improve their spatial skills performance by experiencing spatial training from practicing specific tasks, such as taking drawing classes or playing video games [37]. Daily use of video games and smartphones are indeed producing learners with a new profile of cognitive skills [38,39]. This new profile features widespread and sophisticated development of visual-spatial skills [40]. Therefore, video game players outperform non-video game players in perceptual domains, such as object contrast [41]. They also may have greater short-term memory resources, which may benefit them in tasks requiring static and dynamic object processing. Video game players also have faster perceptual processing skills [42]. Given these elements, video game playing could represent a confounding factor for better scores with 3D printed models. Mental rotation is another potential confounding factor evaluated in our study that exhibits a close relationship. This test has been designed to assess a learner's spatial reasoning skills based on their ability to manipulate two or three-dimensional shapes and patterns. This psychological process, which involves spatially changing the orientation of an object in one's mind, is a representative test of visual-spatial ability that has been explored in the surgical field. Through the use of a spatially complex surgical procedure, such as a Z-plasty procedure, it has been shown that visual-spatial ability is related to initial competence and increases with the spatial complexity of the surgical procedure [43]. On the other hand, it has been suggested that being efficient in learning functional anatomy may require accurate ''visualization of spatial reasoning'' and the ability to use mental imagery associated with mental rotation [44]. Nevertheless, previous contact with video game and mental rotation were not identified as confounding factors in our study, suggesting that 3D object manipulation is poorly influenced by spatial skill predictors.

Moreover, spatial ability exhibits gender differences. On average, females do not perform as well as males on some spatial tasks, especially mental rotation [45,46]. Sex differences favoring males in spatial abilities have also been established in the field of anatomy education [47]. We did not find any gender differences between both randomized groups.

Limitations:

Given the method used, we concluded that the 3D printed model provided a better understanding compared with traditional teaching support but our methodology did not include long-term retention of information assessment for ethical reasons. Highlighting a significant difference between the two teaching supports, we would have disadvantaged the students of the control arm in subsequent school exams. Therefore, after performing the trial assessment, all the students of the control arm were offered lesson on a correction of the clinical case using 3D printed models to avoid any inequity. Moreover, Lille Medical School students are subject to continuous monitoring with regular exams. It would not have been possible to wait long enough to evaluate long-term information retention before allowing students in the control arm to catch up. Considering that it is one of the most important criteria of a teaching method, the absence of long-term retention assessment constitutes the major drawback of this trial.

Another major point was that mean scores achieved by the medical students on the MCQ questionnaire were relatively bad. In order to avoid a selection bias consisting in the fact that some students better worked on the subject than others before the trial, we chose to carry out it in the form of a pre-test. As a result, no student had previously had a specific lesson on this topic. The two groups were therefore not bad, but just naive. This is likely the main point that led to this score. Another element was that assessment consisted in MCQ, in which the answer was counted "correct" for each question only when the 5 items of the MCQ were checked correctly. This probably led to a significant reduced mean score.

Finally, no qualitative feedback was formally collected during this study. Nevertheless, students made several important comments in both randomized groups. All students reported that the 3D printed models (after the control group was allowed to catch up using the 3D models) seemed intuitive at first, but students occasionally experienced difficulty articulating the skull model using the mandible model given the lack of accuracy of the temporomandibular joints 3D reconstruction. Given that 3D printing was performed from bone segmentation from computed tomography, printed models did not include soft tissues, such as temporomandibular joint disc or joint capsule, thus it was difficult for some students to obtain good dental occlusion. This trouble had been anticipated, and a specific explanation on how to obtain the correct dental occlusion was provided during the introductory lecture.

Conclusion:

This prospective randomized controlled educational trial demonstrated that incorporation of 3D printed models of structures with spatial complexity, such as craniofacial fractures, improves medical students' understanding. Including 3D printed models into a progressive clinical case increases understanding by contextualizing hapticovisual data and facilitating precise exploration of specific competences to be acquired by the students, such as biomechanical concepts.

Authors report no conflict-of interest.

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Tables & Figures:

Table 1 : Summary of explored concepts in multiple choice questions

Table 2: Participant demographics

Figure 1: Set of three 3D-printed models, including a model of the midface with the zygomatic fracture and two mandible models (normal and fractured mandibles). Models used in the first part of the clinical case are presented in Fig. 1a. After adding 2 additional mandibular fractures via Computed Aided Design and Manufacturing (CAD-CAM) freeware, we printed a fractured mandible used in the second part of the clinical case (Fig. 2b and c).

Figure 2: Mental rotation test

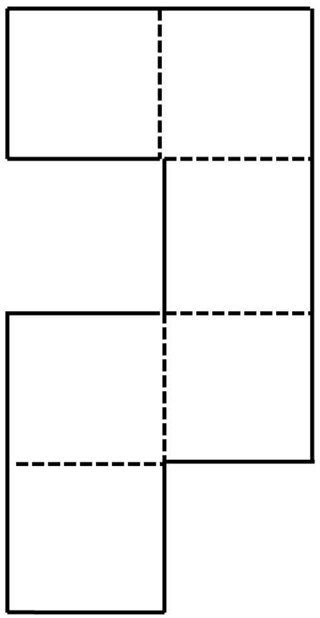
Figure 3: Flow chart of the randomized controlled trial

Figure 4: Box plot representing the global mean score to MCQ in both groups. Bivariate analysis estimated the global mean score at 2.36 in the 3D-group versus at 1.99 in the 2D-group (p value=0.008)

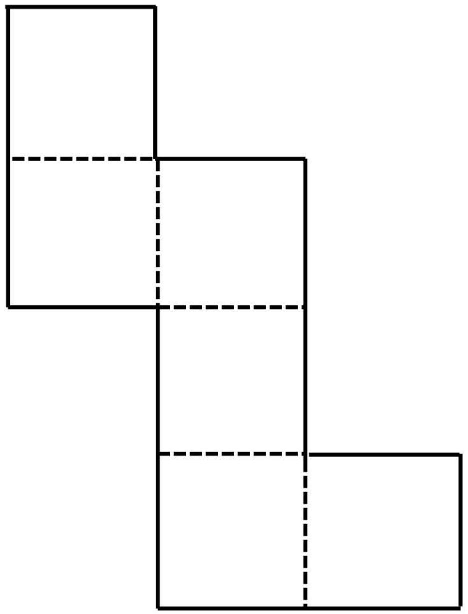
Table 1. Participant demographics

	Population study (n=431)	Control (n=226)	3D haptic (n=205)	p value
Video games playing frequency				*0.744*
Never	134 (31.1%)	64 (28.3%)	70 (34.1%)	
<1 a month	80 (18.6%)	43 (19.0%)	37 (18.0%)	
>1 a month	57 (13.2%)	30 (13.3%)	27 (13.2%)	
> 1 a week	101 (23.4%)	57 (25.2%)	44 (21.5%)	
Every day	59 (13.7%)	32 (14.2%)	27 (13.2%)	
Playing 3D video games (RPS /MMO-RPG)	218 (50.6%)	115 (50.9%)	103 (50.2%)	*0.971*
Success in the cube building test	183 (42.5%)	94 (41.6%)	89 (43.4%)	*0.776*
Prior contact with 3D printing	81 (19.9%)	29 (14.3%)	52 (25.5%)	*0.007*
Sex				*0.686*
Male	188 (43.6%)	96 (42.5%)	92 (44.9%)	
Average general results to previous exams	13.1 (1.74)	13.1 (1.72)	13.0 (1.77)	*0.502*

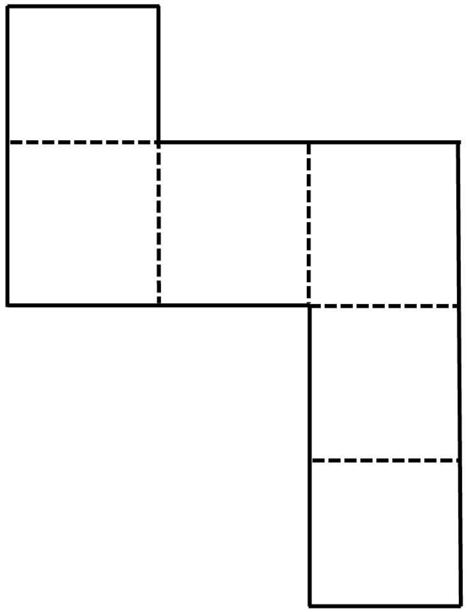
All values are expressed as number (with %) except for average general results to previous exams, which are expressed as mean (with SD).



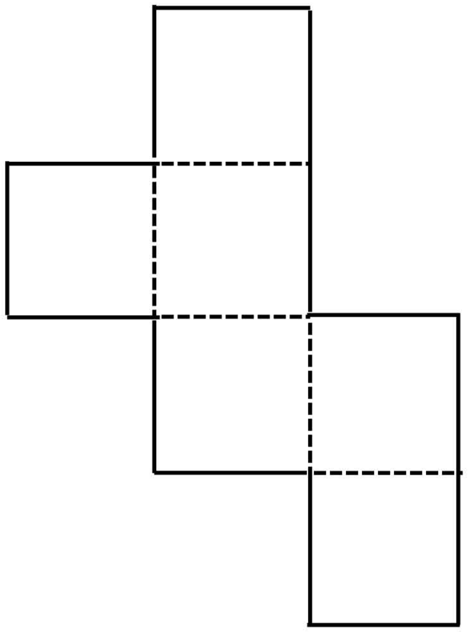
A



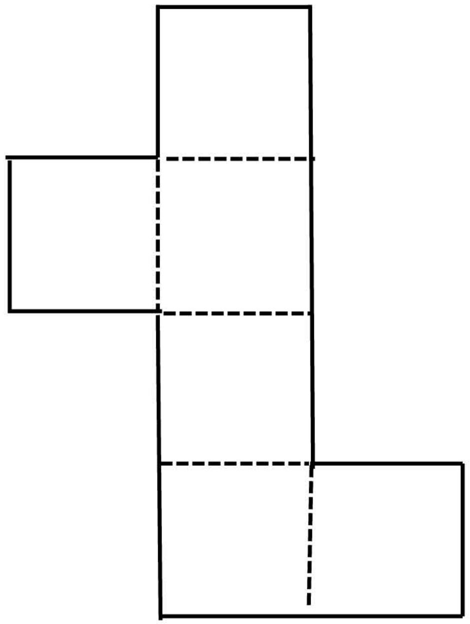
B



C

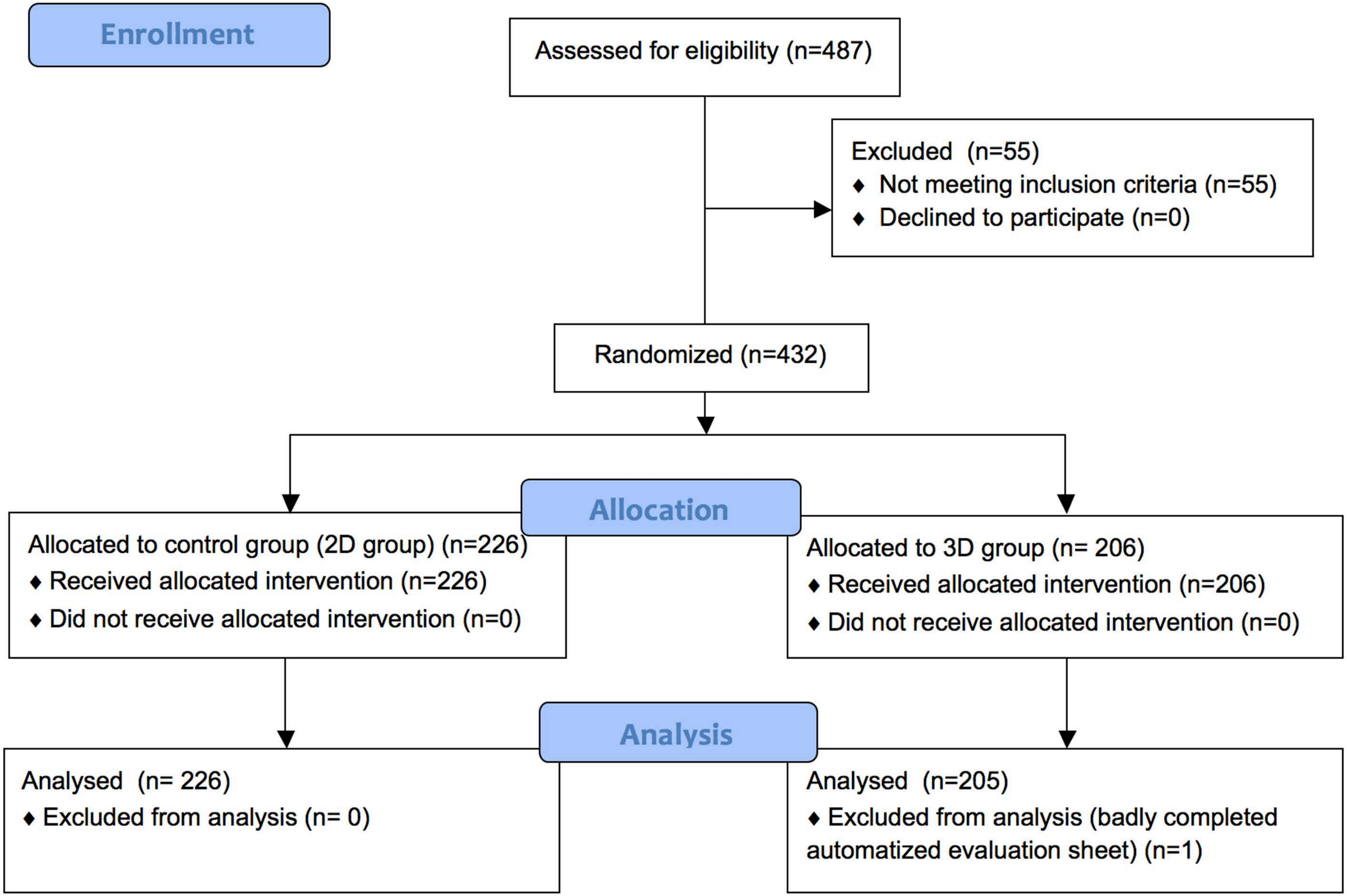


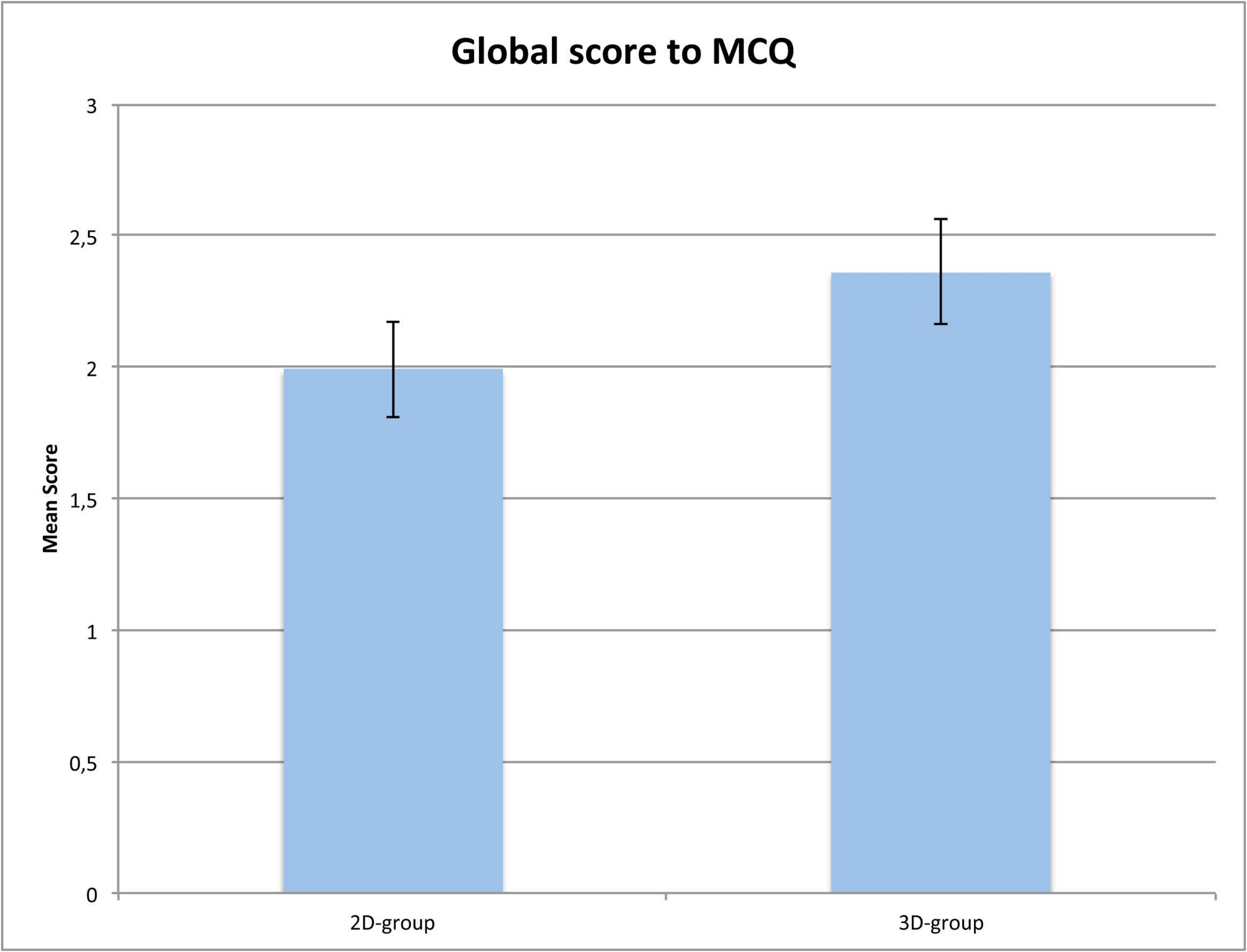
D



E

CONSORT Flow Diagram




Global score to MCQ
Mean Score
3
2,5
2
1,5
1
0,5
0
2D-group
3D-group