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Short Communication

A preliminary study into the impact of using three-dimensional models in forensic anthropology learning and teaching

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ABSTRACT

Forensic anthropology has traditionally relied on two-dimensional (2D) images, such as photographs and sketches, to perform analyses, and disseminate findings. However, as 3D imaging technology advances, it has become more widely implemented into forensic anthropology analysis and practice. Teaching and learning in forensic anthropology still often relies on 2D images, but increasingly three-dimensional (3D) models are available to be used by students training in anatomy and osteology. Additionally, 3D models have been found to be beneficial to comprehension in other contexts within forensic anthropology, such as in the courtroom. The use of these models in the teaching of forensic anthropology is not yet widely implemented and more importantly, the impact on learning is not yet understood. The use of 3D imaging and visualisation in other educational contexts has seen positive results, for example in medical training. To explore this further, a study was conducted using an online activity to compare the comprehension scores of students educated using 2D textbook style images or 3D models on Sketchfab. The results showed that the use of 3D images was not detrimental to comprehension. Students using the 3D models were more consistent in their performance and reported an increase in confidence regardless of prior experience. The results of this study are of particular importance when distance learning due to the COVID-19 pandemic which means that students cannot always learn in a laboratory environment.

1. Introduction

Forensic anthropology applies the anatomical study of the human form to aid in forensic investigations of both living and dead individuals. Training in this discipline relies heavily on an understanding of the healthy and pathological form, function, and development of human skeletal anatomy. Traditionally, skeletal collections provide the basis of osteology laboratory activities which are supplemented with lecture materials, journal articles, and textbooks such as *The Human Bone Manual* [1] etc. As in many fields of study, the teaching materials presented outside of or in accompaniment to the laboratory setting tend to be two dimensional (2D) in their nature. Digital photographs, line diagrams, and sketches are, after all, highly accessible, inexpensive to produce, and easily shared physically or via virtual learning environments. Both experienced practitioners and inexperienced students can use these images alike.

In forensic anthropology training, 2D photographs have, however, been described as inadequate and insufficient educational resources. Bones are not uniform in their texture or simple in their shape, they are curved with many micro and macro features. Poor quality images or poor lighting can erroneously represent such features in human remains [2] causing shadows and distortions that can limit the information forensic anthropologists can gather from them. Moreover, the interpretation of images depicting anatomical material can be difficult when presented in two-dimensions, due to limited depth information [3]. Errickson et al. [4] acknowledge that 2D image interpretation is a complex and difficult process. In photographs, since the 3D object is represented as a 2D image, the 2D image must be processed in the brain as a 3D object [2]. Given that 2D image information is processed in a different hemisphere of the brain to 3D information [5], the extra processing adds complexity to interpretation and difficulty in long term memory storage of information in photographs [6]. Fundamentally, information visually presented in a 2D image of a bone is simplified, altered, and therefore not identical to the bone itself [3]. This could potentially increase the difficulty of understanding and long-term recall of visual representations of human remains in forensic anthropology

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students.

Technological advancement has increased the use of three-dimensional (3D) imaging in many disciplines including forensic anthropology. The use of 3D models in forensic anthropology has been reported in literature to overcome some of the issues associated with 2D images [7]. 3D virtual learning methods have been reported to facilitate students to learn experientially and in a constructive, logical way [8]. In a medical education context, the application of 3D imaging and visualisation technologies improved test scores of anatomy students [9] as well as student feedback [10]. Even in forensic anthropology, the discussion of the role of 3D imaging technologies combined with immersive virtual reality methods has already begun [11]. Within a forensic context, Massive open online courses (MOOCs) such as Durham's Forensic Anthropology and Archaeology (https://www.futurelearn.com/courses/forensic-archaeology-and-anthropology) have also started using 3D virtual models to create an online 'osteology lab experience' with positive learner feedback.

While 3D models are generally regarded positively, the impact of using 3D images in the education of forensic anthropologists is largely unknown. Currently, there is not an empirical demonstration that shows the benefits of its application [2] and Ballantyne [3] highlights that educators must consider how 3D images are used in education; it can be potentially harmful to implement new learning methods and technologies without a deeper understanding of their impact [12]. Carew and Errickson [13] follow this up further, suggesting that a representative understanding of the limitations, challenges, and advantages of techniques within forensic anthropology are needed, which is relevant to education as well as practice of forensic anthropology. Exploring this aspect of forensic anthropology training is therefore necessary, and indeed became more urgent as of March 2020 when we entered in the COVID-19 global pandemic, reducing the opportunity for lab-based training using physical teaching materials and forcing a rapid change upon higher education practises [14,15]. To protect the core elements of student education and meet the course accreditation standards, online equivalents of traditional osteology laboratory sessions were presented. In many cases, this was achieved using open access 3D models of human remains from repositories such as SketchFab (https://sketchfab.com/).

In response to the issues highlighted with 2D materials, and the push to create interactive and engaging virtual learning environments, this preliminary research set out to explore the impact of 3D models on forensic anthropology teaching and learning. Specifically, we address the following questions: 1) Can the use of 3D models improve the comprehension of student forensic anthropologists? 2) Does learning with 3D models change student perceptions of their comprehension? 3) Are 3D images most useful when implemented alone or in conjunction with 2D images?

2. Method

2.1. Initial feedback

During the teaching of a first-year undergraduate anatomy and physiology module at Teesside University, 3D digital models of skeletal anatomy were used to supplement face-to-face seminars (pre-pandemic). General feedback on the use of the models was obtained from self-selecting volunteer students enrolled on the module, via a SurveyMonkey Inc. (https://www.surveymonkey.com) questionnaire (SI 1). Using both open and closed questions, students were asked about their learning experience, perceptions, and preferences when using 2D and 3D models during the module. The responses were coded based on the most prominent themes raised, following the methodology outlined by Chapman et al. [16].

2.2. Learning activity study

A second study was then designed to explore the impact of 3D model use on student comprehension more directly. This study consisted of learning activities and quiz disseminated via SurveyMonkey (SI 2–5). Volunteer students were recruited through virtual learning environment module announcements. Only relevant modules were targeted to ensure the volunteers met the necessary prerequisites as follows: students had to have had at least one lecture in forensic anthropology or human anatomy to ensure recognition of human bone and minimise the potential distressing impact of viewing skeletal human remains. The participants however were not required to have extensive knowledge of forensic anthropology as the study aimed to teach participants new information and test this newly acquired knowledge. All participants provided informed consent and received a de-brief email (SI 6). Ethical approval was provided by the Teesside University ethical review committee (200/19).

Once registered, participants received the online materials and instructions to complete two online activities through the platform, SurveyMonkey. The responses to the online activities were anonymous and the materials were sent to participants in groups rather than individually to avoid the researcher being able to attribute a score or response to a specific participant. Students were systematically assigned to be in either a 2D image (2D group) or a 3D model group (3D group), based on order of registration to ensure equal distribution of participants between the two groups. Depending on their assigned group, participants received either the 2D or 3D reference material. Before familiarising themselves with the reference material, participants were asked to self-evaluate their confidence in their understanding of forensic examination of skeletal material. The same question was then put to the participants again at the end of the learning activity and subsequent quiz to gauge any changes in participant perceptions.

The reference material consisted of a briefing, stepwise instructions, and a short description of three different bone pathologies that may be encountered in an osteological examination: osteoarthritis, osteomyelitis, and osteoporosis. Each pathology description was accompanied by either two different 2D photographs [1,17–23] or web links to two different 3D models on Sketchfab to exemplify the pathology (See SI 7). The 3D models on Sketchfab were generated from real human remains and therefore realistically reflect the type of material that professional forensic anthropologists encounter. While the model capture methods varied, it should be noted that the participants of this study could only view the external surface, regardless of whether internal structures were captured/present in the model. Permission was given by each of the owners/creators to use each of the Sketchfab models in this study. A full list of the Sketchfab models and 3D model creators used in this research is as follows, Durham Archaeology (https://sketchfab.com/DurhamArchaeology), Virtual Curation Laboratory (https://sketchfab.com/virtualcurationlab, models courtesy of National Museum of Health and Medicine – Silver Spring, Maryland), Museum of London Impact Project (https://sketchfab.com/jbekvalac), Digitised Diseases Project (https://www.digitiseddiseases.org/alpha/).

After reviewing the learning materials (2D group SI 2; 3D group SI 3), participants were then asked to take a short online quiz (activity 1; SI 4) through SurveyMonkey, designed to test their new knowledge of the bone pathologies. Both groups received the same quiz, which consisted of a question asking participants to report their course and year of study, and their confidence in forensic anthropology, followed by the six quiz questions. The quiz questions presented either a 2D image (2/6), a 3D model (2/6), or both a 2D image and 3D model (2/6) and required the participant to identify the bone pathology in the image and/or model through a multiple-choice question and then to briefly explain their decision. The 3D models were presented in the form of a screen capture from a Sketchfab model, essentially showing a video of the model rotating from Sketchfab, but without showing model title or details which could have given away answers to the multiple-choice questions. Participants were then asked to fill out a short feedback form (activity 2; SI 5) which asked them to report their confidence in forensic anthropology after completing the quiz, whether they thought that the learning

materials they were provided (2D or 3D) increased their confidence and whether the 2D/3D material alone or in combination were adequate to aid their comprehension.

The data produced in the online activities were analysed both quantitatively and qualitatively. With the empirical data, the number of correct answers and perceived knowledge scores were analysed. Firstly, to determine the impact of 3D models compared with 2D images on the comprehension level of the student participants a Wilcoxon Rank-Sum test was used to establish if the means of the two groups differed. The statistical analysis was performed using statistical software, SPSS (version 26). To determine the impact of 3D models compared with 2D images on the perceived comprehension and confidence of student participants, the average change in perception scores (comparing the before and after confidence scores) and the number of participants who reported they agreed or strongly agreed that the activity made them feel more confident in identifying bone pathology were calculated. Thirdly, to determine the impact of using 3D models alone or in conjunction with 2D images, the average number of correct answers for each group (2D and 3D) on each question type was calculated (2D, 3D, or a combination of both).

As with the initial feedback survey, the qualitative data was analysed using a coding method [16] to categorise the statements and comments into positive, negative, and neutral statements, to then quantify the number of statements in each category for both the 2D and 3D groups. The data was analysed separately to the question scores in this context, so that the analysis of the themes was not biased with knowledge of participant scores. This was performed on the data regarding the adequacy of the image types alone and in combination, as well as on the perceived comprehension and confidence data directly and in the analysis of the language used to explain the reason for the pathology identified in relation to confidence.

3. Results

3.1. Initial feedback

A total of 18 students responded to the initial survey. 2D images received more negative comments which were focussed on a lack of clarity and realism, whereas 3D images received more positive comments, highlighting improved image quality, and finding the opportunity to rotate bones through three-hundred and sixty degrees useful. Neither 2D images nor 3D models received any neutral comments but both imaging modalities were reported to be useful when used in conjunction. This was reflected in the student's preferences. Over half of the participants preferred learning using the 3D models whereas the remaining students preferred a combination of 2D images and 3D models. None of the students reported that they preferred the use of 2D images alone in their lectures (Fig. 1). When asked to explain their preferences (Table 1), comments outlining a preference for 3D models were primarily focused on visualisation, reporting the 3D models provided more realism, detail, and depth in an image that is not complete. The comments which noted a preference for the use of 2D images and 3D models used in conjunction highlighted that 2D images were good when used as a foundation to theoretical concepts, and the 3D models when used to process and apply this information. Additionally, student comments indicated that having a targeted 2D image and a 3D model which can show multiple angles and perspectives together was useful.

3.2. Learning activity study

A total of 12 students (6 per group) took part in the learning activity. Students were enrolled on either the Forensic Science (1), Crime Scene Science (5), Human Biology (1), Digital Forensics (2), Health Sciences (1) Biomedical Sciences (1) or Forensic Biology (1) and were in either their first (1), second (4), or third (7) year of their 3-year undergraduate

Table 1
A representation of the themes from responses relating to the use of 2D and 3D imaging in forensic anthropology lectures and teaching.

Imaging Modality	Themes within positive responses (number of responses within this theme)	Themes within negative responses (number of responses within this theme)
2D	Foundation to theoretical concept understanding (1)	Single perspective/ fragmented view (3) Lack Realism (1) Bone articulation not visible (1)
3D	Realism through details (2) Improved image quality (2) Application to real life scenario Perspective (1) Movement through 360 degrees (4) Useful for learning (1)	Cost of software (1) Accessibility of information (2) Not replacing osteological material (1)
Both	Both 3D and 2D are useful in combination (1)	Neither replace real osteological material (1)

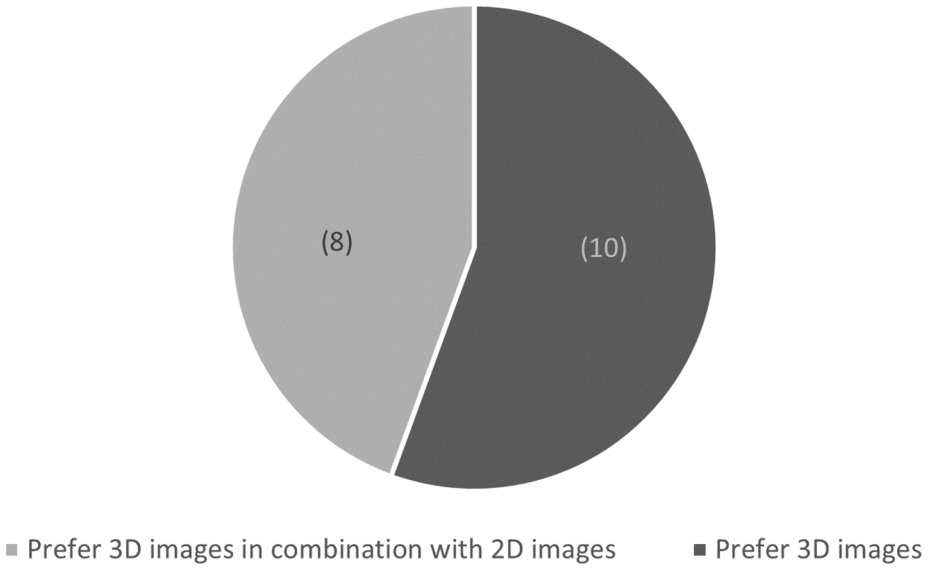

Figure 1. Distribution of student preferences for learning materials from initial feedback responses.

degree.

i) Comprehension (Activity 1):

Students from the 2D group had an average score of 3.5/6 correct answers, whereas the 3D group had an average of 3.0/6 correct answers. As such, there was little difference in average student performance between the 2D group and the 3D group. Indeed, the results from the Wilcoxon Rank-Sum test were not statistically significant ($P = 0.6144$ at a significance level of $a = 0.05$) and we therefore do not have enough evidence to claim that the scores of the two groups are different. However, with a lower standard deviation, the students from the 3D group were more consistent in their scores (Fig. 2).

When students were asked for their reasoning behind their pathology identification, for the most part positive language was used in their responses (Fig. 3). Out of the three types of question, the combination question type received the fewest negative responses (zero).

Although participant scores did appear to increase with participant year of study, due to limited sample size, the authors recommend this trend be followed up in a larger-scale study to examine the influence of experience on the impact of using 2D and 3D learning materials.

ii) Perceived comprehension and confidence (Activity 1 and 2):

Students from both groups generally felt some or a slight lack of confidence in their knowledge of forensic anthropology. Most students answered neutrally or somewhat agreeing/disagreeing with the statement that they had confidence in their knowledge of forensic anthropology, before commencing the activities. For the most part, these scores did not change after the activities were completed (Table 2). Only one participant from the 3D group reported a negative change in their knowledge confidence, whereas one participant from the 2D reported an increased knowledge confidence. From the 2D group, two of the six participants reported that using 2D material increased their forensic anthropology knowledge confidence whereas four of the six students in the 3D group reported that using 3D material increased their knowledge confidence (Table 3).

When the students were asked to explain their knowledge-confidence scores (activity 2), the 2D group tended to use more negative language than the 3D group (Table 4). Further when asked about the adequacy of the learning materials, students reported that the 2D images were less distracting and useful to build on theoretical concepts, but that the 3D images were useful to be able to see the entire structure of a bone. There were also reports that the combination questions were confusing from the 2D group participants and one participant from the 3D group felt that the 2D images were not useful to them due to their inexperience. Finally, participants from both groups felt that they could not comment on their perceived comprehension until they were aware of their scores.

iii) 2D versus 3D alone or in conjunction.

Breaking down which group scored best on which type of question, our preliminary data shows the participants in the 2D group scored best on the 2D questions, whereas the 3D group scored best on the 3D questions (Fig. 4). The average score for both groups for the questions which used both 2D and 3D material was the same. With only two questions representing each question type, the authors recommend a larger-scale study to statistically test the impact of question types further.

When asked about the adequacy of the learning materials (activity 2) participants from the 3D group tended to report that 3D models alone were adequate, whereas students from the 2D group tended to report that 2D models alone were not adequate. For the most part participants from both groups agreed that using 2D images in conjunction with 3D models would be adequate in aiding their comprehension of bone pathologies when examining human remains (Table 5).

When asked to explain their answers, the 3D group tended to use more positive statements whereas the 2D group used either negative or neutral statements (Table 6). In particular, students in the 3D group felt 3D learning materials in isolation were adequate due to their detail, realism, and 360 view. When asked on their views of 2D and 3D materials being used in conjunction with each other, students were mostly positive regardless of which group they were in (Table 6). Only one student of 12 mentioned that using both could potentially be confusing.

4. Discussion

This study was designed to address three research questions; 1) Does using 3D models improve student comprehension? 2) Does using 3D models improve perceived comprehension and confidence? 3) Are 3D models most effective when used alone or in conjunction with 2D images?

4.1. 3D models were not detrimental to student comprehension

With no statistical difference between the average score of the 2D group and 3D group participants, the present research suggests that the use of 3D models does not have a direct positive impact on comprehension level i.e., participants did not score higher in the quiz when using 3D models in their learning material compared with 2D images.

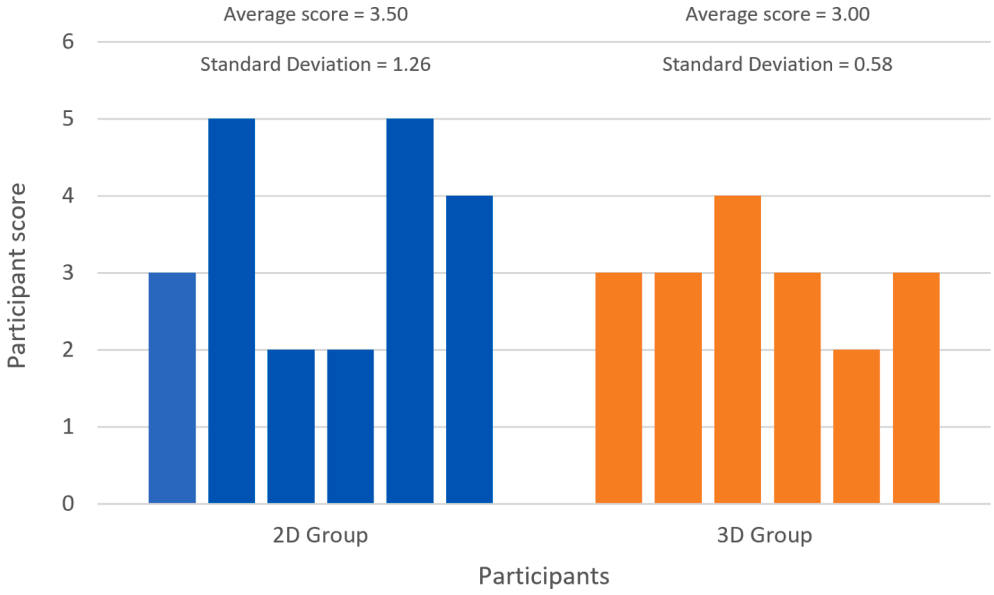

Figure 2. Mini quiz learning activity student scores out of six from both the 2D (blue) and 3D (orange) groups.

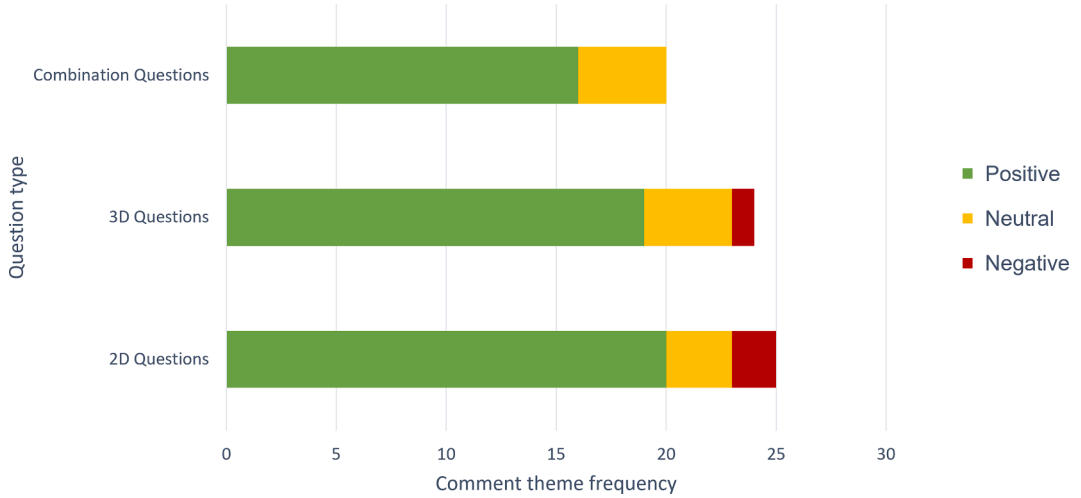

Figure 3. Distribution of positive (green), neutral (yellow), and negative (red) statement themes from the participants in response to activity 1, split by question type.

Table 2
The change in perceived comprehension and confidence, pre- and post-activity, as reported by students when asked whether they had confidence in their knowledge of forensic anthropology.

Group	Participant	Level of agreement pre-activity	Level of agreement post-activity
2D	1	Disagree	Neutral
	2	Disagree	Disagree
	3	Neutral	Neutral
	4	Agree	Agree
	5	Agree	Agree
	6	Neutral	Neutral
3D	1	Neutral	Neutral
	2	Agree	Neutral
	3	Agree	Agree
	4	Disagree	Disagree
	5	Agree	Agree
	6	Disagree	Disagree

Table 3
Number of participants who reported the activity made them feel more confident.

Group	Number of participants who reported activity made them more confident (out of 6) (either agreed or strongly agreed)
2D	2
3D	4

This result differs from the work Lim et al. [9] who found 3D images improved test scores of anatomy students. A much bigger sample size was used by Lim et al. [9] compared to the study presented here and the 3D models in this study were presented on a 2D computer or tablet screen, which should be considered when comparing results. The study by Lim et al. [9] found 3D models did improve comprehension in a teaching context, meaning that there could be further factors influencing how 3D models are used by students.

While the use of 3D models in the reference material did not improve the scores of students, there was a positive impact in terms of consistency. Not only were they not detrimental to participant learning but the scores of the 3D group were more consistent than those in the 2D group. Consistency could suggest more effective learning and reduced 'guessing'. When giving expert witness testimony, a forensic anthropologist that is more consistent is more credible [24], therefore implementing 3D models into teaching and learning can contribute towards best practice, producing credible expert witnesses.

Table 4
A representation of the themes within the positive, neutral, and negative categories of responses relating to perceived comprehension and confidence.

Group	Themes within positive responses (number of responses within this theme)	Themes within neutral responses (number of responses within this theme)	Themes within negative responses (number of responses within this theme)
2D	Least distracting (1)		Not much help due to inexperience in field (1)
	Build on theoretical material from lectures (1)		Difficult to tell difference between pathologies (1)
			Unsure of test scores (perceived knowledge based on score) (1)
3D	Whole structure visible (1)	Info on pathologies beforehand was helpful (1)	Unsure of test scores (perceived knowledge based on score) (1)
	Activity was informative of concepts (1)	3D helpful but combination was confusing (1)	

We saw a general trend of increased scores for the higher years of study. However, this trend did not appear different between the 3D group and 2D group. Both 2D images [3] and 3D models [25] have been described to require a high level of technological knowledge, expertise, and experience to interpret. Therefore, evaluating the appropriateness of a teaching method and when in the learning journey they are best introduced, is important. When pitched incorrectly, frustration and disengagement from students is a risk [26]. Limited data made a clear conclusion difficult to draw, but it seems that undergraduate level of study had little impact on performance in the 3D group in this study. Although not conclusive, we can tentatively suggest that introducing 3D models into teaching practice at any undergraduate level is unlikely to be detrimental and is likely best implemented consistently across all three years to reinforce and build student experience. Further work considering a range of experience levels is highly recommended.

4.2. 3D models were positively received and improved confidence

The use of 3D images was additionally beneficial to the perceived comprehension and confidence of students, as participants who used this material felt more confident after the activity than participants who used the 2D images in the reference material. A study by Preece et al.

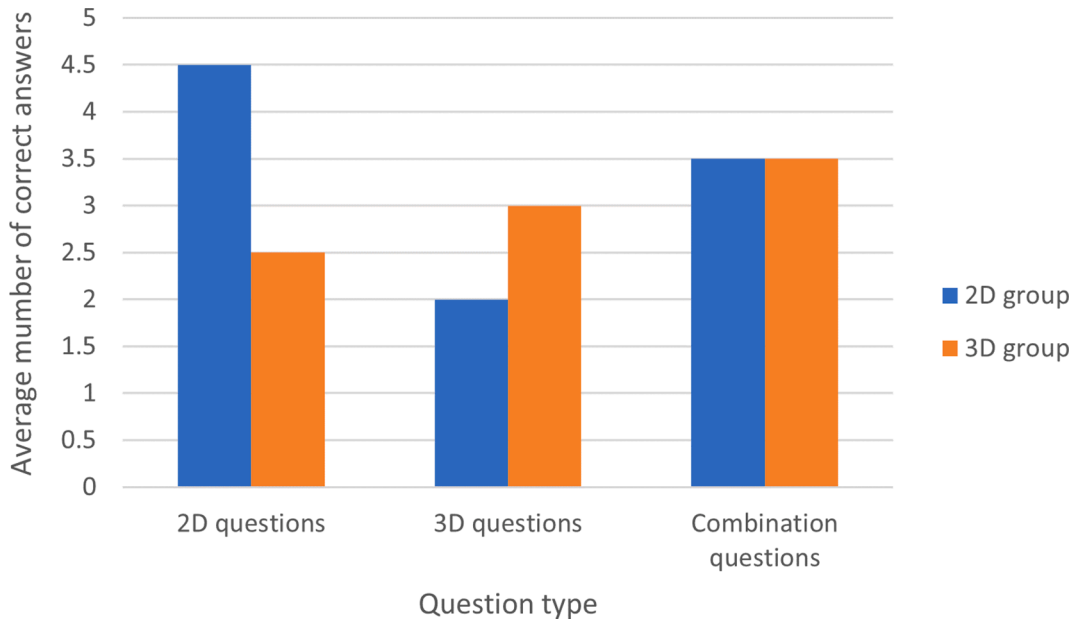

Figure 4. A comparison of average number of correct scores for the 2D (blue) and 3D (orange) groups for each of the three different question types (2D, 3D and combination).

Table 5
A comparison of the number of participants in each group who reported the use of a single image type was adequate to the number of participants in each group who reported a combination of image types were adequate to aid comprehension.

Group	Number of participants who agreed/ strongly agreed their image type alone was adequate (out of 6)	Number of participants who agreed/ strongly agreed that a combination of 2D and 3D images was adequate (out of 6)
2D	1	5
3D	6	4

NB: 2D group reporting that 2D imaging alone was adequate and 3D group reporting 3D imaging alone was adequate in aiding comprehension.

[10] also reported an improvement in student feedback from the use of 3D visualisations in a medical context, indicating that the use of 3D imaging can improve perceived comprehension and confidence of students, in a variety of teaching contexts. The use of 3D models in teaching and learning in forensic anthropology could mean that the extra time required to process information in 2D images [5], is mitigated against. If the information is processed more rapidly and the student appears to understand the concept in less time or recognise a pathology more rapidly for example, their confidence could increase as they feel more competent.

Participants who used the 3D material used more positive or neutral language, whereas the group who used the 2D images used more negative language, suggesting a general positive view towards 3D models. This is further supported by the number of students who felt they were more confident after the activity when directly asked. In terms of perception changes, only one participant changed their perceived comprehension and confidence in each group (one negative change in the 3D group and one positive change in the 2D group).

4.3. 2D image and 3D models work well in conjunction

The advantages and disadvantages of using 2D images and 3D models are often discussed in literature, both in forensic anthropology and more generally. 2D images such as photographs or sketches are reported to be simplified, sometimes erroneous, representations of

Table 6
A summary of the emergent themes from the open-ended responses regarding the adequacy of using either 2D images or 3D models alone and in combination to aid comprehension.

Group	Question type	Themes within positive responses (number of responses within this theme)	Themes within neutral responses (number of responses within this theme	Themes within negative responses (number of responses within this theme)
2D	2D		No mention of 2D only positives of 3D (2) Not enough experience to comment (1)	Single angles limit information accessible (2)
3D	3D	Detail (1) More realistic (1) Better view which aids visualisation (2) Overall liked model use (1)		
2D	Combination	Both helpful (1) More detail in 3D which supports 2D information (1) 3D alone good enough as more information in a complete picture (2)	Needs to be same bone in 2D and 3D image to comment (1)	
3D	Combination	Using 2D and 3D together makes up for limitations in either (1) Both helpful (2)	2D limiting quality of analysis (1)	Both can be confusing (1)

objects which are subject to biases [1,3,5], but have been used for over a hundred years. 3D models also have disadvantages, despite recognition of their vast potential [27]. These discussions highlight disadvantages including ethical issues and a persistent reliance on 2D processes to produce the images in some cases [3]. If used in conjunction however, the limitations and challenges with both 2D images and 3D models, may provide a more comprehensive presentation of the subject. Indeed, the data from the current study does suggest that using a combination of 2D images and 3D models is beneficial to student perceptions of comprehension and confidence when identifying pathologies on a bone.

Our results also indicate the use of 2D images in conjunction with 3D models can act to cement understanding of theoretical concepts, supporting the work of Ballantyne [3]. The combination questions were the only questions to have no negative language used when reporting the reasons for choosing a pathology. Using the 2D images and 3D models in combination maximises on the reported advantages of each imaging modality, such as improved realism and demonstrative value in 3D images [4] and more focussed images in 2D photographs [3]. Some of the disadvantages of the imaging modality can also be mitigated against by using them both in combination. For example, a focussed 2D photograph may counterbalance the extra information presented by 3D models [25]. This also reiterates the implication for the best practice of forensic anthropology, the current study showed participants educated using 3D material to be more successful in scenarios which utilised a combination of imaging modalities, which is more representative of the type of work encountered by forensic anthropologists.

4.4. Wider implications and further work

In many respects the use of 3D imaging and visualisation is still in the early stages of development in forensic fields, but the preliminary results and conclusions drawn from this study are important to begin to understand the implications of 3D visualisations applied in teaching. Biasutto et al. [12] warns of the dangers of not exploring the implications of methods before they are widely implemented into educational practice, as teaching methods can be a barrier to comprehension if they are not appropriate for the purpose. With no detrimental effect to scores, increased consistency, and positive feedback this initial study shows scope for 3D models to be a potentially useful teaching method in forensic anthropology.

This work also has particular importance not only for forensic anthropology as a discipline, but across many practical disciplines during the current and ongoing COVID-19 pandemic [15]. In a situation like the present, where remote and online learning is becoming common practice, it is important to assess the most useful teaching methods to allow forensic anthropologists, and students more generally, to continue to train and learn without detriment. Some disciplines that use online learning have been criticised for a 'one size fits all' approach, not accounting for individual preferences and learning styles [28]. However online teaching has been found to be just as effective as traditional teaching methods for undergraduate nurses [29], and more generally student performance has not been harmed through the adoption of online learning in many American universities [30]. Exploring the methods that allow remote learning to be effective for students is appropriate at the present, as software such as Sketchfab could potentially replace physical collections used to educate students while social distancing prevents students from physically being in a laboratory.

While this study made use of 'ready-made' and publicly available 3D models, it should be noted that the generation of 3D models is becoming increasingly accessible. Surface scanning techniques such as photogrammetry, and structured light scanning can offer more user friendly, quicker, and low-cost alternatives to biomedical imaging techniques such as CT, microCT, or MRI [13,31]. Where the material exists, educators are therefore able to generate their own models, allowing students to interact with the same skeletal features physically as well as digitally in both 2D and 3D, a strategy the authors would highly recommend.

However, despite reducing the ethical implications regarding the handling and degradation of human remains during laboratory sessions, there are also unique ethical considerations with the use of 3D models of human remains. The digital storage and ownership of these images needs to be considered as this practice becomes more widely used [4]. Careful consideration must be applied in terms of safety, including who can access this information and gather personal information of individuals who may not have been alive when these technologies developed and so were unable to consent to donating their remains to this purpose [25]. Additionally, the use of these images needs to be considered [13], as although they are not physical human remains, they are created from information and data from the human remains. There is a need for ethical guidelines in 3D imaging and visualisation of human remains [2], and a need for even more specific guidelines in an educational context [32].

Finally, the authors wish to emphasise that while digital 3D models appear to have a positive impact on student experience, we only recommend them as a supplement to and not a long-term replacement of physical lab sessions. We suggest that where courses are unable to utilise physical remains in the labs due to current restrictions, or run as online only distance courses, 3D models are an excellent addition or temporary solution for providing human remains analysis when face to face teaching is not possible. However, we do not suggest digital 3D models should ever fully replace practical labs, it cannot be stressed enough the importance for forensic anthropology students to gain experience physically handling human remains with respect, the texture, weight, and feel of bone is something that could never be replaced, and the development of the psychomotor skills required to effectively analyse human remains is of great importance. As such our findings support our recommendation that 3D models would be a good addition to face-to-face and online teaching material to supplement 2D images and practical lab sessions.

5. Conclusion

The results of the present study provide some preliminary findings with respect to the use of digital 3D models in forensic anthropological teaching. The use of 3D models was not detrimental to comprehension of pathologies in osteological material and improved consistency of scores by participants. The use of the 3D models also improved confidence and improved success on questions displaying a combination of 2D and 3D imaging modalities. The global COVID-19 pandemic makes the purpose of this study even more poignant as we continue to adopt more remote learning methods. Although further work is needed on a larger scale, this study highlights the potential benefits and challenges of implementing teaching materials that use 3D models in the education of forensic anthropologists and provides initial evidence to support their use.

6. Novelty statement

This work contributes a novel understanding of the impact of using 3D digital models on student learning within the field of forensic anthropology. Specifically, this work provides knowledge of the benefits of using a combination of both 2D and 3D resources in effective learning and teaching practices instead of relying on 2D material alone. Furthermore, it raises points of considerations that need to be accounted for when choosing to implement these types of teaching strategies; data overwhelm and ethics for example.

CRediT authorship contribution statement

Kathryn Craik: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Amber J. Collings:** Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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