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J Paleontol. Author manuscript; available in PMC 2015 August 22.

Published in final edited form as:
J Paleontol. 2014 July 1; 88(4): 727–734. doi:10.1666/13-085.

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BEYOND THE PRINT—VIRTUAL PALEONTOLOGY IN SCIENCE PUBLISHING, OUTREACH, AND EDUCATION

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Abstract

Virtual paleontology unites a variety of computational techniques and methods for the visualization and analysis of fossils. Due to their great potential and increasing availability, these methods have become immensely popular in the last decade. However, communicating the wealth of digital information and results produced by the various techniques is still exacerbated by traditional methods of publication. Transferring and processing three-dimensional information, such as interactive models or animations, into scientific publications still poses a challenge. Here, we present different methods and applications to communicate digital data in academia, outreach and education. Three-dimensional PDFs, QR codes, anaglyph stereo imaging, and rapid prototyping—methods routinely used in the engineering, entertainment, or medical industries—are outlined and evaluated for their potential in science publishing and public engagement. Although limitations remain, these are simple, mostly cost-effective, and powerful tools to create novel and innovative resources for education, public engagement, or outreach.

INTRODUCTION

The opportunity to visualize, reconstruct, and analyze fossils with computational methods has fundamentally changed the field of paleontology in the last decade. Facilitated by advances in hardware and software and the wide availability of high-resolution, non-destructive digitization techniques, the use of digital data in paleontology has become a fast-evolving and innovative field. Powerful new tools and methods allow the visualization of anatomical details and internal structures in fossils (Donoghue et al., 2006; Tafforeau et al., 2006; Witmer et al., 2008; Smith et al., 2009), which are largely inaccessible with traditional techniques or would otherwise depend on exceptional preservation, such as natural endocasts (Case, 1922, 1928; Janensch, 1935–1936). Furthermore, digital models based on fossil specimens can be used to analyze functional and biomechanical properties of extinct organisms (Rayfield, 2007; Anderson et al., 2012; Lautenschlager, 2013a), to evaluate their locomotory (Hutchinson et al., 2005; Pierce et al., 2012), neurosensorial or cognitive capabilities (Lautenschlager et al., 2012), or to virtually reconstruct their development (Haug et al., 2010; Rücklin et al., 2011, 2012, 2014).

These different analyses and applications not only require, but also produce, a vast amount of data. This wealth of digital information, created (often exclusively) for individual research projects, offers enormous, but in many cases still unrealized, potential. Limited by the traditionally two-dimensional forms of print publication, it is still difficult for scientists to communicate and disseminate 3-D data. Three-dimensional models, animations or analytical results must often be reduced to simple, two-dimensional still images, or are provided as electronic supplementary information (e.g., Jones et al., 2012). Furthermore, the exchange of 3-D data is stymied by the lack of digital repositories (for detailed discussion see Rowe and Frank, 2011; Faulwetter et al., 2013). However, 3-D technologies to present, publish, and make such data accessible to the public and scientists already exist. The engineering, medical, and entertainment industries currently make routine use of these technologies (e.g., Jones, 2012; Symes et al., 2012; see www.avatarmovie.com as 3-D movie example) and there is great potential for other fields to follow suit.

This contribution outlines and reviews methods and applications for the distribution and communication of 3-D data and their use in scientific publications, public outreach activities, and education.

MATERIAL AND METHODS

The presented methods and applications are accompanied by selected examples of 3-D models and animations. The following specimens and processes were used to illustrate this publication.

A cast of an articulated skull and dermal shoulder girdle of *Dunkleosteus terrelli* (CM7424, Cleveland Museum of Natural History, Cleveland, U.S.A.) was scanned using a medical computed tomography (CT) scanner. The dermal anatomy was reconstructed in Avizo (Versions 6.3.1 and 7.0.0, Visualisation Science Group) using the program's segmentation editor. In order to reduce the final file size, the resulting surface model was subsampled to 100,000 elements in Avizo using the simplification editor (by means of an edge-collapse algorithm). The model was subsequently imported as a PLY file into MeshLab (Version 1.3.2, Visual Computing Lab–ISTI–CNR), where a universal 3-D (U3D) file was created—necessary for the 3-D PDF functionality (Lautenschlager, 2013b).

An animation of the Upper Cretaceous therizinosaur *Erlikosaurus andrewsi* (IGM 100/111, Geological Institute of the Mongolian Academy of Sciences, Ulaan Bataar, Mongolia) (Clark et al., 1994) was created based on detailed CT scans of the holotype specimen performed at X-Tek Systems Ltd. (now Nikon Metrology), Tring, Hertfordshire, using a XT-H-225ST CT scanner fitted with a special steel honeycomb support to minimize object movement. Scan parameters were set at 180 kV and 145 μA. Data set reconstruction was performed with custom-built software (CT Pro) provided by X-Tek Systems Ltd. creating "vgi" and "vol" files containing 1,998 slices with a voxel size of 145 μm. The endocranial anatomy (including the brain endocast, endosseous labyrinth, and neurovascular structures) was reconstructed (Lautenschlager et al., 2012) and the skull morphology digitally restored in Avizo. The resulting surface models were exported as PLY files and subsequently imported into the open-source 3-D graphics and animation software Blender (Version 2.61, Stichting Blender Foundation) for rendering and production of the animation linked to the QR code (see also Garwood and Dunlop, 2014).

The restored skull model of *Erlikosaurus andrewsi* was also used as a template for a rapid-prototype model printed at the Faculty of Engineering, University of Bristol. Here, the surface model was downsampled to 250,000 elements in Avizo in order to be processed by the prototyping software and exported as a STL file. The model was printed using a Stratsys Fortus 400mc thermoplastic printer.

3-D PDF

Functionality

In recent years, Adobe Systems' portable document format (PDF) has become the universally accepted standard for digital publishing. With the release of Acrobat 7.0 (Adobe Systems Inc.) and version 1.6 of the PDF format (Murienne et al., 2008), Adobe Systems introduced the capability to supplement PDF documents with digital content (Fig. 1, online Supplemental File 1). Based largely on the universal 3-D (U3D) standard, it has become possible to integrate 3-D models into the now ubiquitous PDF format. These 3-D PDFs provide the functionality of regular PDF documents, but also contain digital models, which can be interactively manipulated by the user with the freely available Acrobat Reader software on all major operating systems (i.e., Windows, Mac, and Linux). The 3-D objects can be rotated, translated, and scaled in all three dimensions, but a variety of additional functions also exist for viewing cross-sections, changing light, and transparency settings and taking accurate measurements of these digital models (Tyzack, 2008; Betts et al., 2011). Three-dimensional PDFs can contain different object types, such as multi-component, textured, or even finite element analysis (FEA) models (Lautenschlager, 2013b). This eliminates the requirement for specialist software to access such models, and also avoids issues resulting from the abundance of different 3-D file formats.

Applications

The capability of the 3-D PDF technology to enable direct interaction with digital objects offers immense potential for the communication of 3-D data, and scientific publishing is probably one of the areas that will benefit most from this. Originally developed to disseminate and present 3-D data in the manufacturing, engineering and architecture industries, 3-D PDFs are now also slowly finding their way into scientific publications (Murienne et al., 2008). Although they are now regularly used in biochemistry (Kumar et al., 2008; Vasilyev, 2010), biology (Ziegler et al., 2008; Ruthensteiner et al., 2010; Düring et al., 2013), and archaeology (Betts et al., 2011), 3-D PDFs remain rare in paleontology and are often restricted to supplementary information (e.g., Knoll et al., 2012; Farke and Sertich, 2013) or institutional website content (http://www.oucom.ohiou.edu/dbms-witmer/3D-Visualization.htm), if they are used at all. This is surprising, as paleontology does not differ from the aforementioned disciplines in its descriptive and illustrative requirements, and 3-D PDFs seem to be a particularly well-suited format for paleontological data. Digital data sets of fossil specimens tend to be very noisy and considerably larger than simple CAD models, which could explain the limited uptake of 3-D PDFs in paleontology. However, directly

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embedded 3-D models not only enhance the level of information available to the reader, but in most cases also provide access to the virtual data used in the analysis, thus enhancing the transparency of the presented research (although the raw CT data must still be deposited elsewhere). CT scanning is now routinely performed in descriptions of new fossil taxa, particularly in vertebrate paleontology (Farke and Sertich, 2013), and the integration of the resulting 3-D models into these publications will facilitate comparative and taxonomic studies (Faulwetter et al., 2013). In addition, the usefulness 3-D PDFs is not solely restricted to vertebrate paleontology or models derived from CT scanning. This ranges from Synchrotron-scanned microfossils, to invertebrate specimens and trace fossils, such as dinosaur footprints, acquired with photogrammetry (Lautenschlager, 2013b; Romilio et al., 2013). Furthermore, many forms of electronic supplementary material, such as animations of rotisserie-style spinning 3-D models and pre-rendered movie files (Briggs et al., 2012), will become less important or unnecessary as these models can be accessed directly and with a higher degree of interactivity as 3-D PDFs (Ziegler et al., 2011). Some journals are already beginning to enforce this step by banning supplementary material altogether (Maunsell, 2010).

Three-dimensional PDFs also have applications beyond the field of scientific publishing. The documentation of biological and fossil specimens poses a considerable challenge to natural history collections and museums; making specimens accessible to scientists and to the public is an essential but demanding task. Three-dimensional imaging and digitization of selected specimens, or even whole collections, has been identified as a possible solution to this problem, and many museums and universities are now widely employing 3-D data capture techniques (Metallo and Rossi, 2011; Steinbach, 2011). The resulting digital reconstructions of tomographic datasets can be made available via online repositories, and there are several different strategies for achieving this (Faulwetter et al., 2013; Rowe et al., 2011). However, the plethora of different and often proprietary data formats produced by the various digitization techniques makes dissemination difficult. A case study by Betts et al. (2011) has shown, that by employing the 3-D PDF format, and its capability to integrate objects produced by tomographic techniques (CT, μCT = X-ray micro-tomography, or micro-CT, and SRXTM = synchrotron radiation X-ray tomographic microscopy), surface scanning and photogrammetry such compatibility problems could be largely avoided.

Fossil specimens digitized and made accessible as 3-D PDFs are also of further, educational and didactic value. Paleontology practical classes and assessments necessarily require original specimens for the handling and study of fossil morphology by students. However, appropriate specimens, which have to be well-preserved, available in large numbers and all showing sufficient morphological detail, are an additional basic requirement. Especially for holotypes and other fragile or rare specimens this can be problematic, and access to specimens can often only be provided in the form of two-dimensional photographs or line drawings. By employing collections of digitized teaching material in universities or museums, higher-education students could be provided with 3-D PDFs, which not only allow them to study and manipulate a range of fossil specimens, but can also illustrate important external and internal details. This is already applied at several institutions, but not yet published and a comparative pedagogic evaluation is yet lacking. From the authors subjective, personal observations the use of digital models in higher education are well

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received by the students. Similarly, such digital resources could be used in schools, many of which don't have access to a large paleontological teaching collection. Appropriate teaching material could be provided in collaboration with universities or museums, or simply be downloaded from a publicly accessible repository by students and teachers. The example of a 3-D PDF of *Dunkleosteus terelli* (Fig. 1) was presented at the British Science Festival 2013 and the applicability in public education demonstrated. Some hundred visitors listened to the instructions and around 10% used the interaction with 3-D PDFs. Children ages 5–12 were mainly attracted by the interaction, average time spent on the device was several minutes, and the handling of models was apparently easiest using a touch-screen. The interaction with the computer was apparently more interesting than the physical models provided.

Limitations

Currently, 3-D PDFs still suffer a number of technical problems, which probably also contribute to their currently limited application. The process of converting 3-D models, derived from various digitization methods, into PDF documents, is still exacerbated by the requirement of several different and often costly software tools, as the U3D format is not universally supported (see also Lautenschlager, 2013b). Although other file formats, such as PRC (Product Representation Compact) can be used to embed 3-D models, they are often linked to specific software tools and not widely supported (Barnes et al., 2013). Similarly, 3-D functionality cannot be guaranteed for PDF reader software other than Acrobat Reader. In particular, on Unix-based operating systems, default PDF readers are not capable of accessing the digital content.

Furthermore, authors wishing to include 3-D PDFs in their publications, still encounter the problem that many journals remain reluctant to accept 3-D PDFs in publications, with online submission systems not equipped to process the necessary files (Kumar et al., 2010). Another issue is the increased file size of the final 3-D PDF, which can quickly become unwieldy, especially if the document contains multiple 3-D objects. Drastically downsampled models to reduce file size, on the other hand, might lack the necessary resolution or could introduce artifacts that could change the model morphology.

QUICK RESPONSE CODES

Functionality

Quick response (QR) codes are two-dimensional, matrix barcodes, originally developed by the Japanese company Denso Wave Inc. for the automotive industry and are largely confined to the industry (Ohbuchi et al., 2004). However, because of their quick readability and easy access options, QR codes are now a common sight in advertising, marketing, and the entertainment industry (Flaig and Parzeller, 2011), permitting storage and linking to digital content of any kind, which can even be accessed with smart phones or tablet computers equipped with a camera. Although QR codes are a registered trademark of Denso Wave Inc., the company does not exercise the patent rights and allows a license- and cost-free usage of their product. QR codes can store information in the form of up to 4,296 alphanumeric characters, either as plain text or as a URL address. The latter is commonly

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used to link the code with digital content on the internet (Fig. 2). QR code reader software is usually pre-installed on suitable devices (smart phones, tablets, etc.), but can also be freely downloaded. Similarly, a variety of websites are available for the free and effortless generation of QR codes, whereas a number of online bar code readers are available as well to read QR codes without the need to install additional software applications.

Applications

QR codes have a high potential for applications in paleontology, in particular where quick and easy access to information is required. While digital content in scientific publications can be provided in the form of supplementary data or as 3-D PDFs, this is not the case for conference contributions, namely talks or poster presentations. In particular, the latter are severely limited by the fact that a printed poster cannot convey the same degree of information as animations or interactive 3-D objects. QR codes can be easily created and can link to a variety of objects, such as audio or video files, images, or other document formats (e.g., PDF, 3-D PDF, DOC, HTML). Thanks to the increasing popularity and technical capabilities of smart phones and similar hand-held devices, conference participants could effortlessly access background information for such enhanced poster or oral presentations. This can range from animations and digital models to related publications, virtual copies or even translated versions of the presentation (see Fig. 2). The applicability of the technology was successfully demonstrated by the authors at the Meeting of the Geological Society of America in Charlotte in 2012 in a poster presentation (see abstract Lautenschlager and Rücklin, 2012). Some dozens of academics experimented with the use of the QR code, loading provided videos and models. The average time was several minutes, but dependant on the signal and performance of the device used. The provided signal was not very strong and loading times long. Interaction using the QR code resulted in most cases in a discussion about the technology and the research behind. As a subjective experience we can say that the younger scientists (under 35 years old) were more interested in the technology and the use of QR codes.

The same principle applies to museums and exhibitions. The display of fossil (or other) specimens is not always enough to attract visitors. Interactive displays and digital installations are now becoming the norm and various strategies exist to involve visitors using hand-held devices (Bruns et al., 2007; Mody et al., 2009). However, many of these technologies are expensive and require a large amount of hard- and software infrastructure and local expertise for usage and maintenance. Here, QR codes offer a cost-effective, yet innovative solution, providing the scope for more detail and elective learning opportunities. As exhibits are also used for research, parts of the resulting digital data could be relatively easily converted into the correct format in order to enhance the displayed specimens.

Limitations

QR codes can both be created and accessed easily. However, accessing QR codes requires that the user is in possession of a capable device. Although smart phones appear to have become ubiquitous in recent years, it cannot yet be expected that they are available to all conference participants and museum visitors. Hence, supplementary, and potentially essential, content might not be accessible to a considerable part of the audience. Another disadvantage is the requirement to store the linked data on a public website or server location. In particular, for larger amounts of supplementary content, this data could exceed the available storage capacities. Additionally, it must be ensured that the links and the respective content are permanently available, so that the QR codes do not become invalid after a number of years. Finally, the quality of the provided wifi signal or mobile internet signal is of considerable significance to minimize loading times, which if sufficiently long might make it impossible to load large linked objects such as video files.

RAPID PROTOTYPES

Functionality

Rapid prototyping (sometimes also referred to as stereolithography or 3-D printing) creates physical prints based on a digital template. These objects are commonly created by an additive process, in which successive layers of material are deposited to create the final model. The material used can consist of liquid or powdered polymers, metal, or paper, depending on the printing technique and the system used. Rapid prototyping has been traditionally used in manufacturing, engineering, and the medical industry, but similar to many digitization techniques, such as CT scanning, has become more widely distributed in recent years.

Applications

Similar to traditional molding and casting methods in paleontology, rapid prototyping can be used to create physical copies of fossil specimens. In particular for digital models, which have no physical template, such as 3-D reconstructions of fossils (Sereno et al., 2007) (Fig. 3) or composites created from two or more individual specimens, this technology offers the only possibility to turn digital 3-D models into real, physical objects (Jones, 2012). In addition, for fossils still embedded in matrix, the combined approach of CT scanning, digital preparation, and rapid prototyping enables the study of the specimen without the risk of damage during conventional physical preparation (Torres et al., 2003; Bristowe et al., 2004; Knoll and Rohrberg, 2012). Specimens, which cannot be cast with traditional methods, whether they are too fragile, possess a too complex morphology (in particular, if internal features are of interest) or are otherwise inaccessible, can be reproduced quickly and accurately with rapid prototyping (D’Urso et al., 2000).

Rapid prototype models lend themselves to a variety of further applications. For educational purposes, reproduced models can act as a supplement to existing teaching collections, which, as discussed above, might not always contain sufficient original fossil specimens. Furthermore, models can be printed at different scales. Enlarged in comparison to their original size, they can help users understand the morphology of microscopic fossils or can be used illustrate minute details (Teshima et al., 2010). Models can be printed in different materials or colors to highlight different morphological structures or tissues. For complex models, for example, it is also possible to print the outer surface with a transparent texture in order to revealing internal morphology. Additionally, for museum exhibitions and other public outreach activities (Rahman et al., 2012), rapid prototype models offer a potential to communicate scientific research to non-specialist audiences. Valuable and rare specimens can be made accessible to the public with rapid prototype models, making them comprehensible to a wide audience.

Limitations

Although rapid prototyping techniques have become more affordable in recent years, one of their biggest disadvantages is still the cost of the models and printing materials, in particular when compared to more traditional casting methods routinely used in paleontology. While smaller models can be printed at reasonable prices (well below 100 USD), the costs increase significantly for reproductions of larger specimens or for a large number of different replicas (several hundred USD or more). Furthermore, most rapid prototype machines have restrictions in terms of processible model size (in terms of triangle and file sizes, but also in terms of the physical size of the printed models). Hence, the original digital models have to be downsampled considerably before they can be printed, which may lead to the loss of fine details or insufficient resolution of anatomy. Apart from this, most rapid prototyping software can process “stl” files only, which means that the 3-D models may have to be converted first into this format.

ANAGLYPH STEREO IMAGING

Functionality

Anaglyph stereo images consist of two different color-converted images superimposed onto each other, representing images for the left and right eyes. One image becomes invisible, when viewed through a (chromatically opposite) filter (commonly referred to as 3-D glasses) of the respective color, producing independent left and right images, which then results in a 3-D effect. Anaglyph images are usually presented in red-blue, red-cyan, or red-green color combinations, and the 3-D effect is only visible with the appropriately colored filters or lenses. To achieve the best results, each of the two individual images should depict an object or a scene from a slightly different angle (6°–10°).

Applications

Traditional stereophotographs (or stereo pairs), which produce a virtual depth perception via side-by-side images of the same fossil specimen, have been used in paleontology for over a century (Hudson, 1913; Briggs et al., 2004; Rauhut and Fechner, 2005). However, these stereophotographs require considerable space to accommodate the two images side-by-side in publications, and are often difficult to perceive without a stereoscope (for a comparison see Knappertsbusch, 2002). Although anaglyph stereo images require filtered glasses as well, these are comparatively cheap and readily available, e.g., to order in bulk online for less than 1 USD per item. Furthermore, anaglyph images can usually be generated using the same software that was employed to create the digital models (Boczarowski, 2005), including commercial (Purnell, 2003) or open-source (Haug et al., 2009a) visualization software. This makes anaglyph stereo imaging particularly useful for science publishing, and therefore it has been used in recent years to visualize a variety of fossil structures, spanning different taxonomic, size and methodological ranges (Gatesy et al., 2005; C. Haug et al., 2009; Snelling et al., 2010). In addition, other scientific presentations, restricted by 2-D print formats, such as conference posters (Fig. 4), can also make use of this method.

For exhibitions and other public outreach activities, anaglyph images and 3-D glasses can provide an inexpensive but effective way to actively involve a traditionally passive audience (Rahman et al., 2012).

Limitations

Due to their functionality, anaglyph stereo images need to be reproduced in color. For many print publications, authors will likely have to face increased publication costs, in order to make full use of this method. Furthermore, the 3-D effect of anaglyph images can only be perceived with the respective 3-D glasses. While providing a couple of pairs of glasses for poster presentations is convenient, this is certainly impractical for publications, and readers therefore have to be in possession of these—but this is also true for traditional stereo-pairs. Finally, in comparison to the latter methodology, anaglyph stereo images have the drawback that due to the color conversion process, the images appear distorted, which can result in the loss of information in terms of texture or coloration of objects. This limitation, however, can be overcome by using polarized-light 3-D systems, which does not require color-coded images and might thus provide a future solution.

DISCUSSION

The publishing industry—not only in science and academia—is currently experiencing a paradigm shift in terms of data presentation. Enhanced and interactive media are on the verge of becoming a de facto standard, and are often now expected by the readers/users. Although electronic publications have become increasingly popular in academic publishing in recent years, and in some cases have entirely replaced traditional print formats, there is still a general reluctance to enhance these publications by integrating digital content by both authors and publishers. Many of the applications outlined in this article are often considered to be unnecessary gimmicks, raising the question whether they are needed to present scientific data. We believe so. Virtual paleontology and its methods and technologies rely heavily, if not completely, on purely digital data and results. Communicating results effectively is a must in academia, and paleontology is no exception. Finding appropriate tools to illustrate research is not a new problem in paleontology, nor is it restricted to digital data (Hudson, 1925; Frankel, 2004). Inter- or multidisciplinary approaches such as the use of methods from physics or engineering allow engagement with a public audience, one that is primarily interested in general science or disciplines other than paleobiology. Once the interest in the methods (e.g., 3-D printing or synchrotron technology) captures one’s attention then underlying research questions, hypotheses, and concepts such as evolution can be discussed. Scientific questions and study results are not only for general knowledge but primary cutting-edge research results as well. In light of the increasing demand of public engagement and knowledge utilization by funding bodies, presentations at science festivals or in museums are essential for scientists. The use of media like animated movies, including 3-D tomographic data and models, is a perfectly suited for both generalists and specialists alike and can even be used on the web (e.g., movies on personal web-pages or video-sharing websites like YouTube or Vimeo). The applications illustrated here can only help to further data transparency and enhance data dissemination. We do not suggest that digital methods should replace traditional techniques, or that virtual fossils should substitute original fossils.

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Rather we suggest that the full potential of paleontological research could be achieved through the combination of all available resources.

However, the benefits of this approach extend beyond the scientific domain. Public engagement now forms a substantial part of a paleontologist's job description, and the communication of research results to non-specialist audiences is an increasingly important point for funding organizations. The wealth of digital information produced by the use of digital data in paleontology facilitates this process. Much of the required data already exists and awaits its use beyond the actual research project. By employing digital methods, data could be quickly transformed to bridge the gap between science and the public (Bates et al., 2009).

CONCLUSIONS

The methods and applications presented here exemplify the great potential for communicating paleontological research to both the scientific community and the public. Although some limitations remain, digital techniques constitute powerful tools to use existing research data to create novel and innovative resources for education and outreach.

Three-dimensional PDFs, QR codes, and anaglyph stereo images provide simple and mostly cost-effective ways to visualize 3-D information and enhance the accessibility of (morphological) data for the reader. Rapid prototypes allow the transformation of virtually prepared specimens into physical models and the wider distribution of copies of rare fossil specimens while retaining fine details.

All these new techniques and methods may help to enable the free accessibility of science outside of classical academic institutions, which can only be beneficial for science and society.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENTS

We thank P. Anderson (University of Massachusetts Amherst), M. Ryan (Cleveland Museum of Natural History), and E. Snively (Ohio University) for providing CT-scans of *Dunkleosteus terrelli*. N. Pearce (University of Bristol) is thanked for assistance with the rapid prototyping of the *Erlikosaurus* model. I. Rahman (University of Bristol) thoroughly commented on earlier manuscript versions. R. Garwood and A. Ziegler are thanked for critically reviewing and improving this contribution. This research is supported by a doctoral fellowship to SL by the Volkswagen Foundation. MR was supported by NERC and funds awarded to M. D. Brazeau from the European Research Council under the European Union's Seventh Framework Programme (FP/2007–2013), ERC Grant agreement number 311092.

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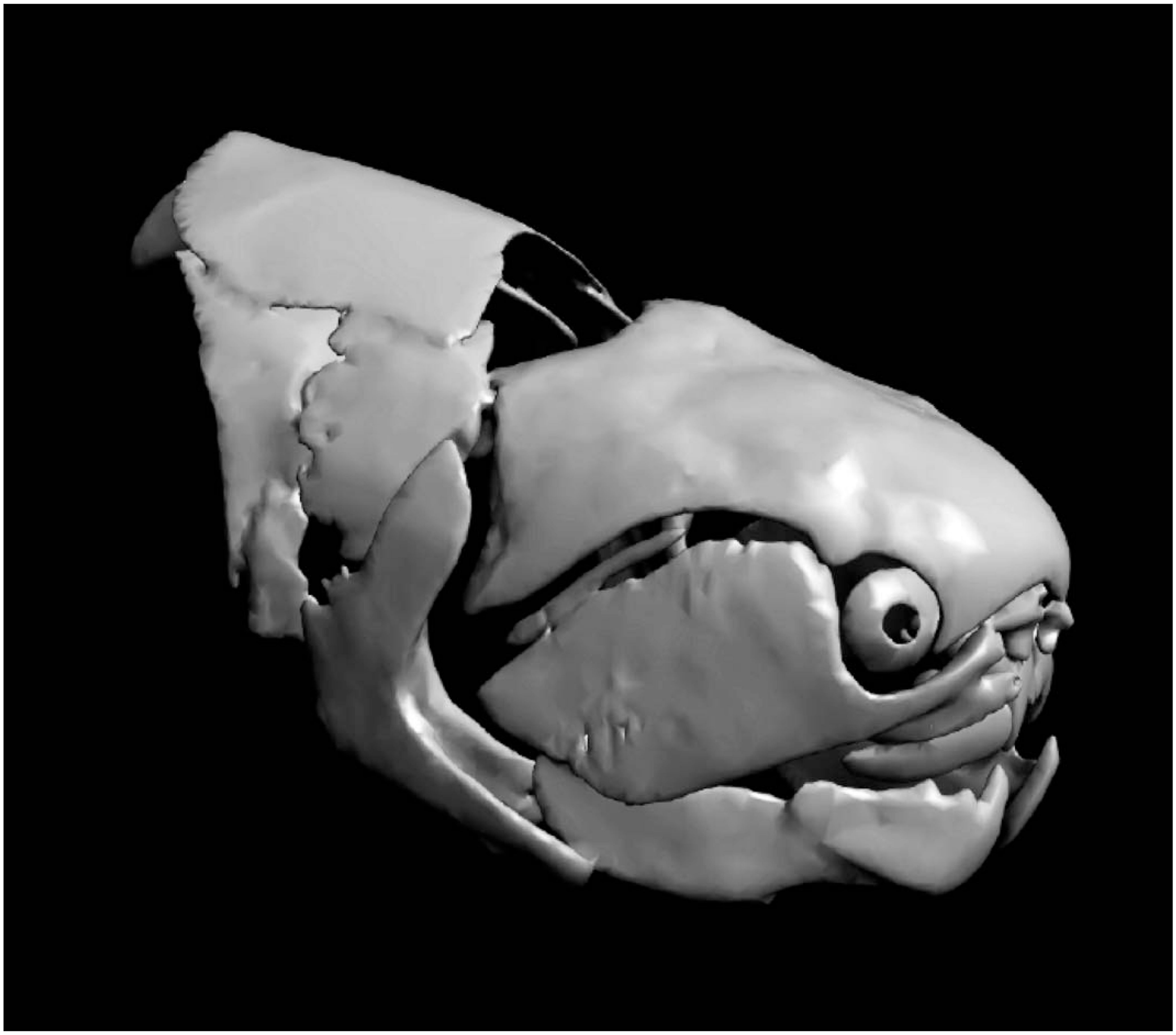

Figure 1.
Interactive 3-D PDF of a digital surface model of the skull and dermal shoulder girdle of *Dunkleosteus terrelli*. Three-dimensional content can be activated by clicking on the figure (Adobe Acrobat Reader version 7 or higher required). (File is also provided as online supplemental material, see Accessibility of Supplemental Material.)

ACCESSIBILITY OF SUPPLEMENTAL DATA
Supplemental data deposited in Dryad repository: http://datadryad.org/resource/doi:10.5061/dryad.390m3.

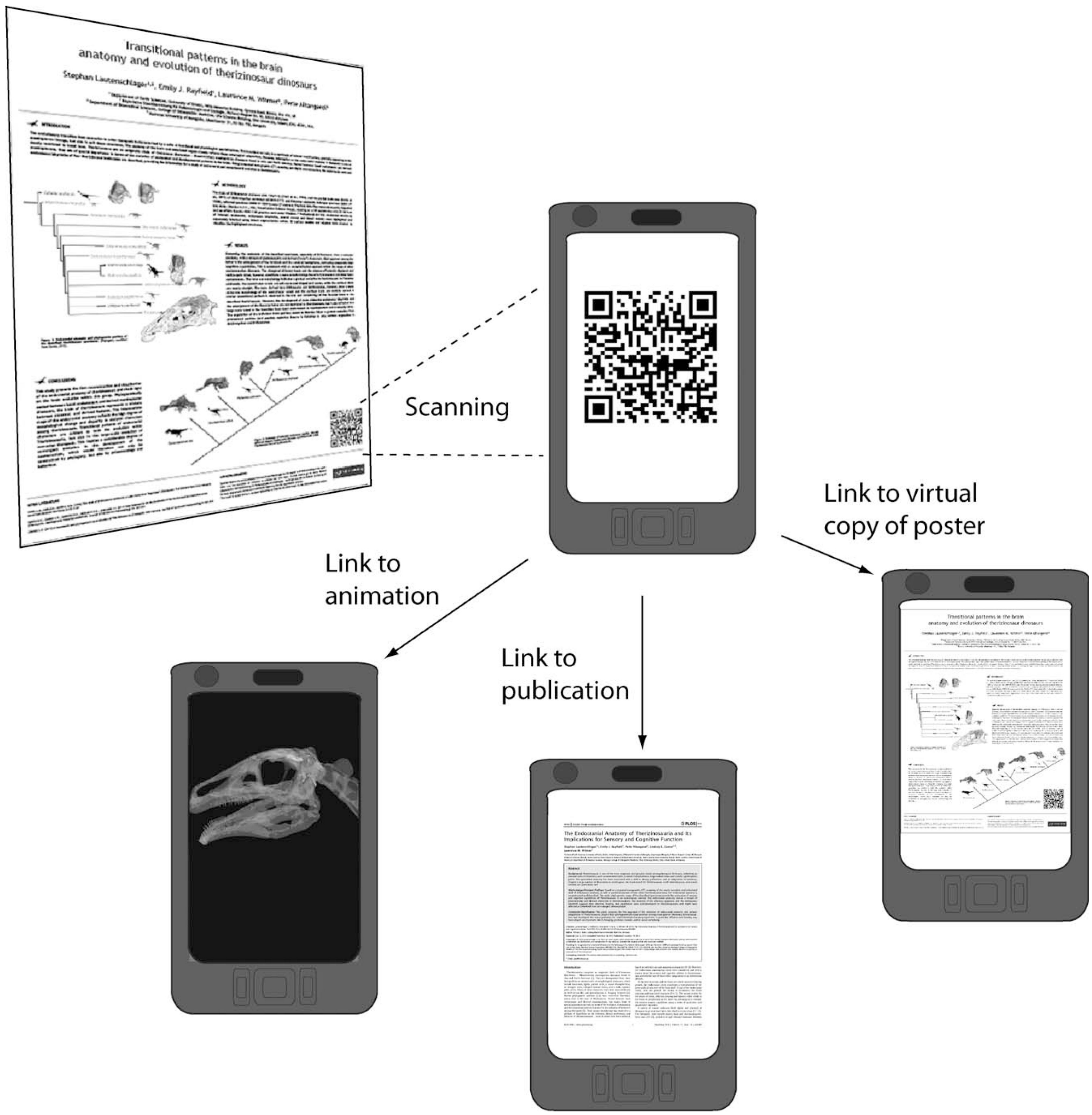

Figure 2.

Functionality of QR codes exemplified by their use on a conference poster to access linked content. The pictured QR code can be used to access a linked animation (see text for details).

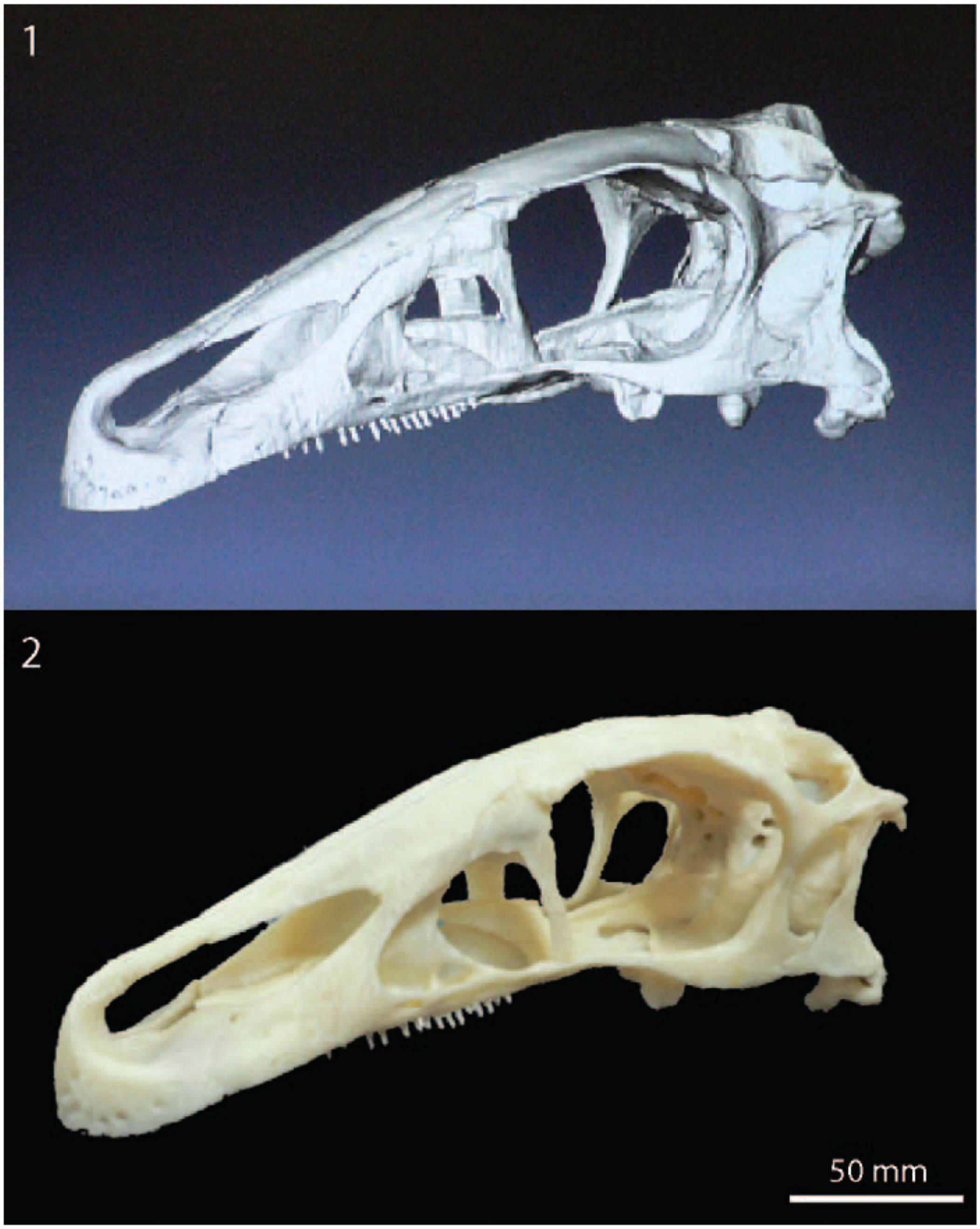

Figure 3.
1, digital model of the reconstructed skull of *Erlikosaurus andrewsi*; *2*, rapid prototype based on digital model.

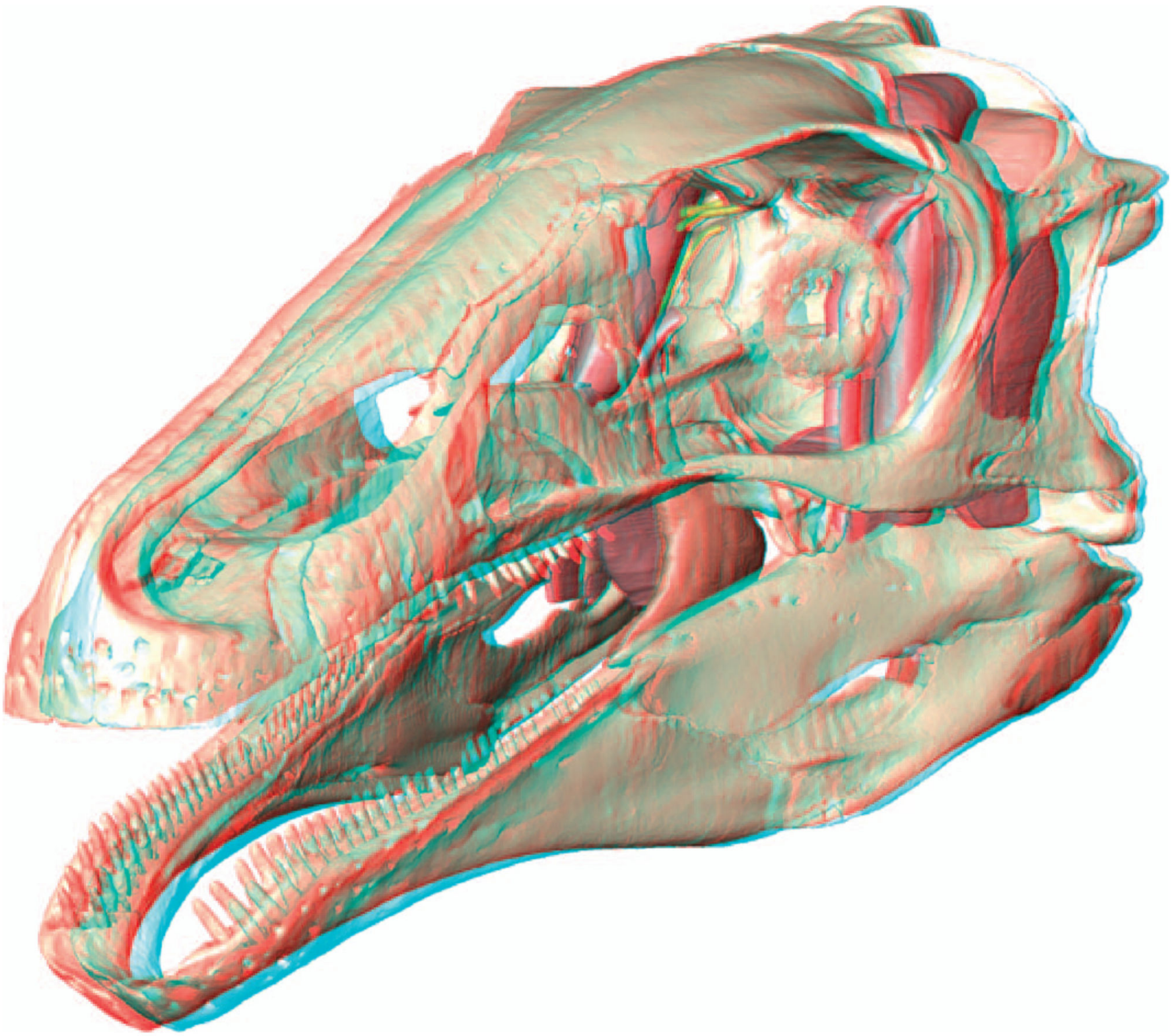

Figure 4.

Anaglyph stereo images of *Erlikosaurus andrewsi* depicting the three-dimensional adductor muscle anatomy. The 3-D effect of the anaglyph image will be visible with red/blue glasses.