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The affordances of 3D and 4D digital technologies for computerized facial depiction

Mark A. Roughley[a*] and Caroline M. Wilkinson[a]

[a] Liverpool School of Art and Design, Liverpool John Moores University. Email: M.A.Roughley@ljmu.ac.uk*, C.M.Wilkinson@ljmu.ac.uk Address: Liverpool John Moores University, Liverpool School of Art and Design, 2 Duckinfield Street, Liverpool L3 5RD, Telephone: +44 151 904 1216,

Abstract

3D digital technologies have advanced rapidly over recent decades and they can now afford new ways of interacting with anatomical and cultural artefacts. Such technologies allow for interactive investigation of visible or non-observable surfaces, haptic generation of content and tactile experiences with digital and physical representations. These interactions and technical advances often facilitate the generation of new knowledge through interdisciplinary and sympathetic approaches.

Scientific and public understanding of anatomy are often enhanced by clinical imaging technologies, 3D surface scanning techniques, 3D haptic modelling methods and 3D fabrication systems. These digital and haptic technologies are seen as non-invasive and allow scientists, artists and the public to become active investigators in the visualisation of, and interaction with, human anatomy, remains and histories.

Face Lab is a Liverpool John Moores University research group that focuses on creative digital face research; specifically the further development of a 3D computerized craniofacial depiction system, utilizing 3D digital technologies in facial analysis and identification of human remains for forensic investigation, or historical figures for archaeological interpretation.

This chapter explores the affordances of such interactions for the non-destructive production of craniofacial depiction, through a case-study based exploration of Face Lab workflow.

Keywords: Craniofacial depiction, Affordance, Haptic, 3D scanning, 4D capture, 3D modelling, 3D printing, 3D animation

Introduction

Three-dimensional (3D) digital technologies have advanced rapidly over recent decades and they can now afford new ways of interacting with anatomical and cultural artefacts. Such technologies allow for interactive investigation of visible or non-observable surfaces, haptic generation of content and tactile experiences with digital and physical representations. These interactions and technical advances often facilitate the generation of new knowledge through interdisciplinary and sympathetic approaches.

Scientific and public understanding of anatomy are often enhanced by clinical imaging technologies, 3D and four-dimensional (4D) surface scanning techniques, 3D haptic modelling methods and 3D fabrication systems. These digital and haptic technologies are non-invasive and allow scientists, artists and the public to become active investigators in the visualisation of, and interaction with, human anatomy, remains and histories. However, an understanding of what these technologies can afford should be a key component in the research and design processes. While the concept of 'affordance' is familiar to sociologists and technologists, it is seldom explored in relation to collaborative art-science projects, even though research findings are often rooted in similar practice and process.

Psychologist J. J. Gibson (1966) coined the term 'affordance' and proposed that we actively seek information through exploratory experiences with surfaces and the relationships between them, and that these experiences are fundamental to the exploration of the creative and innovative ways that people respond to and adapt technology for use in unforeseen circumstances (Smith *et al.*, 2018). Tools afford different actions, and interfaces offer various affordances for interaction. As researchers we should be aware of not only the capabilities of 3D digital technologies but also their limitations (Gaver, 1991). Specifically, this chapter will investigate the interaction and application of 3D digital technology for the non-destructive production of facial depictions, through a case-study based exploration of the activities of the Liverpool School of Art and Design research group, Face Lab.

Face Lab

As part of the ART LABS (Artistic Research and Technologies Labs) Research Centre at Liverpool School of Art and Design, Liverpool John Moores University (UK), Face Lab focuses on digital creative face research, specifically the further development of a 3D computerized facial depiction system. This includes the utilization of 3D technology in craniofacial analysis, animation and facial recognition.

Face Lab carries out forensic and archaeological research and consultancy work, and this often involves the depiction and identification of human remains for forensic investigation, or historical figures for archaeological interpretation. Existing facial reconstruction methods, including those advanced by Mahoney and Wilkinson (2010); Rynn *et al.*, (2010); Lee *et al*., (2012), are used to produce facial depictions for these purposes, and they are enhanced by existing and innovative 3D digital technologies and workflows. Face Lab digital workflows and research outputs have directly influenced current digital human research, especially in relation to the creation of 3D facial avatars and facial depiction.

3D computerized facial depiction

3D computerized facial depiction is now a common procedure. A robust variety of complementary scientific digital methods including those by Evenhouse *et al*., (1992); Davy *et al*., (2005); Mahoney and Wilkinson, (2010); Rynn *et al*., (2010); Claes *et al*. (2010); Lee *et al*., (2012); have been developed to produce facial likenesses from skeletal remains. Wilkinson *et al*., (2006); Short *el al*., (2014); Lee *et al*., (2015); Miranda *et al.*, (2018) have also demonstrated the accuracy of 3D computerized facial depiction methods.

Production of computerized facial depictions for presentation to public audiences may require the use of 3D or 4D surface scanning, haptic 3D modelling, 3D texturing, 3D printing and 3D animation technologies and methods. The most important objective of a facial depiction is to generate a life-like appearance (Claes *et al*., 2010) and it has been demonstrated that 3D models provide unlimited opportunities for production and manipulation of anatomical structures. Furthermore, the flexibility of the 3D computer systems used to create these depictions enable alteration of important parameters such as anatomical individuality (Tan *et al*. 2012) based on age, sex and ethnicity (Evenhouse *et al*., 1992), health status, and angle of view. On the whole these processes have become more efficient, giving more realistic results.

3D computerized models may be expensive to produce, but once created they can be re-used many times with relative ease (Ballantyne, 2011). This is also true when producing complex anatomical forms such as computerized facial depictions. Novel 3D digital interfaces may offer observable affordances because they can offer information about objects that may be acted upon (Gaver, 1991). They benefit multiple users by allowing both experts and non-experts, or those physically distanced from the object, a greater chance of interacting with and understanding the object (Thomson, 2017). Face Lab continues to develop and adopt digital workflows for 3D facial depiction from skeletal remains, afforded by visual and haptic interactions with 3D and 4D digital technologies.

Haptic and visual interactions afforded by 3D and 4D digital technologies for facial depiction from skeletal remains

"The observer may or may not perceive or attend to the affordance, according to his needs, but the affordance, being invariant, is always there to be perceived. An affordance is not bestowed upon an object by a need of an observer and his act of perceiving it. The object offers what it does because it is what it is"

Although J. J. Gibson stated that affordances exist whether they are perceived or not, he offered additional comments detailing how interfaces may offer perceptible affordances that may be acted upon explicitly through exploration (Gibson, 1966). 3D objects can be either digital or non-digital (physical) and can be moved into different positions or planes. This can allow a user to observe the relationship between different structures in space and mentally manipulate objects in three dimensions (Azer and Azer, 2016). Haptics are often a complement to visual sources of information that assist in the formation of a more detailed and comprehensive 3D mental image (Reid *et al*., 2018).

Recently there has been an increased interest in multi-sensory interactions, from augmented reality to immersive virtual reality experiences that are only possible through visual or haptic interfaces with technology. Virtual reality surgical simulators for example, may employ haptic devices to allow the perception of an object through active examination via haptic sensation; by palpating shape and texture of a virtual surface, (Reid *et al.*, 2018). 3D printed objects hold a tremendous volume of information in their physical form, and even a 'haptic glance' can allow for rapid transmission of information from a brief initial touch (Klatzky and Lederman, 1995). As a part of the computerized facial depiction process, haptic devices connected to 3D computer modelling software can allow for the direct touch of digital skeletal remains that are not present together in the same physical environment as the user. Vision and touch are working at the same time here, and without this, the prediction of facial features, such as eyelid folds, could be hindered.

Importantly for facial depiction, 3D digital models cannot be damaged; a constant worry in historical craniofacial reconstruction practice where the practitioner either works directly in clay on the skull or creates a plaster copy of the skull. Challoner and Erolin (2013) describe the additional benefits of virtual 3D models over original specimens including:

- *They can be preserved permanently and will not deteriorate over time*
- *They can be magnified to a greater extent than the original specimen, providing an advantage over the original specimen*
- *The interior structure of the specimen can be shown, so it can be virtually dissected, something which would destroy the original specimen*
- *They can portray the complex anatomical spatial relationships better than traditional 2D images*

The following sections expand upon haptic and visual interactions in 3D facial depiction, which are afforded by clinical imaging and 3D surface scanning, 3D modelling software, 3D printed replicas, and 4D performance capture and 3D animation.

Clinical imaging and 3D surface scanning data

The Face Lab facial depiction workflow predominately operates in a 3D digital space and requires a digital copy of a human skull to produce a facial depiction. Clinical imaging technologies, including computed tomography (CT) and magnetic resonance imaging (MRI), and 3D surface scans are used to obtain 3D models of human remains through visualisation in volume rendering software.

The type of data output from these devices is known as “3D volumetric data” (Decker and Ford, 2017) and provides comprehensive imaging of both external and internal anatomy. However, Claes *et al.* (2010) detail the limitations of 3D surface and CT/MRI scanning technologies when obtaining a 3D volumetric data of a skull. This includes artefacts produced by dental amalgam during CT scanning, the inability of 3D surface scanners in capturing the inner surface of a cranium or shiny metallic surfaces, and often extensive post-processing of the data. Post-processing can often be reduced by choosing the most appropriate 3D surface acquisition method and knowing the limits of specific 3D digitization methods. (Wilson *et al*. 2017)

When 3D volumetric data of a skull is received by Face Lab, an open source volume rendering software, ‘InVesalius©’ (https://invesalius.github.io/) is used to generate a digital 3D model that can then be used in other software for facial depiction. While ‘haptic’ usually refers to touching surfaces, it can also refer to a mode of visual perception that is capable of penetrating a surface to visualise within a given form (Smith *et al*., 2018). This is a particular affordance of clinical imaging whereby manipulation of values of Hounsfield Units and interactions with 3D surfaces through volume rendering in a 3D space can allow the user to see beyond the surface, and from multiple viewpoints at once. This can often raise new questions and sometimes yields important and occasionally surprising new morphological information (Godinho and O'Higgins, 2017).

Figure 1 shows 3D volumetric data and a generated 3D model of a cranium of the Cohen mummy stewarded by Johns Hopkins Archaeological Museum viewed in InVesalius©. The Cohen mummy has a missing mandible and the additional viewpoints available in InVesalius© are especially useful when attempting to predict the shape of the mandible from incomplete skeletal remains. Observable only through 3D visualisation in volume rendering software, anatomical landmark the sella turcica – point X in figure 1 – is essential in accurate prediction of mandible shape from the cranium alone; following methods defined by Sassouni, (1957) and Mahoney *et al.*, (2012). This anatomical point can also be touched when using a haptic interface device in additional software.

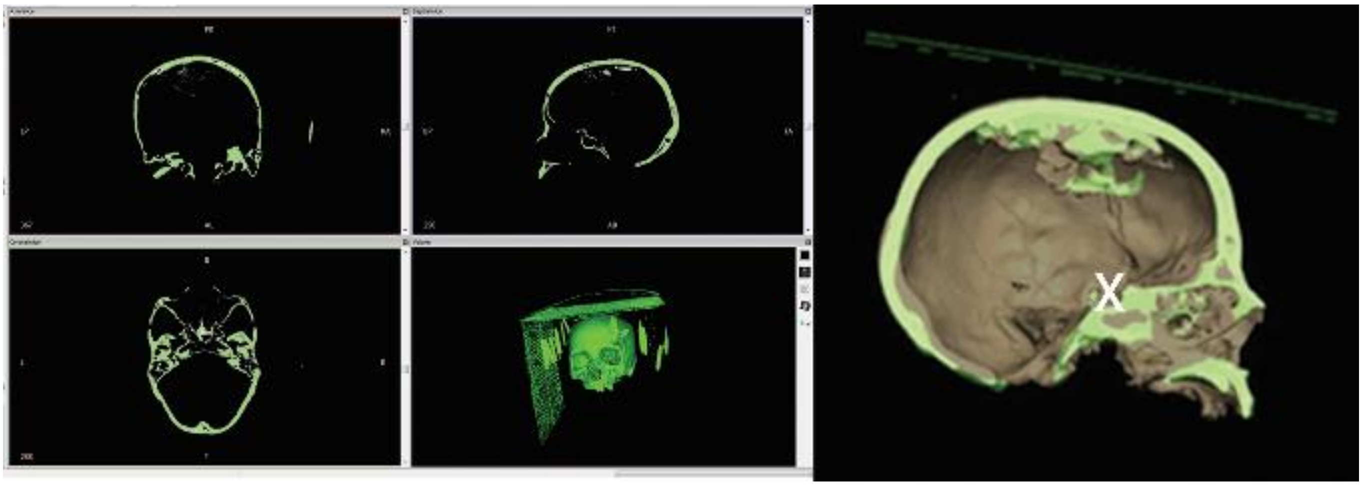

Figure 1: 3D volumetric visualization of a cranium viewed in InVesalius©.

Although 3D volume rendered models from clinical imaging appear more advantageous when visualising human skulls, they are dependent on CT data often only available from clinical institutions (Ballantyne, 2011). 3D surface scanners are a more accessible solution in obtaining 3D models of skeletal remains. Haptic interaction with 3D models generated from both 3D data acquisition methods can be achieved using a 3D Systems© 'Touch X©' haptic interface device (https://www.3dsystems.com/haptics-devices/touch-x) and Artec Studio Professional software. Artec Studio Professional© (https://www.artec3d.com/) is the software native to the Artec3D© series of portable handheld surface scanners and is compatible with the Touch X© device. A variety of 3D model file types can be imported for editing, including those exported from InVesalius©.

Using an Artec 3D© scanner to scan a cranium, for example, results in the generation of multiple digital meshes that are viewed in Artec Studio Professional©. These meshes need to be cleaned up and each scan layer aligned to create one surface that is representative of the physical cranium (Figure 2). The 'eraser' and 'align' tools in Artec Studio Professional© can be augmented with additional touch input thanks to a Touch X© device before an exportable 3D model is produced using the 'fusion' tools. Artec 3D© scanners also capture colour texture information; this can be a particularly useful feature when digitising human remains. The additional textures enhance visual analysis of the surface of the bone, which can often lead to information being gathered that would not have been observed with 3D shape alone.

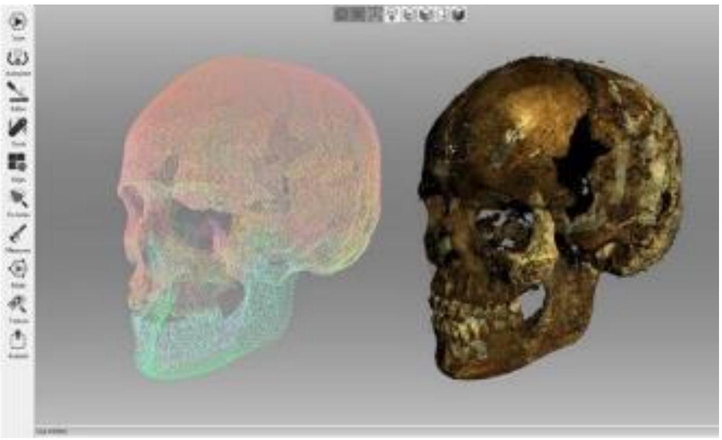

Figure 2: 3D volumetric data of a skull obtained using an Artec3D scanner, and edited and assembled in Artec Studio Professional© using a Touch X© interface device.

Visual and haptic exploration by these techniques allows objects to be examined and identified rapidly and accurately (Klatzky and Lederman, 1995), and this facilitates initial craniofacial analysis at an early stage in the facial depiction process. Additionally, 3D models are then able to be shared online and viewed simultaneously by multiple colleagues in multiple locations; something that could not be achieved with direct observation of only one skull (Nagasawa *et al.* 2010).

In addition to 3D volumetric acquisition of skeletal surfaces, Face Lab carries out scans of facial surfaces and facial features, which are archived in a virtual repository. A high-resolution Artec Spider© handheld 3D scanner (https://www.artec3d.com/portable-3d-scanners/artec-spider), a low-resolution 3D Systems Sense© handheld scanner https://www.3dsystems.com/3d-scanners/sense-scanner) and a high-resolution Di4D© (Glasgow) 4D markerless performance capture and performance transfer system (http://www.di4d.com/systems/di4d-pro-system/) have become part of the Face Lab data acquisition toolkit. 3D surfaces captured by these devices can be used in facial depiction by:

- appropriately selecting and morphing specific facial features, such as ears, lips and noses, to fit a skull following craniofacial analysis
- selecting appropriate facial textures, such as wrinkles, creases and skin colour, to add to the skin layer output from the 3D facial depiction process

The aim is to make the digital depiction process more efficient while also producing more realistic faces. However, further 3D modelling may be required to make the captured facial feature assets more suitable for future use.

3D modelling software

At Face Lab, 3D facial depiction takes place in Geomagic Freeform© software with a Touch X© desktop haptic interface following the computerized Manchester method as defined by Mahoney and Wilkinson (2010). Freeform© has the capability to import a variety of 3D file types exported from clinical imaging and 3D surface scanning devices. It enables the user to efficiently build upon the surface of a digital skull by adding tissue depth markers and pre-modelled anatomical structures, subcutaneous fact and skin layers, and modelling of facial features following anatomical standards (Figure 3).

Figure 3: Utilisation of a Touch X© haptic interface with Geomagic Freeform© to produce a 3D facial depiction

The Touch X© haptic interface is a common force-feedback device adopted worldwide in engineering of mechanical parts and patient specific surgical implants. Force-feedback devices engage proprioception, which is the sense of force and position enabled by tactile and visual cues (Schneider, 2017). As previously mentioned, touching human remains is often key in determining the placement or production of facial features. Keehner and Lowe (2010) describe the advantages of such touch-based approaches,

"The eyes have a single viewpoint, but the hands have multiple 'touchpoints' and thus the fingers and palm can work in concert as a 3D 'shape gauge'. This shape-gauging mechanism is something for which there is no direct equivalent in visual exploration"

and virtual touch using a haptic interface device during the facial depiction process often allows for an almost 'in-life' interaction with skeletal remains that may not physically be nearby (Smith, *et al.*, 2018). It is these additional affordances that have made this device and the accompanying Freeform© software suitable for 3D facial depiction.

Although Freeform© has the capacity to add additional textures to 3D models, such as wrinkles, pores and skin pigmentation, the tools available are not as wide-ranging and effective as those available in mainstream 3D modelling and animation software (Mahoney and Wilkinson, 2010; Vernon, 2011). Pixologic ZBrush 4R8© software is used by gaming companies and in visual effects industries to produce textured 3D models that are consistent with photographs or film sequences (Wilkinson 2005). In relation to the Face Lab digital workflow, the process of texturing the skin layer of a 3D facial depiction created in Freeform© begins by exporting the 3D model and importing into ZBrush 4R8©.

ZBrush 4R8© is similar to Freeform© in that it uses virtual 'clay' to organically sculpt 3D meshes with virtual tools, however, meshes exported from Freeform© contain randomly organised polygon meshes that are not suitable for 3D animation or printing (Briggs *et al.*, 2016). ZBrush 4R8© allows the user to organise these meshes by using the 'ZRemesher' function that quickly produces organised meshes composed of thousands of polygons. The density of these meshes can then be increased to millions of polygons using the 'DynaMesh' function. The more polygons, the greater the surface detail of the 3D model when sculpting (Vernon, 2011).

Following 'remeshing' of a 3D mesh, a UV map must be created. This process – 'UV mapping' – is described by Levine and Yu (2009) as a coordinate mapping function that warps a 2D image containing texture information to is corresponding position on a 3D mesh (Davy *et al*., 2005). A UV map can be created using the 'UV Master' plugin in ZBrush 4R8©. A useful function when UV mapping a 3D model of a face is to protect the facial area of the depiction from UV seams using the 'Protect' and 'Attract' tools. This ensures that no visible virtual seams cross the face, corrupting any future sculpted or painted textures. It is essential to prepare a 3D model in this manner to allow for effective 3D texturing, rendering, animation or printing.

Using the ‘Standard’ brush tool, altering the stroke between ‘Freehand’, ‘Spray’ and ’DragRect’, and applying additional ‘Alpha masks’ to the brush tool, textures, such as wrinkles, creases, pores can sculpted on to the surface of a 3D model; following digital sculpting methods documented by Kingslien (2011) and Spencer (2010). Additional brushes, including the ‘Smooth’ and ‘DamStandard’ brushes from the embedded ZBrush 4R8© library, or custom brushes available for download from online libraries, allow for refinement of the sculpted textures towards a realistic finish.

Additional interface devices such as a Wacom© Cintiq© touchscreen afford new interactions when sculpting virtual clay in ZBrush 4R8©. The touchscreen is pressure sensitive and when an accompanying stylus is utilised, virtual sculpting visually appears more similar to in-life sculpting with clay and wooden tools. It can be hypothesized that these ‘visual and haptic cues’ (Keehner and Lowe, 2010) may have advantages in how we visually perceive virtual touch-based interactions. Figure 4 shows a 3D facial depiction produced in Freeform© and the same 3D model textured in ZBrush 4R8©. Neave, (1998); Wilkinson, (2004); Naini, (2011); and Mullins, (2012) detail age-related face texture changes to the skin, such as crow’s feet, eye bags, neck and forehead creases, sagging tissues and overall roughness, and ZBrush 4R8©’s toolkit aids in creating realistic skin textures.

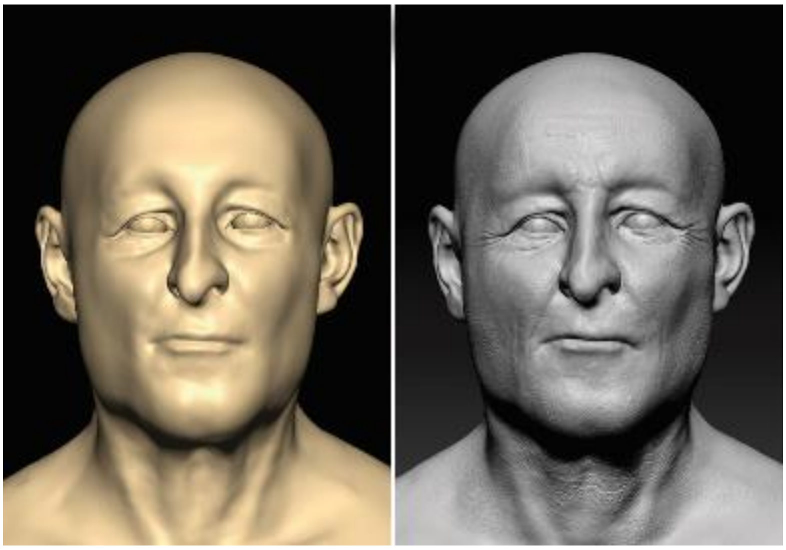

Figure 4: Addition of skin textures – wrinkles, creases and skin folds – using Pixologic ZBrush 4R8© (right) to a 3D facial depiction of a 19th century male from the Fewston Assemblage, Yorkshire, produced in Geomagic Freeform© (left)

ZBrush 4R8© allows the user to add colour to 3D models using its ‘PolyPainting’ feature (Vernon, 2011). The ‘Spotlight’ image projection function also works with PolyPainting enabled, and skin textures from reference photographs can be painted directly on to a 3D model. Additional details can also be painted directly on to the surface with 'PolyPaint' activated - skin pigmentation that become more obvious with age and in later life, for example, skin blemishes and spots of a brownish hue, similar to freckles (Neave, 1998) – and this is demonstrated in figure 5.

Figure 5: Adding skin textures – pigmentation, blemishes, creases – in ZBrush© (right) to a 3D facial depiction of Maidstone Museum's mummy Ta-Kush (left)

Once the texturing processes are complete, UV, texture and displacement maps can be created using the corresponding plugins available in the ZBrush© toolkit. The 3D model mesh can be reduced in density by varying its 'subdivisions,' and can then be exported as an .obj file with accompanying UV and texture maps ready for use in third-party rendering or animation software such as Autodesk Maya© or Blender©. A high density mesh 3D model can also be hollowed to a thickness of approximately 3mm using the 'Boolean' function and exported as an .stl file (with no accompanying texture maps) suitable for 3D printing.

The Face Lab digital 3D modelling workflow described here can permit one 3D facial depiction model to have multiple outputs. Figure 6 is a 3D facial depiction of a 17th Century Scottish Solider known as 'SK22', excavated from Durham Cathedral by Durham Department of Archaeology (Durham University). Three different outputs were produced over a period of one year (as more funding became available), including a 2D render that was composited in Adobe Photoshop CC©, a 3D animation rendered in Autodesk Maya 2018© and a 3D printed replica. This ultimately saves time if a client requests an additional output rather than having to start from scratch; if a 3D printed replica is requested in addition to a 2D render, the preparatory work has already been undertaken and the 3D facial depiction model can be sent for print almost instantly.

Figure 6: Multiple presentation methods of a 3D facial depiction of a 17th Century Scottish Solider – 2D digital portrait, 3D animation, 3D printed replica.

While optic and haptic interactions with 3D modelling software provide additional affordances by means of supplementary interface devices, the Face Lab 3D modelling workflow exists due to the plasticity of existing 3D modelling workflows and tools available in mainstream 3D modelling software packages.

3D printed replicas

Currently, 3D printing a 3D facial depiction is a relatively swift and affordable process, providing a physical output to a predominantly digital process, and 3D printed facial depiction replicas enable both visual and haptic experiences with people from the past. There are many qualities of 3D printed replicas that can be perceived haptically, including texture, hardness, and shape. This can also be true with a single visual glance. Interactions with a physical 3D model allow the user to take in considerable information (Lederman and Klatzky, 1987) about the object and it has been documented that touch can achieve very high levels of perceptual performance (Kilgour and Lederman, 2002).

Face Lab produces 3D printed replicas of facial depictions of archaeological human remains primarily for the museum sector. There is often a request for a 3D replica by a museum or cultural heritage intuition when designing a new temporary or permanent exhibition, as they are seen as more engaging 'artefacts' that allow better interaction using visual and haptic interfaces (Butler & Neave, 2008). The 3D print also allows the head to be viewed at life-size scale and presents the part of a facial depiction that is most objectively accurate – face shape (Wilkinson *et al*., 2006). A 3D facial depiction is produced following the methods listed in the previous section of this chapter, and is then

3D printed in resin using an SLA 3D printer, painted with acrylic paints, and prosthetic eyes, human hair wigs and human hair eyelashes are added. Figure 7 shows a 3D printed facial depiction produced by Face Lab.

Figure 7: 3D printed facial depictions produced by Face Lab: 19th century male from the Fewston Assemblage, Yorkshire

An additional affordance of 3D printed replicas is that they can provide opportunities for those who are visually impaired to touch, feel and 'see' people from history. This haptic affordance is also beneficial for those that are able to see. Kilgour and Lederman (2002) acknowledged that "sighted humans recognise faces almost exclusively through vision but also demonstrated that human faces can be distinguished haptically with levels of accuracy over 70%, whether they are seen solely through touch or using both vision and touch". Studies have demonstrated that additional haptic interface with an object to obtain and make decisions about shape related information, allocates more weight to that sense, enabling perception to be more accurate (Keehner, 2010).

As most 3D printed facial depiction replicas are finished to look as human-like as possible, it is not often possible to touch the model as this could damage the paintwork and additional textures. Within a museum setting an additional barrier exists because most 3D printed replicas are presented behind glass. In an attempt to encourage haptic interaction with a 3D facial depiction, Face Lab have begun utilising translucent or monochrome 3D printed replicas of specific facial depictions. They are often finished with a lacquer that reduces discolouration through repetitive touch and sunlight exposure, and can be wiped clean. A translucent or monochrome 3D print can also offer an effective alternative in presenting archaeological 3D facial depictions to a public audience whereby we do not have supporting DNA evidence to determine skin, eye or hair colour (textures). While it is often possible to update the textures of a painted 3D printed replica at a later date, a 3D printed replica without colour leaves the skin, eye and hair colour open to further interpretation.

In 2016, Face Lab created a 3D facial depiction of a 2,500-year-old mummy known as 'Ta-Kush'. Her remains are stewarded by Maidstone Museum (Kent, United Kingdom) and as part of the museum's plans to refresh their 'Ancient Lives' permanent exhibition - where Ta-Kush had been displayed, and would remain displayed - and humanise Ta-Kush further, the museum sought ideas for the most appropriate method in allowing visitors to engage with Ta-Kush as a person. The museum curators were also keen to ensure that revised ‘Ancient Lives’ exhibition was suitable for visually impaired visitors.

Working with experts from around the globe at intuitions including Maidstone Museum, Face Lab, Kent Institute of Medicine and Surgery, Western University Ontario and University College London Institute of Archaeology, the Ta-Kush story changed as new evidence of her life was uncovered through the affordances of specialist techniques and technologies, including CT scanning. With new knowledge gathered from these investigative procedures, Ta-Kush transitioned from being a 14 year old Egyptian princess to a 40 year old Nubian woman and this not only had an impact on the Ta-Kush re-display but also the commissioned 3D facial depiction.

Within a museum setting a 3D facial depiction aims to display an anatomically accurate depiction of a person from history. However, in the case of Ta-Kush, no DNA analysis was completed that would have allowed the research team to define her approximate skin colour, eye colour and hair colour. This meant that the Face Lab team relied solely on subjective evidence provided by appropriate experts from the multi-disciplinary project team. It was decided that two versions of Ta-Kush would be produced; a full colour 3D CGI facial depiction wearing jewellery and makeup consistent with her status, and a translucent 3D printed replica that would focus on the anatomical shape of the Ta-Kush face, whilst also functioning as a tactile exhibit for visually-impaired museum visitors.

Figure 8: Clear 3D printed facial depiction of Ta- Kush (foreground) and a full colour 3D CGI facial depiction of Ta-Kush (background). Image courtesy of Maidstone Museum.

The 3D printed replica of Ta-Kush is displayed in the museum on a plinth that is at a height accessible for most visitors, and sits in front of the full colour 3D CGI version displayed on a TV monitor (Figure 8). It is the first glimpse of Ta-Kush for the museum visitor, as her preserved remains are hidden behind a screen. In doing this, the museum is fostering an environment that affords complementary interactions with Ta-Kush, from physical action to emotional experience (Gibson, 1966). Many of our everyday interactions with the world involve coordinated and simultaneous visual-haptic explorations, where the hands can touch an object from different sides (Lacey and Sathian, 2014) and vision assists us to reach towards and grasp objects. By touching an object as well as looking at it, we are permitted access to additional information about 3D shape (Keehner, 2010), and in the case of Ta-Kush, we get the opportunity to know more about her through her facial appearance. 3D printing technologies afford the production of likenesses of otherwise fragile human remains, with which visitors may directly interact (Smith *et al.*, 2018).

4D performance capture and 3D animation

We have suggested how 3D facial depictions and 3D printed replicas can make use of optical and tactile affordances, but these outputs can also be enhanced with the addition of sounds; specifically 3D animation outputs. Gaver (1991) noted that sounds can convey information in ways which supplement computer graphics and can reveal alternative forms of interaction with a subject. What if we could see and hear a figure from history speaking and perhaps reciting their own written works? Could we watch an historical Scottish poet reciting his own poetry?

In 2009, Robert Burns was voted 'The Greatest Scot' of all time. His face is depicted in more cities across the world than any other historical figure (https://www.scotland.org/features/commemorations-of-robert-burns-around-the-world), and approximately £157 million a year is generated in Scotland relating to Burns and his poetry (https://www.bbc.com/news/uk-scotland-44106983). In 2010 a contemporary Scots poet and Robert Burns fan, Rab Wilson, began collaborating with Professor of Craniofacial Identification Caroline Wilkinson, to produce a 3D facial depiction of Robert Burns. The facial depiction was re-visited in 2016 and a new multi-disciplinary team set out on a journey to animate Burns reading one of his most famous poems, 'To a Mouse'.

From a partial cast of the Burns skull, along with portraits, craniometrics, silhouettes and written descriptions, Face Lab produced a 3D facial depiction of Robert Burns (Figure 9) following updated facial depiction methods including mandible and facial feature prediction. The 3D facial depiction included the layers of facial muscles responsible for movement, expression and communication. Creating photo-realistic digital humans is a long-standing challenge in facial depiction and it is suggested that a simple solution for producing digital doubles would be to capture the face of an actor (B´erard *et al.*, 2014) and project this onto a facial depiction. For this project Rab

Wilson provided the authentic voice of Burns; he was the current Robert Burns fellow for the Dumfries & Galloway Arts Department and was born and lives in Ayrshire, where he writes and performs poetry in the traditional Scots language.

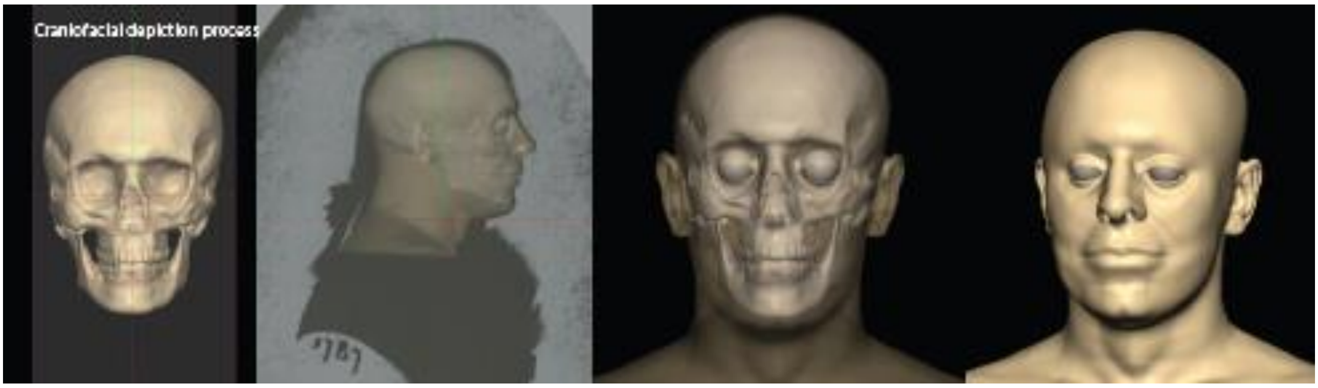

Figure 9: Updated 3D facial depiction of Robert Burns.

Rab was recorded reciting the Burns poem ‘To a Mouse’ using a DI4D© (Glasgow) 4D markerless high-fidelity facial motion capture system© at the 3D Visualisation Unit, University of Dundee. The system recorded the 3D shape, skin textures, movement and voice of Rab, and then Face Lab and DI4D tracked and transferred Rab’s facial movement and voice to the 3D facial depiction of Robert Burns (Figure 10). The 4D performance capture, tracking and transfer methods utilised in this project have been developed by DI4D, however, the application in animating a facial depiction in this manner had never been carried out before.

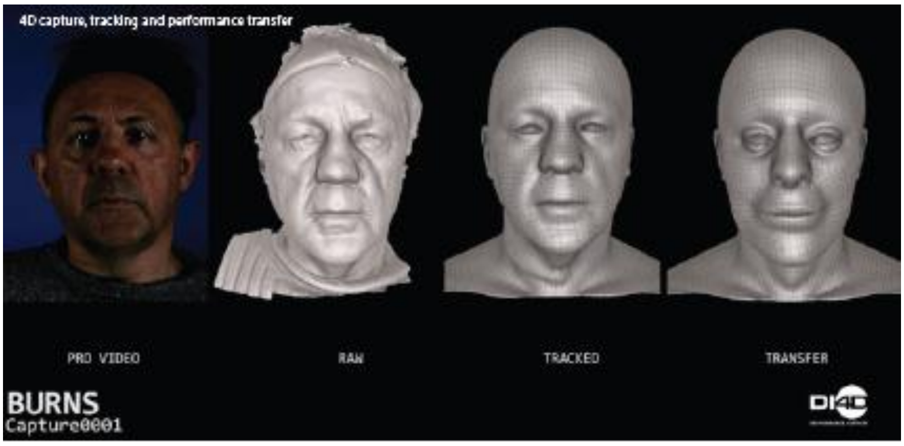

Figure 10: Performance capture, tracking and transfer of Rab Wilson’s facial movement and voice to the 3D facial depiction of Robert Burns. Image courtesy of DI4D (Glasgow).

Face Lab further animated the 3D model of Burns in Autodesk Maya 2018©, using the recorded footage of Rab reciting the poem as a guide (Figure 11), to mimic Rab’s head movements and make adjustments in relation to individual facial muscle movement. Skin textures were added digitally using ZBrush©, taking reference from portraits of Burns that showed his distinctive ruddy cheeks. The final animation (Figure 12) was screened at the Scottish National Portrait Gallery on Burns Night 2018, adjacent to the famous Alexander Nasmyth portrait of Robert Burns.

Figure 11: Further animation of the 3D model of Burns in Autodesk Maya 2018©, using the recorded footage of Rab reciting the poem as a guide.

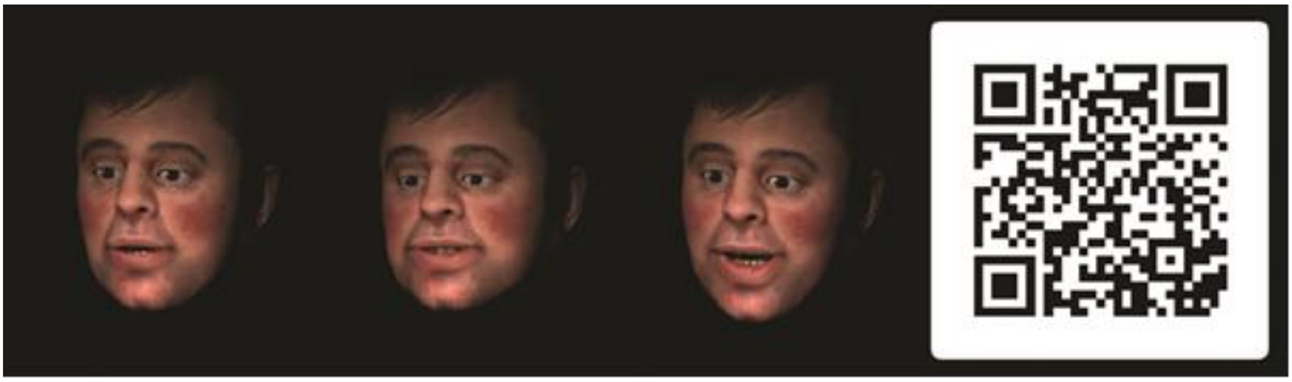

Figure 12: Stills taken from the final Robert Burns poem recital of ‘To a Mouse’. Scanning the QR code will take you to the movie on YouTube.

Through transdisciplinary collaboration and applications of existing technologies to create multi-sensory interactions, the poetry of this Scots Bard has been brought to life for generations to come and can further promote Scottish culture. J. J. Gibson focused almost exclusively on affordances which may be seen, but affordances may be perceived using other senses (Gaver, 1991) and by animating facial depictions of famous historical figures there is real potential to transform the way we interact with people from history; we can not only see them digitally but listen to them speak, recite literature or guide you around a museum.

Summary

Active use of existing digital technologies in 3D computerized facial depiction, including clinical imaging devices, 4D performance capture systems and 3D printers, promote reliable interpretation of human remains and production of accurate facial depictions for presentation to public audiences. Optic and haptic interactions with digital human remains can provide additional affordances that are highly relevant in facial depiction. These technologies often allow the scientist, artist or member of the public to see closer and deeper, make decisions about the unknown and interact more attentively with faces from the past (Smith, *et al.*, 2018).

Face Lab will continue to utilise 3D digital technologies in facial analysis and depiction of human remains for forensic investigation, or historical figures for archaeological interpretation. The affordances of the computer software, techniques and interfaces described in this chapter have contributed to the advancement of a 3D computerized facial depiction workflow. Such interactions can also be harnessed for a variety of biomedical visualisation needs including 3D anatomical modelling for pre-surgical planning or design of custom patient specific surgical implants.

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