The perception of palaeontology in commercial off-the-shelf video games and an assessment of their potential as educational tools.

Thomas Clements *[1†], Jake Atterby, *[1†], Terri Cleary [1,2], Richard P. Dearden [1] and Valentina Rossi [3,4].

1: School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, B15 2TT, UK

2: Independent researcher

3. Museo di Scienze Naturali dell'Alto Adige, Bolzano, 39100, Italy

4. School of Biological, Earth and Environmental Sciences, University College Cork, Cork, T23 TK30, Ireland

*Joint first authors.

† Corresponding author. clements.taph@gmail.com

Video games now comprise the largest sector of the media entertainment industry. Hundreds of video games, spanning a huge variety of genres and platforms, use extinct animals and/or palaeontological themes as a basis for their gameplay. Because of this, many players, especially children, spend long periods of time engaging with, and immersed in, palaeontological concepts and themes. Video games may be the first medium of implicit or tangential science communication they engage with, especially with regards to palaeontology. However, commercial off-the-shelf video games are not primarily designed to be educational tools, and the proliferation of some common tropes can disseminate harmful and/or unethical (mis)information regarding palaeontology. This paper introduces the major types of palaeontological video games and discusses their educational potential. We highlight the most common palaeontological tropes observed in video games, both positive and negative, to better equip science communicators about the perception of palaeontology (and ancient animals) in this massively influential medium that they may encounter when undertaking scientific engagement. Furthermore, by highlighting common misconceptions and harmful tropes we aim to bring awareness to game developers who may be unaware that they could be propagating negative tropes about palaeontological science.

1. Introduction

Video games are the largest and fastest growing sector of the media entertainment industry. In 2020, approximately 2.7 billion users generated an estimated $159.3 billion in revenue; more revenue than the movie and music industry combined (Newzoo Global Games Market Report, 2020). The rise of games playable on mobile devices has massively increased the accessibility

of video games to a broad range of demographics, mainly because they do not require specialist hardware, are often free-to-play, and have huge diversity in regard to subject matter and necessary skill level. Furthermore, gaming related entertainment, such as live-streaming services like the websites Mixer, Twitch, YouTube etc., are hugely popular, with over 12.4 billion hours of gaming live-streams consumed in the first two quarters of 2020 (Stream Hatchet Video Game Streaming Trends Report, 2020). Combined, this indicates that not only are video games increasing in popularity but that, when not playing, many users will still engage with video games by watching others play online via streaming services. Palaeontological science communicators should recognise the size of the captive audience, and how influential the medium of video games is as a resource for engagement practices.

Broadly speaking, video games can be separated into two categories: educational and commercial games. Educational games actively promote learning by introducing information and engaging the user with specific content, known as 'Digital Game Based Learning' (DGBL; see Habgood & Ainsworth, 2011). Video games that focus on specific STEM subjects have been shown to be beneficial to both non-students and students by positively aiding learning outcomes (e.g. Shute *et al*. 2013; Mani *et al*. 2016; Pringle *et al*. 2017; etc.), especially for students who struggle with traditional teaching practices (Mayo, 2009). However, studies also indicate that some users can find educational games patronising (Klopfer & Osterweil, 2013), or lose interest rapidly and disengage, decreasing the likelihood of positive learning outcomes (Kerawalla & Crook, 2005; Habgood & Ainsworth 2011). Furthermore, educational video games are typically niche in their subject matter, difficult to programme (e.g. Pringle *et al.* 2017), difficult to implement (e.g. Mani *et al.* 2016; Mozelius et. al., 2017), and require extensive funding to develop (Annetta, 2008; Mayo, 2009). These games are often made in association with specific outreach projects with limited funding (e.g. Mani *et al.* 2016; Pringle *et al.* 2017), making protracted development an impossibility (Mayo, 2009). It should also be noted that it can be difficult to monitor the learning outcomes from these educational video games (e.g. Mani *et al.* 2016) especially if they are released to the public. Ultimately, educational video games are viable learning aids, but they do not appeal to the wider public.

The second type of video games are commercial-off-the-shelf (COTS) games. These games make up the overwhelming majority of the gaming ecosystem and are incredibly diverse in their genres and themes. Typically, COTS games are developed to a much higher standard of graphics and gameplay mechanics than educational video games (Mozelius et. al., 2017) and are designed specifically to capture the attention of the user by motivating and challenging them in an interactive environment, often reinforcing this through repetition and reward (Brown *et al.*

2014). Despite the dated perception that video games are nothing more than a trivial time sink, evidence suggests that video games can have positive benefits to cognition, motivation, and social skills in players (e.g. Granic *et al.* 2014). Furthermore, COTS games can effortlessly provide early exposure to educational themes and concepts, even if the specific COTS game is not primarily designed for this purpose. Because of the huge variety in genres, engaging gameplay, ability to play online with friends, and high production quality, it has been proposed that COTS games are a resource that could be incorporated into teaching environments (Van Eck, 2006), with multiple studies undertaking utilising COTS in teaching environments (e.g. Charsky and Mims, 2008; Mohanty & Cantu, 2011; Sun *et al.* 2015; Cadwell *et al.* 2017; etc.). Recently, some COTS games have included specific sections of the game that are focused on education: for example, *Assassin's Creed: Origins* (2017, Ubisoft Montreal) and later instalments in the *Assassin's Creed* franchise contain a 'Discovery Tour' mode that removes combat and quests in the game to allow players to explore the games' historical settings accompanied with factual information and quizzes. Generally speaking, however, whilst educational video games often sacrifice entertainment for accuracy, many COTS video games do the opposite (Van Ecy; 2006 Mozelius et. al., 2017; McGowan & Scarlett, 2021), and therefore must be carefully vetted prior to integration into curricula, often leading to increased workload for educators (e.g. Sun *et al.* 2015; Cadwell *et al*. 2017 etc.).

One important and often overlooked aspect of computer gaming is the potential for implicit and tangential learning (Mozelius et. al., 2017; Crowley *et al.* 2021; McGowan & Scarlett, 2021). Implicit (or unconscious) learning occurs when learning takes place in an incidental manner without the awareness of the person engaging in an activity (e.g. Frensch and Rünger, 2003). Conversely, tangential learning is the semi-conscious process of self-education via exposure to a topic in an already enjoyable, non-educational format (Brown *et al.* 2014). Many COTS games impart complex scientific and historical content to their audiences by presenting the topic within fun and engaging game mechanics in a non-scholastic format (see Herrero *et al*. 2014; Crowley *et al*. 2021) and can be used as a tool within a wider educational framework (Herrero *et al*. 2014). However, it is also possible that any implicit and tangential learning from a COTS game may be a completely unintended or entirely accidental element of game design. Consequently, because COTS games are not primarily designed with educational purposes in mind, inaccuracies either intentional (disinformation), or unintentional (misinformation), could have a powerful effect on less informed players, misleading audiences about key concepts and even reinforce harmful stereotypes.

This is particularly pertinent to the science communication community, especially for palaeontology. For over 150 years, ancient organisms have inspired a plethora of popular books, films, cartoons and toys. It should therefore be of no surprise that ancient life is a popular topic for the video game industry. In fact, one of the first 3D games for the home computer was *3D Monster Maze* (1982*,* J. K. Greye Software), a maze game where the player was chased and, unless they could successfully escape, eaten by a *Tyrannosaurus rex* (Figure 1). Since then, the diversity of palaeontological video game genres has greatly increased and is currently a popular theme for COTS games (see Figure 2). This means that a considerable number of people, particularly children, will be introduced to the field of palaeontology through the medium of video games. Because players repeatedly engage with a single video game and new games containing palaeontological themes are released frequently, COTS games have a much greater reach than traditional outreach events.

The aim of this paper is twofold: 1) to familiarise science communicators with the types of palaeontological COTS video games; 2) to identify and discuss common tropes and misconceptions that often arise where scientific accuracy is compromised for entertainment value. This paper seeks to raise awareness to science communicators of the perception of palaeontology (and ancient animals) that the video game-playing public are exposed to, especially those that have been introduced to the subject via these games. Here, we highlight harmful tropes (i.e. unethical behaviour, misogyny, racism, etc.) to inform science communicators of the perception of palaeontology that is disseminated by COTS videogames. Furthermore, this review may be of interest to COTS game writers, developers, and video game artists who may be unaware that they are propagating damaging tropes pertaining to palaeontological science.

2. General introduction to palaeontological video games

In this review, we focus on COTS video games that incorporate fossils and/or ancient animals as one of the playable or interactive aspects of the game, which we term ‘palaeo-video games’. This review does not include games based on human remains or artefacts (archaeology).

Currently, there is a huge diversity of video games that contain palaeontological content. As of 2021, there are over 270 palaeo-themed COTS games available on Steam, the largest digital video game distribution service (PC games only) (Figure 2). It is important to note that this number does not include games that have been released for games consoles (such as the SNES, PlayStation, Xbox etc.) and so the number of palaeo-themed COTS games is much greater. Many of the games available on Steam are made by small development teams and will not sell in large quantities, however, mainstream titles can often sell large numbers of games. For example, by

2020 *Jurassic World Evolution* (2018, Frontier Developments) sold over 3 million copies (Kerr, 2020). Due to the vast quantity of palaeo-themed COTS games, there are titles not explicitly discussed herein.

In this review we do not discuss COTS games only incorporating ancient animals as 'set dressing'. Examples include games such as *The Last Of Us Part II* (2020, Naughty Dog), *Batman: Arkham City* (2011, Rocksteady Studios), and *BioShock* (2007, 2K Boston) that feature levels in museums containing skeletons or animatronic replicas of extinct animals, or *Battlefield* 4 (2013, DICE), which features a hidden 'easter egg' allowing the players to summon a giant *Otodus megalodon* during live multiplayer matches. While some of these games, such as *The Last Of Us Part II*, do have playable museum levels allowing players to interact with fossils, typically the palaeo-content of many of these games is purely aesthetic and, therefore, would be of limited use to science communicators. Another common use of ancient animals is purely cosmetic; many multiplayer games feature 'skins' that the players can unlock to customise their characters, and these often resemble ancient animals e.g. dinosaur outfits in *Fortnite* (2017, Epic Games), and dinosaur themed armoured suits in *Destiny 2* (2017, Bungie Inc.) (Figure 2). These 'skins' are purely aesthetic changes that do not alter the core gameplay and will not be discussed further.

In order to understand the tropes commonly seen in palaeo-video games, it is important to identify the major categories of palaeo-video games available on the market. Despite the diversity of game types and styles (Figure 2), most games align with one of the following categories (though some span multiple): 1) ancient animals as adversaries (Figure 3a); 2) ancient animals as tools (Figure 3b); 3) fossils as collectibles (Figure 3c); 4) ancient animal management simulators (Figure 3d); and 5) ancient animal simulators (Figure 3e).

2.1 Ancient animals as adversaries

This category is, by far, the most common type of palaeontological video game (65% of palaeo-game titles on Steam Figure 2d). Many video games use ancient animals (typically dinosaurs and pterosaurs) as adversaries that must be defeated (i.e., killed) for the player to proceed and continue the game. In this type of game, the ancient animals are programmed to be hostile if approached and/or will actively hunt the player. Examples include *The Legend of Zelda* (1986, Nintendo EAD), *Turok: Dinosaur Hunter* (1997, Iguana Entertainment; Figure 3a), *Trespasser* (1998, DreamWorks Interactive), *Dino Crisis* (1999, CAPCOM), *Tomb Raider* (1996, Core Design), *Peter Jackson's King Kong: The Official Game of the Movie* (2005, Ubisoft Montpellier).

Another type of palaeo-video game within this category is the 'wave shooter', in which the player fights off waves of hostile enemies with a suite of exotic weapons in order to progress. The enemies in these games are presented as cannon fodder that exhibit little or no natural behaviour, swarming en masse to overwhelm the player. Examples include *Dino Stalker* (2002, CAPCOM), *Dino D-Day* (2011, Digital Ranch), *Dinosaur Hunt* (2015, Racing Bros), *Carnivores: Dinosaur Hunter (Reborn)* (2015, Digital Dreams Entertainment LLC), *Wrath of the Goliaths: Dinosaurs* (2018, Ascendence Studios), *Hunt: Primal Reptiles* (2020, HugeLittleStudio), *Prehistoric Hunt* (2020, Antiproto Studios), and *Second Extinction* (2020, Systemic Reaction). Some games subvert this category and allow the option to play as the ancient animals in order to hunt and kill humans, such as *Primal Carnage* (2012, Lukewarm Media) and *Orion Prelude* (2012, DANKIE).

Generally, category 1 games offer very limited educational content. At best, the player can access a glossary of the hostile units which may contain some scientific information, however, many of these games rely heavily on tropes such as monsterification (see below) to make the enemies appear and behave more frightening or lethal. In fact, in most category 1 games, the ancient animals could be replaced by any other generic adversaries (i.e. aliens or zombies) with little effect on core gameplay.

2.2 Ancient animals as tools

Another common use of ancient animals in COTS games is as a tool to help the player progress through the game. One of the most famous and recognisable examples is Yoshi, a fictional omnivorous theropod dinosaur who first appeared in *Super Mario World* (1990, Nintendo EAD; Figure 3b). Yoshi was a mount for the Mario brothers, who rode Yoshi in their adventures to rescue Princess Peach, but Yoshi's popularity promoted him to full sidekick status and has spawned several dedicated sequels (e.g. *Yoshi's Story,* 1997, Nintendo EAD). A variety of other games allow tamed ancient animals to be utilised as mounts, such as *Far Cry Primal* (2016, Ubisoft Montreal), *Ark: Survival Evolved* (2017, Studio Wildcard), *Total War: Warhammer I* and *II* (2016, 2017, Creative Assembly), and *World of Warcraft: Battle for Azeroth* (2018, Blizzard Entertainment), with some games even going so far as to mount weapons such as machine guns and cannons, to ancient animals e.g. *Nanosaur* (1998, Ideas From the Deep), *Dino D-Day*, and *Total War: Warhammer II.*

Ancient animals as tools are also featured in the video game sub-genre of role-playing games (RPGs). In the context of palaeontology, the most famous examples are the *Pokémon* games, in which a diverse group of Pokémon are based on or inspired by ancient animals. In these games the player can catch, train, and fight the creatures in sanctioned competitions in

order to become the best trainer in their respective worlds. Pokémon fossils can be found, revived, and used to battle other trainers as the player progresses through the game (e.g. *Pokémon Red/Blue*, 1999, Game Freak). Similarly, the *Fossil Fighters* series (2008, Nintendo EAD) allows players to take part in detailed fossil excavations, revive the discovered dinosaurs (referred to as vivosaurs), and train them to fight in order to complete the main story.

Similar to category 1 games, category 2 games have very limited educational content but may have some information about the ancient animals in databases or glossaries.

2.3 Fossils as collectibles

Collectibles are a common aspect of COTS games: items found throughout the game setting that the player can collect as they progress and explore through the game. These collectibles are often an optional side quest separate to the main storyline, that provide additional worldbuilding or upgrades, but which in some games are used as resources to craft tools and materials.

Fossils are frequently a form of collectible seen in COTS games (Figure 4). For example, *Red Dead Redemption 2* (2018, Rockstar Games; Figure 4e), features a side quest where the player is tasked to locate 30 fossil specimens across the game world in order to assist an aspiring palaeontologist. Another example is in the Pokémon franchise; as mentioned above, fossils can be found and resurrected by the player in order to complete the secondary objective of the game (Figure 4o) – filling the digital Pokémon encyclopaedia, or Pokédex, with every type of Pokémon that can be found in the game world (e.g. *Pokémon Red/Blue*).

Most other games use fossils as a natural resource, alongside crystals, ore, geodes, etc. that can be used to collect, sell, or build other objects. In *Minecraft* (2011, Mojang; Figure 4n), *The Sims 4* (2014, Maxis; Figure 4f - h), *Starbound* (2016, Chucklefish; Figure 4i - m), *Stardew Valley* (2016, ConcernedApe; Figure b - d), and *Animal Crossing: New Horizons* (2020, Nintendo EAD; Figure 3c, Figure 4p - t) players can collect fossils for a variety of reasons — from displaying in virtual museums or in their own personal collections, to being used as fertiliser. However, in the majority of category 3 games, fossils are also used as (or associated with) in-game financial resources as a tradable commodity. This has implications for the public perception of fossil collecting (see *Representing ethics in palaeontology*).

Virtual fossil collectibles are almost always based on real organisms and often include database entries or facts pertaining to the collectibles items. This has enormous potential for educating the player, provided the information is well researched (see supplementary table 2). However, category 3 games can easily impart misinformation or even disinformation especially when presented in an otherwise informative context.

2.4 Ancient animal management simulators

'Construction and management simulations', sometimes referred to as park management simulators (or park sims) are games where the goal is to construct a financially viable park or zoo by managing the construction, park layout, guest management, animal welfare, and breeding programmes with often very limited resources. Ancient animals tend to be a common focus for park sim games, and they often have a diverse variety of realistically modelled organisms tending to exhibit 'naturalistic' behaviours (although some games are heavily stylized and/or simplistic for aesthetic reasons) for the player to engage with. There are several park sim games based on the Jurassic Park franchise, e.g. *Jurassic Park III: Park Builder* (2001, Konami), *Jurassic Park: Operation Genesis* (2003, Blue Tongue Entertainment), *Jurassic Park Builder*, (2012 Ludia) and *Jurassic World: Evolution* (Figure 3d), but independent franchises based on ancient animals are also popular e.g. *DinoPark Tycoon* (1993, Manley & Associates), *Zoo Tycoon: Dinosaur Digs* (2002, Blue Fang Games), *Parkasaurus* (2020, Washbear Studio) and *Prehistoric Kingdom* (2022, Blue Meridian).

Category 4 games often contain the most detailed compendiums on ancient organisms, allowing the player to find information regarding their required virtual living conditions and about the relevant science and/or discovery of the organism. They can also contain detailed information about fossil sites, fossilisation processes, phylogenetic relationships, and evolutionary processes. As with previous categories, this information can yield useful educational content if accurate, but be misleading if incorrect or disinformation is presented.

2.5 Ancient animal simulators

The last decade has seen the emergence of 'survival simulators' — games where the player can control an individual animal through an entire life cycle in a natural, open world, environment. While many COTS games, e.g. *Yoshi's Story*, *Project Bolan (Dinosaur Game)* (2014, Google), *DinoRun DX* (2015, PixelJAM Games) etc., allow the player to play as an ancient animal. within such games, the player's avatar could be replaced by any other organism without altering the gameplay experience and are not the focus of this category.

In survival simulators, the player's ancient animal avatar must survive by finding water and food (by hunting A.I. controlled animals or, potentially, other players) while avoiding natural hazards and being predated themselves. Typically, these games have focused on dinosaurs, e.g. *Saurian* (2017, Urvogel Games, LLC; Figure 3e), *The Archotek Project* (2017, The Archotek Project Team), *Beasts of Bermuda* (2018, Sastrei Studios, LLC), *Dinosaurs: Prehistoric Survivors*

(2018, Arcupion Art), *The Beasts of 9500* (2020, Dragons), and *Path Of Titans* (2020, Alderon Games) etc., however, some games do focus on non-dinosaurian animals groups such as early hominids e.g. *Ancestors: The Humankind Odyssey* (2019, Panache Digital Games). Survival simulators tend to market themselves as being as scientifically accurate as possible in both their palaeo-environmental and animal reconstructions (e.g. *Saurian*).

Another genre of game within this category allows the player to visit ancient ecosystems as a passive observer. Video games such as *Abzû* (2016, Giant Squid Studios), allow the player to swim through ocean environments inhabited by a plethora of ancient aquatic organisms from throughout geological time. *Robinson: The Journey* (2016, Crytek) utilises virtual reality headset technology to create an immersive experience for the player who must journey through a world inhabited by dinosaurs. This genre of game introduces the player to a diverse range of flora and fauna from the ancient past but is relatively uncommon.

3. Common palaeontological video game tropes

Within the context of this paper, a 'trope' is a recurring theme or motif that occurs across video games. Although many tropes are considered clichés, they are still commonly used throughout popular entertainment as recognisable touchstones to provide familiarity to the audience (see García-Sánchez, 2021). Many tropes seen in COTS video games are shared across the entertainment industry (especially in television and film), however, due to the interactive medium of video games, some tropes are unique to the format. Here we identify some of the most common tropes appearing in video games, to highlight how palaeontological science is represented in pop-culture and the entertainment industry, and to demonstrate that some tropes propagated by the video game industry may be scientifically misleading and/or perpetuate harmful stereotypes.

3.1 Ancient death machines: monsterification

The most frequent use of ancient animals in video games is as enemies for players to combat. Typically, these animals are designed to appear vicious, frightening, and brutish; this is known as 'monsterification'. This is often achieved by 'shrink wrapping' (reducing the organisms' soft tissue until they are just skin and bone. See Conway *et al.* 2012), increasing the animal's body size to exaggerated proportions, and grotesquely exaggerating features like claws, teeth, and horns. However, monsterification is not limited to an organism's appearance — it can also include behaviour such as being unrealistically aggressive, erratic and, most often, mindlessly and noisily torpedoing towards their prey. By consciously combining these aspects, ancient animals are made to appear more terrifying while also physically dissociated from real animals, meaning that

players have a desensitised and guilt-free experience slaughtering them. Interestingly, Jański (2016) found that when extant animals were used as background assets or companions for the player in video games, they were more likely to be accurately represented, whereas when animals were depicted as enemies or tools, their appearance and behaviour was more likely to be inaccurate, exaggerated, objectified and even monsterified. Indeed, some games actively task the player to 'monsterify' ancient animals: *Jurassic World: Evolution* encourages the player to breed dinosaurs to create hyper aggressive monsters in order to have them fight each other for the entertainment of park guests.

Monsterification is not a novel concept nor is it unknown to science communicators. From as early as the 19th Century, palaeo-reconstructions have liberally and creatively portrayed ancient life provocatively as monsters to stir the imagination and these images have permeated into modern popular culture. However, for science communicators there are some important aspects of monsterification that are not normally considered: 1) monsterification is not restricted to carnivorous animals in video games. Examples such as *Orion Prelude*, *Dinosaur Hunt* and *Second Extinction* etc. utilise hyper aggressive herbivores such as stegosaurs, ceratopsians, and ankylosaurs as opponents for the player to dispatch; 2) monsterification is not limited to dinosaurs. For example, *ARK: Survival Evolved* applies some degree of monsterification to almost every animal in the game – several taxa are much larger than their fossil remains indicate (e.g. *Diplocaulus, Paraceratherium* etc.), while the giant fish taxon, *Leedsichthys*, is coated in jagged spikes and scutes, and is depicted as highly aggressive despite fossil evidence suggesting they were filter feeding organisms. Similarly, *Far Cry: Primal* depicts 'ice age' (Pleistocene) mammals as colossal, aggressive monsters, and in the case of some animals, such as mammoths, twice the size of their largest fossil remains; 3) extreme monsterification can lead to a situation where ancient animals are indistinguishable from and/or confused with mythical creatures. In *ARK: Survival Evolved* a wide variety of ancient animals live alongside fictional animals, such as wyverns, basilisks and gryphons, that the player can also interact with and tame. In-game information and even achievements do not differentiate between the mythical and real animals, which could lead to confusion for some players.

Monsterification of ancient animals is not the same trope as video game monster designs heavily based on the appearance of ancient life. This is very common in video games, with examples including *Monster Hunter Rise* (2021, CAPCOM), where many of the monsters clearly resemble theropod dinosaurs, and *Horizon Zero Dawn* (2017, Guerrilla Games) where a post-apocalyptic world is populated by an ecosystem of mechanical creatures loosely based upon

extinct megafauna, including sauropod and theropod dinosaurs, as well as terror birds, giant crocodyliforms and cave hyenas.

3.2 Fossil = dinosaur = Tyrannosaurus rex*: lack of palaeodiversity*

Since their discovery in the 1800s, dinosaurs have captured the public imagination. Today, that popularity has continued, as dinosaurs dominate popular culture — so much so they are almost synonymous with ancient life in the entertainment industry. The video game industry is no different, with the vast majority of video games incorperating ancient animals featuring only dinosaurs (Figure 2c). The perpetuation of this trope poses a challenge to science communicators, as it presents a false impression to the audience that ancient ecosystems lack complexity, as well as diminishing ancient diversity and species distribution through geological time and space.

Yet, even within this trope, the representation of dinosaur diversity is typically limited to a handful of 'iconic' dinosaur species that are perpetually recycled by the entertainment industry (Figure 5). Many of these species are well documented from North Americans fossil sites like the Morrison or Hell Creek Formation (see Dodson *et al.* 1980; White *et al.* 1998), such as *Tyrannosaurus*, *Stegosaurus*, *Triceratops, Brachiosaurus* etc., while other commonly used species are typically predatory (e.g. *Velociraptor*, *Spinosaurus* etc.). Within the video game industry, this recycling of dinosaurs serves a practical purpose: for smaller game developers, building new digital assets can be highly labour intensive and costly. It makes commercial sense to use pre-made, often free, resources (e.g. 3D models, animations, sound effects and reference material) to recreate popular and recognisable dinosaurs, despite this further oversaturating their prevalence in the video game market place. Another group of ancient animals within the overused trope are the 'ice-age' (Pleistocene) animal pair of the woolly mammoth (*Mammuthus primigenius*) and the sabre-toothed cat (*Smilodon* sp.). As charismatic mega-mammals frequently used in media, they are recognisable to the public and often used as more relatable monsters than dinosaurs in some video games (e.g. *Far Cry: Primal*; *The Elder Scrolls V: Skyrim*, 2011, Bethesda Game Studios; *Syberia*, 2002, Microids.).

However, in recent years, there is a growing number of games that use a greater diversity of dinosaur species as an active selling point to market the game. Park building games such as *Jurassic World: Evolution* allows the player to send teams of scientists to real world fossil sites to collect DNA from a host of lesser-known dinosaur species such as *Baryonyx*, *Huayangosaurus*, *Proceratosaurus, Carcharodontosaurus*, *Tsintaosaurus* etc.. Dinosaur simulator games such as *Saurian* often feature lesser-known dinosaurs, while *Ark: Survival Evolved* features an abundance

of relatively obscure dinosaurs (e.g. *Yutyrannus*) but also Permian therapsids (e.g. *Moschops* and *Lystrosaurus*), Mesozoic birds (e.g. *Ichthyornis* and *Hesperornis*) and Cenozoic mammals (e.g. *Chalicotherium* and *Phiomia*). Although, many of these animals are still 'monsterificated', and the game proves the point of this section by referring to every ancient animal in the game as a dinosaur in the in-game information.

As new games seek to find a niche within the gaming ecosystem, there are a number of popular video games featuring and drawing attention to even more obscure palaeo-taxa and time periods. The hugely popular game, *Animal Crossing: New Horizons* tasks players with finding fossils for display within a local museum and, in so doing, introduced players to a variety of relatively niche groups such as *Anomalocaris* (a stem arthropod), *Eusthenopteron* (a sarcopterygian fish), *Acanthostega* (a basal tetrapod) and *Myllokunmingia* (a stem chordate). Interestingly, these fossils (and others found by the player) are displayed in a large phylogeny demonstrating evolutionary patterns in a simple but highly informative manner. Another game, *Abzû*, features a large number of obscure aquatic ancient animals such as ammonoids, *Anomalocaris*, *Arandaspis* (a jawless fish), *Diplocaulus* (amphibian), *Archelon* (giant sea turtle) etc., although there is no context or distinction of where/when these organisms lived for the player. *Ancestors: The Humankind Odyssey* avoids this trope entirely by being specifically set in Miocene Africa, including a suite of time-specific organisms such as *Stegotetrabelodon* (a stem elephant), *Machairodus* (sabre-toothed cat) and *Enhydriodon* (giant otter). All these games introduce the player to organisms and concepts they would have had limited (if any) exposure to in other types of media.

3.3 "Did you know...?": palaeotrivia and palaeodatabases.

In order to help the player understand complex topics or to introduce elements of story, many video games feature in-built encyclopaedias or glossaries containing fact-files about characters, objects and locations integral to the game's setting. In games featuring palaeontological themes, fact files, databases, and bonus trivia provide the ideal opportunity for optional, longer-form, educational content with the potential to inform and provoke further investigation from players, especially those who were not necessarily attracted to the game for the science.

In-game encyclopaedias can be extremely informative. This is particularly common in park management games such as *Jurassic World: Evolution* and the *Zoo Tycoon* series (Blue Fang Games, 2001 - 2017) that feature highly detailed databases about each ancient animal found in game, often incorporating facts pertaining to the organism such as where and when the animal was discovered as well as general information. This information is not necessary to play the game,

but because such databases are detailed and well researched, they often add to the 'scientific' aesthetic of these types of games and are useful educational tools.

More typically encountered is the usage of 'palaeo-facts' within different elements of the game. One excellent example is *Animal Crossing: New Horizons*, where Blathers, the strigiform (owl) museum curator, will regale the player with light-hearted but informative trivia about each fossil presented to the museum (See supplementary table 2). Another example commonly employed is the use of 'palaeo-facts' to entertain the player on loading screens (i.e. a picture the player must watch while the game is initialising). *LEGO Jurassic World* (2015, TT Fusion) uses this tactic to deliver bite-sized informative facts about many of the dinosaur species encountered in the game.

Generally speaking, the inclusion of palaeo-facts and databases in video games are good science communication, if they are well researched. However, if factual information is presented alongside misinformation, it can be difficult for some players to discern the difference. For example, in *The Sims 4* various fossils can be found throughout the game world – including trace fossils, trilobites, plants, and raptor dinosaur claws. However, other fossils items, ranging from the ridiculous (fossilised cow udders) to the bizarre ('perfectly preserved moustaches') are presented as genuine fossil remains. While clearly light-hearted and for comedic effect, the indiscriminate mixing of real and fake fossils presents a challenge for science communicators.

Tangentially, many of the games mentioned in this section have large, dedicated player fan-bases who often form distinct online communities. In order to assist with completing aspects of the games, many players create, edit and maintain sizable publicly editable online 'wikis' (an online database resource). These online encyclopaedias not only provide game specific information but often contain further reading and palaeo-trivia for interested players making them a useful educational resource, however, the degree of moderation and fact checking varies wildly.

3.4 The depiction of palaeontological science

The perception of palaeontology as a scientific discipline is difficult to gauge in computer games. Most palaeo-video games convey good palaeontological communication by explicitly integrating physical and biological processes into gameplay and world-building that will, either directly or indirectly, increase the knowledge of the player. However, most games typically focus on very specific aspects of palaeontology (e.g. fossil collection, genetics, evolution) and can take creative liberties in order to make engaging gameplay mechanics. This can mean the player may get an inaccurate or misleading representation of palaeontological science. We discuss some of these below.

3.4.1 *Geological processes*

Though it is often taken for granted, many open-world video games heavily rely on aspects of climate, topography, biomes and even natural disasters to create realistic settings, the exploration of which can subtly communicate basic earth science to the player. Enormous effort is taken to accurately capture the surface geology, flora and fauna, and variable ecosystems in open world games such as *Red Dead Redemption 2*, allowing players to learn tangentially (see Crowley *et al*. 2021). Other games, such as *American Truck Simulator* (2016, SCS Software) allow players to take virtual road trips across hyper-realistic (albeit scaled-down) sections of the United States including many famous North American fossil localities (e.g. Dinosaur National Monument, Colorado, USA). Other games incorporate geological processes to build the gameworld for the player to explore. *Subnautica* (2018, Unknown Worlds Entertainment) is an underwater survival/horror game based in the crater of a guyot (a submerged volcanic seamount) on an alien planet. The explorable map is separated into distinct biomes, some of which contain large fossilised remains preserved due to the area's specific environmental conditions. The processes of fossils formation (e.g. taphonomy) is explained to the player by scanning the fossils with scientific equipment in their inventory.

As computing power increases, greater graphical fidelity allows more accurate geological features to become standard in computer gaming and as a tangential effect this can be used by science communicators in engagement activities. During the recent COVID-19 pandemic, where travel was restricted, some academic institutions created virtual field trips for their students using technology commonly utilised by video gamers (e.g. VR headsets; Klippel *et al.* 2019). Furthermore, video game engines allow complex geological features to be explored in ways that would be difficult for actual students in the field (e.g. utilising aerial imagery; Klippel *et al.* 2020). This demonstrates that video games have great potential for geological engagement, especially for players who are unable to access key sites due to travel restrictions or accessibility issues, not to mention the reduced environmental cost associated with virtual fieldwork.

3.4.2 *Depicting evolution*

'Evolution' is a common theme in video games, but while video games are potentially a great way to introduce players to the complex process of evolution, it should be remembered that COTS games must prioritise delivering engaging gameplay far above educational content. It should also be noted that the term 'evolution' is commonly used in video games to encompass a host of different game mechanics not accurately representing biological processes, potentially

skewing the player's understanding of the phenomenon. One example of the term 'evolution' being misused is as a levelling up mechanic. In the *Pokémon* franchise, the Pokémon 'evolve' into larger, more powerful forms as they gain more experience and level up, despite the process actually being a type of metamorphosis.

Another common misuse of the term evolution applies to games where novel morphological traits are acquired via predation. In *Spore* (2008, Maxis) players must guide the 'evolution' of their own custom creatures from microscopic organisms to an interstellar empire by acquiring new evolutionary traits by scavenging them from the creatures they ingest (see Poli *et al*. 2012; Herrero *et al*. 2014). This depiction of 'evolution' is also seen in *E.V.O.: Search for Eden* (1992, Enix) where the main character begins as a generic fish, and must acquire teeth, jaws, limbs, and other features by eating prey items as they advance through levels inspired by different geological eras. This gameplay mechanic re-enforces the trope that evolutionary changes are a result of a conscious decision by an organism as opposed to random coincidentally beneficially traits with greater likelihood to be passed to the next generation via natural selection.

Other games tackle evolution as a gradual process with greater nuance, however many of these games are limited by the need for fun game mechanics. In *Cell to Singularity: Evolution Never Ends* (2018, Computer Lunch) the player clicks or taps the screen to acquire currency, which is spent to advance Earth history in short steps. The game is presented as a branching tree with each node representing a new species or event, however the order in which evolutionary milestones are achieved is entirely arbitrary, presenting evolution as a simplified linear checklist of sequential events. Even games accurately depicting ancient organisms and past environments often portray the processes of evolution poorly. *Ancestors: The Humankind Odyssey* depicts the evolution of early humans as distinct leaps from one species to next as opposed to multiple species coexisting at the same time (see Snyder, 2022). Similarly, the game also refers to the levelling-up mechanism of learning new skills and abilities, such as being able to use tools, as 'evolution'. By presenting evolution as an oversimplified, linear process, it also re-enforces the outdated notion that humans are the pinnacle product of evolution.

Conversely, some games approach evolution from a palaeontologist's perspective – using fossils to infer evolutionary patterns. In the puzzle game *Fossil Corner* (2021, Overfull Games), the player is given a box of procedurally generated fossils and is tasked with resolving their family tree by observing morphological character changes through each generation. This introduces the player to the concepts underlying maximum parsimony, a method to generate phylogenetic trees for extinct organisms commonly used by palaeontologists. As such, *Fossil Corner* is a good example of Digital Game Based Learning (DGBL).

3.4.3 Cloning and resurrecting extinct animals

One aspect of palaeontological science that consistently arises in video games is cloning/de-extinction. The *Jurassic Park* (Crichton, 1990) franchise popularised the concept of extracting genetic information from fossiliferous material in order to clone ancient animals (for a review of this topic see Jones, 2018). This concept pervades video games based on the franchise such as *Jurassic World: Evolution* but is also prevalent in many other video games. For example, in *Terraria* (2011, Re-Logic), ancient amber is one of many natural resources that can be collected by the player and each piece has a tiny chance of containing a fossil mosquito. The player can then process the fossiliferous amber using an 'extractinator' to resurrect a pet baby dinosaur. In *Pokémon Red/Blue* the player receives a fossil as a reward and can take it to a laboratory on Cinnabar Island, where a scientist will resurrect the extinct Pokémon. This is taken to the extreme in *Pokémon Sword* and *Pokémon Shield* (2019, Game Freak), where the palaeontologists take the player's fossils, splice them together, and resurrect them into horrific, often unviable, chimaeras.

Because the trope of DNA extraction from fossiliferous material is so prevalent in media, video game players may not be aware that, currently, we are not able to extract viable genetic material from fossilised remains to 'resurrect' extinct animals (although fragmentary fossil DNA can be extracted from some more recent fossils and has allowed important scientific advances in identifying these fossils and placing them in the tree of life (e.g. Buckley and Collins, 2011; Orlando *et al*., 2013; Perri *et al*. 2021; etc.). Generally, there is very little nuance in video games regarding the depiction of the growing field of palaeo-proteomics (i.e., the study of ancient proteins) and the recent advances made in the last decade (see Buckley *et al.* 2018). Furthermore, there is very little discussion in any video games about the ethical considerations of de-extinction (bioethics; see Attwood 2021) and this should be considered by science communicators when discussing this popular and exciting field of science.

3.4.4 *Keeping up with science*

Most media is dated by the science it is based on. A classic example is the *Jurassic Park* franchise, which was lauded for its exciting and scientifically accurate dinosaurs when the first film was released in 1993. However, as the series has progressed, it has chosen to maintain a distinct aesthetic rather than keeping up-to-date with the current scientific understanding (Polo, 2015). Similarly, while video games can be limited by graphical constraints (due to the computing power of the consoles or graphics cards they are designed for; see Figure 5), many games choose

to be scientifically inaccurate because of the need for recycled assets or because they have a specific aesthetic (e.g. *Jurassic World: Evolution*). However, unlike other traditional media, PC and (most) game consoles are connected to the internet, meaning game developers (and even fan communities) can issue updates and 'mods' (modifications) that update gameplay, graphics, or visual assets indefinitely after the games are released. Therefore, new fossil discoveries can be incorporated into game updates to keep games scientifically up-to-date. However, this relies on the game developer issuing updates, which may not be viable due to financial or time constraints. One example of this is *Animal Crossing: New Horizons*, which was released in March 2020. The game contains a skeleton of *Spinosaurus* that the player can find, accession, and mount in their museum (similar to Fig. 4 t). Three weeks after the games release however, Ibrahim *et al.* (2020) was published, which detailed a new *Spinosaurus* specimen from Morocco with a previously unknown tail section of significant scientific and public interest. This hype caused considerable media interest in whether Nintendo Entertainment Analysis & Development Division (EAD), the game developers of *Animal Crossing*, would update the visual asset in line with this new discovery (Watts, 2020; Rochlin, 2020). As of publication, the *Spinosaurus* model in *Animal crossing* has not been updated despite multiple updates to the game.

Inevitably, any released COTS video game will be overtaken by palaeontological advances and rendered out-dated, especially if developers are no longer working on updates for the game. From a science communication perspective, outdated game design can still be used to engage with the public, allowing science communicators to communicate up-to-date science, but also the history of scientific thought, and to explore the ever-shifting process of scientific discovery.

3.4.5 *Depicting palaeontological fieldwork*

Collecting raw materials is an extremely common game mechanic, and often games use fossils as a resource. In most of these games, fossils are acquired by approaching specific types of rock and breaking them with a tool (e.g. *The Sims 4; Stardew Valley, No Man's Sky, etc.)* or by digging holes in specific locations (e.g. *Animal Crossing: New Horizons*; see Figure 3c). In *Red Dead Redemption 2*, fossils can just be collected off the ground (albeit often in hidden or difficult to reach locations) while fossils can be found in *Stardew Valley* by fishing in streams in fossiliferous areas. Because fossil extraction is so common, and often simple, in video games, it can give players the impression fossil extraction is effortless, unmethodical, and skill-less – quite the opposite of the time-consuming, laborious, and often hazardous excavations often required to extract fossils.

Video games can also create the incorrect perception that fossils are a common occurrence in all types of rocks and a destructive approach is required to extract fossil material. This can be problematic as it may not be obvious to amateur fossils hunters that using hammers on fossiliferous rock faces may cause irreparable damage, be potentially dangerous, and in some areas illegal. Recently, local government organisations have started to introduce ethical rock collection policies (see Scottish Geodiversity Forum 2017), which can be disseminated to the public by science communicators.

Some games do take a more nuanced approach to fossil collection. In *Starbound,* fossils can only be uncovered with specialised tools, such as brushes and rock hammers, and failure to carefully extract the fossil-bearing rock permanently destroys the fossil. Once collected, fossils can be placed in customisable display cabinets at the player's base, which features a placard with basic trivia. *Tap! Dig! My Museum!* (2019, Oridio) is a mobile game where the player manages a museum, but also takes part in prospecting and excavating dinosaur skeletons. By tapping the screen, the player can remove layers of rocks piece by piece to find individual bone elements. Although simplified and highly stylised, the game does represent the processes of uncovering and transporting fossils in a fieldwork setting.

Another aspect of palaeontological fieldwork which is not commonly addressed in video games is ethical issues, which are highlighted below.

3.4.6 *Representation of ethics in palaeontological video games*

Palaeontology has a long colonial history with deep rooted extractive and exploitative practises (Monarrez *et al.* 2021). Because many harmful practises (e.g. the erasure of indigenous contributions, the illegal acquisition/removal of fossil material from their country of origin by higher income countries, the refusal to repatriate fossil material, etc. — see Monarrez *et al.* 2021, Raja *et al.* 2021; Cisneros *et al*. 2022) are so ingrained within palaeontological science, they often appear within video games unchallenged with little objective analysis. For example, to clone more dinosaurs and expand your park in *Jurassic World: Evolution,* the player must send dig teams to sites across the globe to extract more fossil genetic material. These dig sites are based on real-world localities, which is a good educational tool. However, many of these sites have strict laws governing the removal and sale of fossils, for example Mongolia, where it has been illegal to remove fossils from the country for almost 100 years. This is ignored in gameplay, obscuring a complex legal and ethical situation players could learn from.

While finding and collecting fossils is an integral part of the enjoyment of palaeontology and is important scientifically, one of the most contentious ethical issues facing palaeontology is

610 the buying and selling of fossils (Shimada *et al.* 2014). The commercialisation of fossil material,
611 especially over the internet and in high-profile public auctions (Shimada *et al.* 2014), directly leads
612 to a myriad of issues including the destruction of fossiliferous sites by illegal fossil hunters
613 (DeMiguel *et al*. 2021; Murphy, 2007), samples being lost to science (Shimada *et al.* 2014), and
614 in the worst case, the illegal exportation and smuggling of fossil material (e.g., Pérez Ortega,
615 2021) has dire real-world consequences, e.g. fuelling humanitarian crises, such as in Myanmar
616 (Dunne *et al.* 2021; Raja *et al.* 2021). There is increasing awareness of the problems of fossil
617 commercialisation, yet, in virtually every game featuring fossils as collectibles, excess fossils exist
618 purely to be sold for profit. For example, in *Jurassic World: Evolution*, the game is designed so
619 any non-dinosaur fossil found by the player must be sold instantly to raise funds. In the space
620 exploration game *No Man's Sky* (2016, Hello Games), the players can journey between planets
621 and find fossils on the worlds they visit, however, these fossils serve no function other than to be
622 sold for in-game currency. Even in games that otherwise represent museum curation and fossil
623 finding in a positive and educational manner such as *Animal Crossing: New Horizons*, fossils are
624 among the most financially valuable natural resources available. Once a fossil has been donated
625 to the museum by the player, any duplicates found can be sold at the local market for in-game
626 currency. These games do little to challenge unethical practises and normalise the
627 commercialisation of fossiliferous material as a standard procedure within the palaeontological
628 community. We therefore suggest it is vital science communicators are aware of the impact of the
629 illegal trade in fossils and incorporate issues such as ethical fossil extraction and fossil ownership
630 into public engagement to counter this narrative where possible.
631
632 *3.5 Male, pale and stale: the depiction of palaeontologists in video games*
633 COTS video games introduce the public to palaeontologists and allied workers, however, the
634 diversity and representation of palaeontologists in video games is very limited.
635 Often scientists and/or palaeontologists are portrayed in video games as old, white, men
636 that often resemble Charles Darwin (e.g. Professor Snail in *Stardew Valley* etc.). Another common
637 trope is the perpetuation of the 'Indiana Jones stereotype' (Fitzpatrick, 2020). For example,
638 *Dinosaur Fossil Hunter* (Demo released 2020, Pyramid Games) is a 'palaeontologist simulator'
639 which aims to simulate fossil discovery, digging, and extraction (even tasking players with
640 jacketing fossils in plaster). However, at the time of publication, the game uses only a white male
641 character model to market the game — complete with stereotypical fedora. Not only does the
642 reliance on these characters re-enforce the perception of palaeontology as a white male
643 dominated science (Panciroli, 2017), but they also propagate the 'brilliant lone scientist' trope

644 (Black, 2019), failing to illustrate the requisite collaborative nature of actual palaeontological
645 science and fieldwork.
646 Some palaeo-video games do have more diverse casts. However, these characters are
647 always able-bodied, often poorly fleshed out characters, and are typically plagued with
648 questionable motives and ethics. For example, in *Jurassic World: Evolution* the player must liaise
649 with Dr Kajal Dua, the head of the science division. However, her character has almost no
650 backstory and often undermines her position as a scientist by tasking the player to undertake
651 ethically dubious missions such as cloning dinosaurs specifically bred to be hyper aggressive
652 when fighting other dinosaurs. Likewise, the cowboy simulator *Red Dead Redemption 2* has the
653 player meet Deborah MacGuiness, an older white woman, digging up fossils on the American
654 frontier of 1899. The player learns that she, like many women in the nineteenth century, was
655 rejected from several universities and that no other academics take her scientific ideas seriously.
656 She resembles, and is most likely inspired by, Mary Anning the most famous of the multitude of
657 female palaeontologists overlooked by their male peers. After the player collects a number of
658 fossils from across the game world to help her with her research, she assembles a biologically
659 impossible chimaera, and reveals she was a terrible scientist all along thus reenforcing the
660 unethical genius and incompetent woman tropes (see Weingart *et al*. 2003). The game could
661 have included some genuine information about the infamous 'Bone Wars' of early American
662 palaeontology, and about women fighting for their place in science but, by including a female
663 character who validates every rejection she was served, a potentially interesting characterisation
664 and story (and the potential to educate players on such) was lost.
665 Historically and stereotypically, non-disabled white men have dominated the narrative of
666 palaeontology, and this in turn has shaped the depiction of palaeontologists in media, especially
667 video games. The systematic lack of diversity in the earth sciences, especially palaeontology, is
668 well known (Bernard & Cooperdock, 2018; Warnock *et al.* 2020). One potential aspect contribuing
669 to the lack of diversity (amongst many) in palaeontology, is the lack of minority role models
670 (Panciroli, 2017). The poor representation seen in COTS video games fails to counteract this —
671 if minority players, who may be prospective students and future scientists, do not see role models
672 represented in games and only see white male faces, they may be discouraged from pursuing
673 their interest in earth science. This is especially relevant to games that are marketed as
674 'palaeontologist simulators' but only contain white, non-disabled, male characters.
675
676 *3.6 Perpetuation of harmful, misogynistic, and racist tropes in palaeo-games.*

Video games have a history of perpetuating problematic tropes, especially ableism, sexism, misogyny, and racism (Nakamura, 2019). Although these tropes are not specific to palaeo-video games, they do warrant attention from science communicators as they can have an impact on how palaeontology may be perceived by players.

A common problematic video gaming trope is the hypersexualisation of women (Beasley & Standley, 2002). Evidence shows that the negative representation of women in video games can have severe negative effects for female gamers including self-objectification and low levels of self-efficacy (see Gestos *et al*. 2018). One of the most egregious examples of casual hypersexualisation seen in a palaeo-video game is found in *Trespasser* (1998, DreamWorks Interactive), where the player's character, Anne, is stranded on a dinosaur infested island. The game does not feature any visual cues for the player (i.e. health or ammunition counters) and so in order to check the health of the character, the player must actively look down to check a heart shaped tattoo on her breast that fades as the player is closer to death. Analysis has shown that hypersexualisation of women video game characters has decreased since the 1990s (Lynch *et al.* 2016) with a notable example being the de-sexualisation of Lara Croft, the protagonist of the *Tomb Raider* franchise, in recent games. While female lead characters are becoming more commonplace (e.g. Aloy, the lead character in *Horizon Zero Dawn*), it should be noted that Lynch *et al.* (2016) found COTS video games still typically depict female characters in secondary roles and that these characters are more sexualised than their male counterparts. Furthermore, within palaeontological video games, sexist and misogynistic tropes can also be coupled with racism, often thanks in part to the perpetuation of the “lost world” fantasy genre, which pervades palaeo-adjacent culture. Based on Arthur Conan Doyle’s book *The Lost World* (1912), wherein an ancient ecosystem is found in the Amazon basin by white explorers, this genre combines palaeontology, colonialism, and the mystification and exotification of indigenous cultures (see Harrer 2018). Many aspects of this sub-genre are harmful – propagating damaging stereotypes, economic oppression, and cultural appropriation. Care should be taken by scientific communicators to not disseminate these damaging tropes if using video games as part of their engagement, and also take further action by actively highlighting and challenging these practises within palaeontology themed media.

4. *Conclusion*

Video games are culturally prolific, and this sector is rapidly becoming one of the largest entertainment markets in the world. Palaeontological themed video games are extremely popular, and because of this, increasing numbers of the public are exposed to ancient animals and

palaeontological science — far eclipsing engagement efforts undertaken by scientists and allied palaeo-workers. Many COTS video games contain elements of good science communication — and some games, especially dinosaur simulators, strive for scientific accuracy. Indeed, aspects of palaeontological themed COTS video games can be used by science communicators to highlight, engage, and educate the public regarding core concepts of palaeontological science. However, as with most types of media, palaeontological video games can contain a suite of negative and potentially damaging tropes. Many of these tropes are widespread issues in the gaming industry (e.g. poor representation, monsterification, hypersexualisation, etc.), but their presence in palaeontological video games specifically detracts from their use as science communication tools. Science communicators, therefore, should undertake careful examination of COTS video games before using them as educational tools. Furthermore, because palaeontological themed video games are so popular, science communicators should be aware of and challenge harmful tropes in their engagement and outreach efforts to the public and, if possible, to COTS video game developers. By raising awareness of these damaging tropes, we can relegate them into extinction.

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Author contributions:

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Competing interests.

The authors declare that they have no conflict of interest.

1972
Pong, a tennis simulator, released by Atari in preloaded arcade machines

1976
Fairchild **Channel F** games console released. First console with 'cartridges', allowing players to change games

1977
The **ATARI2600**, 8-bit video game console, is released in the US. It sells over 27 million units

1981
IBM release **Model 5150**, with MS-DOS, allowing video games to be easily played on a PC

1981
The Chicxulub crater is identified

1980
The first cladistics software is released, making computer-based methods to work out of fossils' family relationships widely available

1982
The **Commodore 64**, an 8-bit personal computer, is launched. Affordable and easily modded, PC video gaming becomes mainstream

1982
3D *Monster Maze* is released. One of the first 3D games to be released for PC, it pits the player against a *Tyrannosaurus rex*

1983
A string of poorly implemented arcade game ports and low quality clone games cause the video game market to crash in the US

1984
First report that DNA can be recovered from fossil material and first 3D CT scan of fossil remains

1985
The **Nintendo Entertainment System (NES)**, an 8-bit console, is released. Selling over 61 million units, the NES reinvigorates the gaming market with iconic games such as *Legend of Zelda* and *Super Mario Bros*

1986
'*The Dinosaurs Heresies*' is published, popularizing the concept of agile and dynamic dinosaurs

1989
Nintendo launches the **GameBoy** - a now iconic 8-bit handheld video game console. It sells over 118 million units

1989
The book '*Wonderful Life*' is published, popularizing the 'Cambrian explosion'

1990
Nintendo launches the **Super Nintendo Entertainment System (SNES).** The best selling console of the 16-bit generation, it is launched with *Super Mario World* in which *Yoshi* makes his first appearance

1993
Dinopark Tycoon is released for MS-DOS and MacOS, one of the first dinosaur management games

1993
Jurassic Park film is released. Over 40 JP video games will be made

1994
Sony releases the **Playstation**, a 32-bit games console. It is the first console to ship over 100 million units

1996
3dfx Interactive launch the Voodoo 1 graphics chip revolutionising real-time 3D graphics for the PC

1996
Pokémon Red/Green is released on the Gameboy, launching the multi-billion dollar franchise

1997
Sinosauropteryx, the first feathered non-avian dinosaur, described

1997
The first person shooter *Turok: Dinosaur Hunter*, is released on Nintendo 64

1999
Walking with Dinosaurs, critically acclaimed documentary, released. At the time, it was the most expensive documentary ever made

1999
DinoCrisis is released on the Playstation, redefining the dino-horror genre

2000
Sony releases **Playstation 2**, a 128 bit sixth-generation console, that becomes the best selling console of all time, shipping over 155 million units

2000
The Paleobiology Database, a community driven digital database of published fossil occurrences, is launched

2003
Steam, a digital video game distribution service that allows PC users to play games without physical copies, launched. In 2020, Steam has over 25 million users

2004
The **Nintendo DS**, a 64 bit handheld console, is released. It becomes the highest selling handheld console shipping over 154 million units

2004
Tiktaalik roseae, a key transitional fossil tetrapod, is described

2004
The Ediacaran period is ratified, making it the first new period to be established for 120 years

2004
World of Warcraft, a massive multiplayer game, is released. Featuring dinosaur mounts in later versions, had over 12 million subscribers at its peak.

2008
Spore, a game that allows the player to guide the evolution of a creature from bacteria to space-faring being, is released

2008
Fossil melanin discovered allowing pigmentary reconstructions of ancient animals

2011
Minecraft is released, going on to be the highest selling game of all time shipping 200 million units. Later versions of the game feature fossils

2014
'*Project Bolan*', a secret game only available when Google Chrome is offline, is released. In 2018, over 270 million games are played per month

2016
Pokémon Go, a free-to-play mobile game, released by Niantic. Pokémon Go has been downloaded over a billion times and has made over $6 billion

2016
Far Cry Primal released. The game is set in 10,000 BC and players can ride mammoths and hunt sabre cats.

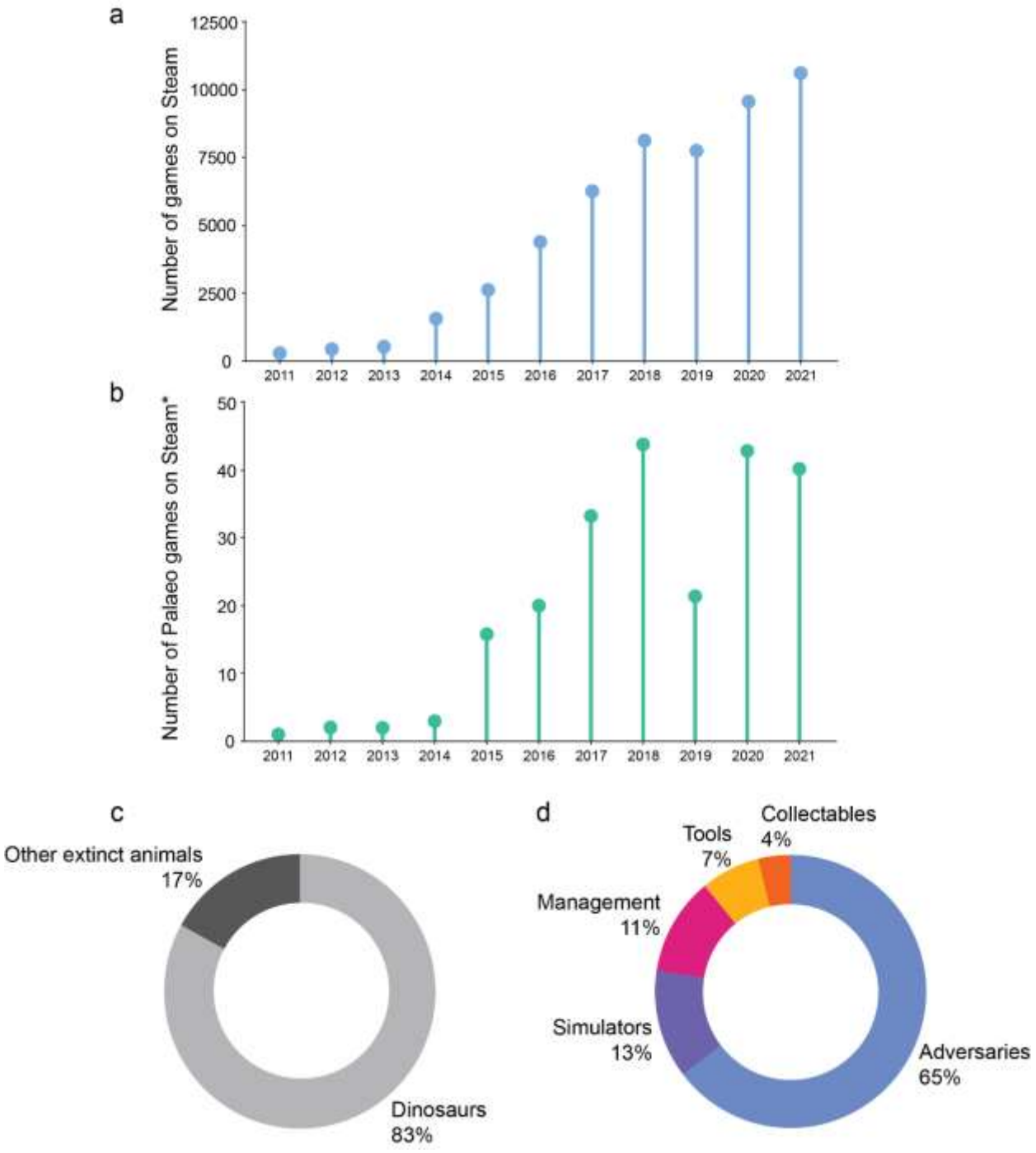
2017
Saurian, one of the first dinosaur simulator games, is released on PC

2017
Borealopelta, an unusually complete ankylosaur 'mummy' is described

2018
Red Dead Redemption 2 is released with the second highest launch in entertainment history, grossing over $725 million in the first weekend. The game contains a secondary storyline featuring a palaeontologist

2020
Sony releases the **Playstation 5** and Microsoft releases the **Xbox Series X** 9th generation consoles.

758 Figure 1. A timeline of major events in palaeontology, video games, and palaeontological video
759 games between 1970 - 2020.
760
761



762
763 Figure 2. a) Number of PC games released per year on Steam, the largest video game digital
764 distribution service. b) Number of games released per year that utilise palaeontological keyword

765 ‘tags’ on Steam. c) Percentage of palaeontological COTS video games on Steam that contain
766 dinosaurs versus those that only contain non-dinosaurian ancient animals (excluding crown group
767 birds). d) Breakdown of palaeontological COTS video games on Steam by categories identified
768 in this paper. Source a: https://steamdb.info/ (accessed March 2022). Source b, c, d:
769 https://statista.com (accessed March 2022). A full list of the palaeontological COTS video games
770 on Steam and ‘tags’ searched can be found in the supplementary material.
771

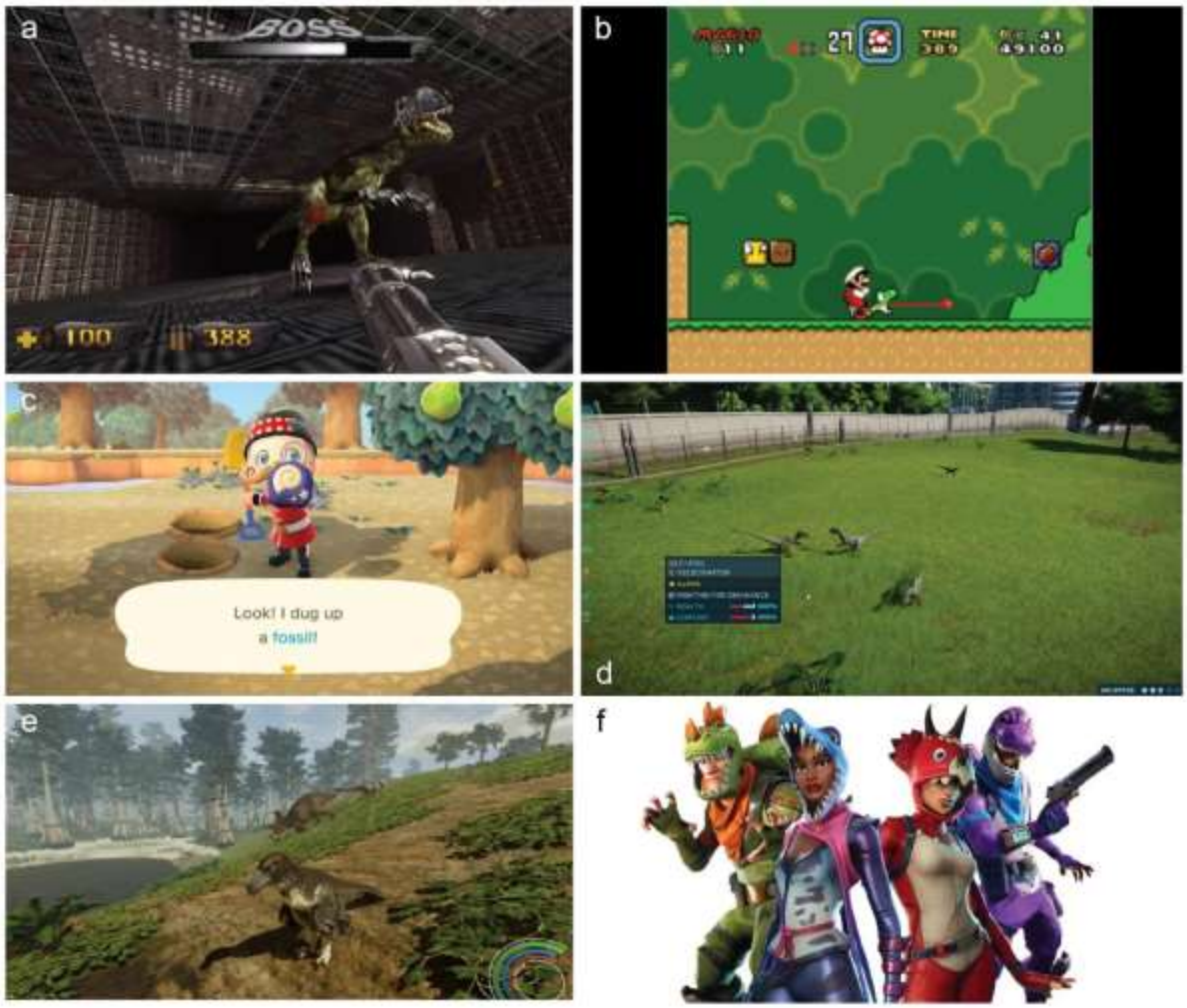
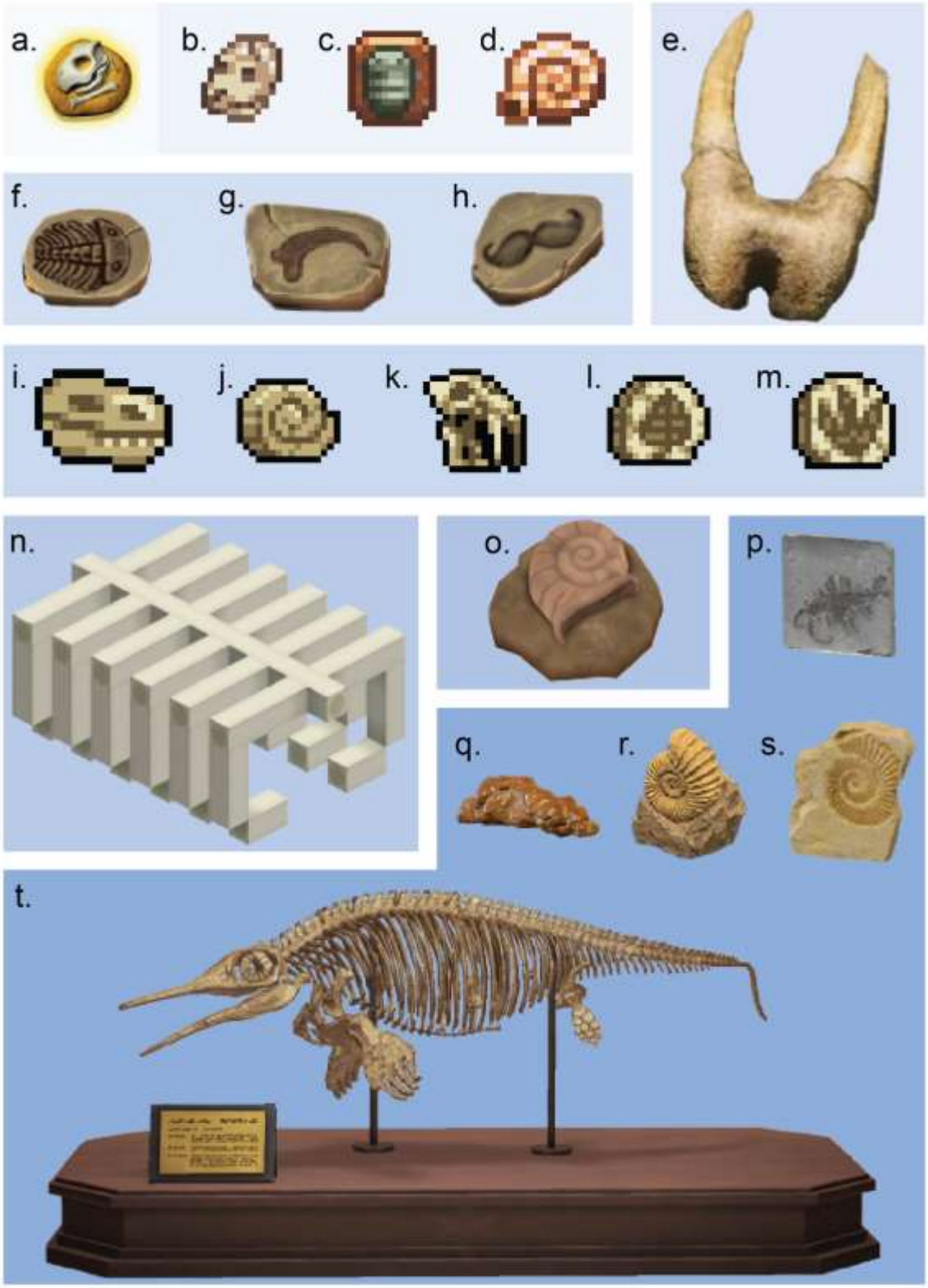


Figure 3. Screenshots of COTS video games that represent the 5 categories of palaeontological video games outlined in this paper. a) Ancient animals as adversaries. The player is fighting a cybernetically enhanced *Tyrannosaurus* armed with laser shooting ocular augments and fire breath in *Turok: Dinosaur Hunter* (1997, Iguana Entertainment). b) Ancient animals as tools. Mario riding Yoshi in *Super Mario World* (1990, Nintendo EAD). c) Fossils as collectibles. The player discovers a fossil in *Animal Crossing: New Horizons* (2020, Nintendo EAD). d) Ancient animal management simulators. A paddock of velociraptors exhibiting modelled in-game behaviours (the alpha is fighting for dominance of the pack). *Jurassic World: Evolution* (2018, Frontier Developments). e) Ancient animal simulators. The player's avatar, a *Dakotaraptor*, sits near a water body while *Triceratops* and *Pachycephalosaurus* graze in the background. *Saurian*, (2017, Urvogel Games, LLC). f) Examples of cosmetic items that are based on ancient animals from *Fortnite* (2017, Epic Games) - often these only change the players character models (and not core gameplay mechanics) and are known as 'skins'.



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787 Figure 4. Examples of fossil collectibles in COTS video games. a) ‘Generic fossil’. b) Prehistoric
788 skull (described in game as a ground sloth skull). c) Trilobite. d) Nautilus Fossil. e) Dinosaur bone

(note: this is a walrus skull). f) ‘Enormous Trilobite’. g) Raptor Claw. h) ‘Perfectly Preserved Moustache’. i) *T. rex* skull. j) Ammonite. k) Sabretooth skull. l) Fossil Fern. m) Footprint Fossil. n) Fossil Rib Cage. o) Helix fossil. p) *Anomalocaris*. q) Coprolite. r) Ammonite s) Shark-tooth pattern (note: this is a *Helicoprion* tooth ‘whorl’) t) completed *Ophthalmosaurus* skeleton consisting of two collectibles – *Ophthalmosaurus* skull (which includes the front flippers and anterior section of the ribcage) and the *Ophthalmosaurus* torso (consisting of posterior ribs, hind flippers, and tail section). Video games: a: *No Man’s Sky* (2016, Hello Games). b - d: *Stardew Valley* (2016, ConcernedApe). e: *Red Dead Redemption 2* (2018, Rockstar Games). f - h: *The Sims 4* (2014, Maxis). i - m: *Starbound* (2016, Chucklefish). n: *Minecraft* (2011, Mojang). o: *Pokémon* series (1999, Gamefreak). p - t: *Animal Crossing: New Horizons* (2020, Nintendo EAD). Virtual fossil collectibles often include database entries – the accompanying facts for these fossil collectibles can be seen in supplementary table 2.

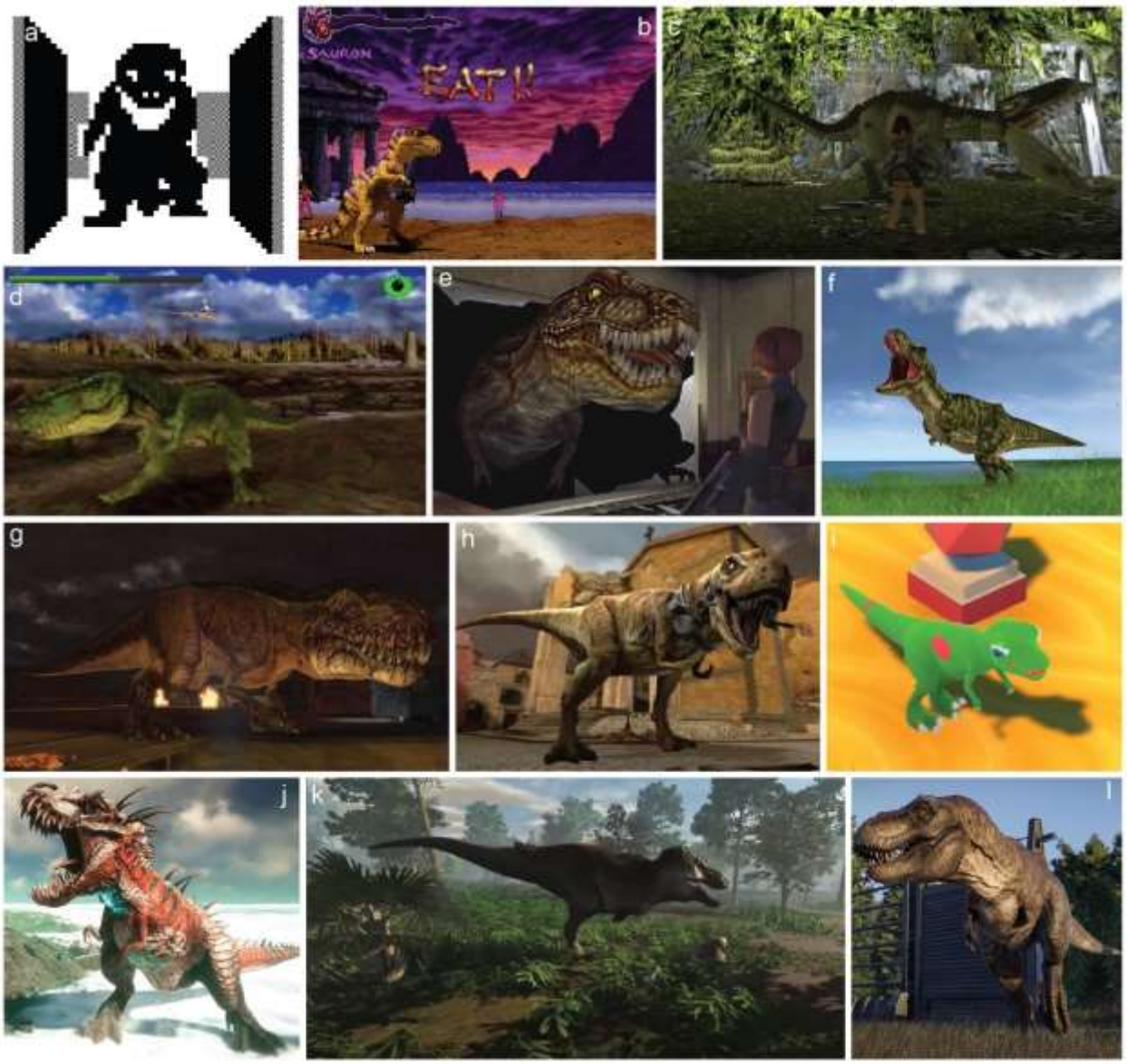

Figure 5. The representation of *Tyrannosaurus rex* in COTS video games through time. a) *3D Monster Maze* (1982, J. K. Greye Software). PC. b) *Primal Rage* (1994, Midway Games West Inc) Super Nintendo Entertainment System. c) *Tomb Raider* (1996, Core Design). Playstation. d) *The Lost World: Jurassic Park* (1997, DreamWorks Interactive). Playstation. e) *Dino Crisis* (1999, CAPCOM). Playstation. f) *Jurassic Park: Operation Genesis* (2003, Blue Tongue Entertainment). PC. g) *Turok* (2008, Propaganda Games). PC. h) *Dino D-Day* (2011, Digital Ranch). PC. i) *Parkasaurus* (2020, Washbear Studio). PC. j) *Second Extinction* (2020, Systemic Reaction). PC. k) *Saurian* (2017, Urvogel Games, LLC). PC. l) *Jurassic World: Evolution* (2018, Frontier Developments). PC.

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