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Natural History Mystery: Immersing Families in a Problem-Solving Game Using Natural History Exhibits

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ABSTRACT: There is a need for a better public understanding of evolutionary relatedness including its relevance to socio-scientific issues such as conservation and health. As venues that play an important role in communicating about evolution, natural history museums have an opportunity to explore novel means of enhancing visitor learning in this area. We describe the design, testing, modification, and evaluation of an immersive, problem-solving educational game on the topic of evolution using specimens on display in a natural history museum. *Natural History Mystery* invites small teams of players to solve a series of puzzles to identify the source of a zoonotic disease. In the process, they use existing exhibits and supporting game components to learn about shared characters, common ancestry, and relatedness. The game was iteratively designed through multiple rounds of trial testing with families and other groups. A summative assessment performed by an external evaluator concluded that, through the game, players had fun, explored the museum in new ways, and felt they learned and developed new skills. The evaluation found that participants learned about evolutionary relationships and made connections between evolution and medical applications. We share details about game/puzzle design and development along with lessons learned, providing a model for other institutions to create their own themed puzzle-hunt game customized to their site.

INTRODUCTION

Evolution is a critical aspect of scientific literacy (American Association for the Advancement of Science, 2001; NGSS Lead States, 2013), forms the foundation for understanding biology (Futuyma and Kirkpatrick, 2022), and is central to grasping emerging socio-scientific issues in the areas of agriculture, conservation, and especially human health (e.g., Pellens and Grandcolas, 2016; Tucker et al., 2016; Winter et al., 2013). Comprehending evolutionary relationships and common ancestry is important for an understanding of modern biology and its applications (Baum et al., 2005; Donoghue, 2005). This connection is particularly apparent in medical research, as highlighted by investigations of recent and emerging zoonotic diseases, including HIV, MERS, and COVID-19. In this research, scientists have reconstructed the evolutionary trees (i.e., phylogenies) of, for example, SARS-CoV-2 and related viruses in order to pinpoint their emergence and understand the zoonotic origins of the disease, tracing it back to bats and pangolins, as well as to understand the timing and source of community outbreaks of the disease early in the pandemic (Bedford et al., 2020; Wacharapluesadee et al., 2021; Zhou et al., 2020). That research, as well as much other research relevant to human health (e.g., the discovery of new medically useful compounds, investigating the progression of cancer and its evolution of resistance to chemotherapies; (Brown et al., 2017; Romano and Tatonetti, 2019), rely, not just on evolutionary reasoning in general, but specifically on an understanding of evolutionary relatedness as visually represented in evolutionary trees. Because they are so important in modern biological thought, evolutionary trees are now ubiquitous and found in textbooks (Catley and Novick, 2008), the popular press (Wade, 2017), popular science books for all ages (Tweet, 2016), and exhibits at informal science institutions (ISIs; MacDonald and Wiley, 2012). Understanding such diagrams may even be important in helping people accept evolutionary theory as an explanation for the diversity of life (Gibson and Hoefnagels, 2015; Walter et al., 2013).

Unfortunately, key evolutionary concepts related to phylogenetics such as common ancestry are difficult to grasp for all age groups (Catley et al., 2012; Dees et al., 2017; Evans et al., 2010; Evans et al., 2012; Spiegel et al., 2012). Even among populations whose interest in evolution is high, such as natural history museum visitors, understanding of key evolutionary concepts is low (Evans et al., 2010; MacFadden et al., 2007). Moreover, interpreting graphical representations of common ancestry (i.e., "tree thinking", a diverse set of skills reviewed by Schramm et al. (2019) is a particular challenge, and understanding of these graphics is often limited and reflects evolutionary misconceptions (Catley and Novick, 2008; Catley et al., 2012; Gregory, 2008; Kummer et al., 2016; Phillips et al., 2012; Torrens and Barahona, 2012). While appropriate instructions can improve understanding of these diagrams, some elements of tree thinking and tree building can be a challenge to develop even at the college level (Dees et al., 2017; Kummer et al., 2016; Novick and Catley, 2017; Smith et al., 2017; Young et al., 2013).

Natural history museums (NHMs) have an opportunity to help build better understandings of evolutionary relatedness, including its relevance to zoonotic disease. Such institutions play a critical role in communicating about evolution to the public (Diamond and Evans, 2007; Diamond et al., 2012; MacFadden, 2008; Suarez and Tsutsui, 2004; West, 2005). Research shows that evolutionary trees are of interest and accessible to museum visitors including young learners (Ainsworth and Saffer, 2013; MacDonald, 2014; Spiegel et al., 2012) and that museum experiences using trees can support understanding of common ancestry and tree-thinking skills (Davis et al., 2015; Phillips et al., 2013). In addition, NHMs have a responsibility to communicate the importance of their collections to research, including the role of biodiversity collections in investigating emerging infectious diseases (Hilton et al., 2020; National Academy of Sciences, 2020). Indeed, Colella and colleagues (Colella et al., 2021) argue that NHMs are uniquely positioned to communicate research findings of societal importance that are based upon human connections to wildlife and the environment, as is the case for zoonotic disease. While the detailed phylogenetic analyses that underlie research into emerging disease are complex and not relevant to most museum visitors, an understanding of the basics of tree thinking and a simple appreciation of the fact that evolutionary relatedness, museum collections, and biodiversity help scientists solve problems related to human health *are* within the grasp of the lay public and appropriate educational and attitudinal goals for NHM experiences.

This context has motivated many efforts to use NHM exhibits to improve visitor understanding of evolutionary relatedness (e.g., Block et al., 2012; Davis et al., 2015; Diamond et al., 2012; Evans and Lane, 2011; Giusti, 2008; Horn et al., 2016). Here, we build on this background by developing and investigating a novel type of museum experience for learning about evolution, common ancestry, and evolutionary trees: an immersive escape-room-inspired puzzlehunt game, funded by an Institute of Museum and Library Services Museums for America award (Grant #MA-249109-OMS-21).

Natural History Mystery is a place-based puzzle hunt game, which immerses players in a setting and narrative, while fostering content-related dialogue and communicating the roles of biodiversity and evolutionary science in solving socio-scientific problems. We selected this innovative format because of its appeal to families: important motivations for family visits to ISIs are to have social, fun, educational experiences (Andre et al., 2017; Falk and Dierking, 2000; Falk et al., 2007; Moussouri, 2003; USS Constitution Museum, 2018); and because we anticipated that such a game would support learning, interest, and motivation.

Several converging lines of evidence support the idea that an immersive game about evolution can support learning in a museum setting. First, it is well established that games of many different types can deeply engage learners and facilitate learning (Bochennek et al., 2007; Burney et al., 2010; National Research Council, 2011; Porcello et al., 2017). Serious games have been shown to increase knowledge acquisition, conceptual understanding, and motivation (Connolly et al., 2012). Second, content-rich interactions among ISI visitor groups, as an immersive game has the potential to initiate, have been shown to support STEM learning in informal environments (Andre et al., 2017). Third, the narrative aspect of an immersive game can also further learning (Jenkins, 2010; Prins et al., 2017; Szurmak and Thuna, 2013). And finally, prior research has found that learners are more interested in science when its implications/applications are connected to their lives (Ainley and Ainley, 2011; Hulleman and Harackiewicz, 2009; National Foundation for Educational Research [NFER], 2011), a connection offered by the game narrative we selected: investigating the source of a zoonotic disease. Exploring how evolution helps solve real-world problems is thought to be an important part of increasing motivation to learn about evolution (Infanti and Wiles, 2015; National Research Council, 2012; Nelson, 2012; Pobinar, 2016; Thanukos, 2010).

In the current report, we provide an overview of the pilot project and describe the game and its goals, a summary of our development process, and the results of trial testing and summative evaluation. Finally, we share lesson learned regarding design and practical elements that would be useful for developing and implementing similar games in other ISIs.

OVERVIEW

Natural History Mystery is gallery-based puzzle hunt game for groups of two to five players including youth aged 7 to 12 with an adult caregiver. It leverages specimens in museum exhibits to explore shared characters to identify the source of a viral zoonotic disease and learn how evolutionary thinking can help solve real-world problems. The game combines elements of activity backpacks, an established museum-learning format in which visitors do hands-on activities while exploring galleries at their own pace (McCormack and Crawford, 2013; Victoria and Albert Museum, 2019), with escape rooms, an engaging and popular game format in which a team is challenged to solve a series of narrative-embedded puzzles encoded in the room's artifacts within a set period of time (Nicholson, 2016; Wiemker et al., 2015). The backpack contains a set of interconnected puzzles that leads visitors through the museum as they gather data from displays, engage with evolutionary concepts to unlock puzzles and artifacts, and ultimately solve the mystery.

While the idea of an educational escape room and of museum-hosted escape rooms are not new, our interviews with developers on 10+ escape rooms of these types indicate that conceptual goals are not typically embedded the puzzle design. Consistent with this, evaluation of escape rooms' use in formal learning environments has primarily focused on engagement, interest, and motivation, not learning (e.g., Borrego et al., 2017; Glavas and Stascik, 2017). Only a few escape games, including our own NIH SEPA-funded pop-up *STEM Escape* project, BranchOut's outdoor environmental education-themed escape games, NISE (Nanoscale Informal Science Education) Network's (2020) *Moon Adventure* game kit, and *INFESTATION* at the Science Museum of Minnesota (a narrative-driven interactive theater, game, and puzzle room experience; Pryor, 2019), target conceptual learning, and none engages visitors with an escape game experience relying on existing exhibits to engage more deeply with science content and specimens.

Game and puzzle development was informed by the theory and practice of both escape game design and evolution education. As advocated by game designers, the play of the game directly relates to the educational content delivered, was designed such that the game experience is balanced with the educational one, and incorporates a variety of puzzle types (Clare, 2015; Wiemker et al., 2015). The game was also designed to incorporate approaches and activities shown to be successful at teaching about evolutionary relatedness. For example, the final puzzle in the game is informed by an instructional booklet for teaching about evolutionary trees (Novick et al., 2012), as well as activities designed for use in class (Eddy et al., 2013; Goldsmith, 2003). Furthermore, all tree diagrams within the game were based on design principles informed by learning research that were developed to avoid reinforcing common misconceptions and facilitate accurate interpretation in ISIs (e.g., Novick et al., 2014), such as using square brackets as opposed to diagonal lines to represent lineages of descent and including an arrow of time on the tree.

We also engaged an advisory team that included an evolutionary scientist, an educator who has created outdoor escape rooms to teach environmental curriculum, and the director of public programs at a large natural history museum, as well as an external evaluator to conduct the summative evaluation.

The *Natural History Mystery* puzzle hunt game was designed to achieve the following goals:

1. Be a fun, memorable experience
2. Spark conversations about evolutionary relatedness within player groups
3. Increase players' understanding of common ancestry and evolutionary trees
4. Heighten players' awareness of evolution's relevance to medicine

Game Mechanics. Over the course of the game, teams will place five major vertebrate clades—lizards, tapirs and rhinos, bears and cats, frogs and salamanders, and bony fish—onto an evolutionary tree based on four traits: number of toes on back foot, number of bones in lower jaw, protected egg/embryo, and tetrapod arm bone pattern. In the first stage of the game, players move sequentially through four gallery locations, collecting data from exhibits to solve a series of four individual puzzles (one related to each trait) to complete the data matrix that outlines which vertebrate clades have which traits. In the last stage of the game, players use this completed data matrix to place the taxa on an evolutionary tree, which is the win condition. Players' progression through the game is mediated by unlocking compartments in a backpack: the materials in each compartment provide the tools needed to solve the current puzzle, which then allows players to unlock the next compartment.

The game provides no didactic instruction on evolutionary concepts or tree reading, only hints or examples of how to solve each puzzle as testing indicated was needed, with an optional answer key for each puzzle. Instead, the game provides the impetus, motivation, and supports for players to engage directly with shared characters and common ancestry at their own pace, discuss possible interpretations of the trees, traits, and puzzle with each other, and test out their different constructed understandings about how these might work. The locks in the game offer a built-in feedback mechanism. Unlocking the next compartment indicates a successful construction of scientific understanding; a failed attempt indicates more exploration is needed. Because the code for each lock is based on correctly completing a line in the char-

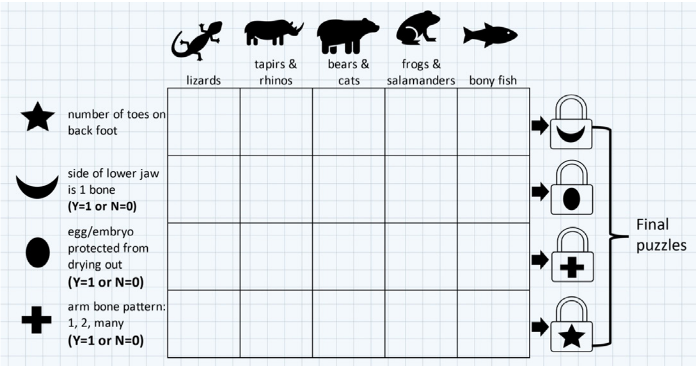

Figure 1. *Natural History Mystery* data matrix.

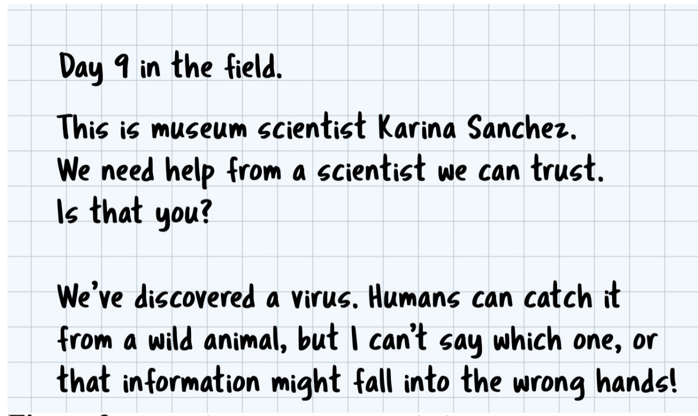

Figure 2. *Natural History Mystery* mission.

acter matrix, unlocking the first four locks also ensures that players go into the final metapuzzle with a correct character matrix, which they will need to solve that final puzzle.

Groups are given: (1) a backpack with four pockets (three locked and one unlocked) that contain the tools and props, which are used, along with information from the exhibits, to solve the four trait puzzles, an open main pocket with locked final puzzle, and optional answer sheet to each puzzle in a side pocket (folded and stapled); (2) a blank data matrix with rows to fill in for each puzzle/trait (Fig. 1); and (3) a laminated folded map with four exhibits marked (the map also contains information used in two other puzzles). Symbols are used to identify the four individual puzzles on the matrix, map, and combination locks on pockets. The solution to each puzzle reveals the code that unlocks the next puzzle/pocket; these codes are used later to gain access a final synthesis puzzle.

Narrative and Player Experience. To start the game, groups receive a brief overview, an orientation to the gallery map and combination locks, and a mission: museum scientists have discovered a virus in a wild animal, and they need players help to use clues and solve puzzles to identify the one that carries the virus, so they can stop the virus from spreading (top section of mission, Fig. 2). This mission frames and motivates players' experience in terms of solving a medical problem, and over the course the game, it will be revealed that they must reason about evolutionary relatedness and trees in order to do so. While the game does not mimic the steps that scientists would go through to uncover the origin of a zoonotic disease – a process that would involve reasoning about genetic sequences and the relatedness of microorganisms not represented by specimens in the museum – it *does* aim to engage players with the basic evolutionary concepts that such analyses are based upon (that different species are related through and share common features because of common descent and that these relationships can be represented by an evolutionary tree) and to explicitly make the connection among museum specimens, evolutionary relatedness, and problem solving in the area of medicine.

The game is designed such that is possible for up to four groups with four identical backpacks to play simultaneously. Each of the four trait puzzles directs players to the next trait puzzle forming a loop (the Arm Bone puzzle directs players to the Toes puzzle), and once all four are complete, the final puzzle can be opened. For this implementation, players start at the Toes puzzle, and so the corresponding pocket containing the tools needed to solve this puzzle is unlocked for players at the start the game. To start a team with a different puzzle, the facilitator would simply unlock a different pocket.

Toes Puzzle. The first puzzle takes players to a large display with over 500 specimens from across a broad range of taxonomic groups. The pocket contains five 'Polaroids' of different sections of the exhibit highlighting part of a specimen that they need to find, and then count the number of toes on the back foot (e.g., Fig. 3). Correctly identifying the number of toes for each group reveals the code that unlocks the Jaws puzzle.

Jaws Puzzle. The next puzzle takes players to a nearly 360-degree diorama of North American biomes. This pocket contains three animal 'x-rays' and a clue card comparing lower jaws composed of one and more than one bone. For three taxa, players match an x-ray to an animal on display to identify the group and then use the x-ray to assess whether its lower jaw is composed of a single bone (e.g., Fig. 4).

Two of the selected taxa are not on display in this exhibit; by following a hidden message on the clue card to 'FOLD MAP', players reveal outlines of bony fish and frog and salamander jaws hidden in a topographical illustration on the back of the map to reveal this trait for the last two taxa (Fig. 5). Correctly assessing this trait for all five groups reveals the combination to unlock the next puzzle/pocket.

Protected Egg/Embryo Puzzle. The third puzzle takes groups to a display of fossil and recent invertebrates with a large evolutionary tree diagram. This pocket contains a small copy

Figure 3. Polaroid clueing players to count the number of toes on the bear's hind foot and enter this number in the trait matrix.

of the tree diagram cut into six pieces, a worksheet with images from the tree diagram and a partially completed row of data, and a locked plastic egg box. This is a two-part puzzle. Players put together their copy of the tree and trace lineages to answer questions about shared characters to complete the worksheet (Fig. 6), which gives them the combination to unlock the egg box. The egg box contains five labeled wooden eggs that indicate which groups have an egg/embryo protected from drying out (Fig. 7). Correctly assessing this trait provides the code to unlock the next puzzle/pocket.

Arm Bones Puzzle. For the fourth puzzle, the map directs groups to the short-legged rhino exhibit. The pocket contains a clue card with an illustration that shows the tetrapod arm bone pattern (Fig. 8, left), two fossil casts, a magnifying

Figure 4. X-ray illustrating that tapirs have a lower jawbone composed of one bone (left); the specimen players must locate in the exhibit to identify the animal in the x-ray (right).

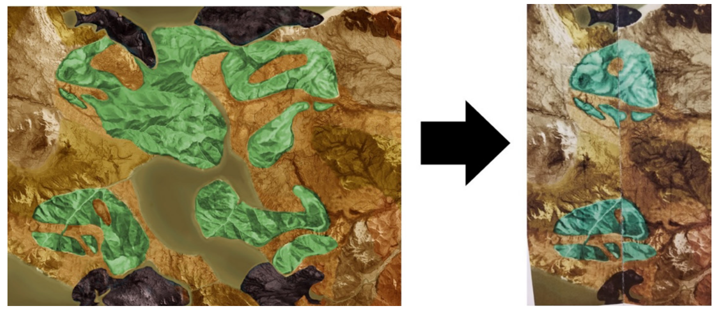

Figure 5. Topographical illustration on map (left); folded to reveal skulls and composition of lower jaw (right).

glass, and a UV flashlight. Players examine the rhino skeleton to assess its arm bone pattern (Fig. 8, right) and follow the hidden UV path marked on the map to assess two other specimens (sabretooth cat and *Xiphactinus* fish). Two of the selected taxa are not on display in these exhibits; participants use the casts to assess the trait for frogs and salamanders and lizards. Correctly identifying which taxa have the tetrapod arm bone pattern completes the last row of the data matrix and reveals the final code needed to unlock the meta-puzzle.

Final Puzzle: Evolutionary Tree and Success Message. Players now have all the information they need to access the final puzzle, which is contained in the main compartment of the backpack. This puzzle does not use specimens on display (and so can be completed at any location within the museum) but requires players to reason about the data they've collected in the previous puzzles. First, players use the codes from the data matrix (i.e., other puzzles) to unlock a folded vinyl mat held shut with four combination locks. The mat has an evolutionary tree diagram on it with traits marked on branches and empty tips to place taxa cards; the virus carrier spot is circled (Fig. 9). Also inside the mat are five taxa cards and four evolution clue cards. Players use their completed

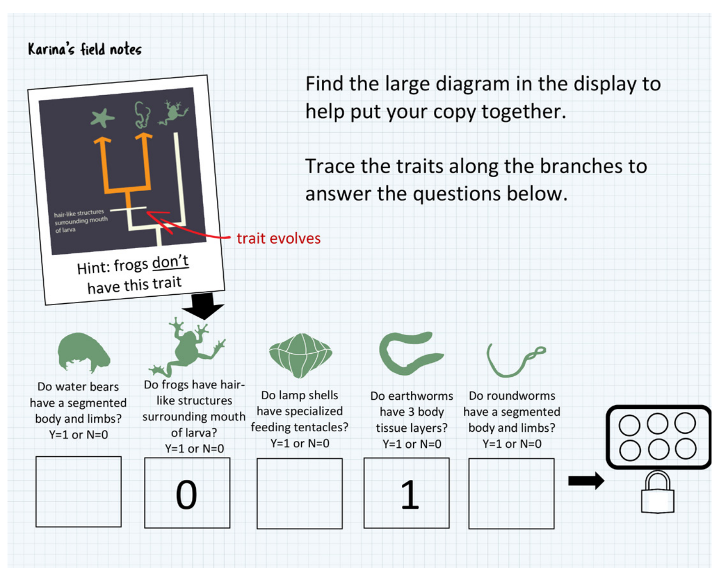

Figure 6. Tree worksheet from Protected egg/embryo puzzle.

Figure 7. Egg box indicating which groups have an egg or embryo protected from desiccation.

trait matrix (along with the evolution clue cards if needed) to place the taxa cards on the tree based on their shared characters. Through placing these cards, players discover that tapirs are the animal carrying the new virus and they reveal a code to unlock a wooden box that looks like a book (Fig. 10). Inside the box is a prize (stickers printed with "I solved the natural history mystery") and a small plush baby tapir that, when squeezed, plays a success message congratulating the team on using evolution to solve a medical problem and prevent a virus from spreading. This message was designed to reinforce the framing narrative for the game and one of the key goals of the experience – for players to appreciate that evolutionary concepts can help solve problems related to human health.

GAME DEVELOPMENT, TESTING, AND EVALUATION

The final version of the game described above was developed through an iterative design cycle, including eight months of development interspersed with formative evaluation, and concluding with a summative evaluation. During formative testing, we conducted three rounds of trial testing with 10 groups (18 youth, 15 adults) to inform and revise game design, puzzles, and props. While the primary audience for the game remains families, we broadened the participant pool for our formative evaluation to include Girl Scouts (grades 3-5), a group of first-year college students (an important audience for university museums), and a group of middle school youth that are part of a program for underrepresented students.

Our first round of testing was done using paper/pencil versions of items, but thereafter we transitioned to more robust material and custom props. During trial testing, we made detailed observations of game play, and recorded data on whether groups correctly completed the puzzle or needed help, whether the tasks/goals of puzzles appeared to be clear to players, what key concepts were mentioned (e.g., evolution, inheritance of traits, relatedness), how they interacted with puzzle props, if participation was adult- and/or child-driven, and the level of engagement (low, medium, high). A set of post-game interview questions asked about what the players enjoyed, the level of challenge, if any parts were difficult or confusing, and what participants would tell others the game was about. After the first round of playtesting, we added a task which asked players to apply the concepts that were the focus of the game by placing a 'bony skeleton' trait card on the final tree; for the college student group, we also had them add a taxon card (a mosasaur with traits listed).

We made minor changes between individual playtests within a round of testing to address small problems (e.g., adding 'fish' to the *Xiphactinus* label on map, removing 'long' from arm bone clue card). Between rounds of testing, we made major revisions to address patterns and challenges that emerged across multiple player groups such as:

- eliminating a first step of inserting Polaroids into sleeves on notebook pages to streamline the Toes puzzle and make the challenge of the puzzle more conceptual and less about puzzle mechanics;
- for the Protected egg/embryo puzzle, producing a small, easy jigsaw puzzle of the invertebrate animals tree graphic for players to manipulate in order to add additional supporting annotation to the diagram and to allow players to physically interact with the graphic by tracing along lineages;
- for the Jaws puzzle, adding example illustrations to the lower jaws clue card to clarify a common misconception about this trait;
- for the Arm bones puzzle, painting one forelimb on the fossil herp casts a bright, contrasting color to make the trait pattern clearer; and
- to address the ongoing problem of navigation within

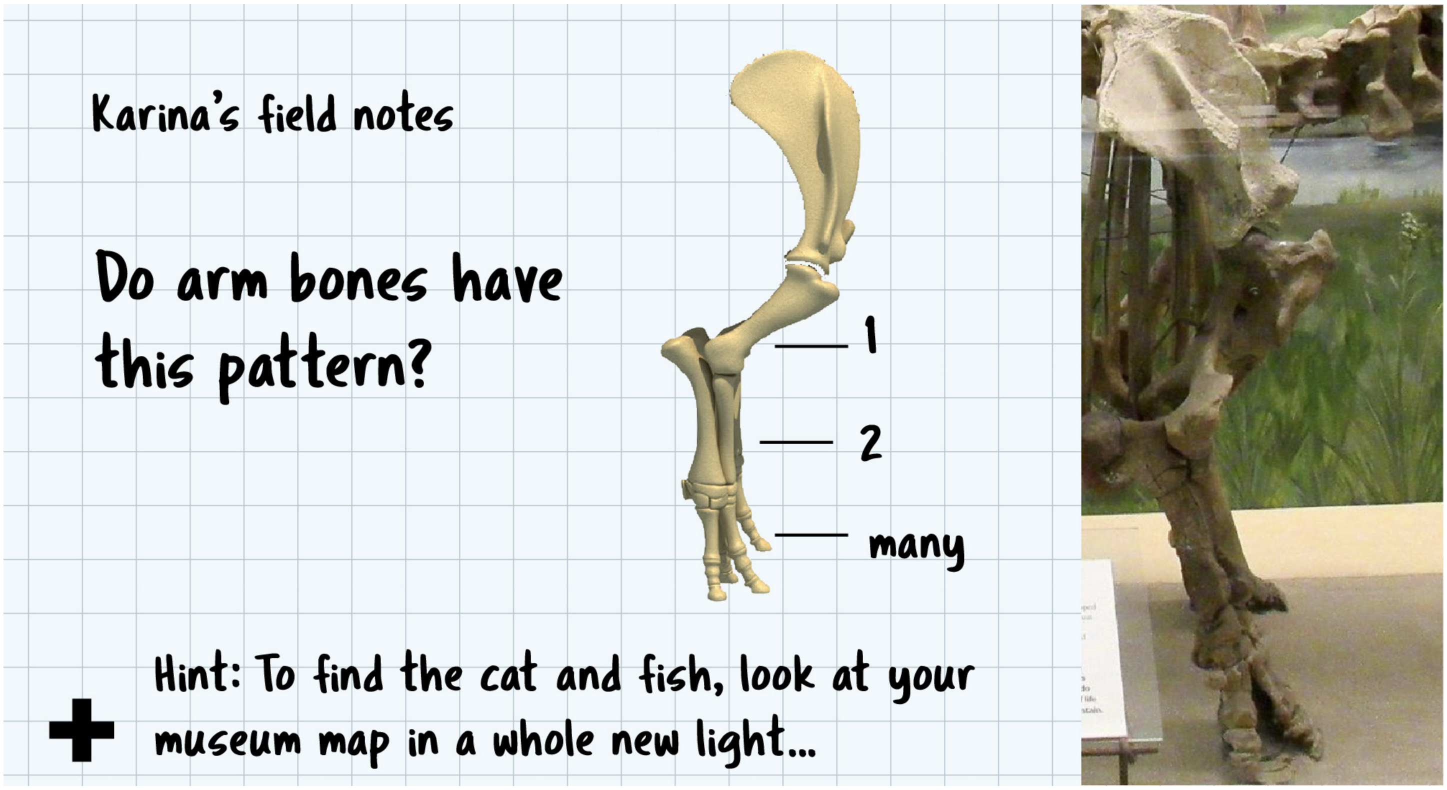

Figure 8. Clue card from the Arm bones puzzle (left); short-legged rhino specimen (right).

the museum, redesigning the map/puzzle prop, for example, by adding exhibit photos and other icons.

Changes that we did and did not choose to make also reflect the feedback that project advisors gave at a virtual project meeting after the initial round of formative testing. This feedback was positive regarding the game design but did highlight how institutional constraints, needs, and supports (e.g., staffing levels) might prevent some NHMs from adopting a game with the format that ours takes. For example, visitors to large tourist-drawing institutions with high entrance fees may be unlikely to devote an entire hour of their visit to a single experience; whereas, in a smaller institution with low or no entry fees (the game's home museum, University of Kansas Natural History Museum, is contribution based), a game such as this can easily provide the motivation for an additional visit and draw new audiences. In the case of *Natural History Mystery*, the game also helps serve its home campus community with its appeal to young adults. Similarly, larger, busier institutions may be concerned about having enough backpacks to meet demand and with the staff required to reset them, while a smaller institution may find the tradeoff involved with tasking desk staff with reset worthwhile if it encourages visitors to engage with familiar exhibits in new ways and more deeply. Feedback from project advisors also highlighted the benefits of a debrief component, which we address below.

After three rounds of trial testing and modification, our external evaluator conducted the summative evaluation with one youth group (four middle-school-aged youth with an adult) and four families (seven youth, six adults). The mixed method summative evaluation employed the observation protocol from formative testing, three interview questions (what players enjoyed, what players learned, and how the game changed how players explored or look at exhibits), and the problem-solving task of placing the 'bony skeleton' trait card on the tree. In addition, all players completed a pre-/post-survey that asked participants to rate their knowledge of evolution, its use to help solve medical problems, and game experience on a five-point pictorial scale.

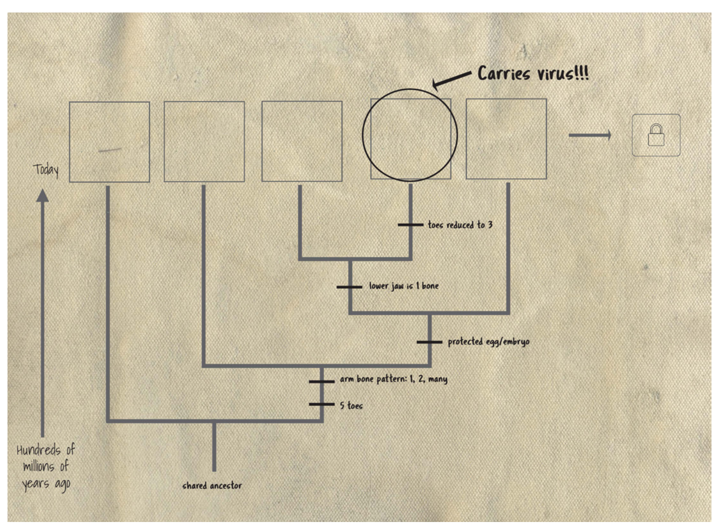

Figure 9. Final puzzle: evolutionary tree mat.

Table 1. *Post-only item results from summative evaluation.*

Item	Mean Rating	Standard Deviation
This game made me more interested in learning about how evolution can help solve medical problems.	4.11	1.02
I had fun playing this game.	4.94	0.24
I learned about science while playing this game.	4.33	1.19
This game helped me look at the museum exhibits in a new way.	4.78	0.43

Ratings: 1 = NO!, 2 = No, 3 = not sure, 4 = Yes, 5 = YES!

Figure 10. Book box containing a plush tapir that plays success message and prize stickers.

RESULTS AND DISCUSSION

Data collected during the trial testing and summative evaluation suggest that *Natural History Mystery* was a fun and engaging experience that communicated important biological concepts and met all four goals outlined above. All groups successfully completed the puzzles and game, regardless of prior museum visits, experience with escape games/puzzles, and prior content knowledge. For the four items in the post-game survey that asked about participants' experience of playing the game, the average scores for each was above 4 out of 5 (Table 1). The average score for the Likert item "I had fun playing this game" is 4.94, with only one participant selecting 4 and all others selecting 5. The average score for the Likert item "This game helped me look at the museum exhibits in a new way" was 4.78, with 4 participants selecting 4 and all others selecting 5. Surveys, interviews, and observations, all suggest that players have fun and are highly engaged; they report liking the individual puzzles, the metapuzzle, and how it made them look at and make connections among exhibits and specimens in new and different ways (goal 1).

Adults and youth report that they learned things, including simple facts (e.g., about fish, arm bones, and tapirs), as well as broader biological concepts related to understanding evolutionary trees (e.g., how animals are connected, the evolution of traits, how to look at things like skeletons and then compare traits across groups; goal 3). Although younger participants often found it difficult to articulate specific content/knowledge items, they nevertheless reported learning and/or thinking about new things. This is reflected in participants' positive response (4.33 out of 5) to a survey item asking their agreement with the statement "I learned about science while playing this game" (Table 1). Participants also say they learned or improved practical skills such as using locks and reading maps, and collaboration skills such as problem solving and teamwork.

To solve puzzles, visitors use information learned during the game, as well as prior knowledge. Most players discuss or mention some evolution-related ideas during play and after (e.g., a body part being the same among different species, that groups have a trait because they got it from some prior ancestor – which are basic concepts important for understanding evolutionary trees) and use these ideas to solve the final puzzle (goal 2). While players do not always articulate or describe ideas as being about evolution or science, the summative evaluation found that participants believed they know more about evolution after playing the game ($t(17)=3.01$, $p = 0.008$), with a moderate effect size (Cohen's $d = 0.71$). In addition, all the youth placed the new trait card, if given to them, correctly on the evolutionary tree and were able to explain the reason for this placement. This evidence suggests that the game increases players' knowledge about evolution (in particular, concepts important to understanding evolutionary relatedness and evolutionary trees; goal 3),

Importantly, players were more likely to agree that evolution can help solve or prevent medical problems after playing the game ($t(17)=3.34$, $p = 0.004$), with a moderate to large effect size (Cohen's $d = 0.79$). This evidence suggests that our framing device for the game (uncovering the origins of a zoonotic disease) had its intended effect – to heighten players' awareness of the fact that evolutionary concepts are relevant to solving medical problems (goal 4).

Natural History Mystery requires approximately one hour to play. While this might seem a long engagement for an activity during a museum visit (as noted by our advisor who directs public programs at a major NHM), formative assessment supported the need for extended engagement to allow players the time to a) orient and way-find within the museum space, b) experiment with interpretations of the puzzles and evolutionary concepts on their own terms and time, and c) deeply engage with the content. Indeed, some groups stopped at other exhibits on route to puzzles to look at specimens on display and talk about its connection the game content (e.g., number of toes on ungulates).

While a shorter game might be more easily implemented, we think that this unique, non-didactic, self-mediated learning experience simply requires more time. We note that participants were engaged throughout the game and expressed interest in playing other versions, with some saying they would have it liked it to be even longer (i.e., more puzzles). This type of experience would work well for institutions that are seeking opportunities to engage visitors more deeply with content and their existing exhibits, and appeal to particular groups (e.g., repeat patrons such as members and inactive or unlikely demographics, such as teens and young adults).

This project and its results demonstrate that a) evolutionary content and concepts can be made accessible to participants age 7 and up with appropriate supports through puzzle design and b) custom puzzlehunts offer a unique and underexplored opportunity for smaller ISIs to help fulfill their educational missions, offer repeat visitors a novel experience in the museum (and potentially attract new visitors), and leverage their existing and potentially static exhibits in a low-cost, interactive format, encouraging visitors to engage with these exhibits on a deeper level.

Lessons Learned. Through the observations we made during our iterative design process and formative evaluation, several clear messages and guidelines for the development of educational, immersive, place-based games, such as ours, emerged. We summarize these recommendations below to aid in the design of game-based projects in museums and other ISIs.

Facilitating Group Dynamics

- Small groups of 2 to 5 players allow everyone to interact with props and contribute to puzzle solutions.
- It is important to limit participants to the target age range (e.g., here, 7 and above) to provide a positive player experience.
- Some support by an adult/caregiver is important for youth groups, especially at the start of the game, and becomes less necessary as the game progresses.
- The level of guidance/direction and role taken by caregivers is variable, and game design must take this into account.

Supporting Learning Goals

- Puzzles should be explicit about science content and developed with specific learning goals in mind to ensure connections are clear to players.
- A debrief component can help reinforce concepts explored during the game experience. This guideline was suggested by project advisors, is supported by literature on escape game design, and also emerged from the observation that players were often eager to discuss their experience after the game. While the current version of the game does not include a debrief because of staffing logistics, we plan to develop a debrief as an independent visitor-led post-game activity (e.g., a handout) over the next year.

Game Design

- Puzzles should be as explicit as possible about tasks without removing challenge; challenge is important for player enjoyment.
- Players enjoyed varied puzzle designs and format, and reuse of a prop or tool in different ways (e.g., map).
- Map reading and wayfinding are challenging and need significant support through design and orientation.
- Players rarely use hints/answers, so game design needs to take this into account.

Institutional Considerations

- Puzzle design is driven by specifics of site, exhibits, and specimens, making generalizations of a particular puzzle arc to other museums a challenge.
- Extended engagement provided more time for participants to explore ideas and exhibits, and was a positive element for participants, but would pose challenges to some venues.
- For many institutions, a debrief component would work best as an independent visitor-led activity that is administered without an educator, but this poses a design challenge.

Design for School Groups. We had originally planned to include a school group in later testing; however, early testing found that design elements that support an engaging game experience do not fit the needs of visiting schools, which typically involve large numbers of students (e.g., entire second grade) with few and/or variable chaperones. We found that our goals for the game were best met by implementing the game as an extended, small-group experience that actively engages all players, fosters collaboration, and allows the time needed to move through spaces and explore puzzles. The extended engagement was an important part of the experience for players to be able to make connections between puzzles and in many cases other exhibits; however, the time commitment necessary to accommodate all students with this experience is more than most schools can devote during a museum visit. We also found that facilitation by an adult was helpful in meeting our goals; however, many schools cannot provide enough chaperones with the needed facilitation skills. Game design for school groups would likely involve shorter, small-group puzzles in limited museum spaces and likely with some staff- or teacher-facilitated components such as a collaborative final synthesis puzzle.

CONCLUSION

Natural History Mystery demonstrated that visitors can learn evolutionary concepts through an immersive game, and that embedding it in a narrative about zoonotic disease can increase appreciation of the relevance of natural history museums and evolution to medicine and public health. The game provides an important foundation in the basic evolutionary concepts needed to understand and use evolutionary trees and raises awareness of how evolution is important to our lives. We can imagine building on the knowledge players developed about shared characters and relatedness, as well as their expanded appreciation that evolution can help solve medical problems, to make more challenging content and ideas accessible. For example, another game, exhibit, or takeaway activity could be created as a follow up to *Natural History Mystery* that explores host switching with an overlaid viral phylogeny to develop a more detailed understanding of exactly how evolution and specimens can be used to track zoonotic disease. More broadly, future work could explore adapting this immersive game format for the specimens and exhibits available in another institution and/or develop similar games that target other biological topics that could be made more accessible through exploration of museum specimens, such as biological adaptation or biogeography.

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ABBREVIATIONS

ISIs: Informal Science Institutions; NFER: National Foundation for Educational Research; NHMs: Natural History Museums; NISE: Nanoscale Informal Science Education

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