Thought-Provoking and Interactive Visual Outreach: a non-traditional approach to science communication through gaming

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ABSTRACT

Traditional scientific writing and education can be hard to engage with and inaccessible. This project evaluates whether a video game about determining the age of hydrothermal vents is more engaging and informative as an outreach tool than a paper about the same subject. This was done by conducting a literature review and writing a review paper, making a game using the Python-based visual novel package Ren'Py, and providing subjects with either the game or the paper, along with an accompanying survey. The results of statistics on these survey results showed that the paper and game performed similarly, except for when subjects were asked which they were more likely to recommend to others. The game's recommendation P-value was a statistically significant 0.044 compared to $\alpha=0.05$. Generally, the results of this study were promising, though the data gathered was not sufficient to conclude if video games were a more informative and engaging outreach tool.

PLAIN LANGUAGE SUMMARY

Traditional scientific writing and education is hard to engage with and can be inaccessible. This study compared survey results for a video game and a paper, both about finding out the age of hydrothermal vents (seafloor volcanoes), to see whether one was a more effective outreach and engagement tool than the other. This was measured by comparing survey results between the game and paper. It was found that while overall the game and the paper performed similarly, the game was more likely to be recommended to others, and its reviews were overall more positive. This is promising, and follow-up actions such as a larger sample size and more time allocated to the project are proposed in this paper.

INTRODUCTION

The interest in this study is in accessibility, non-traditional teaching, and outreach methods in scientific spheres. There are a great variety of ways available to actively engage with the material of science classes, especially those that do not necessarily require a classroom, a lesson plan, or an inflexible structure. These methods of engagement should be utilized more commonly in order to maximize the number of people reached by science communication efforts. Additionally, these methods should be aesthetically pleasing, visually interesting, creatively stimulating, emotionally engaging, or some combination thereof. While I recognize that these descriptions are subjective and difficult to define, it is my hope that by putting more and varied methods of scientific communication into the world, educators and science communicators will be able to make at least one of these descriptors true for anyone they reach, no matter that recipient's personal tastes.

The aim of this proposed research is to make complex concepts clear to an audience with only a generic background in science, and to explain those concepts in a way that is both academically accurate and easy to understand. If successful, this project will broaden the sweep of the scientific-communication arm, as well as allowing me to present subjects to people with little background in them without confusing them into lack of interest. For people who previously had no love for or interest in the sciences, this may inspire in them an interest in the subject and show them that there are many different avenues from which to approach scientific learning. If the subject is sufficiently emotionally compelled, the project may also instill within them a greater care for the subject matter presented in the game, and may result in long-term impacts on how the subject views and thinks about the world around them. It may also encourage the player to follow up on piqued curiosity on their own time, and thus start them on the process of learning through intrinsic motivation.

For many, learning through the consumption of papers or textbooks, or by the passive reception of information from lectures, impedes information retention and lowers engagement (Griffiths 2002; Ritzhaupt and Squire 2013; Chang et al. 2016) By combining entertaining visual elements with the opportunity to engage with and influence the vehicle for learning, I am aiming to reach the subjects of this study on common ground, and allow them to learn without realizing that they are learning. This will allow scientific concepts and interests to more easily reach those for whom a traditional scientific education is difficult or even out-of-the-question for those with limited attention spans or neuroatypical methods of learning.

Background

When one actively engages in learning instead of passively receiving information, it increases one's confidence, interest, and understanding of subject (Ryan 1982; Griffiths 2002; Squire 2006). When one includes play into the mix, it allows further for a non-judgmental engagement with a topic, leading to increased flexibility, creativity, and confidence (Smith and Pellegrini; Rieber 1996; Griffiths 2002; Bowman and Standiford 2015). Play is an essential part of development in children (Griffiths 2002), and multiple studies have shown that its importance continues later in life as well (Kanhadilok and Watts 2014; Diaz-Varela and Wright 2019; Zacharakis 2019). In melding play with an academic subject, it is possible to combine engagement, education, and entertainment (Fig. 1). This allows for greater self-direction (Bowman and Standiford 2015) and experimentation (Holbert and Wilensky 2019) in a consequence-free space, neither of which are often provided in traditional lectures or papers.

Importantly, video games provide an opportunity for dialogic teaching and learning. If one is confronted with tension or a problem during the gameplay experience, and especially if that tension can be linked to the education object of the game, this can provide opportunities for dialogue with other peers who have played the game, and can lead to post-game thinking that lasts well after the subject has finished playing the game (Wu 2016; Arnseth et al. 2018; Holbert and Wilensky 2019). If the format of the game is appropriate, it is also possible to teach through well-designed problem-solving (Diaz-Varela and Wright 2019). This long-term, post-game thinking about a subject is what this project aims to utilize in science communication.

Dimension	Student Development
Cognitive	• Active engagement* • Critical ethical reasoning • Exercising creativity, spontaneity, and imagination • Intrinsic motivation* • Improved problem-solving skills • Learning multiple skills and knowledge bases simultaneously • Self-efficacy, perceived competence
Affective	• Active engagement* • Enhanced awareness of other perspectives • First-person identification improving emotional investment • Increased empathy • Increased self-awareness • Intrinsic motivation* • Raising social consciousness • Social skills development, e.g. cooperation, debate, negotiation
Behavioral	• Active engagement* • Exercising leadership skills • Intrinsic motivation* • Improving team work

* Literature suggests that intrinsic motivation and active engagement have cognitive, affective, and behavioral facets (Eggen and Kauchak, 2012; Fredericks et al., 2005).

Figure 1. Dimensions of student learning through LARP (live-action roleplay) from Bowman and Standiford 2015)

Learning without being aware of being 'taught' is something that continues throughout one's entire life (Zacharakis 2019) and often leads to stronger information retention, flexibility and creativity when introduced to difficulties, a greater sense of enjoyment, and sometimes a strengthened sense of community with the peers that one may be play-learning with (Wenger 1998; Kolb and Kolb 2010; Riley 2018). Learning through play is based strongly on the concept of intrinsic motivation (Malone 1981; Ryan 1982), a concept defined as "doing an activity for its inherent satisfaction rather than for some separable consequence". Almost all play can be categorized as being done for this purpose. Intrinsic motivation is an essential component of games – after all, a game that is a chore to play does not tend to sell very well – and leads to inspiration, creation, and increased dialogue with community (Squire 2006; Wu 2016), the last of which is a goal of science communication and of this study. Notably, all three of these results are similar to those of learning through play. Thus it is reasonable to infer that all learning through play is performed via intrinsic motivation.

Video games are a promising vehicle for this type of 'learning through play'. They are an experience designed to be fully immersive (Squire 2006), with many more complex games featuring dynamic day/night cycles, background noise relevant to the player's location, first-person camera angles, and the ability to interact with the simulated environment in ways that mimic real life. Video games are also possessed of some positive physical benefits, such as improved reaction time and better fine motor skills (Griffiths 2002). All of these attributes can be combined to increase engagement with educational material (Griffiths 2002; Bowman and Standiford 2015; Chang et al. 2016). For those who experience difficulty in traditional classrooms and with methods of learning that require sustained bouts of attention or close focus, a video game – which can be put down and picked back up nearly infinitely – is an ideal vehicle for concepts and information that one wishes to impart to others. For this reason, my hypothesis is that imparting ideas and material through an interactive, story-based format will engage the reader as much as if not more than presenting the materials via a review paper.

METHODS

This project is a cumulation of a game, a paper, and user surveys for both. The premise for the game is simple: the player is a transfer student from a fictional community college to a fictional four-year university, and has been placed in a ‘transfer student orientation class’ with a handful of other transfer students. These transfer students are anthropomorphized versions of hydrothermal vents. As the player goes about their week, they can interact with these characters in the transfer class or in other shared classes, learning about different methods of dating real hydrothermal vents along the way. Each hydrothermal vent has a ‘route’ that will allow the player to befriend them more closely, and each one has an associated method of dating. Choosing a character’s route will allow them to learn more about them and their associated method of dating. Each route has a ‘good end’ and a ‘neutral end’. The ‘good end’ is unlocked if the player selects all the hidden ‘correct’ choices, and contains the fully positive story ending. The ‘neutral end’ is unlocked if the player does not select all the hidden ‘correct’ choices, and contains the story ending that is mostly positive, but could be better for both the player and their selected character.

Science Review Paper

In accompaniment to the game, a fact sheet was assembled based on material presented in the University of Washington’s OCEAN 121, OCEAN 310, and OCEAN 431 classes, as well as the Department of Oceanography’s annual VISIONS cruise, and supplemented with my own efforts in research (Appendix 1). The relevant material was gathered into a chart (Table 1) and then expanded into a review paper covering 3 potential methods of dating hydrothermal vents, their execution, and their relevance. The paper was written to be as closely in accordance with a typical review paper as possible, in order to effectively compare it as a method of outreach to the game.

Table 1. A table summarizing relevant facts about hydrothermal dating. Additional sources can be found in Appendix 1.

Topic	Short summary	Key resources
Dating Methods		
Radiometric	Every radioactive element has a specific period to decay into it's daughter element (half life); given key information the age of a rock can be calculated from the ratio of parent and daughter atoms	McDougall and Harrison 1999; Hamilton 2003
Paleomagnetic	Relative dating; utilizes the earth's periodic reverasal of poles; iron particles in fresh seafloor lava align with magnetic north at the time of their formation; only useful with additional context	Speranza et al. 2006
Bacterial Mat	Relative dating; certain types of bacteria live on products of hydrothermal vents; different bacteria utilize different products; can estimate the ages of hydrothermal vents by comparing bacterial communities	Sylvan et al. 2012; Lee et al. 2015; Sheik et al. 2015
Vent Field		
East Pacific Rise	Eastern Pacific; location of one of the first discoveries of hydrothermal venting	Corliss et al. 1979; Haymon et al. 1991; Ramirez-Llodra et al. 2007
Ryukyu Arc	Western Pacific; hydrothermal flank volcano; high temperature	Goto et al. 2015; Minami and Ohara 2017
Lost City	Mid-Atlantic; Peridotite hosted, low temperature, calcium carbonate hosted hydrothermal system; currently the only one known in the world	Kelley et al. 2005; Lang et al. 2009; Fruh-Green et al 2018

Game Design

The game was developed in Python, using the package Ren'Py (https://www.renpy.org/, January 2021, version 7.4.11), which is designed for the creation of visual novels. The game was presented as taking place across eight days, with the first four days allowing the player to interact freely with the characters of the game (Fig. 2). On the fourth day, the player is prompted to choose one character to focus on, 'locking in' to their route. For the next four days, the game is focused on the character of the player's choosing. For the first four days, players' decisions and their relationship level with the characters were kept track of using initialized blank values that were then added to based on the decision of the player. For example, choosing a dialogue option that the character of the player's choice likes would result in a +1 being added to their 'relationship points' counter (Fig. 3). Some initialized values were numerical and set to 0, and were added to through the course of a conversation. For example, the player can ask a character a series of questions, and upon the 'question' counter reaching a value of 4, a new question will be revealed as an option. For non-number values, such as choosing a gift or a club, a value would be initialized simply as "", which Python reads as a 'fill-in-the-blank", and the selection of a dialogue option would assign a string to the value. For one choice, the player is given the option to select a gift to bring over to a friend's house (`$ gift = ""`). If the player selected a small succulent in a pot, the code would assign the gift value the string "plant" so that the code reads (`$ gift = "plant"`). Later in the game, that value could be recalled, so that the game will inform the player that they have offered the plant to their friend. This allows for continuity and for the players to feel like their actions have an effect on the game, leading to higher immersion.

Along with numbers and strings as initialized values, the code made great use of labels and jumps. These were occasionally supported with if/else statements. Dialogue or menu choices made by the player are finished with a jump statement in the code that takes them to the relevant follow-up portion of the game. In an extreme example, agreeing to help a character with a scheme will jump you to the next scene of the game; refusing will jump you to the neutral end. Most jumps and labels in the game are tied together. The above example would read "`jump character_heist_yes`" at the end of the menu option agreeing to help the character, and would take the player to "`label character_heist_yes:`", with the rest of that scene following behind it. If the player refused to help, the code at the end of the dialogue would read "`jump character_neutral_end`", and take them to "`character_neutral_end:`". Some labels were simply used for organization, without any associated jumps. Some jumps depend on player choices: this is where if/else statements are used. One common example utilizes relationship points and 'random encounters'. In the player character's other classes, the code might read

```
if character_relationship >= 4:
    jump character_bio_interaction
else:
    jump gen_bio
```

indicating that if the player's relationship with the character is greater than or equal to 4 accumulated points, they will unlock an interaction with the character during their biology class that will reveal more about the character and their associated dating method.

Figure 2. What a typical menu looks like in the game.

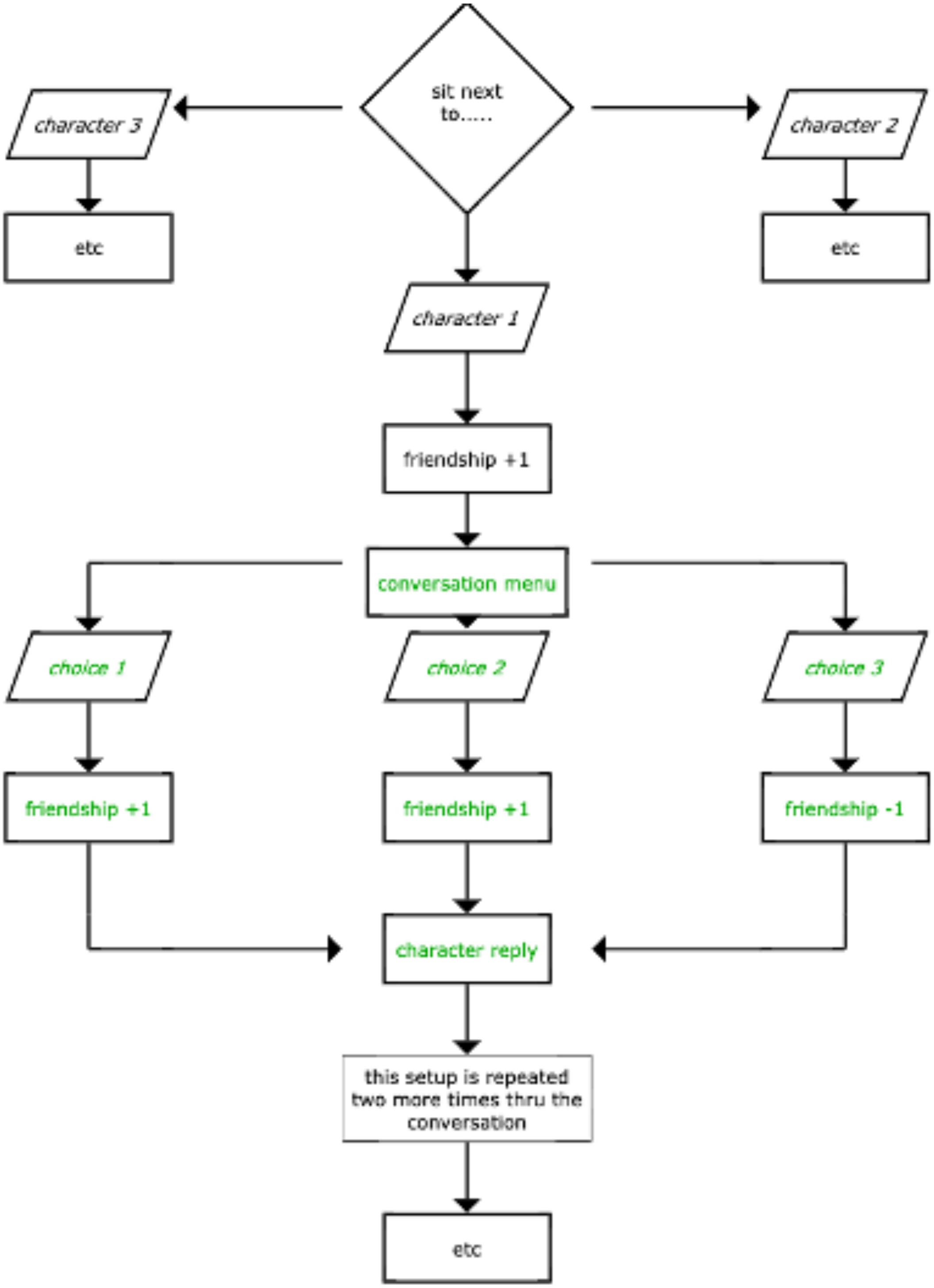


Figure 3. Flowchart of the base code used for decision-making in the game. The majority of choices have two 'Y' answers and one 'N' answer that will allow the player to increase and decrease their relationship with the characters, and which will provide the player with unique/informative dialogue.

Characters were designed to nod to each character's origin in some way. The character based on Lost City hydrothermal field, for example, has a pale color scheme in reference to the calcium carbonate chimneys found at Lost City. The character based on the Gondou hydrothermal field has a belt buckle in the shape of a pilot whale (the Japanese word for which is *gondou*) in reference both to the field itself and the ROV that discovered it. The character based on the Lamont hydrothermal field is designed after the classic 'smart character' archetype, since the hydrothermal vents at East Pacific Rise, where the Lamont field is located, are among the first discovered and therefore most researched.

Survey Development and Dissemination

Surveys were administered alongside the game and the paper, featuring similar questions (Table 2). The content of the surveys was made with reference to Franklin (1995), Baleshta et al (2015), and Cameron (2021). The survey was designed to measure user engagement and likelihood of spread via recommendation.

A beta testing phase was done when the first route (Lost City) was finished. Beta testers (n=8) were evenly divided between the game and a draft of the paper, and were provided with draft versions of the survey. The results and feedback obtained from these beta testers were used to further develop the game, paper, and surveys into their completed forms. Additionally, a subset of these beta testers (n=4) playtested the game through all stages of its development and provided feedback and bug testing for the eventually finalized code. Two oceanographers – a faculty advisor and a graduate student – looked over and provided edits for the paper.

Table 2. A spreadsheet featuring game survey questions and paper survey questions. The four main questions analyzed in this project were 'How informative did you find this?', 'How likely are you to seek further information on this topic', 'How engaging did you find this?' and 'How likely are you to recommend this to a friend or family member?'

PAPER QUESTIONS
How familiar are you with the topic of oceanography, where 1 is 'very unfamiliar' and 5 is 'very familiar'?
How informative did you find this paper, where 1 is 'not informative at all' and 5 is 'very informative'?
How likely are you to seek further information on this topic, where 1 is 'very unlikely' and 5 is 'very likely'?
How likely are you to recommend this paper to a friend or family member, where 1 is 'very unlikely' and 5 is 'very likely'?
How engaging did you find this paper, where 1 is 'not engaging at all' and 5 is 'very engaging'?
Is there a particular aspect of this paper that you liked?
Is there a particular aspect of this paper that you disliked?
Is there anything that you would change about this paper?
Roughly how long did you spend reading this paper?
Did you play this paper's accompanying game?
If yes, did you play it before or after reading the paper?
GAME QUESTIONS
How familiar are you with the topic of oceanography, where 1 is 'very unfamiliar' and 5 is 'very familiar'?
How informative did you find this game, where 1 is 'not informative at all' and 5 is 'very informative'?
How likely are you to seek further information on this topic, where 1 is 'very unlikely' and 5 is 'very likely'?
How likely are you to recommend this game to a friend or family member, where 1 is 'very unlikely' and 5 is 'very likely'?
How engaging did you find this game, where 1 is 'not engaging at all' and 5 is 'very engaging'?
Is there a particular aspect of this game that you liked?
Is there a particular aspect of this game that you disliked?
Is there anything that you would change about this game?
Roughly how long did you spend playing this game?
After completing the game, did you go back and play another route?
Did you read this game's accompanying fact paper?
If yes, did you read it before or after playing the game?

During the full data collection stage, the game, paper, and surveys were sent out to students enrolled in University of Washington's 2022 OCEAN 444/445 class, the 2022 BIOL 213 class at North Seattle College, and posted online at https://forms.gle/sAw8Se5qvvJkPeiD8 for the paper and https://forms.gle/fJb6CbVHzrWeX1Do6 for the game. The net was cast as widely as possible in an attempt to counteract the common habit of many people to participate in the first part of a study but neglect to fill out the survey on it. Bar graphs were used to visualize the results in a clear and easy-to-read manner, while t-tests and ANOVA tests were used to analyzed the data for statistical significance. Both the t-test and the ANOVA compare the means between sample groups, with the null hypothesis being that there is no difference between these means. The t-test can be used to compare two sample groups, while ANOVA tests are for three or more sample groups (Mishra et al 2019). One of the survey questions asks for the subject's familiarity with oceanography (Table 2). This was to ascertain whether their previous knowledge changed how they answered the survey's other questions. While the sample design attempted to create an even distribution of subjects with oceanographic background knowledge between the paper and the game, this was done to be certain that the distribution was effective. An ANOVA test was therefore run to compare the mean of oceanographic familiarity with each survey question. There was no statistical significance between knowledge of oceanography and any of the four main survey questions (see Table 2); thus, a t-test can be run cleanly without having to account for this as a potential factor.

RESULTS

Overall, 41 responses to the surveys were received: with 19 responses for the game and 22 responses for the paper. The results of the surveys show that the subject's oceanographic background has no effect on their responses to any of the four main questions for the game or the paper. The P-value of the ANOVA test (Table 3) for each of the four main survey questions is greater than $\alpha=0.05$, meaning that it is not statistically significant and that the null hypothesis (subjects' previous knowledge of oceanography will have no bearing on their answers to the other four questions) is accepted. Therefore, when running the t-test, the oceanographic familiarity factor did not have to be taken into account.

ANOVA	F-statistic	P-value
informative	2.80	0.50
seek more info	2.80	0.69
engagement	2.80	0.46
likely to rec	2.80	0.32

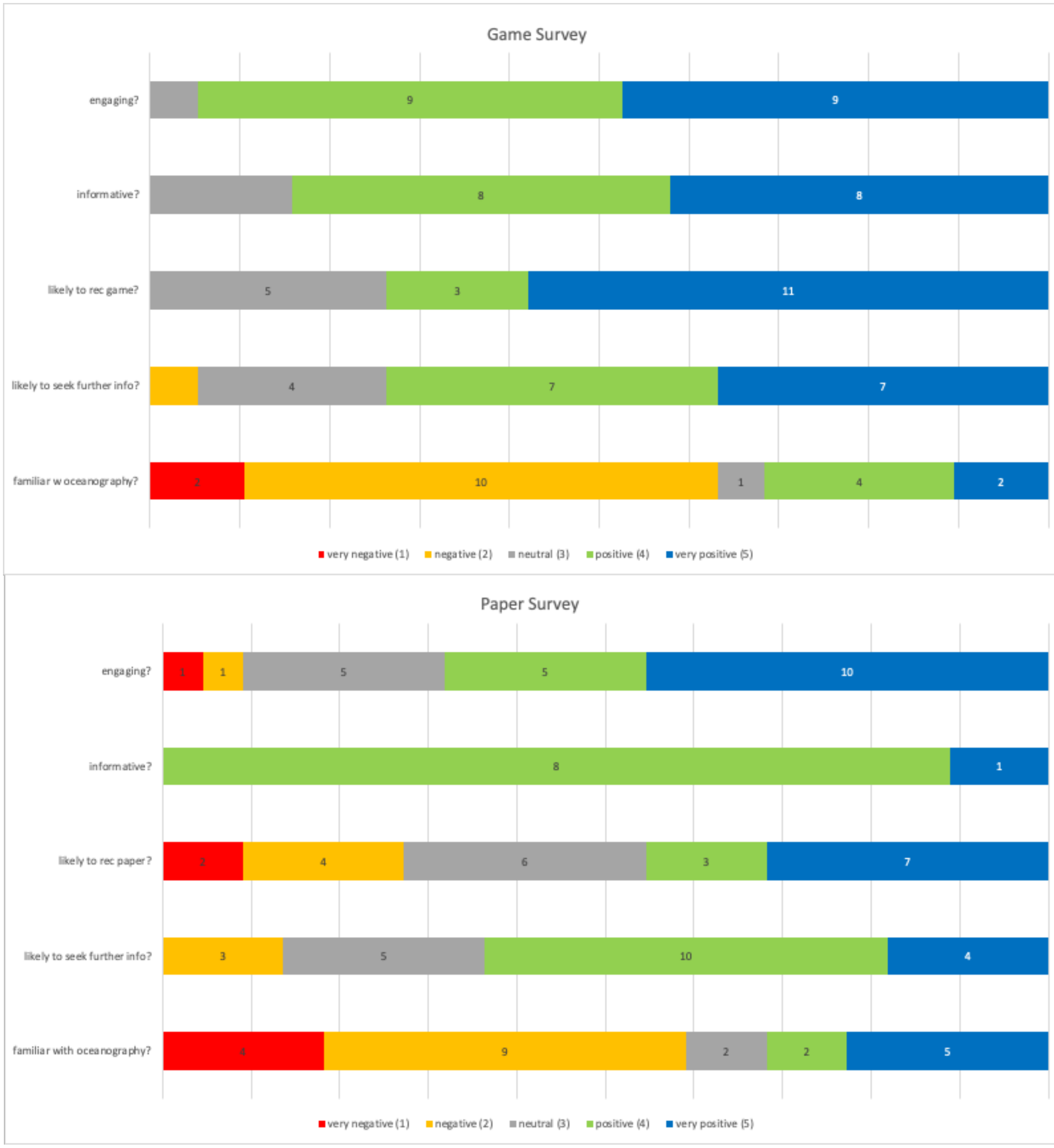
Table 3. An ANOVA test comparing the F-statistics and P-values for the four main survey questions. The ANOVA test's P-values are all above the statistically-significant threshold of α=0.05.

The t-test showed that there is also no statistically significant difference between the game and paper for how informative they were, how likely subjects were to seek more information on their own afterwards, and how engaging the subjects found them. However, the game's P-value for the 'likely to recommend' question is below α=0.05, meaning that it is statistically significant, and that subjects were more likely to recommend the game to others than they were to recommend the paper.

Table 4. T-test comparing the paper and game's means and variances for each of the four main survey questions, as well as the two-tail t-critical and P-value numbers. The game's total number of survey-takers was n=19, and the paper's was n=22.

t-test	Game Mean	Paper Mean	Game Variance	Paper Variance	t critical (two tail)	P-value (two tail)
informative	4.26	4.64	0.54	0.24	2.02	0.06
seek more info	4.05	3.68	0.83	0.89	2.02	0.21
engagement	4.42	4.00	0.37	1.33	2.02	0.16
likely to rec	4.32	3.41	0.78	1.87	2.02	0.02

As seen in the t-test (Table 4), the game's engagement value has a higher mean (4.42) and lower variance (0.37) than the paper's. Likewise, for the informative value the paper has a higher mean and lower variance (4.64 and 0.24, respectively) than the game's (4.26 and 0.54, respectively). This can also be seen visually in Figures 4a and 4b. Figures 4a and 4b were colored in accordance to the survey results. Survey answers were collected on a scale from 1 to 5, where 1 indicates 'very negative' and 5 indicates 'very positive'. '1' (very negative) responses were colored red, '2' (negative) responses were colored yellow, '3' (neutral) responses were colored grey, '4' (positive) responses were colored green, and '5' (very positive) responses were colored blue.



Figures 4a [top] and 4b [bottom]. Bar graphs of the game and paper survey results, respectively. The survey responses were submitted on a scale from '1' (very negative, red) to '5' (very positive, blue)

DISCUSSION

The hypothesis of this study is that imparting ideas and material through an interactive, story-based format will engage the reader as much as if not more than presenting the materials via a review paper.

Informative

Interestingly, there is no statistically significant difference in how informative the paper and game were found by the subjects. This can be taken to mean that the game was at least as effective a vehicle for information as the paper. However, the paper has a higher mean and lower variance (4.64 and 0.24, respectively) than the game's (4.26 and 0.54, respectively), indicating that overall, the paper was rated more informative with less variability in responses when compared to the game. This can also be seen visually in Figures 4a and 4b.

One of the main interests of this study was to investigate whether an outreach method designed to be more accessible and engaging would encourage subjects to seek out further information on their own. Though not significant based on the t-test results, the paper's mean for the information-seeking value (3.68) is lower than the game's (4.05), indicating that more subjects found themselves interested in seeking further information on their own after playing the game than reading the paper. This is a positive indication that the game has potential as an outreach tool with a focus on inspiring intrinsically motivated study. Further, the t-test statistics showed that the game was at least as effective at communicating complex concepts to an audience with wide array of oceanographic backgrounds (indicated by the variety in responses to "how familiar are you with oceanographic concepts" and the results of the ANOVA) and explains those concepts accurately and clearly enough that it was rated as on par with the paper.

Engagement

Further evidence for the null of this study's hypothesis is that there was no statistical difference in the how participants ranked engagement for the paper and the game – though, as discussed below, there are several possible reasons for this. However, there was a statistically significant difference when it came to how likely participants were to recommend the game or the paper. The game-recommendation P-value was 0.02, below the α value, reflected in the paper's mean and variance values (3.41 and 1.87, respectively) in comparison to the game's (4.32 and 0.68, respectively) (Table 4). The paper's lower mean indicates that fewer people were likely to recommend the paper versus the game, while its higher variance meant that it had a wider range of answers on the positive-to-negative scale than the game. This is promising from an outreach perspective: increased potential for the sharing of the game means a higher likelihood of reaching new people. Related to this – though not statistically significant – the game's engagement value has a higher mean (4.42) and lower variance (0.37) than the paper's, (mean: 4.00, variance: 1.73) meaning that on average the game was rated more highly for engagement than the paper, and the variability in responses was lower. The lower variance can be seen in the bar graph results for the game survey (Fig. 4a) when compared to the paper survey (Fig. 4b). The low variability means that subjects more unanimously found the game to be engaging, another positive point for the game as an outreach tool and a method of learning through play.

Limitations of the study

While lacking in statistical significance, the results of this study indicate a positive trend towards the hypothesis that a game is a more effective outreach tool than a review paper. There are several potential reasons explaining why the majority of the results for this study are not statistically significant. The first is a relatively small sample size. As expected, survey engagement was less than 50% that of game or paper engagement: that is, less than half of the people who read the paper or played the game also took the associated survey. While planned for during development, this has limited the project's usable data. The limitations of the sample size were demonstrated between the statistics run for the initial rough draft and those run for the final paper. With the addition of about 10 more responses in the intervening weeks, P-values for all t-tests were smaller, and mean and variance patterns were clearer. Another potential limitation is that hydrothermal vents are a popular deep-sea topic, and it's likely that a number of subjects already had enough of a passing knowledge of them to discourage the seeking of further information or to reduce the 'informative' value. The production quality of both paper and game must also be accounted for: though difficult to test for, it's possible that a fully completed game instead of a demo, or a longer and more in-depth paper, would have changed the survey results and their associated statistics.

CONCLUSION

Though most of the questions surveyed for were not statistically significant, the significant result for 'likely to recommend' and the non-significant result for 'informative' – as well as the average responses to the other questions – indicates the promise of the original hypothesis of this paper: that a game will serve as a more effective outreach tool than a paper. This is encouraging and suggests that further research is worthwhile. Ideally, this project would be presented to an introductory science class of at least 100 students with a variety of educational backgrounds, evenly divided so that one half received the game and one half received the paper. The game would be fully finished and have had sufficient time devoted to it, and the paper would be peer-reviewed and published to ensure that it most fully matches academic standards. The classroom setting would allow for survey-taking to be made mandatory, and the more polished nature of the game and paper would ideally remove some of the concern surrounding the quality of both, and the subsequent effects on subjects' opinions. The administration to a full class would also allow for an expansion of the areas tested; further surveys covering the acquisition and retention of knowledge from the paper versus the game could be administered directly before, directly after, and some time after the paper was read or game was played, and could be used to gauge their respective efficacy as teaching tools as well as outreach ones. Further testing of this game type would hopefully result in more statistically significant engagement/play-based results, and lead to the development of a more effective outreach tool.

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APPENDIX 1

Dating Methods for Hydrothermal Vents: An Overview

Introduction

A hydrothermal vent is a spot on the seafloor where superheated water is discharged. These vents are found worldwide, between depths of 345 m and 4960 m (Beaulieu et al. 2013). Most vents are found at mid-ocean ridges, but they can also be found at volcanic arcs, back-arc basins, and between plates (Beaulieu et al. 2013). Mid-ocean ridges are locations where two tectonic plates are moving away from each other and new seafloor is being formed (Macdonald 2001). Volcanic arcs are chains of volcanoes that form where tectonic plates are converging (Condie 2016). Back-arc basins are spreading centers similar to mid-ocean ridges, but they form at a convergent plate boundary when old oceanic crust subducts (Sdrolias and Muler 2006). (such as hotspots like the Hawaiian Islands or where serpentinization occurs) The fluids in hydrothermal vents become superheated through geothermal processes, typically by seeping into the seafloor, being heated by magma, and then rising back to the seafloor by convection (Macdonald 2001). As the water is heated, it absorbs minerals from the rocks that it travels through. When the fluids come out of hydrothermal vents, they can range between 60C and 464C (Garcia et al. 2007; Haase et al. 2009). The sharp change between these temperatures and ambient seawater (which is an average of 2C) shocks minerals the fluids have absorbed and causes them to precipitate out of the emerging fluid, forming chimney structures (which can grow to 60 m in height; Perkins 2001) and buoyant clouds of warm mineral fluids referred to as “smoke” (Corliss et al. 1979; Palandri and Read 2004). Hydrothermal vents are often characterized as “black smokers" or “white smokers" based on the color of the minerals that precipitate from them. Black smokers tend to higher temperatures and are high in sulphides (Martin et al. 2008), while white smokers are lower temperatures and high in minerals such as calcium and silicon (Colín-García et al. 2016).

Hydrothermal vents host unique communities of animals that rely on energy generated by bacteria from the chemical deposits and hydrothermal fluids of the vents in a process known as chemosynthesis. Vent communities can be hundreds to thousands of times more productive than the surrounding deep sea (Lutz and Kennish 1993). Some animals graze on chemosynthetic bacteria that grows on the hydrothermal vents, while others have formed a symbiotic relationship with the bacteria (Van Dover 2000).

Hydrothermal vents are an important part of the geochemical cycle and host unique ecosystems of bacteria and animals, but what's in it for humans? The minerals precipitated from hydrothermal fluids include copper, zinc, gold, and silver, all of which are in greater and greater demand for electric vehicles and renewable energy technologies (Levin et al. 2020). Further, enzymes produced by bacteria and archea from hydrothermal vents are of interest in biomedical and industrial applications (Rajivghandi and Li 2022). For example, enzymes from *Pyrococcus abyssi* are used for biodegradation processes in the textile industry (Cornec et al. 1998). In addition, hydrothermal vents are important for astrobiology research as 'alien analogs' (Vakoch et al. 2013) and some vents are even considered as possible locations for the origin of life on Earth (Martin et al. 2008).

Overview of Specific Hydrothermal Vent Systems

East Pacific Rise

The East Pacific Rise (EPR) is a mid-ocean ridge that runs along most of the eastern side of the Pacific ocean basin. In the 1970s, the first hydrothermal vents and the unique fauna associated with them were discovered on the Galapagos Rift, a spur of the EPR (Corliss et al. 1979). Spreading rates along the EPR vary, but near the Easter Islands the rate is the fastest in the world, at around 6 inches per year (DeMets et al. 2010). Due to this rapid movement of the earth's crust and subsequent high volcanism, there are large numbers of hydrothermal vents along the ridge - often highly correlated with relatively young lavas (Haymon et al. 1991) - which can almost form a single continuous chain of vents (Ramirez-Llodra et al. 2007). The subsequent ages of hydrothermal vents via radiocarbon dating are correspondingly young, between 10 and 150 years old (LaLou et al. 1985). Following a volcanic eruption, hydrothermal vents develop rapidly: in one observed eruption, the vent evolved in only a week (Von Damm et al. 1995). Vent temperatures measured on the EPR have varied between 350-400C for black smokers and 200-330C for white smokers (Haymon et al. 1991).

Ryukyu Arc

The Ryukyu Arc is part of the Ryukyu subduction zone, a 1200 km long convergent plate boundary that runs from Japan to Taiwan. The subduction zone is composed of the Ryukyu Trench, the Ryukyu Arc, and the Okinawa Trough back-arc (Kizaki 1986). The Gondou Field is a hydrothermal vent field, at water depths between 1330 and 1470 m, on the western flank of Daisan-Kume Knoll in the Ryukyu Arc. Gondou was not discovered until 2014, despite extensive study of the caldera and hydrothermal vent fields found there two years prior (Minami and Ohara 2017). While not uncommon, hydrothermal vent fields on the flanks of ridges and volcanoes are often overlooked with the focus on ridge crest and volcano caldera systems.

Radiocarbon dating estimates the initiation of hydrothermal venting on the flank of the Daisan-Kume Knoll occurred between 2.52–0.03 Ma in conjunction with a volcanic eruption (Goto et al. 2015).

Lost City

Unlike the EPR, the Ryukyu Arc, and all other hydrothermal vent systems discovered to date, Lost City is unique. It was found on the Atlantis Massif, slightly east of the Mid-Atlantic Ridge (a mid-ocean ridge and more typical host of vent systems), in 2000 (Kelley et al. 2005). Lost City is made of carbonate chimneys that are tens of thousands of years old (Fruh-Green et al 2003; Ludwig et al. 2006) and that vent highly basic fluids - roughly the same pH as liquid Drano. Lost City is fed hydrothermal fluids via a process known as serpentinization (Lang et al. 2009). Serpentinization occurs when seawater permeates into exposed portions of the earth's mantle on the seafloor. The primary rock of the mantle - peridotite - reacts with the seawater to form serpentinite, hydrogen, and heat (Lang et al. 2013). The hydrogen and heat go on to create relatively low temperature hydrothermal fluids (~90C) that build Lost City's chimneys (Proskurowski et al 2006, Lang et al 2021; Fruh-Green et al 2018). The system hosts unique microorganisms, dominated by sulfur-oxidizing, sulfate-reducing, and methane-oxidizing bacteria, and methanogenic and anaerobic methane-oxidizing archaea (Brazelton et al. 2006). Methanogenesis - utilizing methane for cellular energy - in the absence of oxygen is an ancient strategy that predates respiration via CO_2 (Muñoz-Velasco 2018), and its presence in bacteria at Lost City, among conditions that provide organic compounds abiogenically (Brazelton 2010, Lang et al 2013) and in a location that has the potential to be repeated across the world (Fruh-

Green et al. 2004), is a strong argument in the favor of Lost City (or somewhere like it) being a potential origin for life on earth (Lang et al 2013, Martin and Russell 2007).

Dating Methods

There are several viable methods to determine the age of a hydrothermal vent. A few common ones are via radiometric dating, paleomagnetism, and measurement of bacterial growth. By dating hydrothermal vents, it is possible to get an idea of their 'life cycles', and to understand the processes that form hydrothermal vents, as well as their role in the ecosystem around them.

Radiometric dating relies on radioactive decay. Radioactive atoms are unstable and decay into different atoms, called daughter atoms. The number of neutrons and protons in the new daughter atom is different from the parent, so it can be either a different isotope - a version of the same atom but with a different number of neutrons - or an entirely different element. The time that it takes for one half of a group of radioactive atoms to decay into their daughter products is known as its half-life, and that time is always the same (McDougall and Harrison 1999). If the half-life of a radioactive isotope and the concentration of its daughter atoms in the sample is known, it's possible to back-calculate the age of a sample and find out how old it is (Hamilton 2003). Since hydrothermal vents exist on geologic timescales, much of their radiometric dating is done with Uranium-Lead (U-Pb) dating, Potassium-Argon (K-Ar) dating, and Rubidium-Strontium (Rb-Sr) dating, though that is only a sample of the many different isotopes available for use. U-Pb and Rb-Sr dating have date ranges from 10 million to 4,600 million years (Bowen 1994; Schaltegger et al. 2015); K-Ar dating ranges from 0.05 million to 4,600 million (McDougall and Harrison 1999). The mineral composition determines which radioactive pair will be used; some rocks will have high concentrations of some elements, and none of others. For example, Uranium-Thorium

(U-Th) dating can be useful for vent systems such as Lost City, since U-Th dating can be used to date samples containing CaCO3 (calcium carbonate), which is abundant in serpentinite-hosted vents (Fruh-Green et al. 2003).

Paleomagnetic dating utilizes the fact that, throughout Earth's history, magnetic north has frequently shifted in orientation, from north to south and back again. Magma contains within it many iron particles, and when magma cools, the iron particles align themselves to be parallel to the direction of Earth's magnetic pole in a process called thermoremnant magnetization. Magnetic examination of the seafloor around spreading centers (where hot magma is quickly cooled) shows north-oriented and south-oriented rock in regular lines across the millenia, like bars on a bar code. While the existence of thermoremnant magnetization in a random piece of rock is of little use for dating, when the context of the rock is known, its general age can be determined. This method is the least accurate of the three listed in this paper, since it requires a good amount of context and can only provide broad information.

Microbial mat dating utilizes the abundance of microorganisms living on vent chimneys to estimate the age of the rock. There are microorganisms found everywhere on earth, including (famously) on hydrothermal vents, and the populations of bacteria and archaea on vent chimneys changes depending on the age of the chimney (Lee et al 2015). For example, a low population of vent-loving microbes on a venting chimney likely means that it's young, while a high population of non-vent microbes on a chimney that is no longer venting likely means that the vent turned off a while ago (Sheik et al 2015). These population makeups are similar across vents (Lee et al 2015). This is because different microbes use different things for energy. Some use the chemicals from the vent fluids, some use the chemicals from the seawater interacting with the rock after the vent stops and the chimney begins to change composition. There's also evidence of ecological succession on both venting and non-venting chimneys, which could be used to estimate how long each microbial population has been there, and thus how old the chimney is (Sylvan et al. 2012).

Conclusion

Hydrothermal vents are found around the globe in a variety of tectonic settings. There are several ways of determining how old they are including paleomagnetism, bacterial growth analysis, and the most common, radiocarbon dating. Hydrothermal vents host rare minerals, and unique communities of animals and microorganisms, some of which may even be the origin of life on our, or other, planets. Dating them may allow us a deeper insight into how they and the communities they're part of form, and thus, potentially, to get a glimpse of the ecology of these unique pieces of seafloor.

Once you have completed the survey for this paper at https://forms.gle/6pf4zCvDcfAa7XUo8, please feel free to play my game at https://ispybluesky.itch.io/hydrothermal-dating !

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