Connecting User Experience to Learning in an Evaluation of an Immersive, Interactive, Multimodal Augmented Reality Virtual Diorama in a Natural History Museum & the Importance of Story

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***Abstract*—Reported are the findings of user experience and learning outcomes from a July 2019 study of an immersive, interactive, multimodal augmented reality (AR) application, used in the context of a museum. *The AR Perpetual Garden App* is unique in creating an immersive multisensory experience of data. It allowed scientifically naïve visitors to walk into a virtual diorama constructed as a data visualization of a springtime woodland understory and interact with multimodal information directly through their senses. The user interface comprised of two different AR data visualization scenarios reinforced with data based ambient bioacoustics, an audio story of the curator's narrative, and interactive access to plant facts. While actual learning and dwell times were the same between the AR app and the control condition, the AR experience received higher ratings on perceived learning. The AR interface design features of "Story" and "Plant Info" showed significant correlations with actual learning outcomes, while "Ease of Use" and "3D Plants" showed significant correlations with perceived learning. As such, designers and developers of AR apps can generalize these findings to inform future designs.**

***Index Terms*—augmented reality, bioacoustics, data visualization, immersive, information fidelity, informal learning, interactive, multimodal, museums, narrative, photorealistic, place illusion, presence, virtual dioramas, virtual reality**

I. Introduction

The main objective of the study was to understand the use and impact of an augmented reality (AR) application in the context of a museum diorama as a way to enhance informal learning and engagement (Fig. 1). To fully understand how the general public uses such new tools and the impact, both an observational ethnographic case study and an empirical user study were conducted (Fig. 2 and Fig. 5). The ethnographic case study used video and audio recordings to capture the behavior and conversation of consenting volunteers during their use of the AR app and compared their behavior and conversation to those volunteers who did not use the app. The objective of the empirical study was to compare learning gains, emotions experienced, impacts on perceptions of ease of use and attitudes between the two conditions. The control condition without the AR app, i.e., the No-AR condition (Fig. 2), offered access to facts and concepts in a booklet with identical educational information as that in the AR app, and the experimental condition with the AR app, i.e., the AR condition was used to compare *authentic learning outcomes* from the AR app design (Fig. 1, 3, 4, and 5).

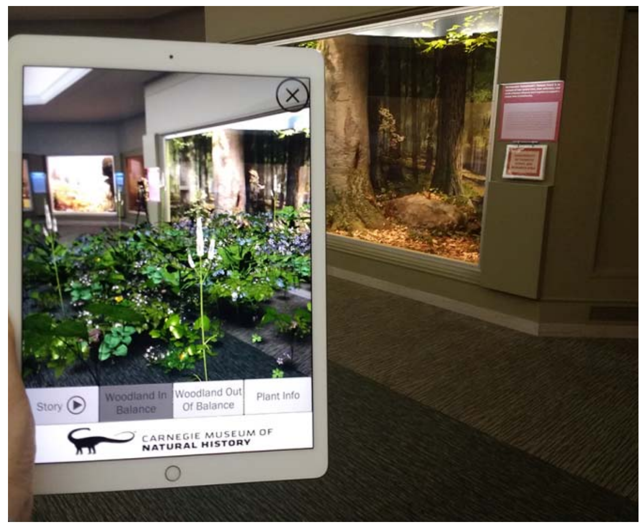

Fig. 1. The AR Perpetual Garden.

Fig. 1. Shows the AR Perpetual Garden App prototype, with a virtual diorama in the form of an immersive AR data visualization contextually important to the Forest Diorama, in the Hall of Botany at the Carnegie Museum of Natural History, used for the July 2019 study. A visitor can walk into the virtual forest understory, hear insects and birds, bend down to see 3D botanical details in the virtual flowers, toggle between two data simulations, listen to the curator's narrative, and access plant facts important for actual learning. The AR Perpetual Garden App was developed in May 2018 as an international collaboration between digital media artists, game developers, and natural history museum scientists and botanists. The prototype shows virtual dioramas in the form of two immersive AR environments that are constructed as data visualizations of plant populations intended to communicate a complex scientific educational narrative about trophic cascades. Visitors can toggle between two AR scenarios in one click: *Woodland in Balance* (Fig. 3) and *Woodland out of Balance* (Fig. 4). The

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app is unique because all of the virtual plants are correct 3D models of real plants vetted and approved by the museum's botanist. The virtual plant plots are data visualizations of the real plant research field data for each scenario. The associated insect and bird bioacoustics represent accurate depictions of the relevant research field data. The user interface allows access to the curator's narrative as an audio story and access to an online plant atlas with plant facts that provide additional information [1].

II. Background

A. *Overview*

The AR Perpetual Garden App was launched in October 2018 and is available for download and use from the Carnegie Museum of Natural History Apple iTunes and Google Play app stores. As the first app of its kind to use AR simultaneous localization and mapping technology (SLAM) [2] to visualize ecosystems based on data, it has already demonstrated value and innovation through its novel design pattern as a virtual diorama. As is often the case with new technology, opportunities to investigate old problems with new solutions have become possible. Recently, AR applications have been created to offer engaging educational experiences [3]; however, there are many design challenges and research questions open to investigation in the both the design of AR applications and their impacts on informal learning.

B. *Opportunities for AR in Museums*

Museums are searching for creative ways to use AR and virtual reality (VR) technology to communicate knowledge and to teach the public about their collections and in scientifically accurate, emotionally powerful, and cognitively transformative ways [4]. AR offers the advantage for learning by allowing context-sensitivity [5] to integrate real and virtual information in spatial-temporal meaningful relationships. One of the most important examples of an interactive, multimodal, and contextual AR application used in a museum gallery for informal learning was implemented in 2015 at the Smithsonian Institution National Museum of Natural History with *The Skin & Bones App*. This app demonstrated the design, development, and deployment of an innovative use of AR combined with a curator's narrative and facts to complement and extend an exhibit, and to make it interactive by overlaying the bones in the exhibit with skin, scales, fur, and feathers to bring them to life. However, learning impacts were not studied [6].

AR has been designed, developed, and researched with educational applications in mind [7]. Early AR-enhanced exhibits for museums suffered from technical limitations, which often restricted the presented digital content to pop-up text, labels, photographs or cartoon graphics [8]. Some AR design factors that have been reported to impact formal education include real-world annotations, contextual visualizations, and vision-haptic visualizations [9]. In a recent review of AR applications used in informal science learning, Goff et al. [10] showed that content and retention were enhanced with AR through increased levels of interest and engagement; however, these studies reviewed collaborative games, so the findings could be attributed to the interactions of collaboration, competition, or social factors of games, and not to the design choices parameters inherent in the AR app.

Fig. 2. Hall of Botany, Forest - Tionesta Scenic and Research Area Diorama: No-AR Condition. A volunteer participant reads the booklit.

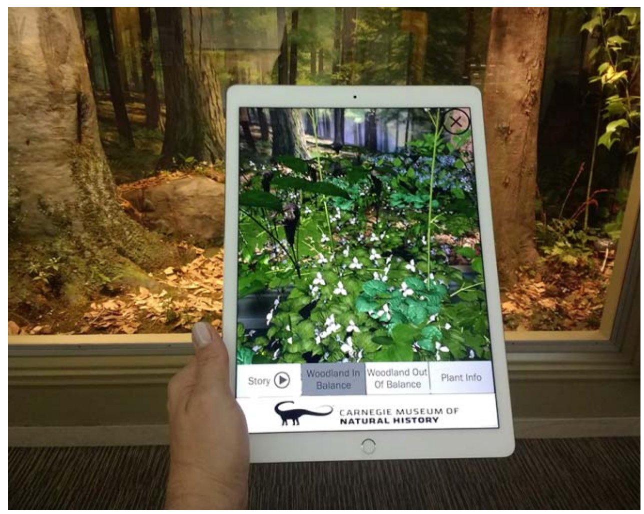

Fig. 3. Hall of Botany, Forest - Tionesta Scenic and Research Area Diorama: AR Condition *Woodland in Balance.*

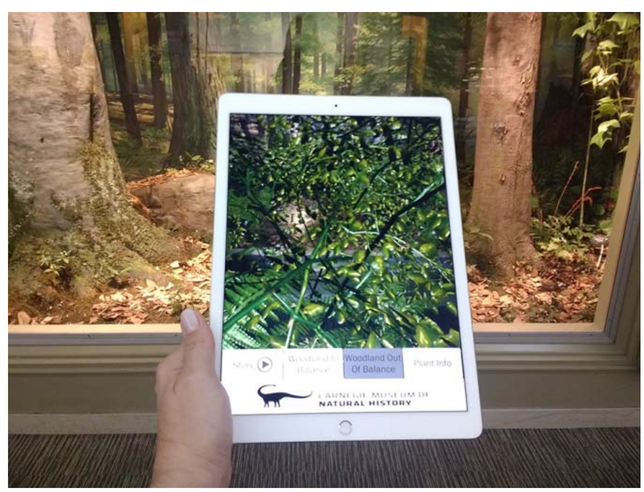

Fig. 4. Hall of Botany, Forest - Tionesta Scenic and Research Area Diorama: AR Condition *Woodland out of Balance*

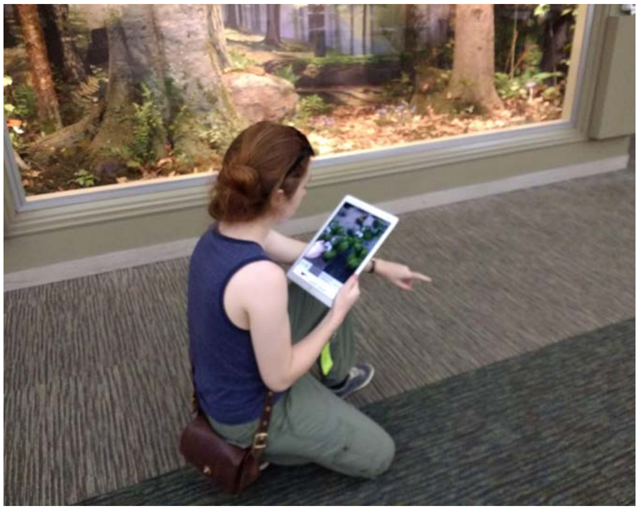

Fig. 5. Participant reaching to touch a virtual flower in the AR Conditiaon.

An important distinction in learning goals and activities between formal education and informal learning environments is free choice [11]. Formal education normally dictates learning goals and activities, where informal learning is self-directed and self-motivated, thus requiring a user interface design to support free choice in exploration, navigation, search, and inquiry [12]. As advancements in technology improve immersive displays and presence [13], visual fidelity becomes photorealistic. Photorealistic contentment could be fake or fantasy or truthful and based on reality. If based on data, the visual fidelity is not only photorealistic but also a data visualization, representing *high information fidelity*. It becomes a communication medium, required for learning, and when combined with free choice in navigation has been shown to double learning outcomes [12].

C. AR Design Factors

Empirical studies of design factors in immersive applications and their relationships with actual learning results are rare [14]. Often, case studies, descriptions of applications, or qualitative studies of prototypes are reported, most without the research design control required for validity or confidence in the findings. Design factors, often referred to as “affordances” unique to immersive technology (AR, VR, and MR, or XR), have not been precisely defined or quantitatively measure for impact on outcomes. Overall, there is a lack of scientific rigor and precision in the interdisciplinary research. One of the most discussed outcomes of immersive technologies is that of presence [15].

In a cautionary piece on virtual field trips, McCauley [16] critiqued the use of immersive VR to achieve presence recognizing the powerful automatic reaction *in-situ* to a virtual whale and acknowledging that immersive experiences promise great opportunities for direct experiential learning. The potential is to deliberately and intentionally design awe-inspiring virtual experiences (powerful emotions that lead to intrinsic motivation and self-directed independent inquiry), to nurture appreciation of the natural world, and to distribute these immersive experiences to those who cannot travel into the wild (power of the virtual as a time and space imagination and knowledge transfer machine, where scale, distance, and costs are tamed). However, McCauley argues that there will be a temptation to replace critical real educational experiences with lower cost virtual substitutions way below educational value and quality required, and thus devalue the real-world field work. When real and virtual field trips have been directly compared for declarative and conceptual knowledge gain, prior research demonstrated the real-world superior for learning overall. However, it also demonstrated that learning outcomes were identical when the content in the virtual matched the real. This study also showed evidence of priming, transfer, and reinforcement with a virtual field trip [17], thus there is a hope that high quality simulations of the natural world have a role, if designed carefully, intentionally, and deliberately and used with understanding of the limitations of their effectiveness.

In contrast to VR which completely replaces the real field of view with a computer-generated virtual world and has operational issues that prevent widespread use in museums (e.g., costs, hygiene, and support staff), AR overlays text and computer-generated graphics on the real world with mobile digital devices that are commonly used by the general public. Azuma [18] argued that AR combines virtual and real objects to offer the ability to interact with objects in real time. AR-enabled devices are becoming widespread, making AR content easily accessible and cost effective especially for museums. When the real and the virtual become integrated and interactive, the resulting perceptual mixture of the real and the virtual is often referred to as mixed reality (MR). This term stems from the definition of the reality-virtuality continuum [19], where the real world and a completely virtual world (VR) form the extremes. Recently, with increased sensitivity of AR to respond to real-world objects, MR has become more interactive, allowing the real-world objects to trigger events for registration and AR interface interaction.

Immersive factors found in VR devices [20] may become stronger in newer AR devices [21], *because presence observed in AR might extend to include the real-world field-of-view to include room-sized, and true-to-life, full-scale AR application* [22], enhanced through the addition of factors of embodied and social interaction available in MR [23]. AR has been shown to be more enjoyable outdoors [24], perhaps also due to the increased richness of information fidelity offered by the details and complexity of multimodal signals of the real-world sensory field-of-view, social interactions and the additional story and emotional cues, all perceived and integrated with the virtual content in the AR field-of-view. After all, reality is the most immersive experience of an environment possible. Past work has shown the importance of design factors in virtual environments for improved learning and emotional outcomes due to graphical fidelity and navigational freedom (e.g., 3D cartoon vs. 3D photorealistic images combinations with predetermined paths vs. free choice in exploration in planned orthogonal contrast studies) [12].

There is a large body of literature on the theory of multimedia learning [25] supporting the benefits of simultaneously presenting text, audio, and visual information to reduce cognitive load and thus amplify learning with multimodal signals. From the perspective of information science, these are simple redundancy cues offering multiple redundant and reinforcing signals in the environment to magnify the strength of the combined signals effect on attention and cognitive processing, but only if there is redundancy in the meaning of those signals [26]. Information-rich salience displays plays a critical role in informal learning by focusing on personalized user attention in virtual environments that are designed for free choice in exploration and inquiry, shown to trigger emotional outcomes, inquiry, and learning results [12], [17], [27]. If information signals are salient, they might trigger attention and interest, enhancing curiosity, and self-directed motivation to learn [27], all highly desirable responses for museum exhibition design. Dioramas of the past may be thought of as physical representations of scientific knowledge and as a type of knowledge artifact. In the past, dioramas were designed to motivate inquiry and provoke questions [28], but lacked interactivity. AR promises to make them immersive and interactive, ideal for informal learning.

D. Design Factors in the AR App

AR design features are under the designer's and developer's control, so understanding their impact is necessary to create useful and meaningful designs for authentic learning.

The taxonomy of the AR app is presented below:

1) Human-computer environment interaction

- Real-virtual context-sensitivity field-of-view
- Real Forest Diorama annotated with AR woodland understory virtual dioramas
- User interface
  - o iPad Pro with the AR app installed
  - o Story button – plays audio when selected
  - o Data visualization buttons – toggle between two scenarios
  - o Plant Info button – WiFi connection to facts in the website plant atlas and field guide, *The Virtual Garden Timeline.*

2) Information-rich signals and factual accuracy to produce high information fidelity

- Plant facts and concepts – vetted and approved by the museum botanist
- Photorealism – textures, models, and morphology vetted and approved by the museum botanist
- Realistic landscape layouts as data visualizations of plant plot research studies
- Soundscapes – data-based bioacoustics
- Story – authoritative curator's narrative
- Multimodal signals
  - o Story audio file that plays when selected
  - o Ambient bioacoustics that reinforce each data visualization scenario
- Data visualization and simulation
  - o Woodland in Balance – based on scientific research data
  - o Woodland out of Balance – based on scientific research data
  - o The user may toggle between two virtual realities in the context of the real diorama for instant visual comparison and contrast to the real diorama or outdoor gardens

3) Navigational freedom – AR embodiment

- Social collaboration, exploration, and conversation in the museum gallery
- Full-body exploration of the entire museum gallery – the user can walk around in a field of flowers covering the entire floor

4) Inquiry – interactive and responsive information

- Story
- Plant facts
- Close inspection of each plant and flower – the user can bend down to look at the 3D virtual models on the floor from any angle (top, bottom, or sides)
- Inspection of each part of the flower (stem, leaf, petal, stamen, pistil, and ovary) by moving the iPad closer to the flower
- Gestures – the user physically moves the iPad closer to the virtual flower to zoom in and out to pan the entire view of a field of wildflowers

III. Research Study

A. Primary Objective

Such a set of complex design factors creates challenges in isolating causal factors especially when conducted in the wild with an ecologically valid sample of the general population. The main objective was to observe the general public in the real-world context with the AR app, and then to measure the impact of design features on user experiences and *actual* and *perceived* learning results, to inform future designs.

B. Research Design

The research study used a between-subject design to test user learning outcomes, perceptions of learning, and usability. There were two conditions: the experimental condition (AR), which used the AR app and the diorama, and the control condition (No-AR), which used a booklet containing the same educational concepts and facts as the AR app. The booklet was required as a baseline control for the first study, and it was of interest to the stakeholder (museum) necessary to assess the costs involved when considering adoption of new technology. Ethnographic and observational data were collected through video- and audio-recorded interactions and conversations. Pre-tests and post-tests on facts and concepts were used to measure *actual learning gains*. Pre-surveys and post-surveys on emotions and attitudes were used to measure and compare subjective attitudes about the two conditions. An additional

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post-survey on user experience was given to the AR app group ($n = 28$) to capture attitudes about the AR design features.

1) *Population and Sample*

The 2017 museum member population includes approximately 31,000 households with reported summer visitation as 97,336 individuals. Based on past data for the month of July, approximately 4,300 individuals were expected to visit the museum from which to recruit participants. Approximately 50 visitors per day entered the Hall of Botany over the nine-day study period, and 56 volunteered between ages 5 and 56 to be participants ($N = 56$) in this institutional review board (IRB)-approved study. The recruitment and assignment of volunteer participants to conditions was not random, as a sample of convenience was used due to the nature of a public exhibit; instead, participants were assigned to the conditions to maintain equal counts per group ($n = 28$) while also attempting to maintain equal assignment of adults and adult-child pairs ($n = 14$), as this is a major factor known to influence learning. Only data from individuals who provided consent were collected and used in the study. Children aged 3-17 who assented and had consent from a parent (or legal guardian) were allowed to participate. Children under 3 years of age or who were unable to provide assent were not included in the study. Adults aged 18 and older were exempt. All IRB protocols and procedures were followed to ensure informed consent and confidentiality. Each participant received a non-identifying number for data collection purposes. They were told to use the AR app or booklet to learn for as long as they wanted and to quit whenever they wanted.

2) *Materials and Measurements*

The PI had two Apple iPad Pros with the AR app installed and a paper booklet with the same information to ensure equal educational content between the two conditions. There were identical pre- and post-tests on facts and concepts for measurement of the percent changes in actual learning. There were pre- and post-surveys to measure subjective evaluations on a 7-point Likert scale, and for the AR condition, ease of use and the AR design factors were measured in a post-survey.

A few of the post-survey questions are listed below:

- How easy was it to “learn” in your experience?
- If you used the AR app, how important was the feature of showing two woodlands scenarios for your learning?
- If you used the AR app, how important were the detailed 3D flower models for your learning?
- If you used the AR app, how important were the sounds of insects and birds for your learning?
- If you used the AR app, how important was the audio “Story” for your learning?
- If you used the AR app, how important was the link to “Plant Info” for your learning?
- If you used the AR app, rate the ease of use of the AR app.
- When did you feel the moment of insight, your teachable moment? Please describe.

IV. Results

A. *Learning Behavior*

Learning behavior was observed to be different between the AR and No-AR conditions. Those in the AR condition walked around the entire gallery. Often, they would bend over, crouch down, or sit on the floor and move the iPad closer to the floor to inspect a virtual flower. Some participants in the AR condition tried to pinch and spread their fingers to zoom in and out. When that interaction did not produce the results they expected they moved the iPad closer to the floor. Some visitors reached out to try to touch a virtual flower for interaction (Fig. 5). Many children ran or romped around, talked excitedly, and shared their finds with parents and grandparents. They acted like children in a real field of flowers, not a museum, demonstrating observational conclusions of a high sense of presence [22]. The participants in the No-AR condition stood quietly in front of the glassed diorama and read the booklet (Fig. 2). A few looked at signage adjacent to the diorama. Conversation, if any, was minimal.

B. *Actual and Perceived Learning Measured with Tests*

It is essential to differentiate between *actual* learning and *perceived* learning. *Actual learning* is measured as the percent change in pre- and post-test scores on facts and concepts, where *perceived* learning is subjective. An independent two sample t-test revealed no difference in *actual learning* between the AR condition ($M = 40.13\%$, $SD = 24.62$), and the No-AR condition ($M = 46.72\%$, $SD = 30.54$), $t(54) = 0.89$, $p = 0.38$, (Fig 6.). However, significant differences were found in the *perceptions of learning* between the two conditions using the post-survey data, (7-point Likert scale). The central tendency of the distributions showed the AR condition ($Mdn = 6$, $SD = 1.60$) to be higher than the No-AR condition ($Mdn = 4$, $SD = 1.32$). A Mann-Whitney U-test showed the AR (*Mean Rank* = 34.95) to be higher than the No-AR (*Mean Rank* = 22.05) condition, $U = 572.50$, $z = 3.01$, $p = 0.00$. The effect size = 0.40, (Fig. 7.).

C. *Dwell Times as a Proxy of Engagement*

Dwell times, often used as a proxy measurement of engagement, showed no difference between conditions. An independent two sample t-test revealed no difference in *actual learning* between the AR condition ($M = 8.98$ minutes, $SD = 6.72$ minutes), and the No-AR condition ($M = 8.15$ minutes, $SD = 3.60$ minutes), $t(54) = 0.58$, $p = 0.57$.

D. *AR App Design Factors and User Experience*

AR design factors and the Ease of Use were rated highly, with all *mode*s = 7. The *median* for each AR design feature were also rated highly: AR Data Visualization Scenarios = 7; AR 3D Flowers = 6; AR Bioacoustics = 6; AR Plant Info = 6; AR Story = 7; and Ease of Use for the AR app = 7, (Fig. 8-13).

E. *Correlations Between Design Factors and Learning*

A Spearman's rank correlation coefficient was used on the AR only condition data set ($n = 28$), (Table □.) to investigate the relationships between each AR app design feature: Story; Data Visualization Scenarios; 3D Flowers; Bioacoustics; Plant Info; and usability (Ease of Use), on *actual* (percent change in test scores) and *perceived* learning outcomes (survey ranks).

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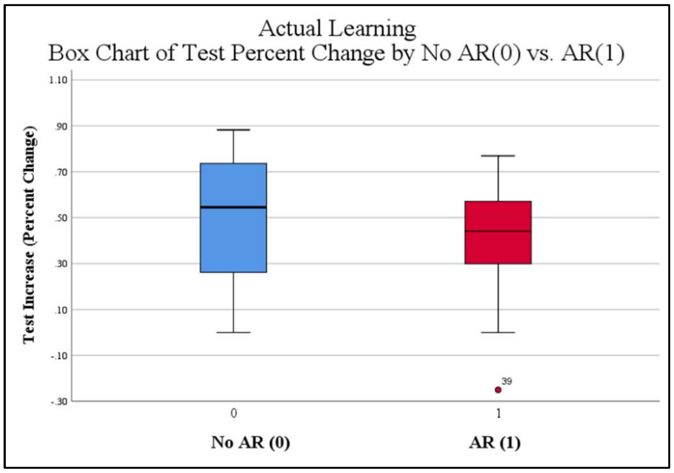


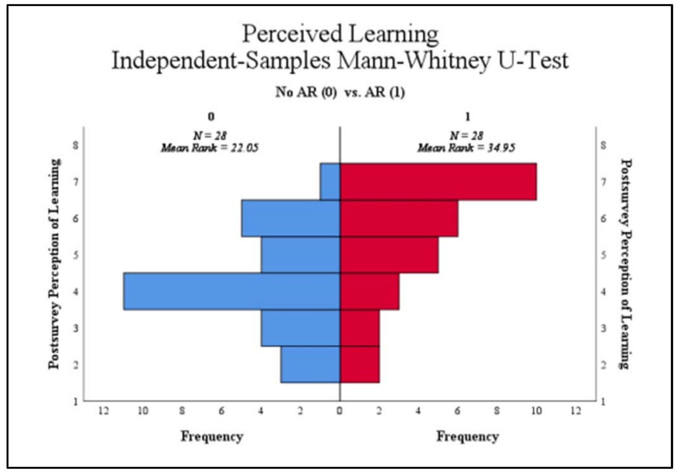
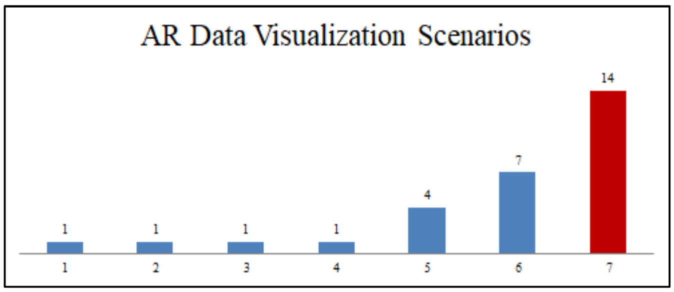


Fig. 6. Actual learning was the same in both conditions (No-AR vs. AR), measured in a *t*-test as the percent change in pre- and post-test scores.

Fig. 7. Perceived learning was different between conditions (No-AR vs. AR), measured in an independent-samples Mann-Whitney *U*-Test.



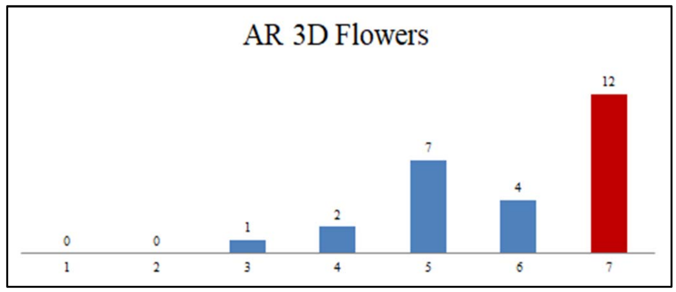
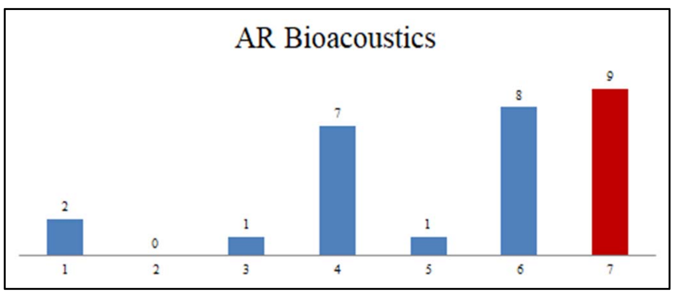


Fig. 8. Likert scale responses to the question, "if you used the AR app, how important was the feature of showing two woodlands scenarios for your learning?" (*median* = 7 and *mode* = 7).

Fig. 9. Likert scale responses to the question, "if you used the AR app, how important were the detailed 3D flower models for your learning?" (*median* = 6 and *mode* = 7).



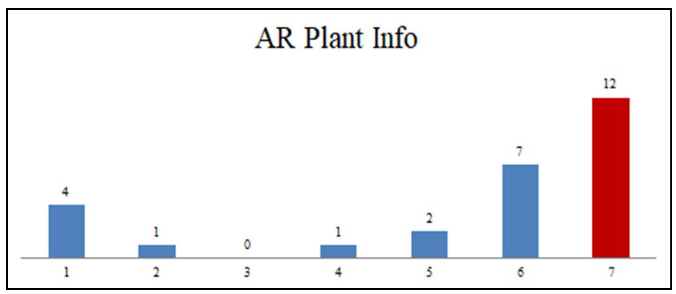
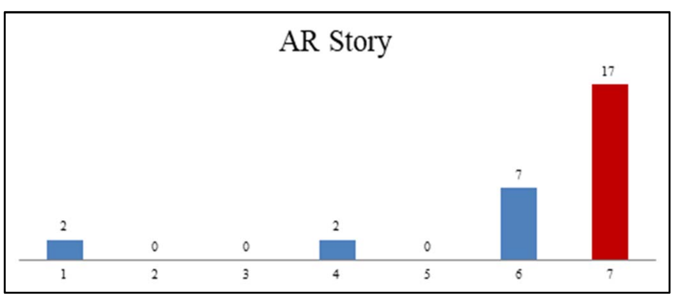


Fig. 10. Likert scale responses to the question, "if you used the AR app, how important were the sounds of insects and birds for your learning?" (*median* = 6 and *mode* = 7).

Fig. 11. Likert scale responses to the question, "if you used the AR app, how important was the link to "Plant Info" for your learning?" (*median* = 6 and *mode* = 7).



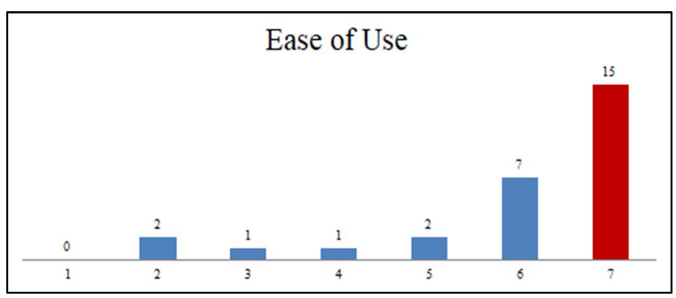


Fig. 12. Likert scale responses to the question, "if you used the AR app, how important was the link to "Story" for your learning?" (*median* = 6 and *mode* = 7).

Fig. 13. Likert scale responses to the question, "if you used the AR app, rate the ease of use of the AR app." (*median* = 7 and *mode* = 7).

TABLE I. SPEARMAN'S RHO CORRELATIONS AMONG VARIABLES OF ACTUAL AND PERCEIVED LEARNING BY AR DESIGN FEATURES

	Variables Measured	*Actual Learning*	*Perceived Learning*	*AR App Design Factors*					
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	Actual Learning	--							
2	Perceived Learning	.25	--						
3	AR Data Visualization Scenarios	.06	.15	--					
4	AR 3D Flowers	.17	.52**	.62**	--				
5	AR Bioacoustics - Ambient Insects and Birds Sounds	.30	.37	.53**	.69**	--			
6	AR Story - Audio Curator Narrative on Trophic Cascade	.41*	.15	.45*	.38*	.56**	--		
7	AR Plant Info - Facts	.41*	.36	.15	.24	.01	.08	--	
8	Ease of Use	.07	.54**	.24	.24	.22	.09	.15	--

a. Note: (N = 28), * $p < .05$; ** $p < .01$

Two significant correlations were found between the AR app features and *actual* learning outcomes: Story (r_s = 0.41, p = 0.03) and Plant Info (r_s = 0.41, p = 0.03). Significant correlations were found between the AR app feature and *perceived* learning: 3D Flowers (r_s = 0.52, p = 0.01), as well as Ease of Use (r_s = 0.54, p = 0.01). Note, that the AR design factors correlated with *perceived* learning are different than the ones correlated with *actual* learning.

There are many other correlations that give valuable insight into the AR design factors of importance, most notably are the highly significant correlations of Data Visualization Scenarios with the 3D Flowers (r_s = 0.62, p = 0.00), Ambient Insects and Birds Sounds (r_s = 0.53, p = 0.00), and Story (r_s = 0.45, p = 0.02), possibly indicating the importance of *information fidelity* for increased AR immersion and engagement.

Significant positive correlations exist between all of the AR design features and AR Story, indicating that these features amplify each other and might multiply the strength of the relationship of story on actual learning impact.

F. Presence, Immersion, and the Gestalt

Presence was not measured in the post-survey questions, yet participants in the AR condition acted like they were in a real field of flowers, thus indicating high presence due to the immersive quality of the AR app [22]. To shed light on the data, the answers to one of the open-ended survey questions (i.e. "When did you feel the moment of insight, your teachable moment? Please describe") are reported as aggregates of the AR app features important to the moment of insight – the Gestalt – that triggered the teachable movement [29]. Five (5) participants did not respond to the question, eight (8) participants reported that the data visualization feature was the most important, nine (9) reported that the audio story was the most important, and three (3) reported that the Plant Info feature was the most important. One reported that he or she needed to learn more, and two (2) more participants provided ambiguous responses.

A few examples of the answers to the cause of insight are listed below:

- Subject ID#2: "Listening to the story"
- Subject ID#8: "When I realized the deer are changing the environment so much" <AR app scenarios>
- Subject ID#23: "The contrast of the stable vs unstable ecosystem. The unstable ecosystem/forest looks more like the forests I see." <AR app scenarios>
- Subject ID#24: "Key topics – trophic" <Story>
- Subject ID#42: "The more I switched from forest in balance to out of balance"

V. Discussion

The first finding is in the observed difference in behavior between the two conditions, indicating higher levels of engagement with the AR apps. Even though a post-survey to measure presence was not gathered, it may be inferred from the observations of the participants in the AR condition, because they behaved as if they were in the real woodland. The second important finding between AR and No-AR conditions is that there is no difference in *actual* learning, but there is a difference in *perceived* learning. The results for *actual* learning outcomes could have been depressed by the unreliable WiFi connection, making access to facts with the AR app unreliable. However, with the high satisfaction reported with a *mode* = 7 for Plant Info, offers counter evidence about the real impact of spotty WiFi. It also highlights the overall importance of the entire technical operational environment for access and information delivery on actual learning outcomes.

VI. Conclusion

The most important AR app design factors are Story and Plant Facts for actual learning outcomes. This finding is not surprising, as one needs access to accurate concepts and facts in order to learn. Given that all of the AR app features were highly rated by participants, it may be argued that all of the features were important for the learning experience. The correlations shed light on the interactions of design features with each other. The comments support the claim that Data Visualization, supported by the ambient Bioacoustics (e.g., a redundant signal) as well as the Story, played an important role in the experience of insight, a Gestalt. Such a design is valuable and important when complex scientific expert knowledge, especially that which is invisible or not part of the individual's personal experience of reality, needs to be communicated or transferred to a naive public quickly.

Museums desire to make informal learning enjoyable because it is an optional experience for the public. Visitors desire casual and fun experiences but not at the expense of learning. In this study, the immersive, multimodal AR annotated dioramas became more life-like, interactive to individual inquiry, and communicative of expert knowledge. Participants using the AR app behaved as though they were in a real woodland. Actual learning was identical between the AR and No-AR conditions; however, learning was perceived to be superior in the AR condition. All AR design factors and ease of use were highly rated by participants, indicating their importance. The AR app design features with significant correlations to actual learning outcomes were the curator's audio narrative in the Story and access to facts in the Plant Info button. These are different than the significant correlations to perceived learning of 3D Flowers and the overall Ease of Use. A more rigorous future analysis is required to fully understand the interrelationships between immersive AR, emotions, learning, behavior, and presence.

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