Trap it! : A Playful Human-Biology Interaction for a Museum Installation

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ABSTRACT
We developed Trap it!, a human-biology interaction (HBI) medium encompassing a touchscreen interface, microscopy, and light projection. Users can interact with living cells by drawing on a touchscreen displaying the microscope view of the cells. These drawings are projected onto the microscopy field as light patterns, prompting observable movement in phototactic responses. The system design enables stable and robust HBI and a wide variety of programmed activities (art, games, and experiments). We investigated its affordances as an exhibit in a science museum in both facilitated and unfacilitated contexts. Overall, it had a low barrier of entry and fostered rich communication among visitors. Visitors were particularly excited upon realizing that the interaction involved real organisms, an understanding that was facilitated by the eyepiece on the physical system. With the results from user study, we provide our observations, insights and guidelines for designing HBI as a permanent museum exhibit.

Author Keywords
Human-Biology Interaction; Tangible Interactive Microbiology; Interactive Biology; Biotic Game; Biotic Processing Unit; Interactive Microscope

ACM Classification Keywords
H.5.2. User Interfaces; K.3.m Computers and education

INTRODUCTION
We developed a new technology that enables museum visitors to tangibly interact with living biological microorganisms (Figure 1); users draw patterns on a touchscreen over a magnified real-time view of photoresponsive microorganisms. The user's drawing is projected onto these microorganisms as light beams, which the cells sense and respond to by changing their swimming

motion. This light-mediated interface is enabled via an interactive microscope built with commercial electronic devices (Figure 3). By solving relevant engineering challenges in designing for stable human-biology interaction (HBI), we constructed a stand-alone system suitable for museum installation.

The novelty of Trap it! lies in the embodiment of real-time, one-to-one interaction between human and microbe. Living organisms have often been incorporated in digital systems to function as sensors, controllers or the interface [14, 20, 29, 34, 35] by the enabling power of emerging electronic- and bio-technologies [28, 29, 36]. Such hybrid digital-biological systems address human tendency to playfully interact with other living organisms and have shown to evoke empathetic emotions that lead to positive behavioral changes among users [8, 11]. In a similar but more direct fashion, the purpose of our system is focused on the HBI itself by the means of digital technology. This allows for people to experience true interactions with the microscopic world without complex biological knowledge and laboratory skills.

The hands-on interactivity of the Trap it! is well suited for museum environment where novel interactive media are increasingly utilized to offer public with learning experiences in engaging ways. Informal science learning in museum environments have been extensively studied and proven effective [7, 26]. The National Research Council
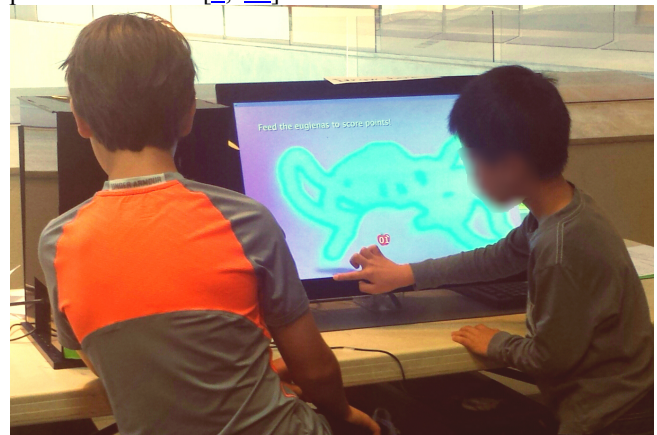

Figure 1. We developed an interactive system for a museum exhibit that enables free-form human interaction with single-celled microbes through a touchscreen and optical hardware.
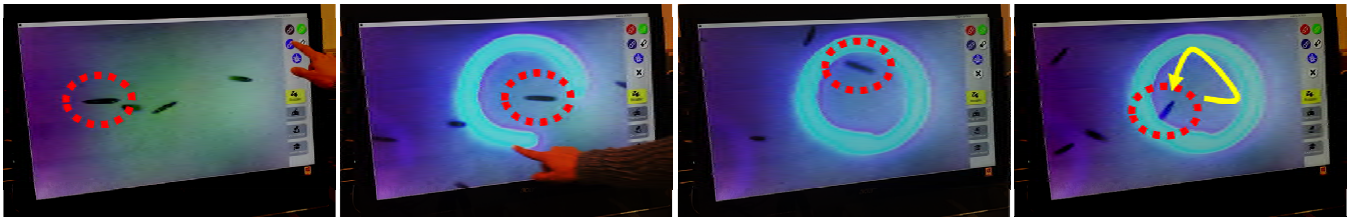
Figure 2. Tangible interaction with the phototactic, single-celled organism *Euglena gracilis*. The image a visitor draws on a touchscreen is projected onto motile microorganisms (red dotted circle) inside a microscope, which is then conveyed back to the screen in real time. These cells avoid blue light and can be trapped in a circle. Yellow arrow, swimming path of the trapped cell.

[30] described among its key items for science learning in informal settings the importance for children to "experience excitement, interest, and motivation to learn about phenomena in the natural and physical world." In the similar context, interactive public exhibits have also successfully shown to promote actively-prolonged and creative engagement among a wide range of users [3, 5, 13, 15-17]. However, when we turn to the field of (micro) biology, these novel interactive media for learning have been essentially absent. Microscopes are usually the only equipment used for microbiology-related exhibits in science museums but the interactivity is limited to the equipment operation or information visualization [30]. To address this gap, Trap it! installation is designed as an interactive biology exhibit piece for science museums, where users can experience microbiology in informal learning contexts, including cognitive, affective and social dimensions.

The goal of this investigation was to understand the general affordances of our system in a field setting, and to determine how it should be curated to become an effective museum exhibit. In short, Trap it! enriches informal learning environments by providing the opportunity for reciprocal exploration of microbiology via its intuitive usability, versatility, and affordances for expression. It elicits rich discussions not only about the phenomenon at hand, but also about the tools used to study microbiology. Users can learn that living cells can be subject to human interaction and manipulation, which constitutes a central point of modern bioengineering. Through proper scaffolding, such experience can generate positive and affective attitudes towards the living microorganisms that might extend to interest in biology in general. In the following sections, we will discuss our design procedures and experimental findings, some of which are closely associated with the general realm of interactive artwork while others are specific to HBI. We believe that this work will inspire many HBI systems for various purposes including art, entertainment, education and engineering, which will further necessitate relevant research questions in human computer interaction.

IMPLEMENTATION

Biological background
Trap it! utilizes *Euglena gracilis,* a phototactic, single-celled protist commonly found in freshwater ponds.

Euglena has been widely used in educational settings due to its robustness and safety [22]. The interaction with the microorganism happens through light stimuli. *Euglena* has a subcellular photoreceptor organelle that allows the cell to change its swimming direction under light stimulus. Phototaxis is dependent on the wavelength and intensity of the light; they accumulate in regions with adequate illumination and avoid areas with very dim or intense illumination [2, 24, 37]. The *Euglena* photoreceptor is known to strongly absorb blue wavelengths [2], prompting a instantaneous photophobic response upon intense blue stimuli that allows real-time interaction with human users.

Hardware implementation
The HBI in Trap it! is mediated by a biotic processing unit (BPU) [29], a set of hardware consisting of a microfluidic chip [36] sandwiched between modified consumer electronic devices (a webcam and a pico-projector) and conventional optical components [21]. A magnified view of the microorganisms and the light projections of drawn patterns are displayed on a 27-inch touchscreen monitor, through which the user controls the BPU. The interaction between a human finger (~5 cm) and *Euglena* cells (~50 μm) is afforded by optical microscopy, which effectively bridges the size-scale difference of three orders of magnitude. Light projection using a projector allows high-dimensional optical input in a microscope that is otherwise a passive instrument. The camera's field of view and the projector's field of projection are pre-aligned and scaled according to the magnifications of the optical system and the display resolution. The microfluidic chip containing the *Euglena* is connected to a batch culture reservoir via a solenoid valve controlled by an Arduino microcontroller board. The chamber is flushed every 4 h to maintain the desired cell concentration (average 3-5 cells in the field of view) and the level of phototaxis. In addition to the screen, users can observe both the projected image and the *Euglena* directly through an eyepiece (Figure 3). Since the BPU is composed of off-the-shelf electronic devices, we expect that interested parties can easily prototype similar systems.

Implementation of user interface
Conceptually, the interface contains three layers: the light projection, the microscopic fluidic world including the organisms, and the overlaid virtual objects. As the user moves his or her finger on the screen, s/he sees lines of the
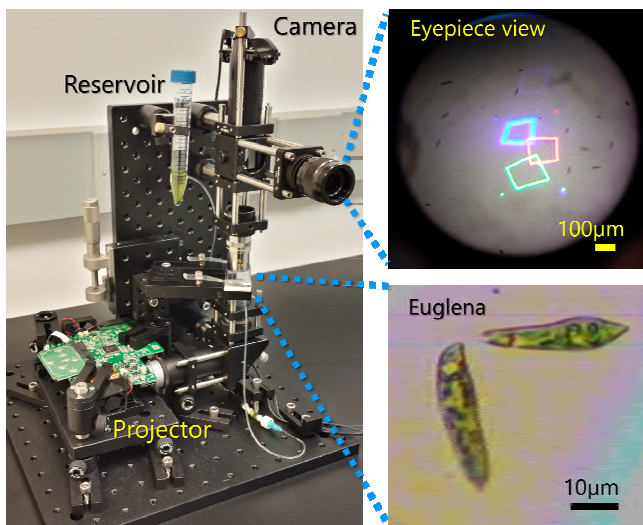
Figure 3. Interactive microscope hardware. In the museum, we added a three-sided enclosure to protect the system. We modified a commercial projector to project light patterns onto a microfluidic chamber with *Euglena*, which were imaged through a microscope via a webcam and an eyepiece.

selected color and width drawn on the monitor (Figure 2). These lines are not rendered graphics on the user interface layer, but are actual projections of the drawings on the microfluidic chip imaged through the microscope. As both the projection and the touchscreen are refreshed at video rate, the HBI happens in real-time. The graphical user interface and the hardware control for imaging and projection are written in the Processing language [27]. We further incorporated image-based real-time cell counting and tracking based on OpenCV for Processing library [9]. We mainly use these features for automated scoring in game activities (counting the number of *Euglena* and tracking their motion within a region of interest).

PRE-STUDY AND DESIGN ITERATIONS

We performed several pre-studies and lab tests prior to the current study with student volunteers and one previous supervised study at the museum (data not shown). Here, we discuss our findings about the design considerations of Trap it! in various aspects of the system, with a particular emphasis as an unsupervised exhibit.

Designing human-biology interaction

The phototactic responses of *Euglena* can vary between photo-accumulation and avoidance depending on the intensity and wavelengths of light stimuli. Initially, we experimented with a range of phototactic behaviors by providing variety of colors and intensities of light stimulus, which also allows users for more flexible drawing. Light intensities can be controlled by digital display value, projector's lamp power and the design of optical system. After iterations, we concluded that *Euglena*'s sharp turns upon encountering high-intensity blue light is more consistent and easier for the users to interpret than other

phototactic responses. Hence, this interaction fosters clear user behaviors such as drawing blue circles around a cell to trap it, whereas subtle feedback prevents users from noticing such distinct behaviors.

However, it is worth noting that biological systems cannot be designed to provide absolutely uniform responses. There exist variations in the sensitivity among a population of cells and noises arising from various factors. These inherent randomness naturally results in unexpected interactions with HBI (e.g. cells escaping from a light trap), which facilitates creative engagement among users [3] (e.g. finding strategies to prevent cells from escaping).

Designing the graphical user interface

During design iterations, we drastically reduced the number of available drawing functionalities from >10 colors with variable pen widths (2~50 μm) to three preset colors (red, green, and blue), one fixed width (~50 μm), an eraser, a reset button, and a blue pointer. These simplified controls offer possibilities of expressive drawings without cluttering the screen, reducing distractions from the desired interactions with the microorganisms. We displayed a manually-drawn light pattern (Figure 4) in the initial screen to inspire users to draw on the screen.

Designing for visualization and multimodal perception

Users mainly perceive HBI through the visual display on the flat panel touchscreen. There were a few limitations and trade-offs considered for the display of the microscope view. First, proper magnification on the microscope needs to be chosen to show individual cells in details while covering enough field of view to observe motion changes of *Euglena*. Considering the size of *Euglena* and the resolution of light stimulus, we used an objective lens of 10× magnification. Secondly, within the limits of the dynamic range of the camera, the exposure and color settings need to be carefully adjusted to show both dark (subcellular structures) and bright (light stimulus) parts of the images. Lastly, the conflict between the aesthetics and the scientific accuracy needs to be considered. Microbiological organisms can be perceived as visually unappealing by some people [12]. When displaying these organisms, one should take account for visual attractiveness, often at the expense of structural details, by proper adjustment of magnification, lighting and color balance.

In addition to the touchscreen display, we added in the system an eyepiece that the users can physically look into. By design, the view through the eyepiece has lower magnification than the camera but shows larger field-of-view, which works as a "zoomed out" view of the screen. The eyepiece provides a tangible interface for HBI which helps the users recognize the "actuality" of the interaction. The act of looking through the eyepiece itself is an additional activity, which supports additional users. The effect of this multimodal perception will be discussed in more detail in the user study section.
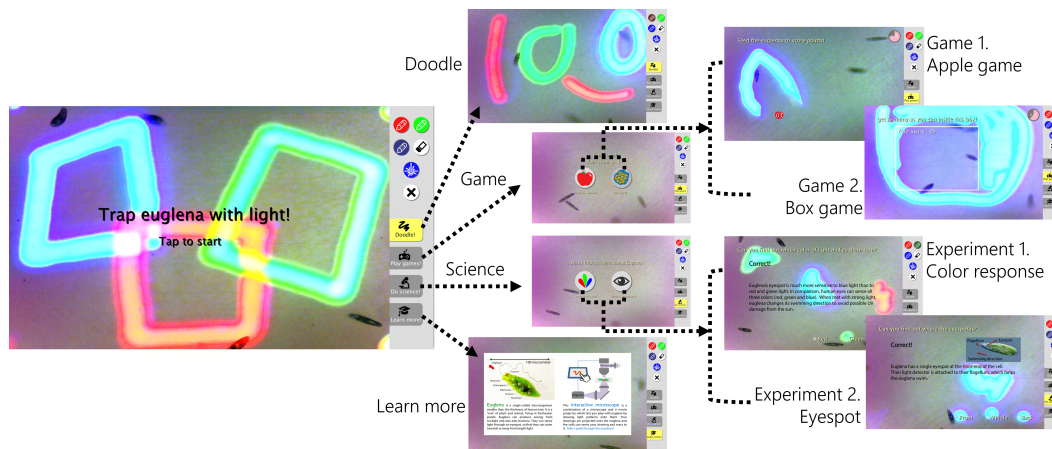
Figure 4. Flow diagram of the user interface and structured activities. The visitor first encounters the instruction to "Trap *Euglena* with light!" **On the side bar, the user chooses from various colors, an eraser, a pointer, and the option to clear the screen. Activities can also be selected (doodle; two games; two experiments; information screen). Also see Figure 6.**

Designing guided user activities

For "walk-up-and-use" museum installation, the initial instructions and tasks should be intuitive and light-weight [15]. To draw users' attention, we tried various call-to-action prompts ranging from "doodle!" and "play with the organisms" to more specific instructions such as "draw with light." We chose "Trap *Euglena* with light!" as the initial prompt because it provided a task that was specific enough for users to know how to begin using the system and because it seemed to foster realization of the HBI (Figure 2). When an interested user taps on the screen, s/he is led to an initially empty canvas with moving *Euglena*.

To provide playful experiences and enhance user engagement, we developed a range of mini-games. The game Apple asks participants to guide cells to virtual apples on the screen, where user scores points when a *Euglena* swims directly "into" the apple. In the second game Box, players seek to trap as many cells as possible in a virtual box within a limited time; the system counts the trapped *Euglena* in real time to calculate the score. We tested but did not implement a third game, River, in which users help *Euglena* to cross a broad blue line across the screen that prevents the cells from swimming from one side of the screen to the other. Games naturally take advantage of the inherent randomness in the HBI; the general strategy of playing is to use light as an obstacle for cells but the same playing strategy does not always work the same way. After pre-tests, we set the game durations to one minute and fixed the initial color settings in all game modes to blue.

A third category of activities is designed to foster scientific experimentation. In one case, the user is prompted to test the effect of color (red, green and blue) on *Euglena*'s behavior. In a second, more complex experiment, users must locate the eyespot in a cell. Alert observers realize that the cell always turns after its front end bumps into the colored region, but not other body regions, indicating that

the sensor is in the front. From internal tests, many users were able to perform self-designed experimentations.

The final activity ("learn more") displays an information screen with basic background knowledge about *Euglena* as an organism as well as information on how the setup works. We included this activity to determine whether users displayed increased curiosity.

In order to foster various forms of exploration, we chose to allow users to freely switch between these activities using the menu bar on the right side of the screen. For more specific group of users, such as students, sequencing these activities in a predetermined order may result in more effective exploration [15]. We chose the combination of sequencing and holistic approach, by always starting the system with the doodle activity and then allowing users to explore other activities at any point during the interaction.

Summary of design considerations

We inferred from these preliminary experiences that an HBI system should include few key features in order to successfully provide HBI experiences to users of various demographics. We found that the basic design principles of interactive museum installations [15, 18] are applicable to the design of interaction in Trap it!. Hinrichs *et al.* [18] has summarized insights for designing interactive information visualization systems for museums: rewarding short-term and long-term explorations, supporting collaborative exploration, making the visualization appealing and supporting various exploration styles. Trap it! fulfills these criteria through its design of biological responses and the user experiences with HBI, rather than the design of digital interface. (1) Clear and immediate biological responses are crucial in rewarding short-term explorations. The initial task ("Trap *Euglena*") that is easily achievable by most users within the first few seconds of the interactions motivates the users to continue their exploration with the system. (2) Versatile activities provided in the system such
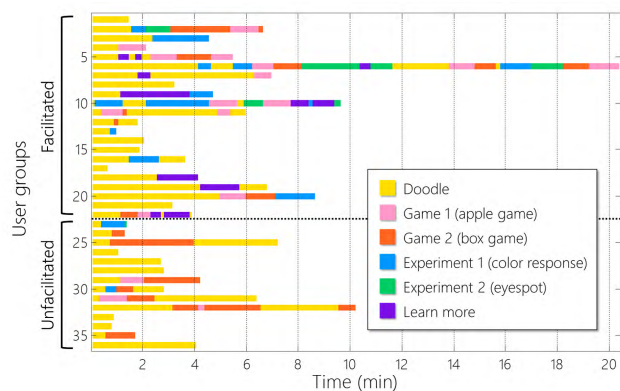
Figure 5. Activity patterns of the 36 user sessions. In the facilitated setting, all activities were explored more evenly, while in the unfacilitated setting, users were mostly interested in doodling and gaming; overall interaction times were shorter.

as drawing, games and scientific explorations rewards long-term interactions and can also support various exploration styles among users. (3) Large screen display and multimodal perception with eyepiece fosters collaborative interaction among group of users. (4) The visualization of microbiological objects should be aesthetically pleasing to users while providing scientifically relevant details.

Furthermore, we extracted additional design considerations that are more specific to HBI for public installations. (5) The BPU setup and its biological content needs to be sufficiently stable and controllable in order to provide each user with an experience that is consistent within desired bounds. (6) On the other hand, absolute control to the level of determinism might not be desired either: The apparent "Will of Its Own" is something people positively associate with life, and absolute control essentially denies this freedom. This makes the distinction in users' perception between a top-down vs. two-way HBI [12]. Biological noise and unpredictability can be considered a stand-out feature in many cases and make a positive contribution to the user experience in HBI. (7) The user interface should be simple and straightforward such that it is not distracting from its biological components, instead, it should emphasize them. Since the multiple layers in the HBI interface could be conceptually confusing, the clarity of interface is important in order to help users understand these concepts and fully experience HBI. (8) Lastly, the system must convey that the organisms are real and alive. Users should be able to realize that the interaction is not simulated but is actually happening in real time, which is one of the key novelties of HBI. In Trap it!, the tangibility of the microscope system and the eyepiece greatly helps users with this realization.

MUSEUM STUDY

Procedure and data collection
We ran a one-day user study at The Tech Museum of Innovation in San Jose, CA, USA to understand the general
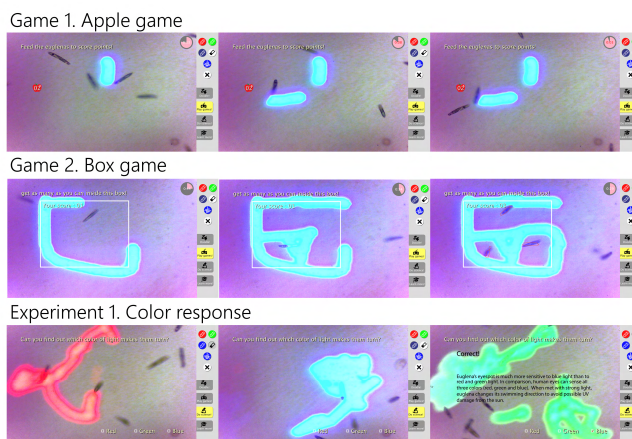

Figure 6. Examples of predesigned user activities. (Top) In Apple, user group 20 guided *Euglena* toward a virtual apple. (Middle) In Box, user group 35 trapped multiple *Euglena* inside a box. (Bottom) In experiment 1, user group 20 tested *Euglena*'s response to three colors. Games last for 1 min.

affordance of the system in a museum setting, both as a facilitated and an unfacilitated exhibit. The pragmatic goal here was to understand the features that work in a museum and to determine how to further develop the scaffold and display to yield exciting, meaningful exhibits.

The study consisted of two phases: facilitated and unfacilitated. In the facilitated phase, one researcher stood near the exhibit and acted as a facilitator by answering any questions and gently guiding visitors with open-ended questions to initiate or further motivate interactions. In the unfacilitated phase, visitors engaged with the exhibit with no assistance from researchers.

There were 36 sessions with individuals or groups, with a total of 98 museum visitors aged 3-50 years. Out of 36 sessions, 28 involved groups of users, such as families with one or more children, adult-only groups, and teen-only groups) and eight sessions involved single users. 22 groups were supervised with facilitators and 14 groups used the system without any assistance.

During the facilitated phase, two researchers live-coded user actions and conversations. In the unfacilitated phase, all three researchers observed and live-coded actions and conversations from a distance (1-5 meters). Concurrently, screenshots were automatically taken every 5 s in both phases. Additionally, a subset of visitors was asked whether they had time for a short interview to provide feedback.

Evaluation of structured activities
Overall, the mean dwell time (the length of the human-system interaction) was 4.18 minutes (SEM = 0.61), with 4.90 minutes for 22 facilitated sessions (SEM = 0.90) and 3.06 minutes for 14 unfacilitated sessions (SEM = 0.61) (Figure 5). These dwell times are successful for a museum setting [6, 16]. This dwell time could be due to the wide variety of activities and/or to the engaging nature of the
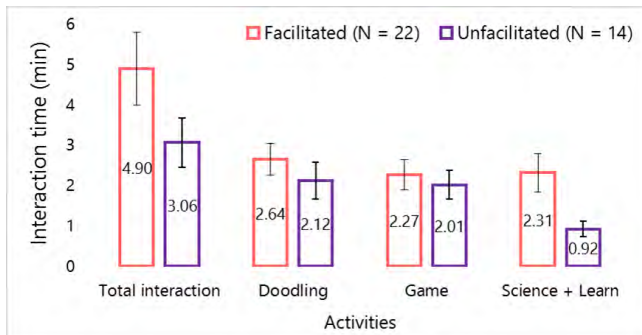
Figure 7. Mean engagement time in the presence and absence of facilitation. During unfacilitated sessions, visitors overall spent less time on the system, which primarily affected the time spent on activities involving experimentation and learning; doodling and game play were equally prevalent. Error bars indicate standard error of the mean.
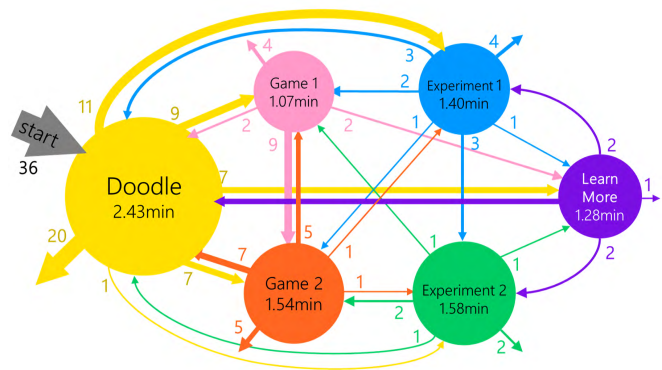

Figure 8. State transition diagram of user progression through activities. Sizes of circles and arrows correspond to average dwell time and transition occurrences, respectively. Outward arrows represent leaving the display. Note that "learn more" is not a final state; users return to one of the other activities

HBI. Users then progressed through a subset of the individual activities in various ways.

As all sessions start in the doodle (or "trap") activity, users began by tapping the screen and familiarizing themselves with the system by doodling on the touchscreen. Not all doodling activities were related to the microorganisms; some users drew images like a smiley face or wrote their names. However, 78% of users tried to follow the activity prompt, by drawing circles around the *Euglena* (the only way to trap them), by tapping or drawing on the *Euglena*, by tapping in front of the cells, or by filling in the entire space. Fifteen user groups experimented with colors other than the blue, which was the initial setting in all activities. Overall, this initial doodling activity encompassed a wide variety of behaviors, which was reflected in the varying activity lengths and number of revisits (Figure 5). The initial activity can thus be seen as a fruitful scaffold for exploring system components and gaining initial familiarity with *Euglena*.

Games were most often selected after doodling. However, in contrast to our in-lab pre-study (data not shown), many users had trouble understanding the games right away. In the game Apple, many users tried to drag-and-drop the apple to the *Euglena* rather than guiding *Euglena* to the apple. A rather counter-intuitive characteristic of the game was the source of the problem; in order to guide the cell to the apple, obstacles must be drawn. 7 out of the 12 user groups who played Apple understood this strategy and drew light walls to make the *Euglena* turn toward the apple (Figure 6). In the game Box, we noticed that many users started by filling the box in with blue – a strategy opposite of the one we had in mind during game design. 8 out of the 14 user groups who played Box understood the strategy and played the game. Some children displayed signs of competitive game play (see below).

"Experiments" were chosen less often than games, particularly in the unfacilitated phase (Figure 5). Out of 9 groups who selected experiment 1 (color response), 4r

groups (all involving adult/teen users) understood and attempted to perform experiments. However, for the second experiment (finding the eyespot), none of the user groups understood what to do. For experiment 1 (color response), the parent in a parent-child pair often ran the experiments (*"let's try different colors," "see, we tested to find out"*) and picked the answers. Some users and most children did not engage in the actual experiment, but rather guessed the answer sequentially. For experiment 1, some users confused the answer selection with the color choices for the experiment. Several users had gained some intuition about *Euglena*'s color responses during previous activities and answered the question right away.

The "learn-more" button was rarely used in both the facilitated and unfacilitated phases. This was the only activity that did not allow users to engage with the living cells through touch, thus interrupting ongoing interactions and communications between people. We conclude that future implementations should provide additional information and instructions as a separate graphic panel or as an online resource for further exploration.

When the activities were facilitated, users interacted with the system longer and explored more options (Figures 5 and 7). In the unfacilitated condition in particular, a significant fraction of groups spent one minute or less with the system, mostly just pushing buttons or looking through the eyepiece. In the unfacilitated conditions, users almost exclusively chose doodling or game activities.

Progression through structured activities
The progression graph through all the activities generally follows their ordered layout (Figure 8). Users began their interaction with the program by performing the "trap" (and doodle) activity initiated by the system. Most groups subsequently transitioned to games, while fewer groups went to the experiments (Figure 5). While the fewest users clicked on the "learn more" activity, only in one case did the users end the session after it; in most cases, users went
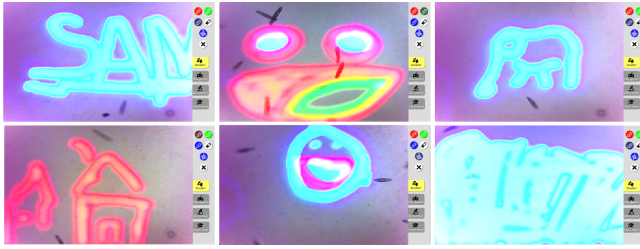
Figure 9. Typical examples of free-form user interactions. Names, animals, and faces were drawn; some younger children attempted to fill in the entire screen.
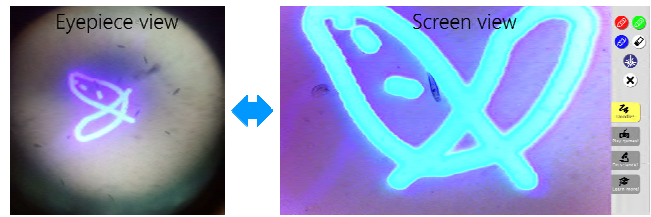

Figure 10. Drawing patterns on the screen while observing the resulting image through the eyepiece (by a single visitor or two visitors) critically empowered many visitors to understand the system's function and to realize real cells were present.
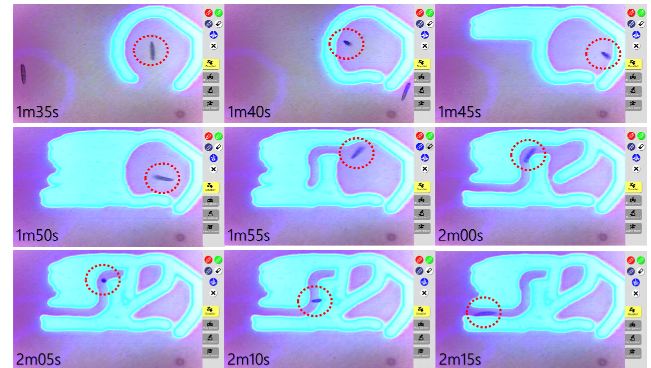

Figure 11. Example of self-activated play interactions by user group 18. The visitor trapped a cell, generated an escape route using the eraser, and observed the resulting behavior. This activity lasted <1 min.

back to an activity after reading the information. This observation should be treated with caution, since in the facilitated phase many users did not actively click on the "learn more" button, but rather asked questions directly to the facilitator; in the unfacilitated phase, the "learn-more" button was never clicked (Figure 5).

Interesting user behaviors
Museum visitors are a very diverse population in terms of age and background [18]. Ideally, an exhibit need to provide each population with an appropriate entry point into the experience and foster interactions between users that lead to extended and deeper experiences. We observed that our system engaged different users in versatile and expressive ways, triggering and stimulating guided and open-ended explorations. Here, we list user behaviors that were not actively prescribed by the system, but instead emerged spontaneously in the course of the interactions. Users were not limited by the designed activities and exhibited creative ways to have fun.

Artistic expression and finger painting
The system allows users to express themselves artistically. Various users drew or wrote during the free doodling activity, although the available colors and widths were not ideal for expressive drawing compared to earlier versions of the software with more color and width choices. We noticed that children younger than 4 years naturally doodling, with some filling in the entire screen.

Eyepiece and recognition of living organisms
Out of 36 interactions, 28 groups involved users looking into the eyepiece (realization). Users were particularly excited by their recognition of the actuality of the *Euglena* and by the realization that whatever they drew on the touchscreen was projected onto the chip. This excitement was reflected in comments about the interactivity *("I trapped it!")*, the actuality of the interaction *("They are real cells!")*, and the system *("You are drawing in here!")*. The eyepiece seemed to play a crucial role in this sequence of realizations, as indicated when people answered the question of when they realized the cells were real. We hypothesize that this realization especially fuels user motivation and interest in further exploring the system, and contextualizes the activity in a meaningful way.

Due to the optical arrangement, the eyepiece view shows a 90-degree rotated and zoomed-out view of the touchscreen view. Many users who did look through the eyepiece went back and forth between the touchscreen and the eyepiece to compare the two views (Figure 9). Some users even drew on the screen while looking into the eyepiece. It was particularly interesting that rather than clumping around the eyepiece or the touchscreen, groups split up between them, taking turns to draw and look. This collective action was reflected in conversations between people. Many users expressed spontaneous excitement *("This is really cool!")* when they first looked through the eyepiece.

Self-activated play
Some users engaged in self-activated play with *Euglena*'s light responses. In the free doodling activity, these users attempted to play with the cells in their own ways, for example by creating multiple traps, trapping and releasing the cells, trapping and cornering *Euglena*, or attempting to guide the cells (Figure 11). We observed that a group of children invented a game of "*guess what I am drawing*" where one person draws on the screen while another person looks into the eyepiece and guesses what the drawing is.

Typical user group interactions
Groups of visitors interacted with each other in various ways. We describe some typical examples below.

Guidance

When multiple people interacted with the system, users who were already familiar with the system explained to novices what one had to do, how the system worked, and what they had discovered. These forms of guidance and information sharing happened in various constellations of youths and adults. For example, some parents walked their younger children through the activities (Table 1). We also observed the opposite scenario when a teenaged boy explained to his father "*to draw a circle around*" after the father's unsuccessful attempts to trap by tapping the screen.

Girl	*"What is this?"*
Father	*"See, you put light in there so they are following it."*
Action	Father looks through eye piece
Action	Girl doodles and fills out boxes.
Girl	*"Where are the little creatures?"*
Father	*"Look through that."*
Action	Girl catches *Euglena* with colored circle.
Father	*"Oh see, look, you stopped them."*
Girl	*"Now tap this, so I look through eye piece."*
Girl	*"Can you change the color?"*
Action	They manage to change the color
Father	*"Oh wow. Guess you can."*
Action	Father asks facilitators about *Euglena* and the system.

Table 1. Transcript of a father helping a girl aged ~6 years.

Collaborative group interactions

We observed collaborative efforts, such as observers suggesting different strategies for drawing and games ("*draw the circle faster," "use blue*"). Many conversations were related to information-sharing *("look here!", "they hate blue"*) or turn-taking *("it's my turn," "I want to draw"*). Interestingly, when several people simultaneously interacted with the system, they took turns to draw on the screen and look through the eyepiece. Therefore, even though the system only allows a single touch input, it can support a number of people simultaneously.

Competitive group interactions

In one particular instance, we observed a group of boys (aged 10-12 years) during the unfacilitated phase who competed for higher scores during gaming. They stayed at the system for more than 10 minutes (user group 32) and even came back later to play more. Their group interactions involved turn-taking *("I want to see!", "Watch the master."*), comparing scores (*"I got two.", "I almost got three."*) and betting (*"I will catch three.", "I'll pay anyone starburst if they can get three."*). Although this behavior was observed once during the study, it provides further evidence for a high level of engagement with this system.

Typical user comments

We categorized all user comments (Table 2) to further illustrate how visitors viewed and interacted with the system in diverse ways.

Category / interpretation	Typical remarks
Positive statement	*"Awesome!"; "This is so cool!"*
Questions about the organisms	*"Are these real cells?"; "What are Euglena?"*
Questions about the system	*"How do I feed it?"; "How does it work?"*
Observations/comments about *Euglena*	*"They are swimming"; "They get stuck in the light"*
Comments on interaction	*"I trapped it."; "Doesn't always work."; "It got out."*
Sympathy with *Euglena* / anthropomorphization	*"Let me tickle you."; "Don't torture."*
Realization/understanding	*"it's actually using light"; "you are actually drawing in here"*
Simulating interactions between visitors	*"Try to circle them!"; "Let me try!"; "Look through here!"*

Table 2. Categorization of user comments about the system.

Opinions expressed by visitors during post interviews

A general picture emerged from nine post-activity interviews. While all interviewees found the system engaging, in eight of the interviews, users stressed the intriguing novelty of seeing both their drawings and their interactions with the real organisms through the eyepiece. The only interviewed group that did not know that the cells on the screen were real organisms was the only group that had not looked through the eyepiece. In contrast, another user stated that he already knew from looking at the screen that they must be real based on "*how they looked and behaved.*" While the interviewees considered the system to be intuitive, all reporting major difficulties in understanding the Apple game, as described above.

DISCUSSION AND CONCLUSION

We conclude that our setup successfully enables HBI as a novel type of museum activity in which visitors can playfully explore and experience the responses of single cells to light. This activity is successful both in facilitated and unfacilitated museum settings. These activities have a variety of stand-out features and provide a flexible constructivist medium [4, 25]. Our user studies inform 8 guidelines (see design iteration section) for developing a permanent installation in a science museum, and highlight the system's utility in other formal and informal learning environments.

Affordances and stand-out features

This system has the potential to constitute a museum exhibit that excites and educates museum visitors, and that naturally draws various types of visitors into the activity. We observed that: (1) everyone, including children, starts drawing right away. (2) System's programmability and various user perceptions and interests allow a wide range of activities, including art, gaming, experiments, playing, etc. This observation is in line with the science, technology, engineering, art, and mathematics (STEAM) paradigm, which tries to include art as a meaningful and generative form of expression, often serving as an engaging entry point into science and engineering (and vice versa) [3]. (4)

Observing through the eyepiece and on the touchscreen provides a novel dual exploration experience in itself. (5) Interaction with the system invoked users' curiosity about organisms and the technical principles underpinning the activity. With proper scaffolding, it can lead to educational outcomes not only in the transfer of relevant knowledge but also in provoking interests about biology in general. (6) Users typically expressed amazement when they realized that the viewed real, living microorganisms; some users made emphasizing or anthropomorphizing remarks. Dealing with real organisms seemed to be a unique and rare experience for the users. (7) The system fosters spontaneous interactions and communications among users, making the experience more enjoyable.

Strategy for permanent installation in science museums
This study demonstrates that the BPU including the hardware and biological material, is robust and stable enough for long-term public deployment. We recommend a daily 2-min check for maintenance, and a biweekly replacement of consumables.

We consider the primary activities of doodling, trapping, and testing for color response to be successful and sufficient for a museum exhibition. The Apple game and experiment 2 (eyespot), on the other hand, were too challenging for most visitors during a museum activity (in contrast with lab-based pre-testing). We will further develop and optimize these activities and instructions through onsite iterations. We plan to simultaneously project the enlarged view on the wall that draws users from a distance, which will likely also be perceived as displaying these microorganisms on three different length scales. In addition, we plan to add an interface that guides users to switch between the eyepiece and the touchscreen to ensure all users experience dual perception (digital and hands-on). Finally, an external information panel about *Euglena* and the system will complete the installation.

As an added feature, the Tech museum's TechTag system [33], an RFID-enabled tag system for personalized museum experiences, will be used to provide additional information to the visitors about *Euglena* and about protists in general. TechTag allows museum visitors to capture and store images and videos which can be accessed via a website with additional information and some learning activities to provide education after the visitors leave the museum floor. Visitor activity can be tracked to determine the effectiveness of the various links and activities in order to optimize the design of the Trap it! activities and also the educational contents on the webpage.

Outlook beyond museum exhibits
Much of the system's potential awaits to be explored, raising novel questions for human-computer interaction and HBI. *Euglena* are widely used in primary-school education and are easily obtained from educational suppliers [22], addressing any safety or logistic issues during wider

dissemination. Possible ethical concerns about this type of biological manipulation are also refutable [12]. The system also fits well with the formal learning content of many school curricula, such as the new science standards in the USA that emphasize biology in 7th grade and scientific investigations during middle school in general [32].

The microfluidic chip used here is a very simple device; in the future, we expect increased structural complexity and versatility [36], including microscopic mazes with integrated actuators and chemicals. For this type of technology, we expect commercial development and price drops consistent with those of integrated circuits [10]. Setups like the one described here would then be usable with effort and cost similar to those of early personal computers [23], current tablets [19], arcade games [31], and school and do-it-yourself microscopes, with similar significant potential for formal and informal education as their electronic counterparts [1, 29, 30].

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