CAREER FEATURE

First-hand, immersive full-body experiences with living cells through interactive museum exhibits

A museum exhibit that enables direct full-body interactions with living microbes immerses human visitors into the microscopic world and could inform the design of future educational life-science technologies.

Science centers and museums play an essential part in inspiring and supporting public understanding of science, technology, engineering and mathematics (STEM)[1,2]. Interactive museum exhibits, where 'visitors… can actually alter a situation based on input,'[3] have been shown to spark interest from the visiting public, promote engagement with natural phenomena, support social interactions, and help content understanding and recall[1,4,5]. As new user interfacing technologies such as body sensors and touchscreens emerge, museums have begun developing exhibits with more wide-ranging forms of interaction. This includes immersive exhibits[6], which have the potential to further increase visitor engagement and exhibit enjoyment[6,7] when compared to more traditional 'tabletop' counterparts[6]. Despite the increasing relevance of biotechnology in society and daily life[8–15], museum galleries that feature living organisms or modern biotechnology, especially on the microscopic scale, have had very limited degrees of interactivity, with even fewer enabling immersion. Thus, there are many open questions regarding technology and interaction design for immersive exhibits.

We developed the immersive exhibit Human-Microbe-Interactive Dance (HMI-Dance) (Figs. 1 and 2a and Supplementary Video 1), which enables direct, full-body interactions between museum visitors and the microbe *Euglena gracilis* ('biology-interactive'). Human silhouettes are detected via an Xbox Kinect, and the silhouettes are projected through a pico projector as bright blue light avatars (Fig. 1a) into a microfluidic chip containing *Euglena*, that is, the 'microscopic world'. *Euglena* are unicellular organisms, approximately 5 μm wide and 50 μm long, that are relatively low maintenance; they can be kept in semiautomated setups for weeks at a time[16–18]. They move away from bright blue light—that is, they exhibit negative phototaxis—and phototactic responses typically occur within 1 s[16,19,20]. Thus, the cells are able to move away from the projected human silhouettes in real time

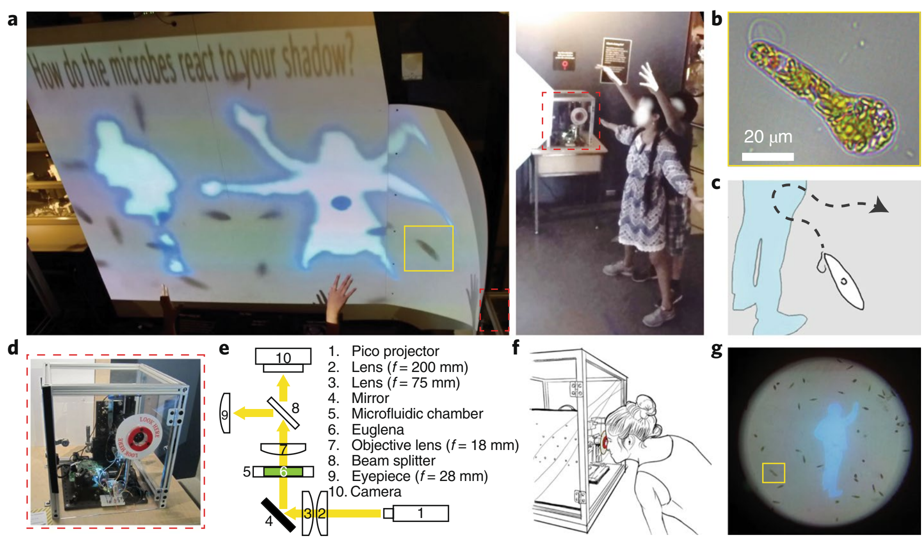

Fig. 1 | The immersive museum exhibit Human-Microbe-Interactive (HMI-Dance) enables full-body interactions between visitors and living microbes. a, Visitor silhouettes are captured by an Xbox Kinect and projected into the microbial world. Yellow box: example of *Euglena* cell. Left: wall projection. Note that the projection screen curves in a right angle toward the exhibit hardware box. The projection screen and the exhibit hardware box are perpendicular to each other. Right: visitors in front of the wall. Red dotted box: exhibit hardware. Visitor faces blurred for anonymity. The two images were taken simultaneously in orthogonal directions. **b**, The exhibit features the unicellular phototactic microorganism, *Euglena*. Image taken from a traditional microscope. **c**, *Euglena* cells swim away from the projected blue light. **d**, Exhibit hardware. (Note the hardware in **a**.) **e**, Schematic of light path from projector through microfluidic chip into microscope. Human silhouettes are projected with blue light through a pico projector onto the sample plane where the *Euglena* cells are held. The silhouettes and the cell responses are captured with a scientific camera, which is then projected onto the large screen using a large projector. **f**, Visitors can also choose to look through the eyepiece to see the silhouettes and microbes. **g**, View through eyepiece showing light projection of human as well as living *Euglena* cells. Yellow box: example of *Euglena* cell.

(Fig. 1b,c). This avoidance behavior is easily observable by museum visitors[16]. The magnifications of the optical pathways were chosen such that the cells would appear to be about half the size of the human silhouette's arm, and so users could encircle single cells with their arms and interact with individual cells (Figs. 1 and 2a). Furthermore, at this magnification, the *Euglena* movement speed appears to match the typical body movements of humans, which allows visitors to react to and affect *Euglena* behavior[21]. Visitors can observe both the cells and the projected light through a microscope eyepiece (Fig. 1f,g), as well as on a large screen onto which a live camera feed of the field of view is projected. On the larger screen, the silhouettes appear approximately life-sized and positioned directly in front of the visitor, as if the screen were a mirror (Figs. 1a and 2a). This is done so visitors can more easily identify themselves on the screen. This exhibit was deployed for three months at the San Francisco Exploratorium, an interactive museum of science, art and perception.

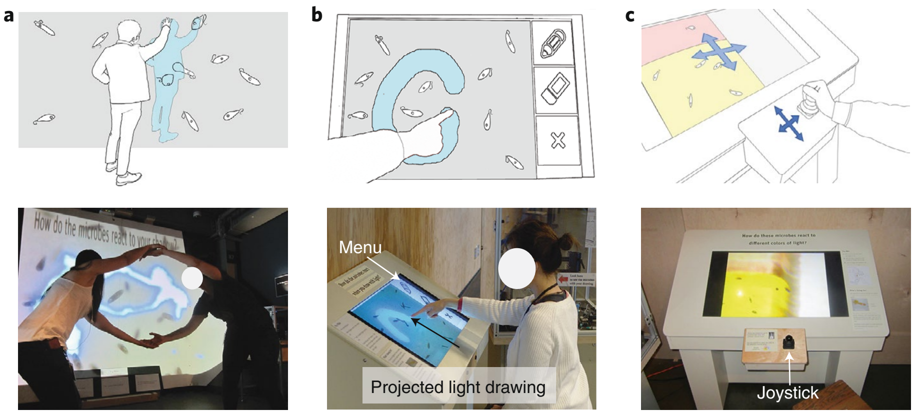

Fig. 2 | Three exhibits were developed for a comparative user study. We evaluated the dimensions of immersive vs. table-top and interactive vs. non-interactive. **a**, Human-Microbe-Interactive Dance (HMI Dance): visitors work together to capture a *Euglena* cell using their full bodies. **b**, Human-Microbe-Interactive Paint (HMI Paint): users draw on a touchscreen, and the drawings are projected onto the sample plane. **c**, Human-Hardware-Interactive Drive (HHI Drive): using a motorized stage, visitors drive the stage around to observe different fields of view. A mosaic of light filters (red, yellow and blue) is placed between the sample illumination and the microfluidic chip. Here, the field of view includes the intersection of the three filters. The blue filter appears white owing to the contrast in the photograph.

To determine if and how the immersive interactions enhanced visitor experience, we evaluated HMI-Dance (Figs. 1 and 2a) against two other exhibits with different interaction modes: 'Human-Microbe-Interactive Paint' (HMI-Paint) (Fig. 2b), a biology-interactive tabletop exhibit, where visitors can draw pictures on a touchscreen that are then reduced in scale and projected in real time (that is, as the user is drawing) onto the field of view, as in the previous Trap It! prototype[16]; and 'Human-Hardware-Interactive Drive' (HHI-Drive) (Fig. 2c), a hardware-interactive exhibit, where users can control the field of view by using a joystick to drive the motorized stage around, as in more conventional life-science museum exhibits. All exhibits were judged to be ecologically valid; that is, a life sciences curator saw each of them as viable exhibits visitors could engage with outside a research study.

The objective for all three exhibits was, first, to enable visitors to explore the light-responsive behavior of *Euglena* and, second, to showcase aspects of the microscope hardware and biotechnology. In HMI-Paint, as in HMI-Dance, the phototactic behavior of the *Euglena* cells is demonstrated by the cells' avoidance of areas illuminated with projected light (Fig. 2b). In HHI-Drive, *Euglena* phototaxis is demonstrated by the differences in cell density in areas illuminated by differently filtered light as well as by the *Euglena* behavior at the borders of the filters. For HHI-Drive, a mosaic of three filters (yellow, red and blue) is placed between the sample and a single white LED. Since the cells avoid blue light, there are typically fewer cells in regions where blue light reaches the sample and more cells in regions where blue light is filtered out (Fig. 2c). For these exhibits, as in HMI-Dance, visitors could observe both the stimulus and the cells through an eyepiece and a camera feed. For HMI-Paint, the camera feed is displayed on the touchscreen such that the light line appears where the visitor touches the screen (Fig. 2b), while for HHI-Drive, the feed is displayed on a screen with the joystick located below the screen (Fig. 2c). In contrast to HMI-Paint and HMI-Dance, users of HHI-Drive could not affect the stimulus being applied to the cells; instead users of HHI-Drive controlled the hardware, so it was considered an 'instrument-interactive' exhibit, similar to other contemporary exhibits in microbiology[22]. All three exhibits also provided visitors with visual access to the exhibit hardware, which was encased in a transparent box (Fig. 1d), to aid visitor understanding of the biological specimen, its behavior, and the exhibit technology.

To ensure comparable user experiences for the user study, all three exhibits were designed to share key features (for example, the same organisms, same magnification, similar hardware, same goals). The interactions were designed to be straightforward so that the exhibit would not require visitors to read instructions (though all prototypes had a label with instructions nonetheless) and would be accessible and attractive to all age groups, although past work suggests that different interaction modalities may lead to different age-based preferences[6]. The three exhibits together enabled the evaluation of both directly interactive versus observational experiences and immersive versus tabletop experiences for museum visitors.

User studies were undertaken to determine whether the exhibits fulfilled their goals of highlighting (i) the *Euglena* phototactic responses and (ii) the underlying technology. Furthermore, we wished (iii) to investigate whether the different interaction modes lead to differences in visitor engagement with the exhibits, and if so, how.

To assess visitor engagement with these exhibits, we observed visitors' naturalistic behaviors at each exhibit through video and audio recordings (Supplementary Fig. 1 and Supplementary Video 1). During the recordings, the exhibits were unsupervised and standalone. We recorded the holding time for the visitors, which is defined as the amount of time a visitor spends at an exhibit and is a well-established measure for visitor engagement[1,23], as well as the user demographics.

Results

The holding times from the naturalistic observations showed a significant difference only between HMI-Paint and the other two exhibits (HMI-Dance and HHI-Drive) (Fig. 3a and Supplementary Tables 1 and 2): HMI-Paint had a statistically significant longer holding time (95% confidence interval (CI): 61–101 s) than both HMI-Dance (95% CI: 32–50 s) and HHI-Drive (95% CI: 36–48 s), but the holding times for HMI-Dance and HHI-Drive were not significantly different from each other.

Of the three dimensions we looked across—subject age group, gender, and group size—we found a statistically significant difference in the age composition of the visitors who used HHI-Drive compared to HMI-Dance and HMI-Paint (χ^2(6, 224 visitors) = 27.6; $P = 0.00011$; Fig. 3b and Supplementary Table 3), with younger visitors favoring the two HMI exhibits. HMI-Dance had the greatest proportion of users under the age of 8, though the difference between HMI-Dance and HMI-Paint was not significant. This suggests that interactivity with the microbes may better engage younger audiences.

Because there were differences in visitor engagement with each of these exhibits, we wished to gain insight as to how these differences arose. To do this, we conducted a study with cued visitors in which visitors were recruited to use the exhibit and interviewed by museum staff before and after using the exhibit. The interview responses as well as the holding times were

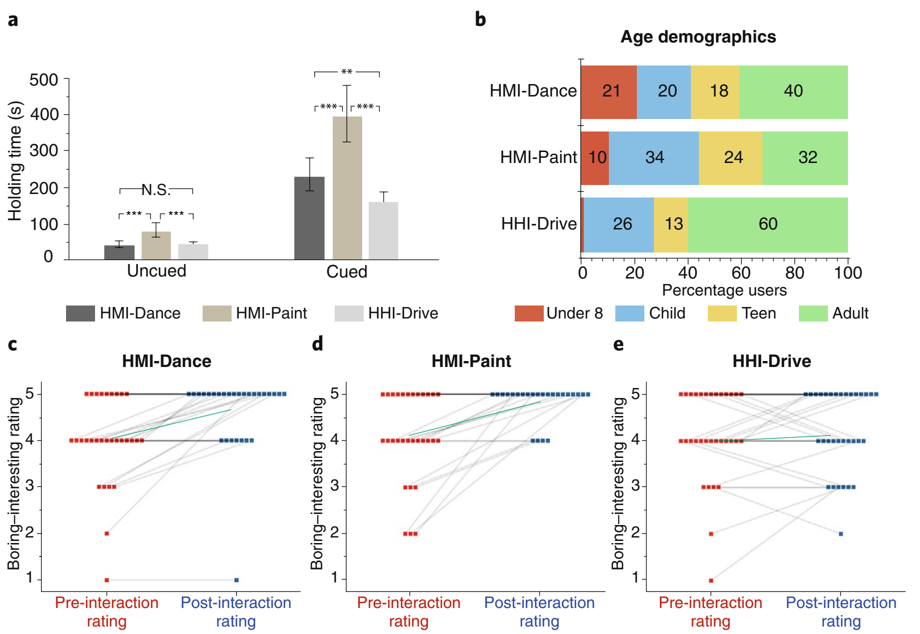

Fig. 3 | The three exhibits showed differences in their resulting visitor engagement. a, Holding time data for studies with cued and uncued visitors. HMI-Paint tended to have the highest holding time. HMI-Dance had a higher holding time than HHI-Drive for cued visitors, but not for uncued visitors (difference for uncued visitors was not significant, N.S.). Cued visitors tended to stay longer in general. $^{**}P<0.01$ and $^{***}P<0.001$ (uncued, Games–Howell post hoc test; cued, post hoc Tukey test). **b**, Age demographics in the uncued study suggests that the HMI exhibits are more attractive to younger audiences, with full-body immersion attracting the greatest number of younger children. **c–e**, Likert ratings for the statement 'I find microbes interesting' (1: Boring, 2: Somewhat boring, 3: Neutral, 4: Somewhat interesting, 5: Interesting) from the study with cued visitors. Red data points are the pre-interaction rating, blue data points are the post-interaction rating, gray lines connect the pre- and post-change for each user, and the green line connects the average pre- and post-interaction user ratings. While all users of the human–microbe interaction exhibits reported a positive or non-negative change in interest in the *Euglena*, some users of HHI-Drive reported decreased interest in the microbes.

recorded and qualitatively coded to gauge how different aspects of the technology and interactivity affected visitor engagement (see Supplementary Methods for more details). We note that due to the visitor–staff interactions in cued studies, there is a possibility of a pleasing bias from the study participants (that is, with the staff member present, recruited visitors may have shown greater attentiveness and focus on the exhibit than they would have otherwise). Thus, these data are considered the best-case scenario for visitor reactions to the exhibits.

For the study with cued or recruited visitors, the holding time results showed statistically significant differences between all three exhibits (Fig. 3a and Supplementary Tables 4 and 5): HMI-Paint had the highest holding time (95% CI: 324–480 s), followed by HMI-Dance (95% CI: 190–281 s) and then HHI-Drive (95% CI: 133–189 s). The higher holding time of HMI-Dance compared to HHI-Drive suggests that HMI-Dance may afford better engagement over HHI-Drive in the best-case scenario since there was no statistically significant difference between HMI-Dance and HHI-Drive in the uncued study. We also note that while HMI-Dance had a lower holding time than HMI-Paint, these differences may be due to the specifics of the user interface: HMI-Paint does not require visitors to stand still or hold a pose to observe *Euglena* reactions to light, which may make it easier to explore the phototactic behavior and thus encourage longer holding times. Conversely, HMI-Dance does not require much forethought to initiate engagement, as the silhouettes are automatically captured and displayed; thus, it may be more accessible to younger children.

Visitors were also asked to rate their overall exhibit experience on a five-point Likert scale from *Boring* to *Interesting*, and how interesting s/he found the *Euglena* on a five-point scale, before and immediately after exhibit usage. The results agree with the cued visitor holding times: visitors tended to report higher interest in HMI-Dance and HMI-Paint (median = 5) compared to HHI-Drive (median = 4). Furthermore, users of HMI-Dance and HMI-Paint both reported an increase in interest in *Euglena* (median pre- and post-interaction ratings: 4 and 5, respectively, for both exhibits) while users of HHI-Drive did not (median pre- and post-interaction ratings: both 4) (Fig. 3c,d and Supplementary Table 6). In both HMI-Dance and HMI-Paint, no users reported a negative change in the pre- and post-interaction Likert ratings, whereas for HHI-Drive, 7 of 32 users reported a decrease in interest in *Euglena*. This indicates that there may be advantages to the HMI platform compared to the HHI platform for increasing visitor interest.

To assess whether the exhibits fulfilled their goal of helping visitors learn that *Euglena* respond to light, we asked users what they noticed about the *Euglena* from the exhibit. More users of the HMI setups reported on the phototactic responses of *Euglena* (HMI-Dance: 25/30, HMI-Paint: 30/30, HHI-Drive: 15/32). We note that failure to report on the response could be due to various issues, including biological variability or preoccupation with other aspects of the exhibit. Other things visitors commonly reported noticing included the physical characteristics of the *Euglena*, such as shape, color and appearance (HMI-Dance: 17/30, HMI-Paint: 16/30, HHI-Drive: 22/32) and the general motion of *Euglena* without reference to phototactic effects (HMI-Dance: 9/30, HMI-Paint: 21/30, HHI-Drive: 25/32). These differences suggest that the different interaction modes may highlight different aspects of the biological content to visitors.

Exhibit usage also highlights the importance of the eyepiece in providing a sense of scale, aiding visitor understanding, and increasing visitor interest[16] in all three exhibits. For all exhibits, about 80% of visitors (HMI-Dance: 25/30, HMI-Paint: 24/30, HHI-Drive: 26/32) used the eyepiece. Almost all of these visitors reported that the eyepiece made the exhibit more interesting (HMI-Dance: 22/25, HMI-Paint: 24/24, HHI-Drive: 26/26). The eyepiece helped some of these users gain a clearer understanding of what was happening in the exhibit (HMI-Dance: 6/25, HMI-Paint: 5/24, and HHI-Drive: 3/26). Users of HMI-Dance (10/25) and HMI-Paint (6/24) mentioned that seeing the stimulus through the eyepiece made it interesting; in contrast, only one user of HHI-Drive noted seeing the stimulus through the eyepiece. There is weak indication in visitors' interviews that the eyepiece did indeed help a few visitors realize that size scales were being bridged for all three exhibits (HMI-Dance: 3/25, HMI-Paint: 4/24, HHI-Drive: 5/26);

visitors mentioned, for example, that '[they] got an idea of how much magnification [they] were looking at,' and that '[i]t was cool to see the scale change.' Users of HMI-Dance and HMI-Paint also found that the eyepiece helped them better understand that they were interacting with the microbes, reporting, for example, that 'we could see our shadows in the Petri dish with them.' Users also tended to report that the eyepiece highlighted that the exhibit featured real, living organisms (HMI-Dance: 2/25, HMI-Paint: 8/24, HHI-Drive: 1/26), that they enjoyed the feeling of looking through a microscope (HMI-Dance: 4/25, HMI-Paint: 6/24, HHI-Drive: 5/26), and that they enjoyed the better visual quality (HMI-Dance: 8/25, HMI-Paint: 3/24, HHI-Drive: 10/26) and larger field of view (HMI-Dance: 5/25, HMI-Paint: 8/24, HHI-Drive: 16/26). Furthermore, three users of the exhibit (2 users of HMI-Paint and 1 user of HHI-Drive) explicitly stated that seeing the exhibit hardware enhanced their experience.

Interestingly, some visitors (6/30) who used HMI-Dance indicated that they felt like they entered the microbial world (for example, 'Usually I see [microbes] under microscopes, so [it was] interesting to be in their environment'). This feeling was unique to the HMI-Dance experience. For one user of HMI-Dance, this immersion seemed to bring up ethical valuation[24] of the experience ('it's their world in there you're invading'), although ethical valuations and thoughts were also found in visitors' interview responses apart from feelings of immersion (2/30 users of HMI-Dance and 6/30 users of HMI-Paint expressed emotional concern for the *Euglena*). In contrast, only 1 of the HHI-Drive users expressed concern.

We draw several lessons that inform the design of future interactive biotechnology exhibits[21]. First, direct interaction with the microbial sample does seem to promote visitor engagement with the exhibit and seems to draw user attention to the phototactic behavior of the cells. Second, we found evidence that eyepiece usage adds to the user experience, helps visitors gain a better understanding of the biotechnology, and highlights the miniaturization of the stimulus in the two biology-interactive exhibits. Third, we note that the visual quality of the cells is important to visitors, with many visitors preferring the view in the eyepiece to the larger image (either on the projector screen or the touchscreen) specifically because it is clearer. Many visitors appreciated the ability to examine subcellular structures within the *Euglena*, which establishes a minimum magnification and resolution for such systems. Finally, we find that the full-body experience does seem to foster the feeling of entering the microbial world for some visitors, which is unique to the immersive experience.

Conclusions

We developed a new interaction paradigm for informal learning spaces that enables full-body interactions between humans and living microbes (Fig. 1). This HMI-Dance prototype was deployed at the Exploratorium museum for a total of three months, demonstrating that such full-body interactions are technologically and logistically possible in the museum context. We evaluated this HMI-Dance against two other ecologically valid interactive exhibits (Figs. 2 and 3), finding that each interaction mode affords unique opportunities to highlight various aspects of the exhibit and cell behavior. Our user studies demonstrated that this type of exhibit can foster the feeling of immersion into the microbial world and can successfully draw attention to the bridging of size scales between human and microbes—in particular as both 'meet' in each other's worlds, on the wall and inside the microscope (Fig. 1a,g). Our work reveals and emphasizes important design considerations for future educational life-science technologies, especially when transcending size scales in the life sciences. This, along with other educational technologies[13,15], demonstrates new ways for the lay public to build understanding and appreciation of the modern life sciences and biotechnology, and broadens the possibilities in public STEM education[25].

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article. ❐

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Author contributions

Project idea: I.H.R.-K, S.A.L., J.M., K.Y.; manuscript preparation: A.L., J.M., I.H.R.-K; hardware: A.L., S.A.L., A.W.; software: A.L., SA.L., C.B.; installation: A.L., C.B.; user study design: J.M.; data analysis oversight: J.M.

Competing interests

The authors declare no competing interests.

Additional information

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Study description	User studies were undertaken to determine if the exhibits fulfilled their goals of highlighting (1) the Euglena phototactic responses and (2) the underlying technology. Furthermore, we wished (3) to investigate whether the different interaction modes lead to differences in visitor engagement with the exhibits, and if so, how? To assess visitor engagement with these exhibits, we observed visitors' naturalistic behaviors at each exhibit through video and audio-recordings. Because there were differences in visitor engagement with each of these exhibits, we conducted a study with cued visitors in which visitors were recruited to use the exhibit and interviewed by a museum staff member before and after using the exhibit. The interview responses as well as the hold times were recorded and qualitatively coded to gauge how different aspects of the technology and interactivity affected visitor engagement
Research sample	The sample was taken from visitors of the Exploratorium who interacted with the exhibits we designed on weekends. Visitor ages span all generations and genders. As the study was done for a museum exhibit, museum visitors were the demographic we were concerned with. There was no apparent bias in the uncued study. However, for the cued study, all interviewed visitors were 8 years or older for communication and consent reasons.
Sampling strategy	For the study with uncued visitors, we videotaped visitors over 10 days, collecting approximately 14 hours of visitors' naturalistic behavior for each of the three exhibit prototypes (Fig. S1, Movie S1). The display screen (the large screen projection for HMI-Dance, the touchscreen for HMI-Paint, or the monitor for HHI-Drive) was also recorded during the user interactions (Fig. S1, Movie S1). A coder reviewed the recordings systematically sampling every third visitor, who came as part of a distinct group as separated by three minutes or more. This buffer is to assure that one group was not influenced by the prior. We eliminated visitors who stayed at the exhibit for less than five seconds, not an adequate amount of time for exhibit use. For visitors who met our criteria, we noted their gender and age group, and recorded the size of the group they were with and their holding time, from the time they stopped at the exhibit to the time they turned and left the exhibit. For the study with cued visitors, a data collector approached every third visitor who (1) appeared 8-years or older, the target age group for this exhibit, (2) was in a group of two or three since most visitors who come to a science museum visit in groups, and (3) crossed a predetermined imaginary line near the exhibit. We asked this person and her/his group to participate in our study, which involved using a new exhibit while talking with each other about what they were thinking and doing and answering a few questions immediately before and after their experience. Visitors who agreed to participate signed a written consent form to be audio and video taped for the study. To minimize the impact on the participants' overall museum visit, we tried to keep the interview time under 10 minutes. Otherwise, visitors were welcomed to spend as long or as short of a time using the exhibit as they liked. We logged when the group began their interaction and when they indicated to the data collector that they were done. One person out of each group was randomly selected for the pre and post interaction interview.
Data collection	For the study with uncued visitors, we videotaped visitors over 10 days, collecting approximately 14 hours of visitors' naturalistic behavior for each of the three exhibit prototypes (Fig. S1, Movie S1). For the study with cued visitors, a data collector approached visitors for interviews.
Timing	Data collection occurred on various weekends between July 2016 and July 2018. Weekends were chosen to avoid heavily biasing the sample towards under-18 visitors, who tend to visit the museum on school field trips.
Data exclusions	For the uncued study, a coder reviewed the recordings systematically sampling every third visitor, who came as part of a distinct group as separated by three minutes or more. This buffer is to assure that one group was not influenced by the prior. We eliminated visitors who stayed at the exhibit for less than five seconds, not an adequate amount of time for exhibit use.
Non-participation	No participants declined to be interviewed for the cued studies.
Randomization	Participants were allocated into groups based on the exhibit prototype that they used.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☐	☒ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics

See above.

Recruitment

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Ethics oversight

Ethical and Independent Review Services e&I IRB#2 at the Exploratorium

Note that full information on the approval of the study protocol must also be provided in the manuscript.