Design and Evaluation of Graphical Feedback on Tangible Interactions in a Low-Resolution Edge Display

Sean DeLong
York University
Toronto, Ontario, Canada
seand@cse.yorku.ca

Ahmed Sabbir Arif
University of California
Merced, California, USA
asarif@ucmerced.edu

Ali Mazalek
Ryerson University
Toronto, Ontario, Canada
mazalek@ryerson.ca

ABSTRACT

We used the LED array around the edges of a custom tangible as a low-resolution display to provide users with real-time visual feedback on the current state of the system. We developed a guideline for mapping different types of edge feedback to different tangible interactions. We evaluated its effectiveness in two user studies. The first is an informal study, where experienced biologists worked with an existing tangible-tabletop biological system. The second is a formal study, where novice participants worked with a new tangible-tabletop biological system. Results of these studies suggest that edge feedback provides a better understanding of the system, increases user confidence, and can be useful in other interactive systems. Results also suggest that the proposed feedback mapping is intuitive and easy to remember.

CCS CONCEPTS

• **Human-centered computing → Displays and imagers**; **Interaction techniques**.

KEYWORDS

graphical feedback, visual feedback, edge display, passive tangibles, active tangibles, point lights, tabletops, biology, leds

ACM Reference Format:

Sean DeLong, Ahmed Sabbir Arif, and Ali Mazalek. 2019. Design and Evaluation of Graphical Feedback on Tangible Interactions in a Low-Resolution Edge Display. In *Proceedings of the 8th ACM International Symposium on Pervasive Displays (PerDis '19), June 12–14, 2019, Palermo, Italy*. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3321335.3324954

1 INTRODUCTION

Ullmer et al. [27] defined tangibles, also known as tokens, as "discrete, spatially reconfigurable physical objects that typically represent digital information". A tangible could be either passive or active. Passive tangibles employ a one-way communication model, typically from the tangibles to other interactive devices, hence cannot reflect changes in the digital model. Active tangibles, on the other hand, maintain a two-way communication between the tangibles and other devices, therefore can reflect changes in the digital model. Passive or active tangibles, together with other interactive devices, form a tangible user interface [27].

Feedback is an important part of interactive systems. It communicates the results of an interaction, making it visible and understandable. Feedback answers questions across four categories, specifically the user's location on a chain of tasks, current state of the system, future state of the system, and the outcome of an action [20]. Feedback not only informs users of whether they are moving closer to accomplishing a task or not, but also when errors occur and how to address them.

Prior studies showed that feedback can provide users with a better understanding of the system, facilitating a swift transition from novice to expert [13]. However, most current tangibles are passive and do not provide any feedback on tangible interactions [23]. They usually rely on an additional device to provide feedback (e.g., an interactive tabletop), confining the interaction space within the proximity of that device. Some tangibles provide visual feedback on the display, when available (i.e., notification window), but this feedback often occludes the information on the screen. It also typically requires a user action upon receipt (i.e., a tap to discard a notification window) affecting the natural flow of the task at hand [2]. In this paper, we propose augmenting tangibles with a low-resolution edge display (Figure 1) to provide real-time visual feedback on user interactions and the current state of the system.

The paper is organized as follows. We start with a literature review of existing work exploring non-graphical displays for visual feedback. We then discuss the motivation of the work and propose a guideline for mapping different types of edge feedback to different tangible interactions. We apply it to an existing tangible and tabletop system to demonstrate its effectiveness. First, we evaluate it in an informal investigation. Then, we apply it to a new system to further evaluate its effectiveness in a formal study. Finally, we conclude with speculation on future extensions to the work.

2 RELATED WORK

Harrison et al. [9] explored the types of information conveyed by a single-color point light in current devices, and investigated whether their design space could be enriched by using varying light intensity over time. They identified twenty-four different light behaviors, and based on an evaluation, recommended eight of them to use in a mobile device domain (such as, different beacon, brightness, flash, pulse, and blinking behaviors). Xu and Lyons [33] developed two smartwatch prototypes to demonstrate that low-resolution edge feedback could offer smart capabilities. The first prototype was augmented with four LEDs in the four directions and the second was augmented with twelve LEDs arranged corresponding to the hours on a watch face. Both used different colors, brightness, and blinking

PerDis '19, June 12–14, 2019, Palermo, Italy

ACM ISBN 978-1-4503-6751-6/19/06…$15.00
https://doi.org/10.1145/3321335.3324954

patterns to provide users with feedback on different smartwatch apps and their respective parameters.

Visual feedback on tangible objects is not as well explored. Almost all current tangibles provide visual feedback on an integrated display screen when available [3, 12, 16, 17] or on an external display, such as an interactive wall [14, 26] or interactive tabletop [25, 32]. Some have also explored lights [10] and other forms of feedback, such as haptic [21–23] and auditory [4]. Several tangibles provide visual feedback through a small number of LEDs [6, 18, 28]. However, no prior work has explored the full potential of low-resolution edge display in the context of tangibles.

3 MOTIVATION

3.1 Ease of Use

In theory, edge feedback should require fewer mental and perceptual activities than other feedback types. Particularly, textual and graphical feedback require users to move their foci from one part of the visual field to another and usually require a user-action upon receipt (i.e., a tap on the screen to remove the notification window). These restrict the possibility of task parallelism and reduce user performance both in terms of speed and accuracy [2]. Edge feedback takes advantage of the ambient vision modality, freeing the perceptual load in the parallel foveal and auditory modalities [30].

3.2 Independent/Off-the-Table Interactions

Edge feedback could also extend the support for independent interactions with active tangibles. In a tangible and tabletop system, it could aid users in performing actions off-the-table since they could confirm and verify the actions through the feedback provided on the tangibles, without being reliant on the tabletop display. Some existing tangibles (e.g., Siftables [17]) support independent interactions by providing visual feedback on an integrated display screen. Yet, this often occludes the information on the screen. Edge feedback is free from this limitation.

3.3 Group Interactions

Edge feedback could further extend group interactions with tangibles, where multiple tangibles are used to interact with the system. Many systems provide visual feedback on an external display for group interactions (e.g., stacking), which forces users to work in proximity to the display. This also limits independent interactions with the tangibles. Some active tangibles provide visual feedback on integrated display screens. However, when stacked, users could only see the display of the top tangible. Some active tangibles (e.g., Stackables [12]) attach the display on the side to address this, but are not intended for tabletop interaction since the side-screen is difficult to see when on the table. Low-resolution edge display augmented tangibles address this by providing feedback directly on the tangibles that is visible even when tangibles are stacked.

3.4 Extensibility

Although we explore edge feedback in the context of active tangibles, low-resolution edge displays could also be added to other interactive systems (i.e., wearable devices and computer accessories).

4 FEEDBACK MAPPING

Table 1 proposes a guideline for mapping different types of edge feedback to different tangible interactions. This guideline is inspired by Harrison et al. [9] and Xu and Lyons's [33] findings and current practices in consumer products (e.g., [1, 8]) and has been evaluated through a series of informal lab tests. Apart from notifications on direct interactions through tap, touch, tilt, shake, flip, rotate, and tactile buttons on the tangibles, and indirect interactions through another device or system, Table 1 also provides guidelines on how to notify the users of a valid or an invalid group interaction, such as stacking and neighboring. Figure 1 illustrates several types of edge feedback from the Actibles. Recommendations from [29] were used for determining how categories might be nominally coded. Particularly, the use of few categorical colors (between 5 and 10) and separation of those colors in the CIELUV color space were considered in the feedback mapping [29, p. 123]

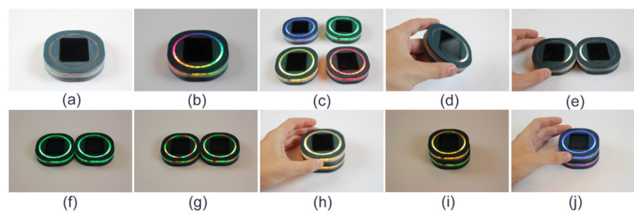

Figure 1: Edge feedback on different tangible interactions: (a) inactive tangible, (b) turned on tangible, (c) tangibles representing different items, (d) tilt notification, (e) neighboring notification, (f) valid neighboring, (g) invalid neighboring, (h) stacking notification, (i) valid stacking, and (j) invalid stacking.

5 DEMONSTRATION

In this section, we demonstrate how augmenting an existing system with a low-resolution increases its functionality and usability, and provides users with a better understanding of the system.

5.1 Custom Active Tangibles

We used custom active tangibles, called Actibles for our research. The software and hardware implementations of Actibles can be found in [7]. Actibles implement LED feedback through an array of 24 RGB LEDs in a circular pattern, which communicate with applications over a TCP/IP server. Preset functions were programmed for each of the feedback animations, which can be called by applications to reflect the system's state.

[1] Pulse or flash rates may differ for different tangibles and systems [27], but must occur for a limited number of times, preferably once or twice
[2] Or any other color representing a neutral state
[3] Or the full array if the angle or direction cannot be determined or is irrelevant
[4] Illumination represent values, that is brighter or dimmer for higher or lower values, respectively
[5] For instance, if three tangibles are nearby/stacked, represented by color x, y, and z, then all tangibles will use alternating colors x-y-z
[6] If an invalid tangible/s cannot be determined then all tangibles blink in red (or a color picked to represent error)

Table 1: Edge feedback on direct/indirect tangible interactions.

#	Manipulation	Interaction	Action	Edge Feedback
Single Tangible	Direct On /off-the-table	Changes via tap, touch, tilt, shake, or tactile buttons	Turn on a tangible	*Pulse/blink[1] in multiple colors & change color to white[2]*
			Detection confirmation	*Blink along the edge corresponding to tilt/rotate angle[3]*
			Change an item	*Change color to represent the new item*
			Change a value	*Change illumination[4]*
			Remove an item	*Change color to white*
			Turn off a tangible	*Turn off display*
	Indirect	changes via another device or systems actions	Change an item	*Change color to represent the new item & pulse/blink*
			Change a value	*Change illumination & pulse/blink*
			Remove an item	*Pulse/blink & change color to white*
Multiple Tangibles	Direct On /off-the-table	Neighboring	Detection confirmation	*Blink along the edges that have been neighbored*
			Valid combination	*Change all tangibles to alternating colors[5]*
			Invalid combination	*Pulse/blink the invalid tangible in color red[6]*
		Stacking	Detection confirmation	*Flash along all edges*
			Valid confirmation	*Change all tangibles to alternating colors*
			Invalid confirmation	*Pulse/blink the invalid tangible in color red*

5.2 Interactive Tabletop

A MultiTaction, 1397*mm*, 1209.6 × 680.4*mm* touchscreen area at 1920 × 1080-pixel resolution [19], placed horizontally on a custom stand was used as an interactive tabletop. It detected the tangibles using its default 2D fiducial marker tracker.

5.3 Sparse Tangibles

We picked Sparse Tangibles [3], an existing tangible and tabletop biology system to demonstrate the effectiveness of the proposed feedback mapping. Sparse Tangibles enables collaborative exploration of gene and protein networks on an interactive tabletop using active tangibles. Its custom tangibles were also augmented with LED arrays, but they were not used to provide feedback.

5.4 Tangible Interactions

The system enables users to select an organism or a gene network and construct expressive queries using active tangibles. To load a network on the tabletop, the user first navigates to the intended organism/gene by performing vertical swipes on the tangible touchscreen, selects the item by tapping, and then places the tangible on the tabletop. To perform a query on the loaded network, the user picks up another tangible, selects a query parameter, such as hub density, and stacks it on the other tangible/s. This updates the network to display only hubs that meet the selected criteria. The user can remove an item from a tangible by shaking it.

5.5 Feedback Mapping

We assigned different feedback types to all supported tangible interactions and state changes based on Table 1. We used the colors green and blue to represent organisms and genes, respectively, since they are commonly used in biological network visualization tools. Similarly, we used red and white to represent errors and neutral states. These color choices were informed by [29].

Figure 2: A researcher demonstrating the active tangibles augmented with LED arrays to the participants before the informal evaluation.

6 AN INFORMAL EVALUATION

We invited five experienced computational biologists to our lab to interact with the customized Sparse Tangibles system, in which the active tangible interactions were augmented with edge-display feedback as described above (Figure 2).

The participants were all employees of a biomedical research center. Their age ranged from 20 to 39 years, on average 29.6 (SD = 6.8). Three of them were male, and two were female. They all had experience working with biological networks. Three of them responded that they frequently work with biological networks and two responded that they occasionally do.

All participants arrived together. We then demonstrated the system and allowed them to interact with it. They were then asked to fill out a short questionnaire involving the following questions: (Q1) edge feedback enhances tangible-tabletop interaction experience, (Q2) provides a better understanding of the system and system events, (Q3) facilitates off-the-table interactions, and (Q4) will be useful in other interactive systems. A seven-point Likert scale was used for the questionnaire.

Table 2: Results of the informal evaluation.

	Question	Disagree	Neutral	Agree
Q1)	*User Experience*	0%	60%	40%
Q2)	*Understandability*	0%	40%	60%
Q3)	*Off-the-table*	20%	60%	20%
Q4)	*Extensibility*	0%	20%	80%

7 AN EXPERIMENT

The informal evaluation highlighted some design considerations for an empirical evaluation. Firstly, the feedback should be representative of the system's state, which is implemented through LED color. It is also important that there aren't too many states (colors) for the user to keep track of. Furthermore, the informal evaluation revealed that the LEDs' coded color differed significantly than their perceived color in some cases, and thus the blue color category was changed to purple.

One participant (female, 31 years) said, "[Paraphrased] The system can be more useful for exploring biological systems." This informed the use of a food chain exploration application, a simple biological system. Another participant (female, 20 years) mentioned that the feedback would be useful for filtering or comparison interactions. This inspired the use of a tree structure, in which feedback is instrumental for testing relationships between different nodes. Using these design considerations, we conducted an empirical study to further investigate the usability and usefulness of edge feedback and the proposed feedback mapping convention.

7.1 Tangible-Tabletop System

The system, a simple implementation of a hierarchical tree structure, was designed to test the effects of feedback (Figure 3). Conceptually, every category in the system is represented by a node, with relationships between them being represented by links. Five general categories were implemented: Producers, at the topmost level of the tree hierarchy, were assigned the color green. Herbivores, Omnivores, and Carnivores, all being children of Producers, were assigned the color yellow. Decomposers, being the bottom most general category and a child to Herbivores, Omnivores, and Carnivores, were assigned the color purple.

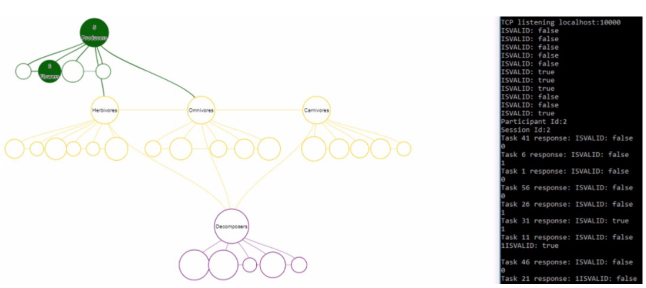

Figure 3: A screenshot of the system, along with the automatic logging mechanism (right).

7.1.1 System Navigation. Actibles, the primary devices through which the system was controlled, can each represent a single node. A user can navigate through the tree with the Actible via tilting and touch gestures.

7.1.2 System Interactions. In the food chain system, three types of relationship tests were implemented: parent-child, sibling-sibling, and container-contents. These relationships can be tested through Actible neighboring interactions, where direction is considered. Testing of parent-child node relationships can be tested by bumping the bottom of the Actible representing the parent node to the top of the Actible representing the child node. Testing of sibling-sibling node relationships can be tested by bumping the left or right side of an Actible to right or left side of the other Actible. Testing of container-contents relationships can be done by stacking the Actible representing the container onto the Actible representing the contents. The result of the relationship test is valid if the test accurately reflects the relative positioning of the nodes in the hierarchy. Otherwise, the result of the test is invalid.

7.1.3 System State Feedback. An Actible can reflect the state of the system in two ways. First, the Actible's LEDs can replicate the color of the node it represents. Secondly, it displays the name of the current node along with the container it is contained in, with the current node's color as the screen's background color.

7.1.4 System Interactions Feedback. The system shows the result of relationship testing in two ways. The first form of feedback of a relationship test is entirely on the screen of the Actible after a relationship test, the result (either valid or invalid) is displayed as an alert popup that must be tapped to continue Actible use. The decision to add a confirmation that the user must acknowledge is informed from informal and pilot testing and from the literature. We observed users either "missing" on-screen popups when their duration was too short or tapping to dismiss them anyways when their durations were longer. The second form of feedback from a relationship test is through the Actible's LEDs. If the test is valid, the Actible displays a query animation, incorporating the colors of the two tested nodes. If the test is invalid, the Actible again displays a query animation, but this time incorporating the colors of the two tested nodes along with a red error color.

7.2 Task Definition

Tasks in this system were defined as three components: Node A, type of relationship between Node A and Node B, and Node B. A statement about the relationship between any two nodes in the food chain (e.g., Decomposers contain Producers, Carnivores is parent of Decomposers, etc.) was given, and participants were asked to determine if that relationship was valid or not by using the system. Their responses, being either "true" or "false", were compared against the ground truth tree hierarchy to determine if they were successful in that task. The type of active tangible interaction to test the relationship varied based on where the nodes fell in the hierarchy.

7.3 Task Selection

Task selection of the user study revolved around three main considerations: difficulty, task type, and task validity.

First, since navigation of the tree always started at the root node, some nodes took longer than others to navigate to. Consequently, some tasks required more navigation than others to complete. Hence, tasks were classified based on the minimum number of navigation actions required to complete them, as follows: easy (2-4 actions), moderate (5-7 actions), and difficult (> 8 actions). An even distribution of these difficulty levels was assigned to the participants, so that each received an equal mixture of easy, moderate, and difficult tasks.Tasks required different active tangible interactions based on which relationship was being tested.

7.4 Apparatus

Similar to the informal investigation, this study also used the Actibles [7] and a MultiTaction interactive table. However, we developed a new tangible-tabletop biological system for the study, discussed in a later section. In addition, the study used an Acer Aspire 40 cm HD laptop to substitute for the tabletop to explore off-the-table interactions. The study also used a Google tablet to enable participants to respond to a post-study survey using a digital form.

7.5 Participants

Twelve participants from the university community took part in the user study. Their age ranged from 19 to 55 years, on average 26.64 years (SD = 10.06). One participant refused to disclose his age. Nine of them were male and three were female. All were experienced touchscreen users (on average 6.1 years of experience, $SD = 4.9$). None of them used a tangible-tabletop on a regular basis. They were compensated with $10 for participating in the study.

7.6 Design

We used a within-subjects design for the study. There were two conditions: feedback and no-feedback. The conditions were counterbalanced to eliminate the effect of learning. There were 12 tasks per condition. All participants performed the same tasks, but in a random order to eliminate a potential confound. Hence, the design was: $12 participants \times 2 conditions \times 12 tasks = 288 tasks$ in total.

7.7 Procedure

Participants were first lead into a quiet area where the study was held. They were asked to sign a consent form before performing any task. A brief introduction (∼ 5 minutes) of the tangible-tabletop system was given to each participant. This included a description of the food chain tree-hierarchy (which was visible to them), the active tangibles, and how the active tangibles were used in the system. The modes of feedback were also described.

Then, the experimenter performed a brief demonstration (∼ 10 minutes) of the system on a tabletop to show how to work with the system. The visual tree hierarchy was visible during the demonstration. A maximum of four example tasks were performed to showcase all different types of feedback, including feedback for a valid and an invalid neighboring and stacking.

Participants were then asked to perform the two sets of tasks, one with and another without edge feedback. Half of the participants started with the feedback and the other half started with the no-feedback condition. A small break (2-5 minutes) was given between the conditions. The tasks were presented to them in a random order, and were performed with the visual tree removed to investigate off-the-table interactions. As can be seen in Figure 4, participants

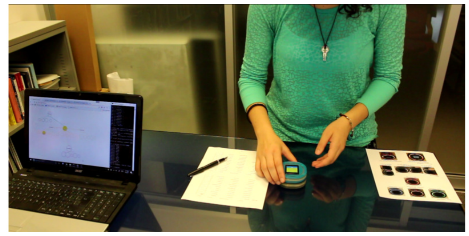

Figure 4: A volunteer participating in the final user study.

primarily interacted with three components during the study. The task list (center) contained all tasks the participants needed to complete for the session, in order. The user was instructed to write down their answer to each of the tasks as they completed them. The system cheat sheet (right) was given to the participant as a reference in case they were unsure about any interaction or feedback of the system. This is a common practice to alleviate the effects of learning a novel system [11, 15]. The two Actibles were the primary component through which the user performed the study. After the completion of all tasks, participants were asked to fill out a post-study questionnaire on a seven-point Likert scale using a tablet.

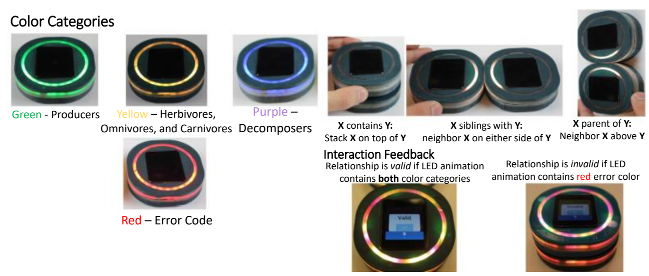

Figure 5: The cheat sheet used during the study.

7.8 Metrics

The following metrics were calculated during the study. Task completion time (minutes) is the time participants took on average to perform a task. Success rate (%) is the average percentage of correct answers by the participants. Touch interaction (#) is the average number of touches performed per task on the tangible interface.

8 RESULTS

We used a repeated measures ANOVA for all analysis. Figure 6 summarizes the results of the experiment.

8.1 Task Completion Time

An ANOVA failed to identify a significant effect of condition on task completion time ($F_{1,11} = 0.04, p > .05$). On average participants took 11.94 ($SD = 4.15$) and 11.56 ($SD = 3.83$) minutes to perform a task during the feedback and no-feedback conditions, respectively. Figure 6 illustrates this.

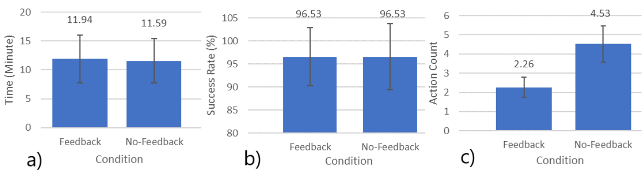

Figure 6: Results of the experiment. a) Average task completion time in each condition. b) Average success rate in each condition. c) Average touch interaction per task in each condition. Error bars signify ±1 standard deviation

Table 3: User feedback from the experiment.

	Question	Disagree	Neutral	Agree
Q1)	User Experience	16.7%	16.7%	66.6%
Q2)	Learnability	33.3%	8.3%	58.4%
Q3)	Off-the-table	41.7%	16.6%	41.7%
Q4)	Extensibility	8.3%	25.1%	66.6%
Q5)	Performance	33.3%	8.3%	58.4%

8.2 Success Rate

An ANOVA failed to identify a significant effect of condition on success rate ($F_{1,11} = 0, p > .05$). Average success rate for the no-feedback and feedback conditions were 96.53% ($SD = 6.33$) and 96.53% ($SD = 7.18$), respectively (Figure 6).

8.3 Touch Interaction

An ANOVA identified a significant effect of condition on touch interaction ($F_{1,11} = 100.26, p < .000005$). On average participants performed 2.26 ($SD = 0.53$) and 4.53 ($SD = 0.95$) touch interactions per task, taking on average 3.81 ($SD = 1.45$) and 8.82 seconds ($SD = 3.01$), during the feedback and no-feedback conditions, respectively. A Tukey-Kramer test revealed that participants performed significantly more touch interactions with the no-feedback condition (Figure 6).

9 USER FEEDBACK

Upon completion of all conditions, participants were asked to complete a digital form on a tablet. It presented them with statements about their overall experience and performance, ease of use and learnability, off-the-table interactions, and extensibility of/with the low-resolution edge display. They were asked to rate the statements on 7-point Likert scale, where "1" represented "strongly disagree", "4" represented "neutral", and "7" represented "strongly agree". Table 3 summarizes the user feedback results.

10 DISCUSSION

Results revealed that participants took about the same time to perform the tasks and yielded comparable success rate (Figure 6) in both conditions. This suggests that edge feedback did not improve their performances. Yet, interestingly, user feedback revealed that most participants felt that edge feedback improved their overall performance (Table 3 Q2). Participants perceived a positive impact of edge feedback on their performance, despite having no measurable impact (similar to the informal study, Q1 and Q2).

Similar to the informal study, most participants found our feedback mapping intuitive and easy to remember (Table 3 Q2). They also felt that edge feedback and the convention used for feedback mapping can be useful in other interactive systems (Table 3 Q4). Comparatively more participants felt that edge feedback further enabled off-the-table interaction than the participants in the informal study (Table 3 Q3) This could be because in the final study participants used the system for an extended period of time, giving them a better grasp of the system. Inexperienced users might find edge feedback more useful since the final study recruited inexperienced biologists to work with a biological system.

This finding, along with some of the qualitative findings of this and other work ([5, 22, 27, 31, 32]), tease out insights to the practical benefit of using ambient lighting for feedback. The first is that color is an effective way of coding categorical information regarding a system's state. Whether it be a physical type of transit station (bus, subway, or street car [24]) or an abstract type of organism, ambient feedback can convey nominal information without using screen space on a device. Furthermore, it constitutes a mode of feedback of user interaction that is parallel to, not necessarily a substitution for, conventional onscreen feedback. In our system, information about an organism can be displayed on screen, whereas its broader type can be inferred from its color. To generalize, for devices that are smaller in screen size, the screen is a great place to display acute, precise information, where ambient light feedback can display broader, scoping information.

11 CONCLUSION AND FUTURE WORK

We proposed augmenting tangible objects with a low-resolution edge display to provide real-time visual feedback on the current state of the system. We presented a guideline for mapping different types of edge feedback to different tangible interactions. We demonstrated its effectiveness in an informal evaluation that revealed that visual feedback provided by the low-resolution edge display provides a better understanding of the system, and can be useful in other interactive systems. We also conducted an empirical study that revealed that while edge feedback reduces the number of touch interactions required to complete a task, it has no effect on completion time or success rate. The decrease in touch interactions shows that edge feedback removes the need to dismiss conventional, onscreen feedback alerts or dialogue boxes, also eliminating the homing time required to do so. Finally, edge feedback augments onscreen feedback in a parallel fashion, so tasks that require simultaneous use of ambient and foveal vision might reveal a more distinct difference in task performance. In the future, we will extend our guideline to support more actions and explore edge display in the context of smaller tangibles that cannot incorporate 24 LEDs.

ACKNOWLEDGMENTS

We thank Brien East for his help with the Actibles hardware and Nauman Baig for his help with the user study. This work has been supported in part by NSF grant IIS-1320350, NSERC, the Canada Research Chairs program, the Canada Foundation for Innovation (CFI), and the Ontario Ministry of Research and Innovation (MRI).

REFERENCES

[1] Amazon. [n. d.]. Amazon Echo. https://www.amazon.com/dp/B00X4WHP5E [Online; accessed 2017-01-21].

[2] Ahmed Sabbir Arif, Benedikt Iltisberger, and Wolfgang Stuerzlinger. 2011. Extending mobile user ambient awareness for nomadic text entry. *Proceedings of the 23rd Australian Computer-Human Interaction - OZCHI '11*, 21–30. https://doi.org/10.1145/2071536.2071539

[3] Ahmed Sabbir Arif, Roozbeh Manshaei, Sean Delong, Brien East, Matthew Kyan, and Ali Mazalek. 2016. Sparse Tangibles: collaborative exploration of gene networks using active tangibles and interactive tabletops. *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16*, 287–295. https://doi.org/10.1145/2839462.2839500

[4] Saskia Bakker, Debby Vorstenbosch, Elise van den Hoven, Gerard Hollemans, and Tom Bergman. 2007. Weathergods: tangible interaction in a digital tabletop game. *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07* 2007, 151. https://doi.org/10.1145/1226969.1227000

[5] Christopher Campbell and Peter Tarasewich. 2004. What can you say with only three pixels? *Proceedings of the 6th International Symposium on Mobile Human-Computer Interaction - MobileHCI '04* (2004), 1–12. https://doi.org/10.1007/978-3-540-28637-0_1

[6] Lee Chia-Hsun, Ma Yu-Pin, and Jeng Taysheng. 2003. A spatially-aware tangible interface for computer-aided design. *CHI '03 extended abstracts on Human factors in computing systems - CHI '03*, 960. https://doi.org/10.1145/765891.766094

[7] Brien East, Sean DeLong, Roozbeh Manshaei, Ahmed Sabbir Arif, and Ali Mazalek. 2016. Actibles: open source active tangibles. *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces - ISS '16*, 469–472. https://doi.org/10.1145/2992154.2996874

[8] Google. [n. d.]. Google Home. https://madeby.google.com/home [Online; accessed 2017-01-21].

[9] Chris Harrison, John Horstman, Gary Hsieh, and Scott Hudson. 2012. Unlocking the expressivity of point lights. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, 1683. https://doi.org/10.1145/2207676.2208296

[10] Doris Hausen, Sebastian Boring, Clara Lueling, Simone Rodestock, and Andreas Butz. 2012. StaTube: facilitating state management in instant messaging systems. *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction - TEI '12*, 283. https://doi.org/10.1145/2148131.2148191

[11] Amy K. Karlson, Benjamin B. Bederson, and John SanGiovanni. 2005. AppLens and launchTile: two designs for one-handed thumb use on small devices. *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '05*, 201. https://doi.org/10.1145/1054972.1055001 [Online; accessed 2019-02-19].

[12] Stefanie Klum, Petra Isenberg, Ricardo Langner, Jean-Daniel Fekete, and Raimund Dachselt. 2012. Stackables: combining tangibles for faceted browsing. *Proceedings of the International Working Conference on Advanced Visual Interfaces - AVI '12*, 241. https://doi.org/10.1145/2254556.2254600

[13] Gordon Kurtenbach and William Buxton. 1994. User learning and performance with marking menus. *Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI '94*, 258–264. https://doi.org/10.1145/191666.191759

[14] Mathieu Le Goc, Pierre Dragicevic, Samuel Huron, Jeremy Boy, and Jean-Daniel Fekete. 2015. SmartTokens: embedding motion and grip sensing in small tangible objects. *Proceedings of the 28th Annual ACM Symposium on User Interface Software Technology - UIST '15*, 357–362. https://doi.org/10.1145/2807442.2807488

[15] I. Scott MacKenzie and Shawn X. Zhang. 1997. The Immediate Usability of Graffiti. In *Proceedings of the Conference on Graphics Interface '97*. Canadian Information Processing Society, Toronto, Ont., Canada, Canada, 129–137. http://dl.acm.org/citation.cfm?id=266774.266792

[16] Ali Mazalek and Ahmed Sabbir Arif. 2014. Mobile-based tangible interaction techniques for shared displays. *Proceedings of the 16th international conference on Human-computer interaction with mobile devices services - MobileHCI '14*, 561–562. https://doi.org/10.1145/2628363.2645668

[17] David Merrill, Jeevan Kalanithi, and Pattie Maes. 2007. Siftables: towards sensor network user interfaces. *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07* (2007), 75. https://doi.org/10.1145/1226969.1226984

[18] Jane Meyers, Jeffrey LaMarche, and Michael Eisenberg. 2010. Craftopolis: blending tangible, informal construction into virtual multiuser communities. *Proceedings of the 9th International Conference on Interaction Design and Children - IDC '10*, 242. https://doi.org/10.1145/1810543.1810581

[19] MultiTaction. 0. MultiTaction. https://www.multitaction.com/ [Online; accessed 2017-01-21].

[20] Joe Natoli. 2014. Feedback: 5 Principles of Interaction Design To Supercharge Your UI (5 of 5) | Give Good UX | Joe Natoli. http://www.givegoodux.com/feedback-5-principles-interaction-design-supercharge-ui-5-5 [Online; accessed 2017-01-17].

[21] Donghan Park and Hyunseung Choo. 2016. Vibration based tangible tokens for intuitive pairing among smart devices. In *Human Aspects of Information Security, Privacy, and Trust*, Theo Tryfonas (Ed.). Springer International Publishing, 48–56. https://doi.org/10.1007/978-3-319-39381-0_5

[22] James Patten and Hiroshi Ishii. 2007. Mechanical constraints as computational constraints in tabletop tangible interfaces. *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '07*, 809. https://doi.org/10.1145/1240624.1240746

[23] Esben Warming Pedersen and Kasper Hornbæk. 2011. Tangible bots: interaction with active tangibles in tabletop interfaces. *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, 2975. https://doi.org/10.1145/1978942.1979384

[24] Qian Qin, Michael Rohs, and Sven Kratz. 2011. Dynamic ambient lighting for mobile devices. *Adjunct Proceedings of UIST '11* (2011), 51. https://doi.org/10.1145/2046396.2046418 ISBN: 9781450310147.

[25] Jun Rekimoto, Brygg Ullmer, and Haruo Oba. 2001. DataTiles: a modular platform for mixed physical and graphical interactions. *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '01*, 269–276. https://doi.org/10.1145/365024.365115

[26] Jan Richter, Bruce H. Thomas, Maki Sugimoto, and Masahiko Inami. 2007. Remote active tangible interactions. *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*, 39. https://doi.org/10.1145/1226969.1226977

[27] Brygg Ullmer, Hiroshi Ishii, and Robert J. K. Jacob. 2005. Token+constraint systems for tangible interaction with digital information. *ACM Transactions on Computer-Human Interaction* 12, 1 (1 3 2005), 81–118. https://doi.org/10.1145/1057237.1057242

[28] Danli Wang, Yunfeng Qi, Yang Zhang, and Tingting Wang. 2013. TanPro-kit: a tangible programming tool for children. *Proceedings of the 12th International Conference on Interaction Design and Children - IDC '13*, 344–347. https://doi.org/10.1145/2485760.2485841

[29] Colin. Ware. 2004. *Information visualization Elektronische Ressource: perception for design.* Morgan Kaufmann. https://books.google.ca/books?hl=en&lr=&id=UpYCSS6snnAC&oi=fnd&pg=PP1&dq=Information+visualization:+perception+for+design&ots=33yu6lVNof&sig=WVIMXPvq_QLWehIq2QaFacpvvBs#v=onepage&q=Information%20visualization%3A%20perception%20for%20design&f=false

[30] Christopher D. Wickens. 2008. Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50, 3 (June 2008), 449–455. https://doi.org/10.1518/001872008X288394 Publisher: SAGE PublicationsSage CA: Los Angeles, CA.

[31] Amanda Williams, Shelly Farnham, and Scott Counts. 2006. Exploring wearable ambient displays for social awareness. *Extended Abstracts on Human Factors in Computing Systems (CHI'06)* (2006), 1529–1534. https://doi.org/10.1145/1125451.1125731

[32] Andy Wu, Jung-bin Yim, Eric Caspary, Ali Mazalek, Sanjay Chandrasekharan, and Nancy J Nersessian. 2011. Kinesthetic Pathways: a tabletop visualization to support discovery in systems biology. *Proceedings of the 8th ACM conference on Creativity and cognition - CC '11*, 21. https://doi.org/10.1145/2069618.2069624

[33] Cheng Xu and Kent Lyons. 2015. Shimmering smartwatches: exploring the smartwatch design space. *Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction - TEI '15* (2015), 69–76. https://doi.org/10.1145/2677199.2680599