Evaluating prototyping kits for smart citizens

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INTRODUCTION

Cities characterized by their use of ubiquitous information and communication technologies (ICT) to make better use of their resources have come to generally comprise the new paradigm, “smart cities.” Local context factors generally described by [21] significantly affect what initiatives cities take to make it “smart.” However, these initiatives are often implemented in a top-down fashion that can marginalize the expectations of its citizens [13].

An alternative approach to the notion of a smart city is by centering its conception on its citizens, thus referred to as “smart citizens.” This perspective may allow for a more bottom-up construction of a smart city. However, an important issue for this is the limited means that citizens have in significantly taking action and bringing about change in urban planning [11]).

Whereas smart city initiatives may involve some citizens at some point in the design and development process, they are not necessarily involved in the development of the technologies they would be expected to use. However, people do have the ability to produce a wealth of knowledge, ideas, and things by using open technology such as physical computing prototyping kits in community hackerspaces and living laboratories [7,24]. A prototyping kit generally consists of a microprocessor and some electrical components with documentation on how to get started on a physical computing project. The “maker” movement, for example, is a major development in the popular do-it-yourself (DIY) community that has taken advantage of the accessibility of ubiquitous computing components and interest in the software and programming governing them [1].

There now exists a market for these curious, often non-expert users of hardware prototypes. One of the most popular items is the Arduino board, an open-source electronic prototyping platform. The company also produces the Arduino Starter Kit that includes the board, some common electronic components, and a book describing how to produce a set of projects with the contents of the kit, from a blinking LED to an interactive lamp. The maker movement has also contributed to a new form doing civics and having citizenship: “civic hacking” [28].

Our research goal is to examine the usability and design characteristics of these prototyping kits and develop a set of design considerations for a kit dedicated to smart citizens for civic hacking. This work is in the scope of “citizen-ability,” the pursuit of citizen user experience design for strengthening the efficacy of citizenry and its polity [11].

RELATED WORK

Smart cities are often characterized by their use of ubiquitous technologies like sensors and information communication technology (ICT) [21]. We first looked to studies on the domestic use and installation of sensors [5] and home as infrastructure for smart citizens [3] to explore evaluation methodologies and design principles for prototyping kits in general and in this setting. There has also been strong consideration and classification of extant issues with Internet of Things (IoT) devices [2], like sensors, to help guide what issues to be aware of when evaluating kits. Finally, we looked to recent publications on projects similar to kits, such as the Textile Interface Swatchbook [12] and the Blind Arduino Project [19].

In addition to technical issues, subjective meanings and issues may emerge from the interplay between individual sensors and other objects [16]. By studying the user experience of these ecologies of ubiquitous computing artifacts and the people who stand to benefit directly and indirectly, we can discover how meanings of smart cities are constructed by the end users, or smart citizens. We also see inspiration in challenges to top-down urban ubiquitous computing, where smart cities may be realized as a “messy infinity of 'Little Brothers' rather than one omniscient 'Big' Brother” [9] doing urban prototyping through kits that enable design as a bricolage practice [9,29]. For example, many art installations and public displays are created by individuals and small collectives in order to share data about or solicit data from its citizens. These are examples of how kits can be potentially empowering to allow people to participate in IoT work [10].

However, these interactive works and other literature reviewed did not provide any insight to citizens contributing technologies that impact citizen-ability. Therefore, we suggest that introductory technologies like prototyping kits would be worth studying for design opportunities toward this end.

METHODOLOGY

This paper describes our first step: evaluating the usability of prototyping kits in order to explore design considerations of technologies for citizen-ability. We chose three of the most popular prototyping kits:

- Arduino Starter Kit
- Canakit's Raspberry Pi Ultimate Starter Kit
- Sparkfun's Starter Pack for Intel Edison

In coordinating this evaluation, we generally considered digital divides as defined by Selwyn [25]. As we described, smart cities are generally composed of many different technologies working together for some civic end. As such, a prototyping kit can be one form of ICT in itself and another form in its end, as modified by its user. As such, it's important to consider what barriers people may experience to discovering, accessing, using, and making with the kit. We used different methodologies to get at each of these.

Discovery & Access

As we have described, discovering kits is common within professional, educational, and hobbyist communities around physical computing. We first sought to lower the floor to accessing prototyping kits, so we began by using heuristics described by the Principles of Universal Design (UD) [27]. We used the Guide to Evaluating the Universal Design Performance of Products (UDPP) [26], which included an operational guide to applying UD to the design process. For each heuristic, it provided a Likert scale for degree of agreement and notes field that the evaluator can use to build a mixed profile for the subject under evaluation. We evaluated this method with Brian Jones, an expert in accessible design and prototyping with an Arduino kit as reference. The results of this are in the following section.

Effective Use

We then evaluated how a user could effectively access and learn how to use a kit through exploration. For this, we wanted to employ a cognitive walkthrough with users (CWU) [14], which includes the commonly used usability method of cognitive walkthrough (CW) [30] and a think-aloud technique based on the CW findings. This ideally would remedy the shortcomings of a CW alone, which does not include users in the process, while also providing our expert perspective that would be valuable for comparing systems [14]. We intended to recruit members from the AoT LAMBS group, another research team in our lab who were all working on a smart city project with prior experience with prototyping kits; however, we were unable to secure enough time or IRB approval. Instead, we completed a normal CW with modifications to fit the context of a prototyping kit rather than software and products as it was designed to be used for. After each walkthrough, researchers completed a system usability scale (SUS) with respect to their kit and task for summative evaluation.

Making and Participating

In addition to the cognitive walkthroughs, we conducted a semi-structured interview with Bill Eason (RNOC), Matt Swarts (IPDL) and James Hallam (IPDL) who are experts in physical prototyping in a smart city domain. The interview consisted of open-ended questions regarding their past experience with prototyping kits, projects related to smart city technology, and insights to what are critical overlaps between the two. We used these experts' experience in making and advising on short-term and long-term projects in this domain to create a corpus of design considerations. We also looked to the Principles of Universal Design [26], Nielsen's usability heuristics [22], and the Universal Principles of Design [17].

We compiled all of these considerations and pruned ones that were clearly not applicable to our space, still yielding over 100 individual items in this corpus. To organize and validate these considerations, we organized a focus group to conduct a brief interview and card sorting exercise [20,23]. We invited our interview participants as well as others familiar with prototyping kits and our smart citizen domain to participate in this session. We sorted these into 19 preliminary themes, which were then sorted further into 10 categories of design considerations by combining like themes and comparing to existing heuristic guides, cited previously.

FINDINGS

For each of the methodologies described, we have organized several areas of initial findings: suggestions for applying UD to prototyping kits, usability characteristics of the kits reviewed, heuristics developed from these findings, and an evaluation of the kits using these heuristics. These are followed by a discussion of why these findings would be useful to the design and HCI communities.

Universal Design for Kits

Our initial question for evaluating prototyping kits was whether the Principles of Universal Design (UD) be used to evaluate the usability of prototyping kits [18]. We found through our interview with an accessibility and prototyping expert that UD was developed primarily to evaluate a use case or end product, something that is an end in itself. Whereas a kit is a sort of platform or infrastructure, a means to an end. As such it would not be as appropriate to directly apply UD as it is to kits.

However, we did find that many of the principles still applied and could yield useful insight to UD. Principles 1, 2, 4, and 7 all in our opinion could apply as-is. Principle 6, "low physical effort," could apply. In speaking with our expert in accessible design, we found that the other principles assumed a product with well-defined interaction points, whereas kits' interactions are purposefully left undefined as an exercise for the user. Individual components, especially the documentation and prototyping board itself, could be evaluated meaningfully with UD, as is the case with projects like the Blind Arduino Project [19]. However, we suggest that a holistic set of principles for evaluating kits in terms of accessibility should be done component-by-component and then use the design considerations we present later in this paper to form a meaningful whole.

Usability of Existing Kits

We employed a cognitive walkthrough (CW) method [30] to assess and compare usability of the reviewed kits, generally considering both our own experience and what users we identified would experience with these kits. We followed our walkthrough with a standard SUS questionnaire. The SUS is a set of ten statements that participants can indicate their level of agreement or disagreement on a five-point scale. Scoring the SUS followed the original formulation [6] with an adjective scale [4] for practical reference.

Raspberry Pi:

According to the manufacturer's website, the vision is for kids all over the world to use the Raspberry Pi to learn programming and understand how computers work". The Raspberry Pi had the lowest SUS scores of any all the microcontrollers we evaluated. The manufacturer vision for having kids as the target user shows a wide disconnect from the actual design. The manufacturer's website states that the microcontroller can do everything you'd expect a desktop computer to do, from browsing the internet and playing high-definition video, to making spreadsheets, word-processing, and playing games." The kit itself contained no initial setup instructions and the extra components given were simple LED's and pushbuttons. An OS has to be installed in order to do anything with the microcontroller, so setting it up assumes the user has access to the internet, a monitor, a keyboard, and a mouse. Once the OS is installed, the LED's and pushbuttons provided in the kit facilitate a small fraction of the intended use cases of the microcontroller.

Arduino:

Arduino starter kit comes with a project guide book, standard components, breadboard and the processor block. While evaluating Arduino, it was fairly easy to follow the documentation. Software installation was fairly straightforward. The first project in the tutorial provided detailed circuit diagram and highlighted the steps to follow. It is quite easy for a novice user to set up the system quickly and start prototyping. GPIO pins are on board for Arduino and it does not come with any discrete I/O. Nor does it come with SD card, Wi-Fi adapter or Bluetooth connectors. User needs to buy them separately.

System Usability Scale (SUS)

Averaged together for each kit, researchers' SUS scores yielded a 68.3 (good) for Arduino, 42.5 (poor) for Raspberry Pi, and 35.0 (awful) for Edison kits. While the SUS is a "quick and dirty" tool, its use over 20 years to date have demonstrated statistical strength [6] and thus we suggest that further study using SUS for kits would allow more statistically significant results.

Development of Heuristics

We conducted interviews with experts, categorized their insights in dozens of topics, and then formed ten key design heuristics for prototyping kits for smart citizens.

Interviews

Eason was more focused on deployment aspects for testing. His insights were more focused on technical concerns and the access to people and places. Cost in terms of money and electrical power were two of the most critical limitations to a project, especially for communication. Power was also an issue in maintaining data, as non-volatile memory like an SD card or enough power to use Wi-Fi or cellular networking are required for a large-scale deployment in a city. A dedicated clock module rather than virtual is also important to anything needing a timestamp. He also said that a strong educational background, including electrical engineering, programming, and network security are all important to a successful project. Finally, as the object of prototyping is generally to inform a large-scale deployment, he found significant value in having access to certain people and social networks to be able to use certain resources and infrastructure. For example, the only way to monitor public transportation with significant accuracy was to work closely with their IT department and their contacts at his university who had established a relationship previously.

Swarts was more focused on the prototype as a proof of concept and testing in the wild, rather than Eason's more deployment-minded view. He was also primarily concerned with power and connectivity but was knowledgeable of design alternatives for the sake of the prototype. For example, an alternative to a device being continuously powered would be to toggle them only when a reading needs to be taken. Or when prototyping, it's important to start with cheap sensors that will degrade over time, and then switch with a higher performing but more expensive sensor when deploying. Finally, when deploying, both Swarts and Eason remarked about the device being recognizable as benign and non-threatening. Swarts went a step further to suggest a way for the device to also disclose what information is being collected, saying that he didn't like to use cameras as they had the potential to collect information that may be sensitive. A microphone or proximity sensor in many cases, he said, could be used in place of a camera with the same results but with less power consumption, space, weight, and privacy concerns.

Hallam provides an abundance of insights from his experience guiding and instructing students through maker prototypes. He provided us with several key high-level topics of consideration: exploring barrier of entry, understanding motivations driving purpose, and bridging the gap between prototypes and product deployment. Provided us with several sub contexts of exploring the barrier of entry. The first is wayfinding and signage, which is communicating what people can get out of something and communicating limitations and benefits the system. The next sub context is recognizing the need to minimize barrier of entry for accessing infrastructure with respect to the affordances of the device and the infrastructure that it needs. Lastly, there is balancing difficulty, which means understanding the tradeoffs between how much should be taught and redundancy. If things are too easy, and not much can be done with the system, people will abandon it. If they system is too hard and they can't get anything done, they will also abandon it.

Motivation and purpose was initially not in our schedule of considerations, so we were fortunate to obtain insights into this topic. Along with exploring the barrier of entry, motivation and purpose is helpful in understanding users within the context of the problem space and how to intrinsically lower the floor. Insights include understanding the distinction between being motivated by a problem and being motivated by opportunity, in which being motivated by solving a problem is much stronger. For example a good motivator can be the lack of access to substitutes to solving a problem. Another good motivator is being able to solve problems that people think about all the time.

Hallam also explained to use the importance of bridging the gap between real world and prototypes as a key to providing an accurate vision of the end goals of prototyping. The gap can be bridged by having community support is needed for sustainable technology solutions. IoT devices need other people in the system. To get this, there needs to be some community value.

Focus Group

Experts are invited to help categorize what we have learnt and parsed from the cognitive walkthrough and interviews. We also include other design consideration from Universal Principles of Design and Nielsen heuristics.

Methods:

We printed all the design consideration on cards. Participants were asked to do the following tasks:

- Merge similar themes
- Distill into useful categories (shoot for 5-20 words)
- Identify 10 of the most important from the useful categories

In addition to categorizing all the consideration, they had been asked to add consideration of their own. After all the cards and additional consideration written by the participants were on the table, the participants start to read all the card and group these based on similarity. If there are considerations that do not fit anywhere, they should not be forced into a group. Finally, we researchers summarized each of the 19 categories to help combine like groups. We settled on ten categories that we developed further into heuristics, which we discuss in the following section.

DISCUSSION

We have found from the literature reviewed that there is significant tension between top-down smart city initiatives versus bottom-up, but we also find a great deal of inspiration from new forms of making together, such as the maker and hacker communities, especially in civic interests. We have also learned that there may be significant issues of usability and appropriate design of artifacts designed by those who are not end-users. This is also true of smart city technology, in that citizens should be centered in the design of components of and ultimate realization of their smart city. By informing kit designers, engineers, and programmers about these usability issues, we believe they may better understand and design for the needs of smart citizens, they could more appropriately put to market solutions that feed this movement.

Heuristics

From our focus group findings, we distilled these insights down to ten key groups design considerations for citizen-ability in prototyping kits.

1. **Provide Robust Documentation:**
   Provides documentation that makes clear the purpose and capabilities of both the kits and its individual elements. Elements of the kit should have labels, safety warnings, and support information. The level of expertise should be specified and regardless of expertise level, documentation should express complex material in the simplest way. There should be sample projects provided to aid in exploration and understanding, but kits should not be limited to those projects.
2. **Follow General Design Principles:**
   Should eliminate assumptions by clearly stating what components and the level of expertise required to carry out tasks. Critical microcontroller interactions should be designed for capabilities: the cognitive and physical limitations of the target user. Designing for capabilities is

the incorporation of simple and intuitive use through aesthetic and minimalistic design. Kits should be designed for quality within themselves with the expectation of quality system inputs.

3. **Provide Hands-On Understanding of Components:** Should facilitate the understanding of the value that comes from incorporating hardware with respect to how connectivity and it is serviced. Components should be sturdy enough to be handled from experts to novices.
4. **Obtain Usability by Promoting Learnability:** Learnability should be priority. There should be wayfinding to guide users through struggles to facilitate learning, whilst minimizing unnecessary constraints in the learning process. Documentations and guidance should rely upon recognition over recall. Similar parts should be expressed in similar ways to improve both learnability and usability. Software should be leveraged for the development environment so that users can use common IDEs for multiple kits.
5. **Tolerate Errors:** Should be designed to help navigate, avoid errors, and minimize negative consequences. There should be provisions of redundant elements for only when active elements fail for less critical elements, especially for systems where interruptions in performance is tolerable. Should be able to maintain stable performance in the case of element failure or radical changes in system loads.
6. **Support Compartmentalization:** The system should be able to be divided into multiple, smaller self-contained systems, minimizing the number of elements in the kit while providing multiple elements of different types for critical system for robust support.
7. **Reduce Security Threats:** Should reduce possible incoming and outgoing threats with basic security. Devices should be recognizable by anyone to not be suspicious or endangering. There should be defensible space features to deter unsolicited tampering or vandalism.
8. **Deliver Network Connectivity:** There should be a way to access digital networks and access network security knowledge. There should be a way to datalog through powerful cycles, in addition to having non-volatile memory and data should be able to be sent of frequently.
9. **Promote Motivation of Purpose:** There should be some level of user control and freedom to make multipurposed devices at affordable prices. Users should be able to use kits to solve problems of high cadence as well as have ways to solve problems where there is a lack of access to substitutes.
10. **Be Sustainable Through Community Driven Support:** For sustainable solutions there needs to be a community support so there must be some community value. Providing means and designing for community support helps bridge the gap between prototype environments and the real world.

What Would a Smart Citizen Kit Look Like?

We have compared the contents of kits under study as well as components our participants have used for their projects and classified the components into the following seven categories.

We also suggest, perhaps self-defeatingly, that there should not be a kit for smart citizens in the same way that the Arduino is for makers, Raspberry Pi is for education, and Intel Edison is for competent programmers. Rather, as we've learned, experienced prototypers know what they're looking for and don't need a kit, and beginners may have significant difficulty in getting started with kits without guidance. The topic of building for one's city may also be out of the scope of a kit, as we found from the focus group that there is a large gap between building for one's self or community and building for your city. As such, we consider our work to be useful in going forward with this research space but also to have practical considerations for civic hacking form an electronics perspective.

For example, a business like Sparkfun or Adafruit may consider compiling components with these heuristics in mind and packaging it in a unique way. Or an educational curriculum could be influenced by these considerations where the educator could be assumed to have some experience and initiative to prepare lessons for these heuristics. However, the concept of a kit could be unpacked more to consider either a user- or activity-centered design, where the Arduino Starter Kit is well thought out for a driven maker and a hypothetical Sparkfun/Adafruit kit as we described could be better compared to a puzzle or Lego kit where the point of the kit is simply to build what's on the front of the box, like a weather station or person counter. The marketing and instructional simplification would significantly lower the floor to participation, and the components would be common prototyping components. This would be more focused on the activity of building for a smart city with less attention directed to who may be using it. For example, this

FUTURE WORK

We found provocative results from these evaluation and design methods, although, they are statistically weak due to our time constraints, scope, and resource constraints. Therefore, we suggest a broader usability study in addition to the cognitive walkthroughs. It would be important to qualify CW participants results with their past experience using prototyping kits as their involvement in curriculum at our university is not uncommon. This could be followed by a NASA Task Load Index (TLX) [15] in order to gauge the cognitive load required to complete a task.

In applying these design considerations to an ideal kit for smart citizens or citizen-ability in general, we look to studies like [7,8] and [31] for inspiration in a controlled study of these to derive more robust heuristics and test the usability of these new kits. This could follow a similar methodology as the works cited or as we suggested previously, depending on the research question. We would also like to include more kits that have come up in conversation with our participants, including Basic STAMP, Grove Starter Kit, and Particle Photon.

Finally, we suggest using our ten design heuristics to conduct a heuristic walkthrough [32] of existing kits in order to verify our heuristics and derive design considerations for a kit specifically to facilitate citizen-ability.

CONCLUSION

Our research seeks to help design for making. Makers may appreciate knowing what technology is best to start working with, and even experienced makers would not likely use a particularly complicated product. By figuring out what characteristics of prototyping technology is most usable for citizens to design and build with, we can inform the creation of new technologies that accelerate the transition from curious citizens to smart citizens. We hope that this research will help smart citizens in actively building their future city and future world.

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