The Social Impact of STEM, Experienced: Studies With an Engineering Design Concept for Smart Devices

Massachusetts Institute of Technology

**Proceedings of the ASME 2017 International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE 2017
August 6-9, 2017, Cleveland, Ohio, USA**

DETC2017-68399

THE SOCIAL IMPACT OF STEM, EXPERIENCED:
STUDIES WITH AN ENGINEERING DESIGN CONCEPT FOR SMART DEVICES

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ABSTRACT

The government has been allocating multi-billion Dollar budgets to STEM (science, technology, engineering and math) education. Several programs aim to educate girls about STEM and STEAM (STEM and arts). It's a national goal to create equal opportunities for all genders and increase diversity in STEM fields.

We propose that the emerging values and social needs of middle school girls must be considered when creating learning experiences for them, and that appropriate design experiences can make engineering problems engaging and relatable. It has been shown that purposefulness is a critical factor for making engineering attractive to girls. Compared to boys, girls initially perceive engineering to be less socially impactful, yet girls place a higher value on social impact at an earlier age.

This paper provides a broad review of relevant literature. It is proposed that creative, innovative engineering activities with perceived social impact may motivate middle and high school girls and build their confidence in the ability to impact people's lives with technology they create. This work tests this hypothesis using different forms of a design activity that enables students to collaboratively build personal and wearable smart devices. Examples of creations based upon this design toolkit include medical bracelets, physical activity monitoring, and other devices.

The paper outlines the development of the toolkit and design activity through various stages of abstraction, and provides novel ways of prototyping design experiences. Three stages of development are implemented and tested with adolescent girls, offering new working methods for the human-centered, iterative process of designing such a toolkit. The first stage of toolkit prototypes consists of sketch models with a physical and digital component; focus groups were used to gain in-depth qualitative data. The second stage of toolkit prototypes consists of cardboard prototypes that allow for interaction mimicking the final design experience. It was used to gather data on design interests of different gender and age groups. The third stage of toolkit prototypes, consisting of computing devices with a simple interface, allowed for conducting experimental workshops to quantitatively investigate participants' self-efficacy and design and engineering interest both before and after the intervention.

A fundamental change in many girls' mindset was observed in multiple experiments. Findings about requirements for design activities with similar goals are summarized and supported though responses of female middle-school students, who participated in the presented studies.

BACKGROUND: THE NEED FOR ENGAGING REAL-WORLD IMPACT IN STEM EDUCATION

It has been shown that girls' grades in math and science fall behind boys' between grades 6 and 8 [1], a time in life when girls' self-perception changes significantly and, consequently, their interest in science and engineering drops compared to boys' [2]. To help solve these educational challenges, the US government has allocated $3 billion of the 2017 budget to support STEM education [3]. Studies have shown that show self-efficacy, one's belief that one can solve a specific type of problem, diverges between boys and girls at this time [4].

Self-efficacy has been shown to predict students' motivation, future behavior and career choices [5], which makes it an especially important parameter.

Once middle school girls fall behind, girls statistically underperform in STEM subjects until they reach college, where they tend to choose non-STEM majors [6]. Dweck [7] attributes this to girls' greater fear of failure, which especially limits their performance in math and sciences. She finds "in junior high school, these girls traditionally have begun to fall behind their male counterparts in achievement, especially in math and science achievement" [7]. Engineering challenges sometimes appear intimidating or irrelevant to many girls [8]. By contrast, Instagram, Snapchat and other apps are very popular among the

teen demographic, especially among girls [9]. As these mostly graphical apps require users to manipulate a number of elements to compose any work they share, it may be argued that they trigger girls' creativity. The emerging needs of middle school girls, e.g. belonging, must be considered when designing learning experiences for them.

Collaborative experiences in math and engineering projects have been shown to increase girls' confidence, interest, and aspirations in the same fields [10,11]. The correlations between individual and peer interest in STEM and increased interest in collaborative environments that impact girls were notably absent in teenage boys [11,12]. Halpern [13] and Wang [11] also find that "girls appear to respond more positively to math instruction if it is taught in a cooperative or individualized manner, rather than a competitive manner, and from an applied/person centered perspective, rather than from a theoretical/abstract perspective" [11]. Lavy and Sand [14] present similar conclusions. Moreover, girls are more likely to take advanced science and math classes in high school if their female friends have performed well in the same classes [10]. Meece and Courtney [15] find that individuals who feel strongly about gender identity value achievement higher for activities they perceive as appropriate for their gender. Math and science in particular are perceived as male domains. To let these girls partake in the opportunities presented by STEM, these fields must be presented in a way supported by their gender value system. Female stereotypes typically encourage girls to "be communal (e.g., socially skilled and helpful)" and "gravitate toward activities that emphasize interpersonal relationships." [10] Furthermore, at an age when boys still play, girls are more concerned with social relevance, partly manifested in aesthetics [16]. A survey conducted by Girl Scouts of the USA of boys and girls at ages 8 to 17 indicates girls are more likely than boys to aspire towards altruistic goals, like helping others, helping animals and the environment, making the world a better place, and being nice to others [17]. Social context and purposefulness an especially strong motivator for girls [18,19].

In fact, purposefulness has been shown to be a critical factor for making engineering attractive to girls. Margolis, Fisher and Miller find girls are not interested in learning about computers if they don't see a personal application, whereas boys are curious to learn how they work [20]. While relatedness is a motivator for both boys and girls [21,22], this relatedness requires social context for girls, while for boys an engineering context is sufficient. . Medical or social applications are especially interesting to girls [23]. In a comprehensive study with over 3000 individuals, the National Academy of Engineering (NAE) determined that while it is more important to girls that a potential career path "can have a positive impact on people's lives", it is also less obvious to girls than it is to boys that engineering "can have a positive impact on people's lives" [24]. Together, these two factors contribute to girls losing interest in engineering. Thus it is critical to present engineering as relevant, socially rewarded, and meaningful.

PRIOR ART: CONSTRUCTIONIST EDUCATION

With national support for STEM education [3,25,26], a number of learning experiences have been developed. Some of these studies have targeted girls or focused on collaborative STEM learning. A number of the experiences can be described as "constructionist" learning activities. The term *constructionism* was coined by Seymour Papert who used it to describe experiential learning through the creation of meaningful products, by using a designed set of materials to achieve an educational goal in the learner [27]. Constructionism is thus a form of "learning through creating" and sometimes presented as a process comprising the four steps: making, personalization, sharing, and reflection [28]. It is based on both Jean Piaget's and Lev Vygotsky's ideas about constructivism, a form of learning where knowledge is not merely transferred but achieved through individual experience and discovery [29–32]. Sherry Turkle has contributed to the idea of constructionism *via* her concept of evocative objects, meaning physical objects that are endowed with meaning through the creative process [33].

Resnick and Rosenbaum [34] have developed guidelines for "tinkerability" in construction kits, acknowledging Papert's [35] and Turkle's [33] principles around constructionism. Central characteristics are the user: is never left in the dark; can start playing without prior training, and; can explore various applications. They give examples for such kits, but do not qualify a desired or expected learning effect. Although not explicitly stated by the authors, fulfilling their design requirements provides a flow experience with continuous user engagement [36], individual relevancy [37] and relatedness, creating an internally motivating activity [21].

Little Bits (www.littlebits.cc), one of these examples, is an electronics toolkit with magnetic connectors, which encompasses various signal-processing elements. An online community allows users to share projects and not just share the results, but also the creation process, a strategy that Little Bits found very useful for ensuring hardware projects are communicated well. Although the kits were shown to generally lower barriers to entry into electronics experimentation [38], motivational dimensions have not been examined and detailed user demographics are not available.

Jewelbots (www.jewelbots.com) is a reprogrammable bracelet that was created in 2014 to raise girls' interest in programming [39]. Limited research is available exploring its educational results.

The LilyPad Arduino is focused on e-textiles [40]. Connecting electronics with fashion, it creates a similar learning experience. It entails sewing with conductive yarn and does not provide a simplified programming interface. It may very suitable for a more advanced audience with an interest in fashion and technology, e.g. girls who enjoy creating or decorating fashion and may already have initial familiarity with electrical engineering.

To complement these existing solutions with the findings from literature about girls' social motivations and dispositions, a new concept is developed in the following.

CONCEPT

The proposed solution toolkit and design experience has been developed with the emerging needs of teenage girls in mind, as laid out in the literature. It brings together the experimental and intuitive nature of constructionism with the social purposefulness of product design, specifically smart device design.

Based on prior art, the requirements for embraced for the proposed design toolkit were:

- potential for creating range of different solutions with social impact, e.g. including medical devices
- supporting creative freedom and ownership (agency)
- low barriers to entry
- wide range of challenge levels
- real-time transparency of interaction
- social context of creative activity, e.g. group projects and sharing of creations
- aesthetic appearance (to be refined in focus groups)

The proposed design toolkit consists of a wearable or smart device with attachable sensors that can be programmed with a graphical, cloud-based tool, as schematically depicted in figure 1. This activity, conceived in 2013 [41] and now developed as "Qwartzi" [42], will allow users to build their own smart devices, such as a smart watch, medical bracelet, physical activity monitoring or other device. Thus, a variety of products or experimental setups can be created, potentially serving the needs of a variety of design learners.

Figure 1: Concept of the presented design toolkit. A wearable or smart device with (potentially attachable) sensors can be reconfigured wirelessly by using a graphical web application.

In its current form and with changes implemented in response to the presented studies, the toolkit consists of a wireless microcontroller with a display and attachable sensors, which can be programmatically extended using a graphical programming interface. The graphical programming interface runs on any internet-connected browser. Possible creations based on this toolkit include custom activity trackers, smart home devices, simple health devices, etc. The Qwartzi website can be used to share creations and copy from other users. This design toolkit makes technical creativity more socially relevant to teenagers and other socially motivated learners.

In the following sections, the process and three studies that gave rise to the current embodiment of the toolkit and envisioned design experiences are outlined.

STUDY I: PRELIMINARY INTERVIEWS

Preliminary interviews and focus groups were conducted to investigate adolescent girls' needs and perspectives in practice, to define the design requirements in more detail, and to receive feedback on early prototypes of the concept.

Research Method

After ideating toolkit concepts, a proposed toolkit was first prototyped using non-functional sketch models and presented to multiple focus groups before running formal experiments.

There were *3* focus groups of 3-4 individuals, as well as an interview with a single girl. Focus groups were generally structured into an hour of conversation, followed by an introduction to the prototype design toolkit. The conversation was open. Discussion topics discussed included: School and classes, hobbies, social network and sources of reward, every-day problems, use of technology, perceptions of engineering. Whenever possible, questions were asked as follow-up to previous answers or to natural conversation between focus group participants. (A common flow: "Are you all at the same school?" – "Do you like it there?" – "What bothers you about [science class, people, etc., depending on previous comments] ?" – "Why? / How?")

Device sketch models were created in modeling clay and foam as depicted in figure 2a. Other sketch models had a round or square shape. It was explained that sensors could be attached to create a functional wearable or other smart device.
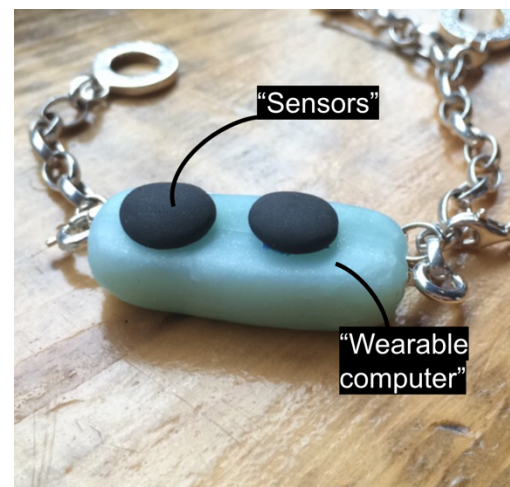

Figure 2a: Photo of a sketch model prototype device that was presented in the focus groups

Prototypes for the configuration interface were drafted and shown on an iPad Mini, as illustrated in figure 2b. The sketch model prototypes were explained briefly, for example: "Imagine

<div align="center">3</div>

this is a device that can measure things like temperature, motion, etc., and it is connected to an app where you can make it detect when something happens. In this example, my friend Suzi is alerted when my heart rate exceeds this number."
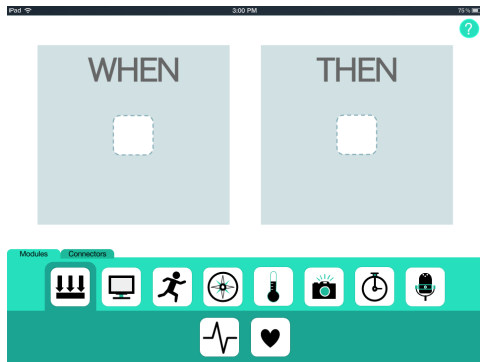

Figure 2b: Digital interface model as shown to interviewees on an iPad Mini

Using these preliminary tools, several notable observations were made.

Results

In one interview, when asked about perceptions about engineering, a group of 12-year-old girls replied with stereotypes such as designing and building bridges and other civil engineering activities. After thoroughly exploring the toolkit, in the later part of the focus group, one girl asked: "Wait, is this 'engineering'? This is so cool!" It thus appeared that presenting the toolkit led to more relatable understanding of engineering than the girls previously had; with a rapid change in mindset.

Another observation, which was repeatedly observed over the course of multiple focus groups, was girls who originally described themselves as "not very creative" and "not interested in engineering" were overcome with very creative ideas once they grasped the concept of the design toolkit. For example, participants asked "could you make a safety device that tracks your GPS and your heart rate and alerts people via text?" In many cases they detailed out specialized design ideas.

A possible interpretation of this finding was the reasoning that most K-12 learners have a creative energy based on their interests and exposure to different problems they encounter, and these ideas only come to light when the student is empowered with the tools to realize them.

Aesthetic requirements were also refined in the focus groups. Many girls said that a compact design would be very favorable. Girls strongly favored a square shape over a round, watch-like shape. Different colors were also important to some. In general, many girls requested a graphical interface with low barriers to entry to ensure inclusiveness independent of prior technical experience.

STUDY II: 2D PROTOTYPES: MAPPING THE DESIGN SPACE

Since the preliminary interviews yielded positive initial results, it was important to test the design activity as an experiential process. In order to obtain experimental data early on, inexpensive cardboard models representing a possible device interface were employed.

Research Method

The design experience was prototyped as a creative task at an exhibit at the MIT Museum for the Cambridge Science Festival event. Kids and teens were prompted to come up with a design for a wearable device or other smart gadget solution. The cardboard and sticker graphics are depicted in figure 3. Different sensors and output methods were presented to them to give them ideas. To prototype the creative experience, an interface draft was transferred onto cardboard with a representation of the configuration app that had formerly been successfully tested in focus groups.
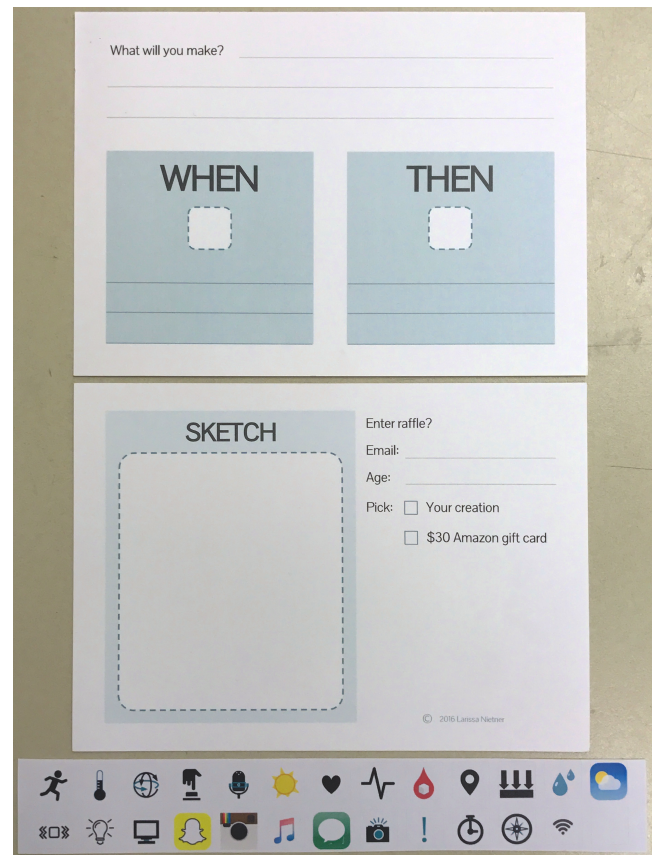

Figure 3: Front side and back side of carboard prototypes and print template for stickers. These were used for the design activity at the MIT Museum.

The cardboard dimensions were 5x7 inches, close to that of an iPad Mini, to be consistent with preliminary interviews and focus groups. The interface was conceived as a *when-then*

4

schematic (condition and action) with symbols to go in each of both sections. Symbols were realized as stickers about the size of app icons. Sensors icons and indicator icons were designed in a way that would be intuitive to the young learners, often much different from how technical components are usually represented.

Icons not only reflected sensors that could be in a wearable device, but also other sources of information or media that might be familiar; so the participants would not feel limited to the wearable device space should they wish to create something outside this constraint. The potential scope was expanded beyond wearables in order to allow for an investigation into participants' design interests. Symbols of popular mobile applications were chosen for those data sources not covered by the developed sensor representations, such as teens' main communication apps, as identified in earlier focus groups.

The backside of each cardboard prototype had a prompt for sketching the invented device as well as a section asking for information with the incentive of entering a raffle.

A completed version is depicted in figure 4, showing that participants did not have to limit their ideas to the space provided.
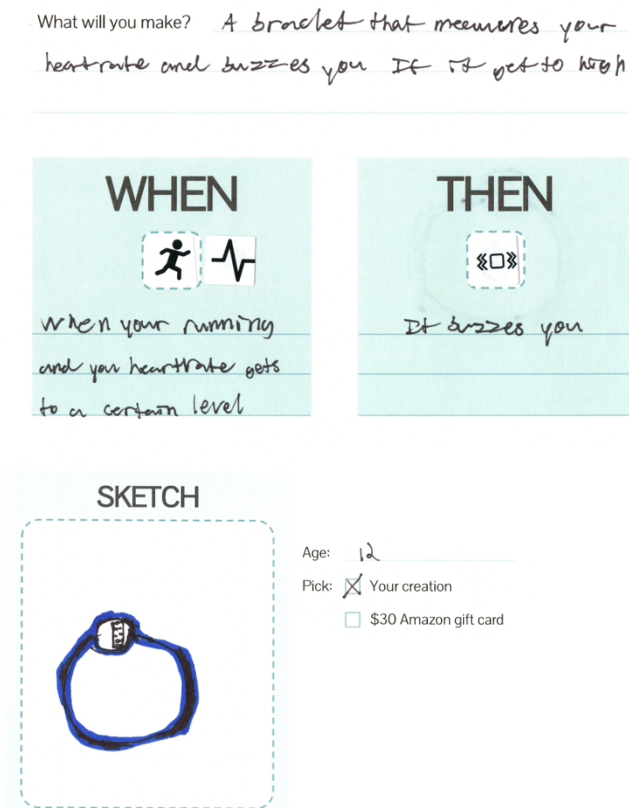

Figure 4: Cardboard prototype as completed by one of the participants (personal information redacted)

Results

35 participants chose to complete the cardboard prototype. Of these, 26 participants revealed their age. The average age of all participants was 13.4. The average age of all participating minors was 10.6 (excluding 3 participants 24 years or older). There were more girls than boys who chose to participate.

The outcome from the design experiment was a map of the design space by age and gender, which may be useful to design educators. It displays what kind of device kids chose to design, as shown in figure 5. It can be seen that the older girls and boys embraced the idea of wearable devices for health, safety, and stress mitigation purposes, but these topics are of little interest for the girls up to the age of ten and boys up to the age of 12 that we surveyed. A cut-off age was observed around 11 for girls and 13 for boys, which is about when puberty sets in. While even young girls were very excited about this design concept in general, their desired project ideas were more embedded in the playful context of sports, taking photos and playing music, or simply purely artistic expressions of ideas around the form, shape and color of a wearable device. All age groups showed an interest in triggering music and using weather information.

Design Space by Age and Gender

Gender	Age	Wearable?	Health	Stress / Wellbeing	Safety	Privacy	Smart Home	Text Notification	Weather	Music	Picture	Device Technology	Action / Sports	Looks only
Male	8	No										x		
Male	11	Yes										x		
Male	12	Yes								x			x	
Female	4	Yes							x	x		x		
Female	6	Yes							x		x			
Female	8	Yes												x
Female	8	Could be								x				
Female	9	Could be									x			
Female	9	No							x					
Female	9	Yes	x											
Female	10	Yes											x	x
Male	13	No		x						x				
Male	14	Yes							x		x			
Male	14	Could be	x		x					x				
Male	14	Yes	x		x									
Female	12	Yes	x		x									
Female	12	No					x	x			x			
Female	13	Yes	x		x					x				
Female	13	Yes			x									
Female	13	Yes				x	x		x					
Female	14	Yes	x	x								x		

Figure 5: Design space map of different age groups for both boys and girls surveyed with the cardboard prototypes

Figure 6 shows a photo of the booth at the MIT Museum with girls engaged in the design activity.

Figure 6: Photo of the activity with cardboard prototypes at the MIT Museum

STUDY III: ELECTRONIC IMPLEMENTATION AND WORKSHOP PROCEDURE

The findings from the previous two stages of initial testing were used to guide the transformation of the design activity concept into a workshop that would allow participants to design working devices.

Based on preliminary workshops with the MIT Museum [43], "Science Club for Girls" [44] and "Buckingham Browne and Nichols" school in Cambridge [45], a workshop was planned and conducted with a group of 10 girls from "Big Sister Association of Boston" [46], each with their respective mentor. The design toolkit provided was a working implementation of the concept of a configurable modular smart device with an early version of a corresponding graphical interface [41]. Wireless microcontrollers were programmed to accept acceleration, pulse, or temperature sensors. The workshop was planned for 1h 45 min. The structure is summarized in table 1. This workshop format was followed with a group from Big Sister Association of Boston and it was adapted from a longer schedule that was created in cooperation with a group from Science Club for Girls.

Research Method

It was expected that by making engineering problems more engaging and relatable, it would be possible to build self-efficacy and intrinsic motivation in middle and high school girls and to promote creativity and "invention" of innovative products.

Based on this premise, pre- and post-workshop questionnaires were drafted with the following elements: (1) self-efficacy questions, (2) interest questions, (3) general feedback, and (4) motivation-related questions.

The questionnaire was constructed to answer the following questions:

Table 1: 1h 45 min schedule for the design workshop with working prototypes

5 min	Complete pre-questionnaires
10 min	Introduction to wearables, sensors, input / output
5 min	Intro to toolkit with example
25 min	Activity: Create application with toolkit based on examples and own ideas
10 min	Break
25 min	Continue building activity
10 min	Present to another match (groups of 2 matches), critique (2 x 5 min)
5 min	Reflect upon product purpose
15 min	Present to the class
10 min	Post-workshop questionnaire

- Can the presented toolkit help girls increase self-efficacy in "technical creativity"?
- Can the presented toolkit help girls increase self-efficacy and interest in STEM?
- Is STEM interest coupled to self-efficacy more through "technical creativity" or product design skill, than through math self-efficacy?

Separate question clusters for self-efficacy and interest were used to specifically answer these research questions. To test a potential increase in self-efficacy in "technical creativity" and self-efficacy and interest in STEM, different questions were added about aspects of each. To test a possible correlation of STEM interest with technical creativity vs. math self-efficacy, a question was added about math self-efficacy as well.

The design activity was tested with a group of 10 girls, brought together by Big Sister Association of Boston as discussed earlier; the average age was 13.3 years old. As a control group, 11 students at a school science club completed the same design tasks. 9 students of the control group, 8 boys and 1 girl, submitted the same pre- and post-questionnaires as were completed by the all-girls group. The average age of the control group was 12.9 years. A significant change in self-efficacy was not expected in the control group, since this group had been thoroughly exposed to STEM before. Also, being predominantly male, the control group was expected to already perceive engineering as socially relevant prior to the intervention, in addition to being motivated by factors that may not have been addressed by this activity (e.g. competition).

In the limited 1h and 45-minute time frame, ideas could rarely be fully transformed into complete, working products (with a few exceptions). The group presentations gave projects some closure, although it was expected that this time limitation and thus limited realization of projects would allow for only moderate growth in engineering self-efficacy and interest. However, a rapid change of mindset was expected, based on the experience in the earlier focus groups.

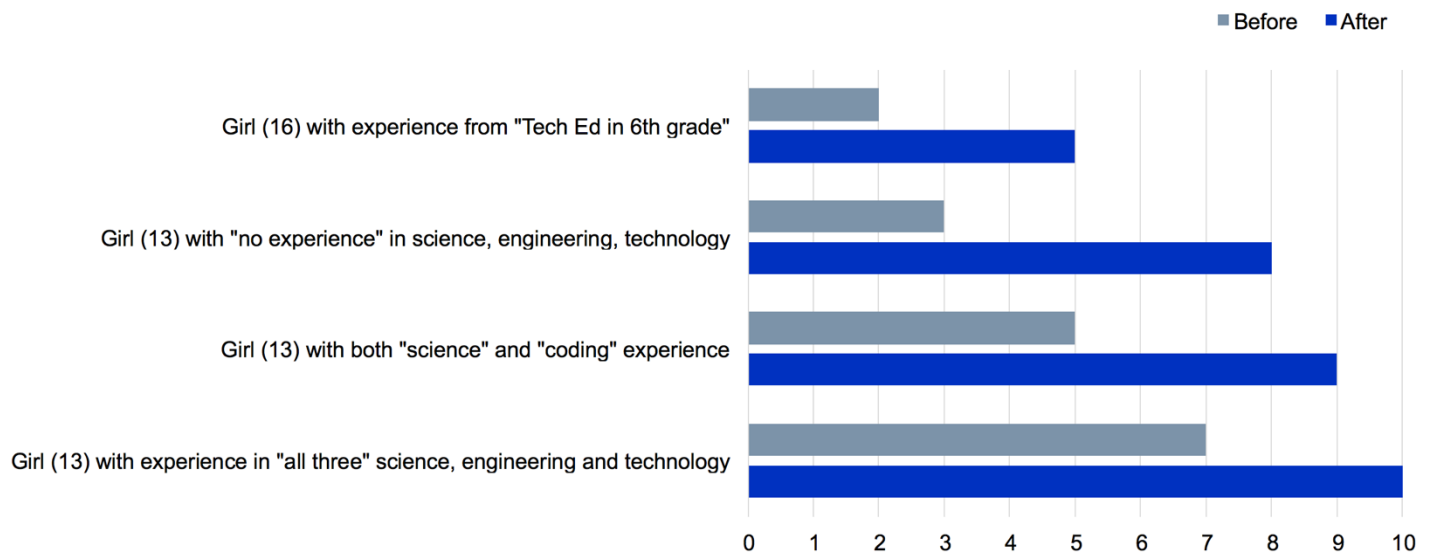Self-efficacy in "Create technology that has an impact on people's lives"

Figure 7: Self-efficacy in "creating technology that has an impact on people's lives" (on an 11-point scale) before and after the workshop respectively for four different participants. The increase in self-efficacy for paticipants with prior exposure shows that the engineering design activity has impacted the participants beyond other STEM experiences, including engineering workshops, coding and science classes.

Results

Comparing pre- and post-workshop questionnaires, there was a general increase in self-efficacy and interest in STEM and product design. A noteworthy point was that girls both with and without prior coding experience reported a much higher perceived confidence for "Come up with a product that people like and use" – a gain between 0 and +5 points on an 11-point scale. A similar gain was seen with regard to "Create technology that has an impact on people's lives." For example, a girl who stated she had no prior experience in science, engineering or technology, reported an 8-point self-efficacy rating in this category, from 3-points before the workshop — a 5-point increase. Another girl who stated she had prior experience in both science and coding reported a 9-point self-efficacy rating after the workshop compared to 5-point before the workshop — a 4-point increase. It can thus be concluded that there is evidence that this activity with real-world elements achieves its goal of conveying the experience of social impact of STEM, i.e. "with engineering I could have an impact on people's lives", a key factor identified by the NAE (2008) study [24], since even girls who had prior exposure to science or coding could benefit from this activity in a way that surpasses other learning experiences.

Individual answers to the self-efficacy question "create technology that has an impact on people's lives" are detailed in figure 7, as this represents one of the most significant findings of this study. The remarkable increase for the participant that stated no prior experience is expected, since this might be the first

meaningful introduction to an engineering-related activity, which provides an "easy" opportunity for self-efficacy increase.

The average change values and standard deviation of the change values in the self-efficacy questions of the all-girls group is summarized in table 2. The self-efficacy results of the control group are summarized in table 3. As explained in the previous section, a notable change in self-efficacy was not expected in the control group.

Table 2: Increase in self-efficacy for design and engineering among 10 girls with an average age of 13.3 years

Self-efficacy questions (11-point scale)	Average change	Std. dev.
Come up with a product that people like and use	**2.0**	1.94
Come up with useful product ideas	**2.3**	2.67
Realize a product that has technology, like a thermometer	**1.2**	2.86
Solve math problems, like find the equation for a line	**0.8**	1.40
Solve science problems, like design an experiment that looks at 2 different factors	**1.5**	2.42
Create technology that has an impact on people's lives	**1.5**	2.12
Obtain skills to be an engineer	**0.9**	3.28

7

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Table 3: Self-efficacy change in the control group, a science club (12.9 years average age).

Self-efficacy questions (11-point scale)	Average change	Std. dev.
Come up with a product that people like and use	**-1.0**	1.83
Come up with useful product ideas	**-0.8**	1.69
Realize a product that has technology, like a thermometer	**-0.2**	2.13
Solve math problems, like find the equation for a line	**0.5**	1.22
Solve science problems, like design an experiment that looks at 2 different factors	**0.3**	1.90
Create technology that has an impact on people's lives	**-0.3**	2.07
Obtain skills to be an engineer	**0.0**	2.88

The interest related questions are summarized in table 4. Note that "I would enjoy creating technology for people" changed the most significantly. It can be observed from the results that self-efficacy and interest regarding questions using official terminology such as "product design" or "engineering" changes to a less significant degree than for concrete examples. These terms were not discussed as part of the workshop; thus no significant change is expected.

Table 4: Improvement in interest or self-perception among 10 girls with an average age of 13.30 years. Terms like engineering or product design were not discussed in the workshop

Interest questions (7-point scale)	Average change
Product designers can have a positive impact on people's lives	0.4
Engineers can have a positive impact on people's lives	0.6
I would enjoy creating technology for people	1.2
Engineering has a positive impact on my life	0.3
In my career, I would definitely like to have a positive impact on people's lives	0.0

The project design scope reflected the discoveries from experiments documented above. Many were wearable devices, but other contexts came up as well. A set of examples from the all-female group:
- A baby monitor that checks in on body temperature
- A device with an email news update
- A fitness tracker that triggers songs, depending on performance
- A smart basketball that measures impact and flight parameters

Students were generally positive about the design experience, but asked for more guidance. Some of the comments from the general feedback page in our post-workshop questionnaires reflect that important goals were achieved by meeting requirements set out early on:
- Having social impact:
"I liked how we thought of ideas to impact people's lives."

- Ownership, constructionist ideal:
"I liked that we got to make our own ideas."
"I like that we were encouraged to be creative."

- Sharing:
"I liked the part of sharing ideas with others."

- Dimensions unique to this implementation:
"It was fun using sensors."
"I enjoyed the making of my custom fit-bit."
"It was cool to basically create an app."

DISCUSSION

The studies reveal that it is indeed possible to convey to girls the experience that they can have an impact on people's lives with engineering – the key factor according to important findings cited in the prior art section, including the NAE (2008) study [24]. What is needed is an experiential activity that lets female students experience their own "technical creativity" as socially impactful. A constructionist approach, in which students design and build something of their own accord, something physical, personalized and shareable, is particularly suitable for achieving this goal. This work presents a concept of a design activity that takes into account the needs of middle and high school girls, and the implementation of this concept over many stages. It also shows both quantitative and qualitative results of the interaction with this design activity.

The different design stages of the toolkit provide insightful example for testing interactive design experiences at the early stages of development. The paper outlined the process and experiments used to develop the kit, and what as learned along the way.

In a first study, physical and digital sketch models were used to communicate the concept and appearance in focus groups and interviews. One key finding was that, once "given the tools" to think about solving problems in a certain way, middle school girls showed a spike in creativity and a rapid change of mindset was observed by the researchers. In a second study, cardboard and stickers were used to mimic the design experience. One important result was a design space map, illuminating tendencies in design interest by different age groups and genders. In a third study, a simple implementation of a working modular smart device was used in an experimental workshop with both a group of 10 girls and with a predominantly male science club as a control group. Self-efficacy and interest questions were used before and after the workshop to gauge the effect of the design activity on students' perception and motivation. Similar to the initial focus groups, data indicated a rapid change in mindset.

8

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Engineering perception was not significantly improved, as the terms 'engineering' and 'product design' were not discussed in the experimental workshops.

A limitation of the developed and presented is that, up to the implementation presented here, it has not encouraged activities around action or play, which might be more appropriate to younger students. The addition of features such as music outputs could address this limitation.

The findings from this project encompass design spaces of relevance to different age groups for both male and female learners. These broader motivational factors are a crucial foundation to design education and may be applied much beyond the scope of this project and K-12 design pedagogy.

As education, empowered by means of digital learning, is ready to give students more freedom and provides more personalized and more self-driven ways of learning, it is important to address those individual needs with appropriate context options. Only if the relevance aspect is satisfied will many middle-school-aged girls be intrinsically motivated and fully benefit from discovery-driven design education, serving technical education and beyond.

FUTURE WORK

The presented design activity needs to be complemented with activity guides, examples, and more mechanisms for providing immediate feedback. It was found that providing guidance does not merely consist of asserting structure, but rather providing clarity about the state of objects and tools at any given time to allow the learner discovery in design. These can be implemented both in the platform itself and on an accompanying website. The presented experiments lay out design affordances of different age groups, which will be helpful in creating an optimal learning experience for different audiences. With such improvements in place, the study should be expanded to get more reliable data about the efficacy of the concept. The design workshop may be repeated in a format following the one presented here. Additionally, focus groups may provide deeper insight to participants' self-perception, motivational factors, and design interest. Figure 8 illustrates the interdisciplinary composition of this research project as well as its deliverables.

The hardware, software, and online sharing infrastructure are scaled and improved and will be available to the public as "Qwartzi" beyond this research.

Possible venues for deployment of this toolkit are after-school clubs and classes. Also, the online sharing network might help reach students that are home-schooled or whose schools do not have the resources to offer product design or coding activities. While traditional school curricula may not provide for design and engineering learning per se, the presented toolkit might create the opportunity for project-based learning in science or math classes. This could bridge the disciplines and help students to take charge of technical experimentation and experience the real-world impact they desire.
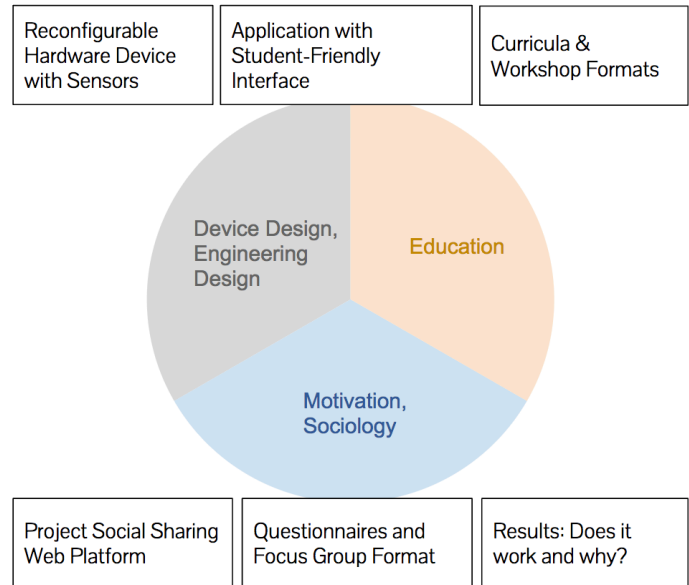

Figure 8: Scope of this project. An interdisciplinary work between Engineering Design, Education Research and Motivation Research, its deliverables are not limited to the design toolkit itself, but also motivational dimensions.

REFERENCES

[1] Rooney, P., Hussar, W., Planty, M., Choy, S., Hampden-Thompson, G., Provasnik, S., and Fox, M. A., 2006, *The Condition of Education*, National Center for Education Statistics, Washington, DC.

[2] Santiago, V., Sevo, R., Jesse, J., and Cosgrove, M., 2006, *New Formulas for America's Workforce 2: Girls in Science and Engineering*.

[3] The White House, 2016, "Fact Sheet: President's 2017 Budget Invests in American Innovation: R&D, Innovation, and STEM Education" [Online]. Available: https://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_fact_sheet_2017_budget_final.pdf. [Accessed: 03-May-2016].

[4] Schunk, D. H., and Lilly, M. W., 1984, "Sex Differences in Self-Efficacy and Attributions: Influence of Performance Feedback," J. Early Adolesc., **4**(3), pp. 203–213.

[5] Zimmerman, B. J., 2000, "Self-Efficacy: An Essential Motive to Learn," Contemp. Educ. Psychol., **25**(1), pp. 82–91.

[6] Ceci, S. J., Williams, W. M., and Barnett, S. M., 2009, "Women's Underrepresentation in Science: Sociocultural and Biological Considerations.," Psychol. Bull., **135**(2), p. 218.

[7] Dweck, C. S., 2000, *Self-Theories: Their Role in Motivation, Personality, and Development*, Psychology Press.

[8] Anderson, N., Lankshear, C., Timms, C., and Courtney, L., 2008, "'Because It's Boring, Irrelevant and I Don't like Computers': Why High School Girls Avoid Professionally-Oriented ICT Subjects," Comput. Educ., **50**(4), pp. 1304–1318.

[9] Lenhart, A., 2015, "Teens, Social Media & Technology Overview 2015," Pew Res. Cent. Internet Sci. Tech.

[10] Dasgupta, N., and Stout, J. G., 2014, "Girls and Women in Science, Technology, Engineering, and Mathematics STEMing the Tide and Broadening Participation in STEM Careers," Policy Insights Behav. Brain Sci., **1**(1), pp. 21–29.

[11] Wang, M.-T., 2012, "Educational and Career Interests in Math: A Longitudinal Examination of the Links between Classroom Environment, Motivational Beliefs, and Interests," Dev. Psychol., **48**(6), pp. 1643–1657.

[12] Riegle-Crumb, C., Farkas, G., and Muller, C., 2006, "The Role of Gender and Friendship in Advanced Course Taking," Sociol. Educ., **79**(3), pp. 206–228.

[13] Halpern, D. F., 2004, "A Cognitive-Process Taxonomy for Sex Differences in Cognitive Abilities," Curr. Dir. Psychol. Sci., **13**(4), pp. 135–139.

[14] Lavy, V., and Sand, E., 2015, *On The Origins of Gender Human Capital Gaps: Short and Long Term Consequences of Teachers' Stereotypical Biases*, 20909, National Bureau of Economic Research.

[15] Meece, J. L., and Courtney, D. P., 1992, "Gender Differences in Students' Perceptions: Consequences for Achievement-Related Choices," Stud. Percept. Classr., pp. 209–228.

[16] Pressler, M. W., 2006, "Bored With Her Toys," Wash. Post.

[17] 2008, *Change It Up! What Girls Say About Redifing Leadership*, Girl Scouts of the USA.

[18] Andrus, S. H., Kuriloff, P. J., and Jacobs, C. E., 2015, "Teaching Middle School Girls More Effectively," Indep. Sch., **74**(3), pp. 16–18.

[19] Jacobs, C. E., Kuriloff, P. J., Andrus, S. H., and Cox, A. B., 2014, "Reaching Girls," Phi Delta Kappan, **96**(1), pp. 68–73.

[20] Margolis, J., Fisher, A., and Miller, F., 1999, "Computing for a Purpose" [Online]. Available: http://www.cs.cmu.edu/afs/cs/project/gendergap/www/purpose.html. [Accessed: 03-Jun-2015].

[21] Ryan, R. M., and Deci, E. L., 2000, "Self-Determination Theory and the Facilitation of Intrinsic Motivation, Social Development, and Well-Being," Am. Psychol., **55**(1), pp. 68–78.

[22] Sansone, C., and Harackiewicz, J. M., eds., 2000, *Intrinsic and Extrinsic Motivation: The Search for Optimal Motivation and Performance*, Academic Press, San Diego.

[23] Andrews, J., and Clark, R., 2012, "Breaking down Barriers : Teenage Girls' Perceptions of Engineering as a Study and Career Choice," Société Eropéenne pour la Formation des Ingénieurs, Brussels (BE).

[24] National Academy of Engineering Committee on Public Understanding of Engineering, 2008, *Changing the Conversation: Messages for Improving Public Understanding of Engineering*, National Academies Press.

[25] The White House, 2015, "Advancing Equity and Empowerment in Science, Technology, Engineering, and Mathematics (STEM)," whitehouse.gov [Online]. Available: https://www.whitehouse.gov/blog/2015/09/15/advancing-equity-and-empowerment-science-technology-engineering-and-mathematics-stem. [Accessed: 16-Dec-2015].

[26] Girl Scouts, 2015, "Girls in Science, Technology, Engineering, and Math (STEM Program)" [Online]. Available: http://www.girlscouts.org/program/basics/science/. [Accessed: 10-Apr-2015].

[27] Papert, S., 1980, "Introduction: Computers for Children (Mindstorms)," *Mindstorms: Children, Computers, and Powerful Ideas*, Basic Books, Inc.

[28] Brennan, K., 2013, "Learning Computing through Creating and Connecting," Computer, **46**(9), pp. 52–59.

[29] DeVries, R., 2000, "Vygotsky, Piaget, and Education: A Reciprocal Assimilation of Theories and Educational Practices," New Ideas Psychol., **18**(2–3), pp. 187–213.

[30] Vygotsky, L. S., 1980, "Chapter 6: Interaction between Learning and Development," *Mind in Society: The Development of Higher Psychological Processes*, Harvard university press.

[31] Singer, D. G., and Revenson, T. A., 1997, "Chapter 1: Jean Piaget and His Theory," *A Piaget Primer: How a Child Thinks*, ERIC.

[32] Ackermann, E., 2001, "Piaget's Constructivism, Papert's Constructionism: What's the Difference," Future Learn. Group Publ., **5**(3), p. 438.

[33] Turkle, S., 2011, "Introduction: The Things That Matter (Evocative Objects)," *Evocative Objects: Things We Think with*, MIT press.

[34] Resnick, M., and Rosenbaum, E., 2013, "Chapter 10: Designing for Tinkerability," *Design, Make, Play: Growing the next Generation of STEM Innovators*, pp. 163–181.

[35] Papert, S., 1993, "Chapter 7: Instructionism versus Constructionism (The Children's Machine)," *The Children's Machine: Rethinking School in the Age of the Computer*, Basic Books.

[36] Csikszentmihalyi, M., 1991, *Flow: The Psychology of Optimal Experience*, Harper Perennial, New York.

[37] Brophy, J., 1999, "Toward a Model of the Value Aspects of Motivation in Education: Developing Appreciation For..," Educ. Psychol., **34**(2), pp. 75–85.

[38] Bdeir, A., 2009, "Electronics As Material: LittleBits," *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, ACM, New York, NY, USA, pp. 397–400.

[39] Lee, M., and Lee, M. R., 2015, "Beyond the Wearable Hype," IT Prof., **17**(5), pp. 59–61.

[40] Buechley, L., Eisenberg, M., Catchen, J., and Crockett, A., 2008, "The LilyPad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education," *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, New York, NY, USA, pp. 423–432.

[41] Nietner, L., and Nill, S., 2016, "Modular Wearable Computing Device."

[42] "Qwartzi" [Online]. Available: http://qwartzi.com/. [Accessed: 18-Feb-2017].

[43] "MIT Museum" [Online]. Available: http://web.mit.edu/museum/. [Accessed: 09-Jun-2016].

[44] 2015, "Science Club for Girls" [Online]. Available: http://www.scienceclubforgirls.org/. [Accessed: 03-May-2016].

[45] "Buckingham Browne & Nichols" [Online]. Available: http://www.bbns.org/. [Accessed: 09-Jun-2016].

[46] "Big Sister of Boston" [Online]. Available: http://www.bigsister.org/. [Accessed: 09-Jun-2016].

11

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