Building Blocks of the Maker Movement: Modularity Enhances Creative Confidence During Prototyping

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Abstract Can we enable anyone to create anything? The prototyping tools of a rising Maker Movement are enabling the next generation of artists, designers, educators, and engineers to bootstrap from napkin sketch to functional prototype. However for technical novices, the process of including electronic components in prototypes can hamper the creative process with technical details. Software and electronic modules can reduce the amount of work a designer must perform in order to express an idea, by condensing the number of choices into a physical and cognitive "chunk." What are the core building blocks that might make up electronics toolkits of the future, and what are the key affordances? We present the idea that modularity, the ability to freely recombine elements, is a key affordance for novice prototyping with electronics. We present the results of a creative prototyping experiment ($N = 86$) that explores how tool modularity influences the creative design process. Using a browser-based crowd platform (Amazon's Mechanical Turk), participants created electric "creature circuits" with LEDs in a virtual prototyping environment. We found that increasing the modularity of LED components (i) increased the quantity of prototypes created by study participants; and (ii) increased participants' degree of perceived self-efficacy, self-reported creative feeling, and cognitive flow. The results highlight the importance of tool modularity in creative prototyping.

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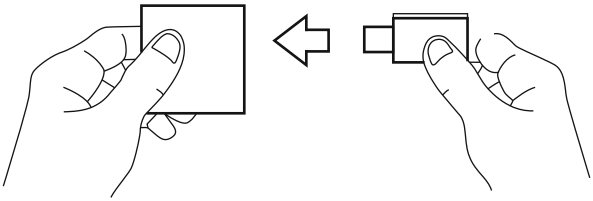

Fig. 1 Plug-and-play interaction with electronics modules

1 Introduction: Modules for Makers

Can we enable anyone to create anything? Maker culture encourages those with ideas to empower themselves with the *creative tools* to make their ideas tangible. In the world of electronic devices, the rising availability of novice microcontroller platforms, desktop physical fabrication tools, affordable electronic components, and a global online community, has fuelled more designers to *hack, mash* and *glue* their way to working electronic prototypes (Hartmann et al. 2008). Hundreds of DIY fabrication facilities, *Fablabs*, have emerged over the years to provide public spaces for digital-physical prototyping, ranging from laser cutters, and computer-controlled milling machines, and 3D printers (Anderson 2014). Tools that were once only accessible to large companies, or required professional knowledge, are now within reach of ordinary citizens. In the electrical domain, novices can now chose from a growing array of premade electronics modules, such as sensors and actuators (Fig. 1), that hide much of the technical detail into plug-and-play LEGO-like building blocks (Sadler et al. 2015a, b). These emerging tools have strong implications for Design Thinkers who wish to transform low-resolution prototypes from paper and duct-tape, into functional interactive devices. But what are the core building blocks that might make up electronics toolkits of the future, and what are their key affordances? Here we propose the idea that *modularity*, the ability to freely recombine elements, is a critical affordance for novice prototyping with electronics. What are the creative trade-offs with more modular electronics blocks? Do these blocks help or hinder the creative design process?

1.1 Modularity and the Black Box

When faced with a creative challenge, designers are encouraged to create many low-resolution solutions in a limited time period. These prototypes tend to highlight the essence of an idea, rather than the technical details of implementation. However prototyping with software and electronics can slow down the creative process by (i) requiring prior technical knowledge and (ii) introducing potential for errors in implementation. By using pre-defined modules, a designer may add blocks that encapsulate a desired functionality, while hiding the technical details. Here we define modules as encapsulated blocks of functionality that can be added to or removed from a system independently (Baldwin and Clark 2000).

A component with a high degree of modularity has fewer dependencies on outside variables. In prototyping, this implies that modules enable designers to freely try combinations of parts, much like adding bricks in a toy construction kit. For example if the designer decides to add a green LED light to a prototype, a plug-and-play interaction is a more modular interaction than building a light circuit from basic components. We can think of the light module as a “black box” that does not reveal its inner details, but rather emphasizes the core functionality. For designers who are trying to create novel solutions, the idea of “black box” that cannot be modified on the inside seems counter to the idea of creative freedom. On the other hand, the “black box” approach allows the designer to focus on the high-level design decisions such as, “Should we include a light?” before diving deeper into technical requirements such as, “What value of resistance should we include to limit the current?” Prototyping with black-box modules therefore has tradeoffs between flexibility and ease of use. The goal of this research is to better understand the effects of these modular tradeoffs on the designer’s creative ability.

2 Background

2.1 The Modularity Tradeoff: An LED Example

What does high or low modularity look like with electronic components? Consider the following example of two multi-color light emitting diode (LED) components shown in Fig. 2. In the example of “low modularity,” a low-cost tri-color LED can be added to a programmable microcontroller by connecting four individual pins, and choosing 3 appropriately sized resistors. In this case, the LED does not contain all of the components required to function reliably, and a designer must choose the correct resistors from thousands of possible resistance values.

Making an incorrect connection, or choosing a resistor that is too small or too large, results in a non-functional light. In the “high modularity” example, a self-contained

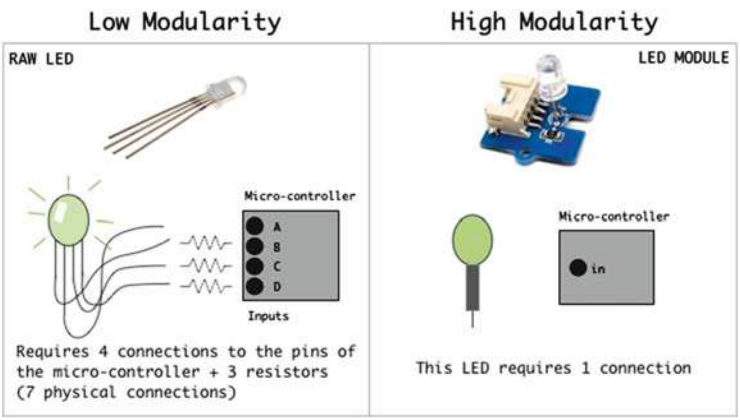

Fig. 2 Comparing the modularity of two LED components

Table 1 Comparing modularity trade-offs (+++ is best)

Metric	Less modular	More modular
Number of steps (to combine)	*More steps required*	+++
Difficulty threshold	*Increased initial difficulty*	+++
Error probability (success variability)	*Increased chance of error*	+++
Component cost	+++	*More expensive*
Technical learning	+++	*Reduced technical learning*
Flexible functionality	+++	*Harder to modify*

LED module contains the necessary components to function properly and a single connection to the outside world. In this case, an expert has made the resistor choices in advance, and the module has a simplified single connection interface. This module reduces the outside variables that may lead to errors, such as choosing bad resistors or plugging in the component in an opposite polarity. These contrasting examples illustrate that a key difference in prototyping with modules is that they tend to reduce the variability, difficulty, and number of steps required to combine components, in exchange for reduced flexibility and increased cost. These trade-offs are summarized in Table 1. Modules may be a poor choice if one's goal is to educate a designer on the technical aspects of a system, since the details are hidden. However, if the primary goal is to enable functional prototyping of a creative idea as quickly as possible, then modules are effective candidates. Modules are therefore the "chunks" that enable a designer to incorporate a whole unit of functionality; in much the same way that cognitive chunking (Miller 1956) enables efficient clustering of complex information. Here the authors use the concept of a "chunk" as equivalent to a module, as proposed by the design decomposition work of Pimmler and Eppinger (1994).

2.2 Prototyping Metrics

During prototyping we assume that an ideal creative toolkit will enable a designer to confidently create many prototypes in a given time frame, allow diverse ideas to be expressed, and place a designer in "the zone" of continuous cognitive flow. Since modularity tends to reduce the difficultly and number of steps required to create a prototype, we hypothesize that increasing the modularity of prototyping tools will have positive effects on:

1. **Prototype Quantity**: The number of distinct prototypes created in a given time period.
2. **Designer's Creative Feeling**: The degree to which designers feel they are in a creative state.
3. **Self-Efficacy**: The confidence that a designer has in his or her ability to create prototypes. (Csikszentmihalyi 1992).
4. **Cognitive Flow**: The degree to which a designer feels that a task's difficulty level matches one's perceived abilities (Csikszentmihalyi 1992).

The above metrics have interconnected effects on one another. For instance, prior research has shown that designing several prototypes in parallel can contribute to an increase in both the quantity and creativity of prototypes produced (Dow et al. 2010). This research focuses on the above metrics as general indicators of a desirable prototyping experience.

2.2.1 Bandura's Self-efficacy and the Confidence to Create

Creating prototypes with technology can be difficult for a technical novice. A designer who lacks a technical background in electronics and sensors, for example, may be less confident in his or her ability to make working prototypes that include electronic components. Bandura (1977) refers to the measure of a person's confidence in his or her ability to achieve a task as *self-efficacy*. In this research we consider a specific aspect of self-efficacy, referred to as *creative self-efficacy* (Tierney and Farmer 2002). For a prototyping task, we aim to understand how the qualities of a tool will encourage designers to feel confident in their ability to create. Prior work on the use of novice electronic prototyping toolkits found that using modular building blocks can be an effective way to encourage more fluid prototyping (Hartmann et al. 2005). The core premise of Hartmann's work is that modularity hides some of the technical details and reduces the perceived and actual difficulty to play with an unknown component. However, to the authors' knowledge there is limited prior data on the cognitive effects of modularity during creative prototyping.

2.2.2 Cognitive Flow and Modularity

Designers often describe a creative episode as a sustained burst of focused energy on the task at hand, where time fades into the background and one gets into *the zone*. The cognitive psychologist, Mihaly Csikszentmihalyi (1992), describes this state as a *flow state,* and his work has shown that being in a state of flow is positively correlated with creative performance. Csikszentmihalyi's work describes the typical conditions required to trigger a flow state, and found that flow is modulated by a balance between one's perceived skill and the perceived difficultly of a task. If a task is too challenging for a person's current skill level, Csikszentmihalyi's model predicts a state of anxiety. Similarly, if the challenge of a task is low and the perceived skill is high, the person may be in a state of low arousal or boredom. The flow state is characterized by a balance of challenge and skill, in a *channel of flow,* which is linked with higher task performance and creativity (per Fig. 3). This model has been validated by many researchers whose work illustrates the positive relationship between flow and task performance (Engeser and Rheinberg 2008). From Hartmann et al.'s work we see that modularity changes the prototyping experience by promoting components as "chunks" rather than as individual technical details. However, current research has yet to measure modularity's role in inducing a flow state during a design activity.

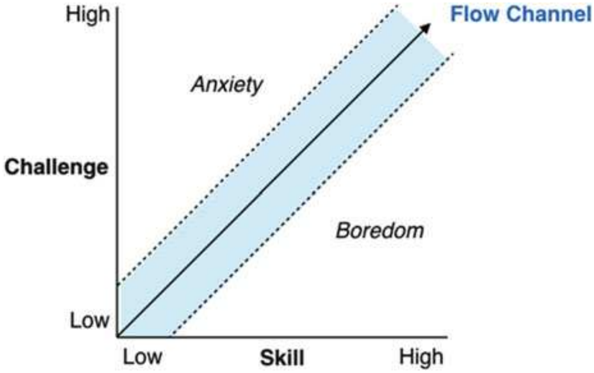

Fig. 3 Flow as a balance between skills and challenge (Csikszentmihalyi 1992)

3 Related Work

In order to examine the effects of tool modularity on the creative design process, we need a repeatable and modifiable task to serve as a basis for measuring prototyping performance. The methods we chose were modeled on two prior studies, one examining conformity in creative generation tasks (Marsh et al. 1996), and another by Kulkarni et al. (2014) that uses a crowd-sourced method to explore a creative prototyping task.

3.1 Conformity in Creative Generation Design Tasks

Marsh et al. (1996) illustrated that presenting design examples to participants prior to a generative design task influences one's creative output. Participants were shown pre-made examples of alien creatures and then asked to draw as many unique creatures as possible in a given period of time. The study found that showing design examples in advance increased the degree of conformance among design ideas. We consider this study as a strong model of a creative prototyping task, with a controlled manipulation. Specifically, we see a parallel between electronic modules and the pre-made design examples in the study by Marsh et al., since modules can be considered as pre-made units of function that a designer is provided in advance and may choose to include in a prototype.

3.2 Timing Effects on Creative Output: A Crowd-Sourced Design Task

In building on the prior study, Kulkarni et al. (2014) examined how creative output is affected by the timing when design examples are shown to study participants. Their research found that early and repeated exposure to examples increased creative design performance, as measured by the number of uncommon and novel features created by study participants. There was a correlation between exposure to examples and conformance, but this did not reduce the number of unique features incorporated into ideas. Most notably, this study showed the feasibility of using a crowd sourced web-based platform to recruit participants ($N = 81$) and collect a large number of prototype alien ideas using Amazon's Mechanical Turk. The use of a software environment to test creative prototyping is advantageous since it allows controlled modification of the environment. Our work builds on these two studies, in terms of "imagining alien creatures" as a creative prototyping task, but adapts the task to the creation of "electric alien circuit boards" with colored LED modules. To the authors' knowledge, no prior work has specifically examined the effect of modularity on creative output, self-efficacy, and cognitive flow.

4 Methods

Our research aims to understand how modularity affects creative prototyping from both quantitative and qualitative perspectives. For a controlled design task, we hypothesize that:

H1 Increasing the modularity of a prototyping tool enables designers to generate a higher quantity of prototypes in a given period of time.

H2 Increasing the modularity of a prototyping tool increases a designer's creative feeling, perceived self-efficacy, and cognitive flow. [Conversely, increasing a designer's exposure to technical details while prototyping (e.g., through the number of wiring options) decreases these cognitive measures.]

To test these hypotheses, we provided a generative prototyping challenge to a broad group of participants, and varied the degree of tool modularity for each participant. Based on a modified version of the prototyping task by Kulkarni et al., we asked participants to create as many unique and novel electric alien creatures as possible in a 10-min period (Fig. 4). We provided the following prompt, adapted from Marsh et al.:

> Imagine a planet like earth existing somewhere else in another universe. It is currently uninhabited. Your task is to design new creatures to inhabit the planet. The creatures in this world are very special, since they all are made up of tiny electric blocks. With 10 minutes allotted, draw and describe as many new and different creatures of your own creative design as you are able. Duplications of creatures now extinct or living on the planet Earth are not permitted.

We developed an HTML/Javascript based circuit creation tool that allowed participants to drag and drop colored LED's or draw grey paint on a 16×16 circuit board (Fig. 5). Users could submit as many prototypes as they wished in the time allotted, as well as provide a verbal description of each prototype. Participants were

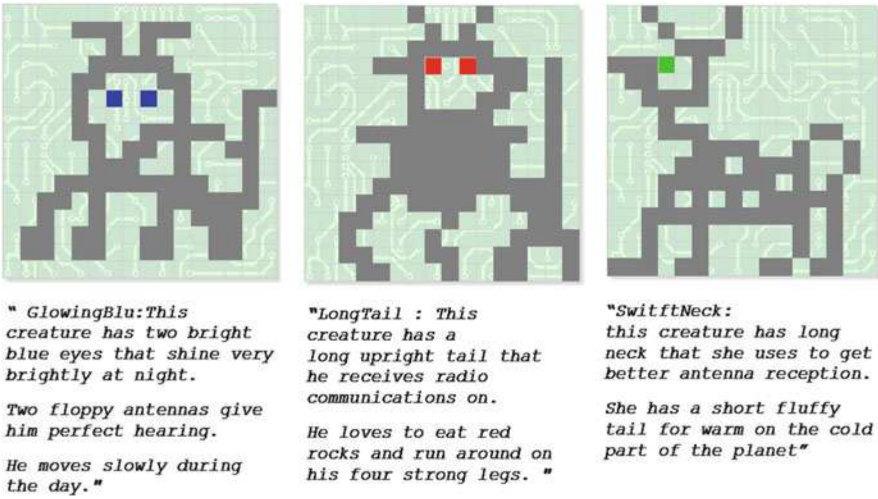

Fig. 4 Example electric creatures shown to the participants

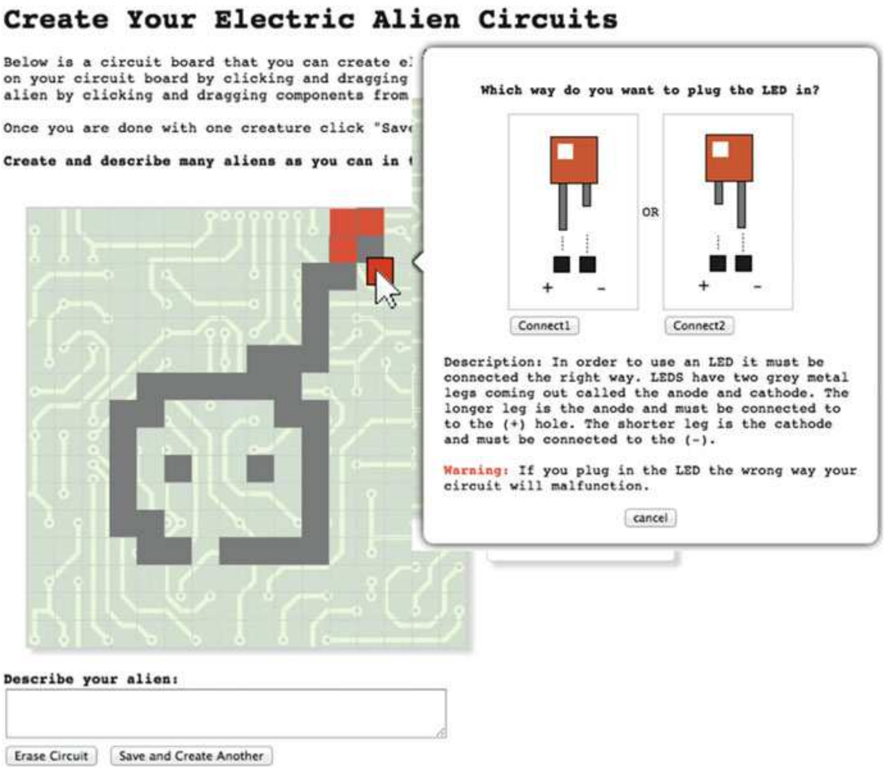

Fig. 5 The alien circuit interface where participants could drag LEDs onto a 16×16 grid

asked to physically arrange and describe each circuit board design, where each circuit would be a visual representation of a novel creature. The LED components were presented as a possible design option to add “virtual” colored lights. Using this software representation of a circuit allowed us to manipulate features of the interface for three user groups.

4.1 Participants and Groups

We recruited (N = 86) participants on Amazon’s Mechanical Turk with a compensation of $1.00 USD per participant (48 male, 38 female, average age 36 years). Users were filtered to include only fluent English speakers located in the United States. Participants were randomly assigned to one of three groups. The control group was able to freely place LEDs on the circuit board as encapsulated modules, without interruption. When participants from Groups A or B attempted to place an LED on their circuit, they were interrupted by a technical description of LED polarity, and asked to plug in wire leads in the correct orientation before they would appear on the circuit (Fig. 6). Groups A and B have less modular interactions, as described in Sect. 2.1, since there is an additional choice that must be made before successfully adding each LED. Group B differed from Group A, in that they were presented with a randomized LED orientation and randomized plug orientation.

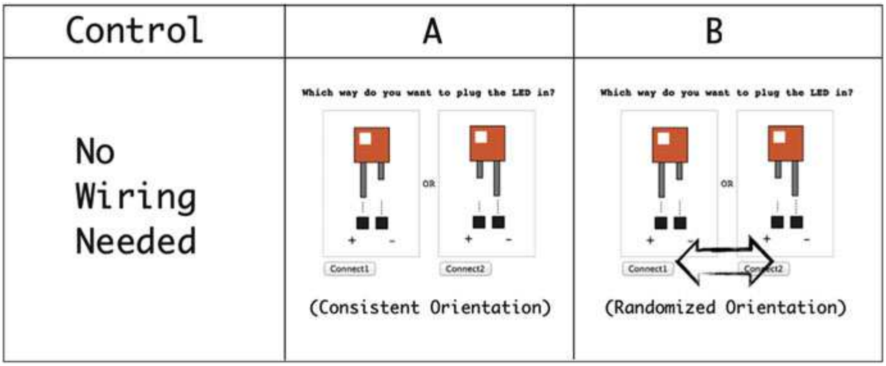

Fig. 6 Three groups. Groups A and B were given a technical description of LEDs. Participants had to select the correct wire orientation for the placement of each LED

4.2 Procedure

Each participant engaged in four steps: (i) pre-survey, (ii) description of task and creature examples, (iii) 10 min task, and (iv) a post-survey. Before and after the task, participants were asked to rate their level of confidence in prototyping with electronics, and their current feeling of creativity on a 1–7 point Likert-type scale, with 7 being the highest. At the end of the study, cognitive flow was measured using the flow short scale survey developed and validated by previous studies on flow (Engeser and Rheinberg 2008). We logged usage statistics, such as the number of creatures created and the number of LEDs used per participant. For each group we computed the (Y_1) average quantity of creatures created, (Y_2) average number of LEDs used, (Y_3) average change in creative feeling between pre-task and post–task surveys, and (Y_4) average change in perceived self-efficacy.

5 Results

All participants ($N = 86$) attempted to create creatures, and the virtual circuit building exercise appeared to be an effective design task for generating diverse prototype ideas (Fig. 7). Qualitatively we found that the 16×16 grid was sufficient to express creative ideas and most participants provided colorful verbal descriptions. Statistically comparing the control group with each group (two-tailed *t*-test), we found the following results (summarized graphically in Fig. 8):

1. **Prototype Quantity:** Participants in Group B made significantly fewer creatures than the Control. (2.42 vs. 3.47, $p < 0.05$). Both Group A and B used fewer LEDs than the control group ($A = 16.6$ $B = 12.62$ vs. $\text{Control} = 27.6$, $p < 0.05$). There was no statistical difference between the prototype quantity of Group A and the Control (3.43 vs. 3.47, $p > 0.05$).
2. **Self-efficacy and Creative Feeling:** Both the Control and Group A reported an increase in creative feeling and self-efficacy after the design task (+0.57 and +0.47, and +0.5 and +0.44, respectively). Group B reported a decrease in creative feeling and self-efficacy (−0.58, −0.37, on the 7-point Likert scale), and these changes were significantly different than the Control ($p < 0.05$).
3. **Cognitive Flow:** Group A had an increased flow score compared with the Control (4.99 vs. 4.56, $p < 0.05$). There was no statistical difference between the flow scores of Group B and the Control.

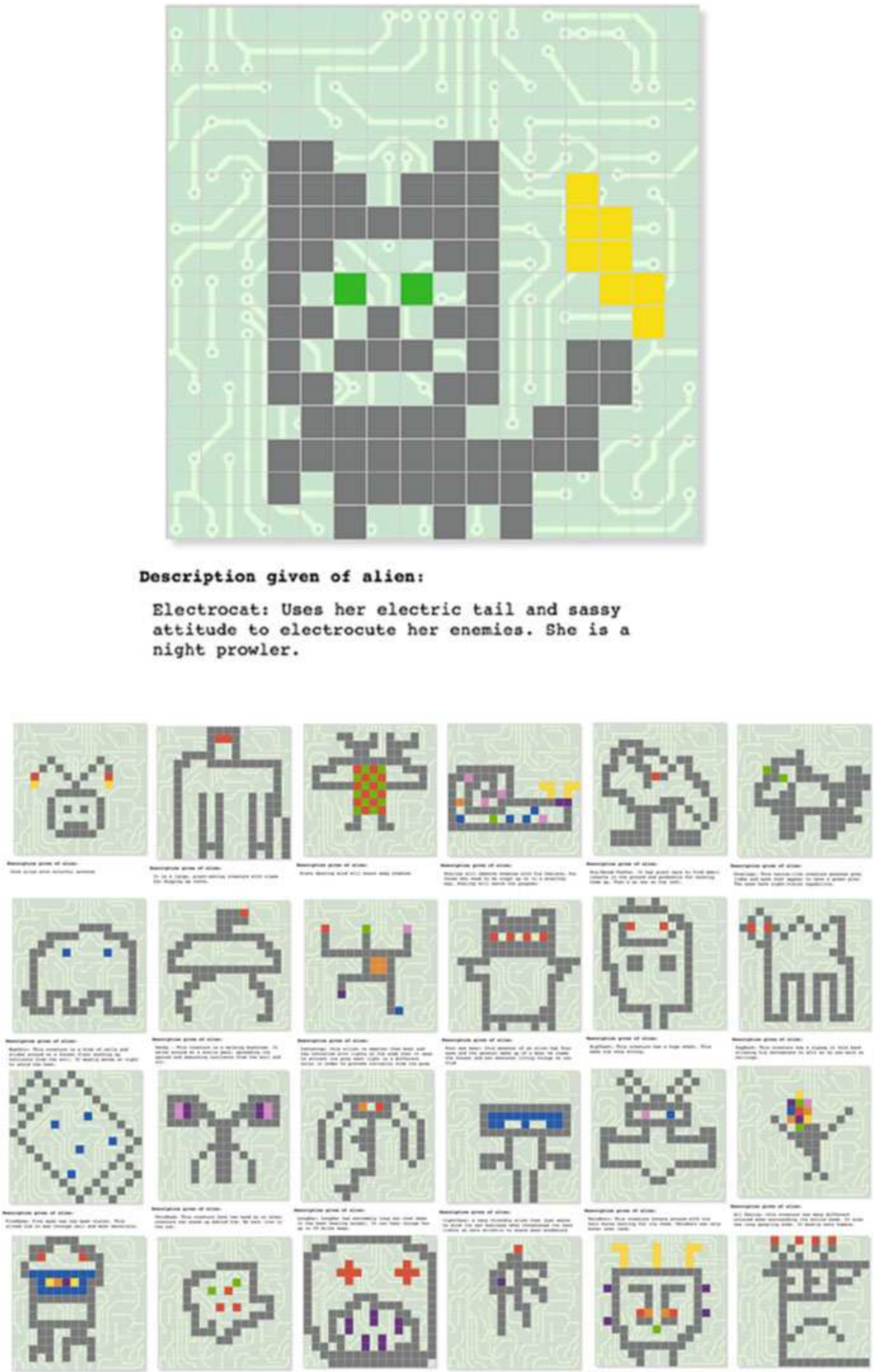

Fig. 7 A sample of creatures created by participants, illustrating the diversity of creatures

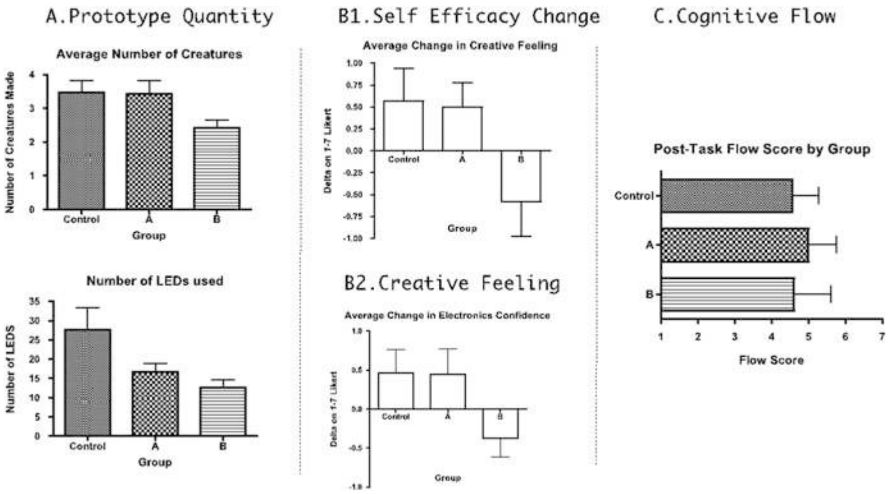

Fig. 8 Summary of prototype quantity, self-efficacy change, creative feeling and flow across groups

6 Discussion

The results of this study show that we can measurably increase a designer's perceived self-efficacy and creative feeling through the use of modular prototyping tools. In contrast, exposing designers to a higher degree of technical detail while prototyping (e.g., through having one select the correct wire orientation for each LED) had a significantly negative effect on design performance, as evidenced by a decrease in prototype quantity, self-efficacy, and creative feeling for participants in Group B. It appears that repeated exposure to technical interruptions while prototyping can create a cumulative barrier to one's design creativity. The act of wiring individual LEDs diverted time away from the task of creating, which was seen through the reduced quantity of ideas generated by Group B. However, the increase in cognitive flow observed in Group A (the group presented with a consistent wiring orientation for each LED) suggests that exposure to technical choices that require minimal cognitive interruption contributes to a state of flow, which corresponded to an increase in creative feeling and self-efficacy. The findings from this study underscore the importance of increasing the modularity of technology design tools to encourage playful prototyping and creative expression. While this pilot study shows promising results with a software simulation and crowd-sourced participants, future work will focus on matched cohort testing with physical parts, rather than simulated circuits. Also, we aim to evaluate how modularity impacts objective measures (i.e., prototype quantity, accuracy, and functionality) associated with the designs produced.

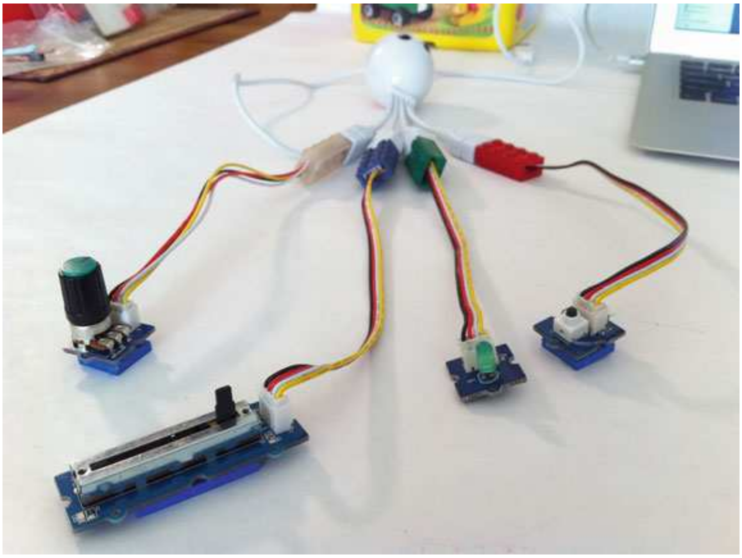

Fig. 9 The Bloctopus physical prototyping toolkit: an example of a modular electronics and software toolkit (Sadler et al. 2015a, b)

6.1 Translating to Physical Toolkits

This research highlights that modularity increases the novice's confidence to create prototypes in a constrained domain. While the prototyping task was virtual, we expect to find comparable results when adapted for physical toolkits, and this is the focus of ongoing work. The *Bloctopus* physical prototyping toolkit of Sadler et al. (2015a, b) shows an initial technical implementation of a plug-and-play electronics system that prioritizes black-box modular interactions, and interfacing with physical LEGO blocks (Fig. 9). Future work is exploring how to overcome the functionality ceiling that is linked with a black-box module approach (Sadler et al. 2015a, b). This ongoing work has highlighted that both the software and electrical domain can benefit from increased modularity. We see such *integrated* hardware-software modular interactions as the first step in a more universally accessible prototyping toolkit.

7 Conclusion

We present a creative prototyping user study with N = 86 crowd-sourced participants, on a virtual LED circuit task. The study tested the hypothesis that modules can reduce the difficulty of prototyping by hiding technical details into cognitive chunks. The findings demonstrate with empirical evidence that modularity has creative benefits on prototyping tasks. Specifically, the results show that increasing the modularity of design tools allowed participants to create more prototypes, and significantly increased designers' feelings of creativity, self-efficacy and cognitive flow. This study lays the groundwork for an understanding of how modular tools amplify creative prototyping.

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