



Paper Circuits vs. Breadboards: Materializing Learners' Powerful Ideas Around Circuitry and Layout Design

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Abstract

This exploratory study compares how young people (ages 15–16) learn circuitry concepts and layout design principles important to electrical engineering using one of two educational circuitry toolkits: paper circuits and traditional solderless breadboards. Paper-based prototyping kits are representative of a trend that incorporates new materials and approaches to integrating arts into traditional STEM disciplines. Extending prior research on how non-traditional toolkits enhance learning of electrical engineering outcomes, including basic circuitry concepts (i.e., current flow, polarity, and connections), this study examines the material affordances and design choices of the kits that contribute to youth's understanding of more advanced circuitry layout design principles, including space allocation, placement of electronic components, and routing. Results indicate that paper circuits better afford the learning of layout design principles for printed circuit boards (PCBs) with large effect sizes. This study illuminates how the materials of educational toolkits uniquely solicit body- and material-syntonic patterns of activity, and thus differentially engage learners' powerful ideas around circuitry and design principles. This investigation encourages careful consideration of the material affordances of some toolkits over others for learning purposes.

Keywords Electrical circuit · Breadboard · Paper circuit · Printed circuit board (PCB) · Circuit design · Electrical engineering · Constructionism · Syntonicity

Introduction

Electrical engineering involves the design and production of a range of artifacts, from smart microdevices and robotics to supercomputers and citywide power systems (Gross & Roppel, 2012; Rauf, 2021). With the proliferation of new technologies and the systems that manage and renew electricity, electrical engineering is among the most transformational agents of societal change in the twenty-first century. The study of energy is typically introduced in elementary science classrooms, where electric circuits are positioned as tools for the learning of what energy is, how it is conserved and transferred, and how it can be utilized in

technologies for the benefit of all (NGSS Lead States, 2013). The design of devices that operate with electrical energy is part of the recent movement of the Career and Technical Education (CTE) pathways for high school students. These newer CTE courses and programs—previously known as vocational education—provide more hands-on activities to support the development of technical skills that lead to certificates, apprenticeships, jobs, and relevant experience for college (U.S. Department of Education, 2019). Circuitry design principles, therefore, are central to the skills needed to extend a prototype into a mass-produced technology capable of widespread change.

With the launch of the Maker Movement at the turn of the twenty-first century, the emergence of new maker toolkits is changing the way we engage electrical engineering, including new on-ramps into learning advanced electrical engineering. For example, the introduction of sewable and playdough-based circuits into educational environments have illuminated ways that changing our materials have strengthened learning outcomes and broadened access to the big ideas of electrical circuits (Peppler & Glosson, 2013; Peppler et al., 2018). Promising innovations such as these alert us to

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the need to re-examine our STEM tools and materials and better align them to our targeted learning objectives. This manuscript strives to push beyond basic circuitry learning to target a broader array of advanced concepts important to the design and creation of new printed circuit boards (PCBs), including space allocation (i.e., floorplanning), placement of electronic components, and routing (Kularatna, 2008; Mitzner et al., 2019; Webb, 2016; Wilson, 2018).

For this study, we use two types of toolkits used for circuitry learning and making: paper circuits and the solderless breadboard. The objective for this comparison is to closely examine the educational opportunities to engage in targeted electrical engineering concepts and assess how features of each toolkit afford or obstruct possibilities for learning. In this study with pre-college participants, we address the following research questions: How do each of these toolkits impact the learning of simple circuitry, including polarity, current flow, and connections? How do each of these toolkits impact the learning of advanced circuitry design principles, including space allocation, placement of electronic components, and routing? In the process, we discuss the design features of the kits that seem to best support learning outcomes and illuminate how each set of materials uniquely solicit body- and material-syntonic patterns of activity, thus differentially engaging learners' powerful ideas around circuitry and design principles. This study extends previous empirical work on the different roles that toolkits and materials play for learning circuitry (Peppler & Glosson, 2013; Peppler et al., 2018). By performing systematic studies on recent electronic tools and materials, we seek to understand how to shape equitable participation of teenage learners and illuminate design principles for future toolkits to effectively support learning.

Background

Constructionism and Powerful Ideas

The current work is built on the theoretical foundation of Papert's constructionism. This body of thinking grew out of Piaget's developmental theory of constructivism. Constructivism focuses on developing mental models: structures in the mind that become more complex as learners grow and are able to more accurately categorize and represent new information in their minds. Following Piaget's work, Papert shifts our understanding of learning out of the head alone and places emphasis on representations out in the world. Papert asserts that learning happens in especially meaningful ways through the construction of artifacts—abstract or physical—that can be publicly shared and reflected upon.

In particular, the constructionist concept of powerful ideas helps illuminate some of the big ideas in circuitry design that may lead to more learning and innovation in the future. These ideas may be new to the learner, or entirely new innovations, but discovering them opens unimagined possibilities in ways that more traditional, instructor-focused methods cannot. According to Papert, a constructionist approach that involves building and creating with materials and artifacts results in a type of learning that is more intimate and less fragmented than much school learning. A goal here is for learners to develop deeper ideas of important concepts; learners should have opportunities to "get to know" and "explore" a body of knowledge through interaction and creation. Papert also thought the body should work in parallel with objects to illuminate powerful ideas. This idea, known as body syntonicity, takes into account the body as part of the constellation of materials in a learning environment by designing maps or parallels between the body and the objects being manipulated. For example, in Papert's LOGO settings, youth would often physically map the path of the turtle with their own bodies, gaining unique understandings of the computing concepts they used. More recent work has examined the new possibilities at the intersection of body syntonicity and the tools and materials used in learning—an expansive theoretical concept known as material syntonicity (Keune, 2022). We take a related stance here as we are interested in how tools and materials for circuitry learning prompt particular actions and intra-actions, potentially leading to varied understandings of advanced circuit layout design.

For the later grades in particular, the use of such embodied and tangible manipulatives is sometimes lost in classrooms, especially as the concepts become more abstract and demanding. A goal of the current work is to explore whether some forms of learning to design circuits better support both body and material syntonicity, and thus making the powerful ideas of circuit design more accessible.

Foundational Concepts About Electric Circuits

Electric circuitry concerns the formation of various electric components into a closed loop that allow electrons to flow, producing work along the way (e.g., Glisson, 2011). A simple electric circuit can be constructed with an energy source, connected with conductive paths to a load (e.g., light bulb). An electric load is a component or system of components that consumes electrical energy. Prior research has demonstrated that the teaching of electric circuitry

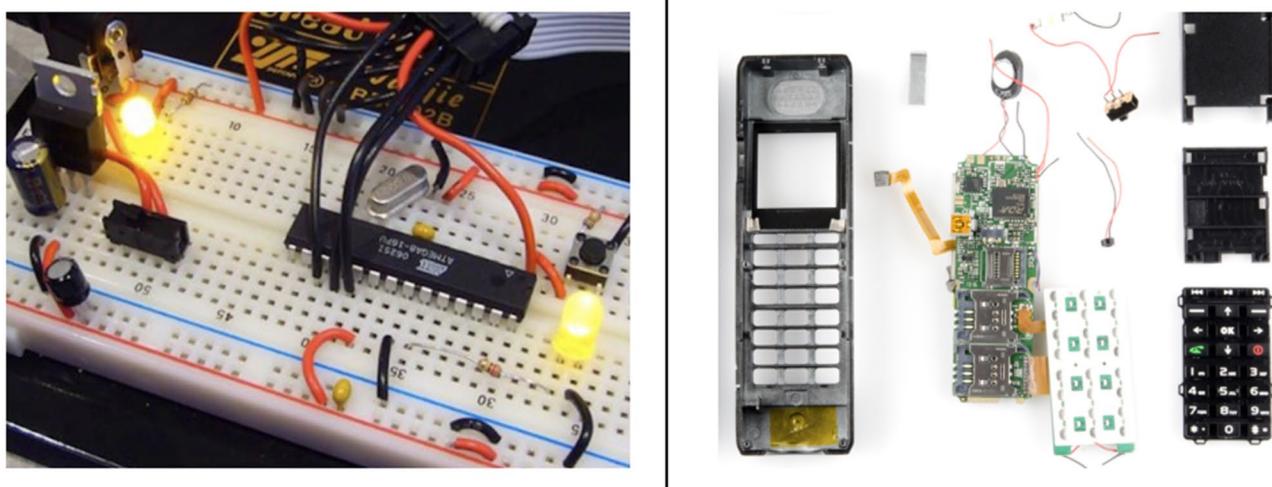


Fig. 1 Examples of a circuit prototype on a solderless breadboard (left) and of a PCB with internal electric components of a cell phone (right)

frequently produces common conceptual misunderstandings, particularly in the areas of current flow, connections, and polarity (Osborne, 1981, 1983; Shipstone, 1984, 1988; Peppler & Glosson, 2013).¹ In fact, Fredette and Lochhead (1980) found that misconceptions related to polarity were still present in college students. However, research demonstrates that attending to the tools and materials used to teach circuitry can lead to profound learning outcomes around these persistently challenging concepts, even for children as young as 4 years old (Peppler et al., 2018). Prior work with a playdough electronics kit showed preschool children demonstrating learning about current flow, connections, and polarity as well as gains in their ability to discuss circuitry concepts after seven play sessions (Peppler et al., 2018). This body of research has begun to demonstrate that tools and materials seem to have an impact on circuitry learning for middle-school youth as well. Electronic textiles were used to teach circuitry to a group of middle school youth, who were then tested on their understanding of current flow, connections, and polarity. The outcomes of this work demonstrated that assessment scores improved significantly on these concepts after ten 2-h sessions (Peppler & Glosson, 2013). As important as these three targeted circuitry concepts (i.e., current flow, connections, and polarity) are to understand electrical circuits, there are more advanced circuitry concepts that warrant further exploration. Within this space, other research has used toys and e-textiles to prompt

novel circuitry solutions with undergraduate learners, and used debugging/problem-solving as a circuitry assessment metric with high-school learners. Together, these lines of research suggest that exploring the affordances of multiple tools used to teach advanced circuitry concepts and ideas may allow designers and educators to make more informed choices to improve and enhance circuitry learning across educational levels. This is only one small sub-area of the ongoing effort toward more effective and useful assessments within the larger maker movement, both in formal classrooms and in informal learning environments (e.g., Wardrip et al., 2021). The current study illuminates advanced circuitry and layout design principles—fundamental areas of electronics and engineering education—that can be uniquely learned with these particular sets of tools and materials.

Circuit Prototyping: Breadboards and PCBs

One of the most common toolkits for electrical circuit learning in electrical engineering labs is the solderless breadboard. The use of solderless breadboards for prototyping electric systems is to temporarily fix electronic components in place and their different connecting wires. Breadboards are often made of wood, glass-reinforced plastic (fiberglass), or thermoset polymers or plastics (epoxy) with fasteners made out of metallic nails, pins, or springs to hold the components.

The different components are not permanently secured with solder so any circuit can be built and taken apart to change its configurations. Solderless breadboards are often the preferred toolkit in electrical engineering labs and industry for their convenience in the creation, design, and testing of prototypes of electrical devices (Fig. 1).

¹ Current flow concerns the movement of electrons around a circuit. Connections refer to the joining of different elements in a circuit (Osborne, 1983; Shepardson & Moje, 1994). Polarity relates to the location and orientation of positive and negative terminals in a circuit and their impact on current flow.

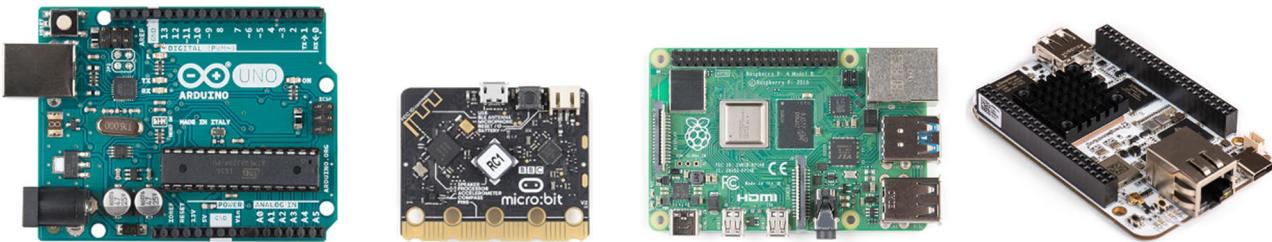


Fig. 2 Current high-tech circuitry toolkits as exposed PCBs. From left to right, the microcontroller boards, Arduino UNO R3 and micro: bit v2, and the single-board computers, Raspberry Pi 4B and the BeagleBone® AI

If a circuit prototype works according to requirements, the designer may decide to create a more permanent solution on a printed circuit board (PCB), replacing the bulky breadboard with a lighter and smaller support surface and all wires with conductive traces of copper. The configuration of an electric circuit increases in complexity as the number of components increases (Fig 1).

PCBs are made out of non-conductive material laminated with conductive metal in between providing structural support to hundreds of connections for micro-electronic components.

PCB Layout Design Principles

There are three general design principles that experts consider when designing PCBs: (1) space allocation or floorplanning, (2) placement of components, and (3) routing or trace positioning (Mitzner et al., 2019; Webb, 2016; Wilson, 2018). Adequate space allocation considers the constraints of cost, speed of data transmission, and manufacturing capabilities (Wilson, 2018). Another general principle is the placement of components, which usually depends on a variety of considerations, such as heat avoidance, signal interference, and performance (Wilson, 2018; Mitzner et al., 2019). Lastly, the positioning of traces or connections between elements ensures that elements are connected to the power source and ground, as well as avoiding cross of conductive paths (Wilson, 2018). Due to the ongoing increase in complexity of electronic devices, electrical engineers and circuit designers commonly utilize electronic design automation (EDA) software² (e.g., Altium Designer, OrCAD, Fritzing, EAGLE) to assist with the design of PCBs (Cohen, 1988; Fan, 2001; Hedges & Olkins, 1985; Sawilowsky, 2009; Thompson, 2002; Wilson, 1956; Zaiontz, 2020). EDA software allows designers to follow the three general design principles of space allocation, placement of components, and routing, in addition to other important considerations in the layout of PCBs.

² We did not use electronic design automation (EDA) software in this study but we want to acknowledge the predominant use of EDA software and digital simulations in the industry over physical prototypes due to their effectiveness in designing complex electronic devices.

Maker Circuitry Toolkits

The Maker Movement brings a revival of do-it-yourself (DIY) projects and fosters the use and creation of diverse maker toolkits for projects. Examples of maker toolkits range from sewable and playdough-based circuits to high-tech microcontrollers and single-board computers (Fig. 2). Though maker toolkits may be used in industry for prototyping purposes of “real-life” applications on control systems, these toolkits are generally different from circuitry and control tools used in industry. For example, the high-tech end of the maker toolkits could control industrial processes after receiving input from connected sensors. They could control timing or sequential tasks, but they are not built to withstand harsh industrial environments, nor are easily programmed as programmable logic controllers (PLCs), the specialized devices used in industry for control purposes. Nonetheless, circuitry toolkits can scaffold learning of practices of electrical engineers, particularly those that design circuits.

Methods

We collected data for this study as part of a series of week-long programs for youth offered by an art + science museum partner. We designed two analogous workshops centered on circuitry using educational circuitry toolkits: (1) traditional solderless breadboards and (2) paper circuits. Each workshop included pre- and post-tests to assess the understanding of circuitry, such as current flow, polarity, and connections, and the practice of circuit layout following the design principles for component placement and (wire) routing or trace positioning. We used a coding scheme informed by previous studies (Peppler & Glosson, 2013) to analyze the pre- and post-circuitry diagram assessments.

Research Questions

The research questions guiding this study are:

Table 1 Percentage of participants ($N=21$) with prior experience level with circuitry toolkits

Prior experience with:	Never	A little	A lot
Circuitry kits in-school	25%	70%	5%
Circuitry kits out-of-school	85%	15%	–
Paper craft experience	15%	70%	15%

- How do each of these toolkits impact the learning of simple circuitry, including polarity, current flow, and connections?
- How do each of these toolkits impact the learning of layout design principles, including space allocation (or floor planning), placement of electronic components, and routing?

Setting and Participants

We implemented the two circuitry workshops in the Science Gallery Museum housed in Trinity College, Dublin (Ireland), a midsize city with a population of 1.2 million. This museum is a partner organization for a larger project that investigates ways to engage youth with STEM + Art-related content. Science Gallery provides educational programs at no cost during week-long workshops and hands-on activities usually related to their exhibits. The museum exhibits are designed from contemporary societal issues and presented to the audiences from an intersectional perspective informed by the disciplines of science, technology, art, and design. The workshops of this study coincided with the museum's exhibition on issues of sustainability and environmental impacts of plastics. During the week, youth engaged in an exhibition tour, collaborative design projects and workshops. One of those workshops was our circuitry workshop.

Table 2 Activity excerpt from curriculum for day 1 of the workshop

Breadboard condition	Paper circuit condition
<p>5 min: introduce tips and tricks of the tools</p> <ul style="list-style-type: none"> The breadboard is used as a common base to place and connect various loads or small electronics components to an energy source [Show one breadboard and take the tape off from the back of one to show metal strips. Take one of the metal strips off to show clips.] Metal strips with clips make connections with the different loads [insert one of the LEDs]. Rows on the breadboard share the same metal clips. Power rails or busses deliver current vertically The board is divided into two sections by a space down the middle. The two sections do not share the same power rail <p>15 min: simple circuit with 1 LED</p> <ul style="list-style-type: none"> Each participant should have all materials from the breadboard kit Have students light up 1 LED without showing them how to. Encourage exploration, collaboration, and persistence Encourage students to use jumper wires and not to place the LEDs right in the power rails Using your finger or a pencil, help participants to track the movement of the particles (electrical charges) with a finger from the battery holder (+), through the LED (load) and back to the battery holder (-) 	<p>5 min: introduce tips and tricks of the tools</p> <ul style="list-style-type: none"> Place the copper tape as a continuous piece rather than separate pieces, even when turning corners. The adhesive on the bottom side of the foil makes a weak connection Fold a corner of the page for the battery to be placed. Have the flap over the battery and hold it in place with a binder clip Stick the LED stickers onto the foil, on top of the tape not underneath <p>15min: simple circuit with 1 LED</p> <ul style="list-style-type: none"> Distribute the rest of the paper circuit kit per participant Have students light up 1 LED using the simple circuit template. Encourage students to connect the LEDs on top of the copper tape not on the bottom Help participants to track the movement of the particles from the battery holder, through the LED (load) and back to the battery holder After participants finish lighting up their 1 LED on the template, ask them to fold it in half so the LED shines through it. Ask them if they see something they could make with the light Ask the participants to draw a design to include the shining LED and make a greeting card or just a picture They can make a card by folding the paper in half first then creating the circuit on one side of the inside of the card. This makes the light shine through when they close it. Another way is to just have the lights on the outside

See Appendix 3 for a full overview of the curriculum

Regarding participant selection for the study, the partner museum recruited students on its website, social media, and through information flyers mailed to schools, particularly those in socio-economic disadvantaged areas or very rural areas. Youth participants registered online to a weekly session according to their availability and preference. We did not disclose the type of toolkit they would engage with to ensure that the differences between the conditions were not due to their preference.

Because PCB design and manufacturing are generally introduced in the classroom at college level and not before, this study targeted youth ages 15–16 years old. Twenty-one youth were included in the study sample; 12 participants for the breadboard group (6 females and 6 males) and 9 participants for the paper circuit group (7 females and 2 males). Table 1 shows the number of participants by level of experience prior to their assigned workshop. The majority of participants had never experienced either working with breadboards or paper circuit toolkits.

The Circuitry Workshops

Each circuitry workshop consisted of three 1-h sessions held throughout the week-long program at the museum. In session 1, participants took a pre-test to assess their prior knowledge on basic concepts of circuitry before being introduced to the basic components and concepts of creating a circuit. The introduced concepts were power source or batteries, current flow, conductor, load, circuit, and polarity. The basic electronic components were a 3-V battery, battery holder, LEDs, and conductive material (e.g., wire) depending on the type of toolkit used. The challenge for the first session was to use these components and create a circuit to light up one LED. In session 2, participants were taught how to

light up additional LEDs in the circuit, as well as introduce a switch. At the end of the second session, the participants were challenged to include one switch to turn on and off a LED. In session 3, participants were first shown how a pre-programmed microcontroller board could be used to turn on and off the provided LEDs (the programming of the board was out of the scope of these workshops), followed by open-ended collaboration time where teams could create a project that integrated the electric components. At the end of the last session, the participants took a post-test which assessed the understanding of the same content of the pre-test.

The curriculum was uniquely created for the purposes of this workshop and was enacted identically across the two conditions. Each condition introduced key terms (e.g., conductivity, current flow, load, resistance) and their relationship to the materials used, and followed a similar overview of activity. Where material differences necessitated instructions specific to each condition, the corresponding instruction was used in the other condition to minimize differences in how concepts were presented in each group (Table 2).

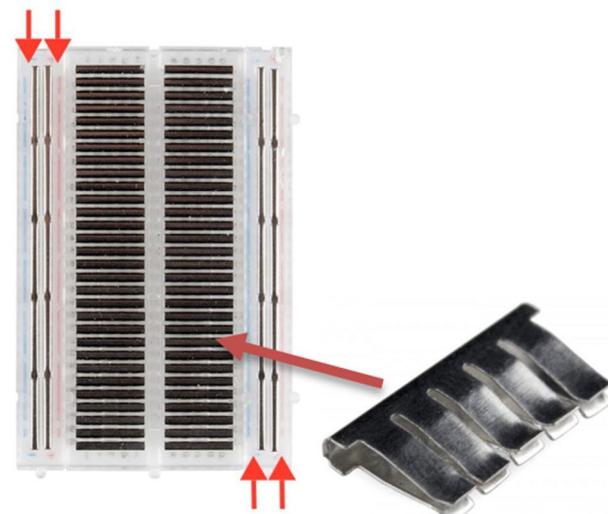
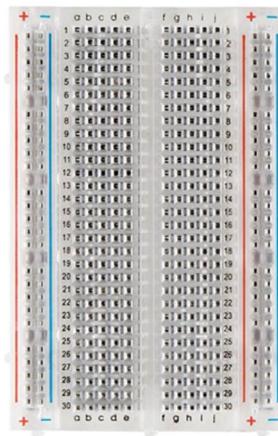
Toolkits

The two toolkits explored in this study were the traditional solderless breadboard and a paper circuitry toolkit, Chibitronics™ (Qi, 2012; Qi et al., 2015). Both toolkits were used to create circuits without the need of soldering to attach and connect electronic components.

Breadboards contain arrangements of tiny holes and metallic strips of clips, framed by two sets of vertical metal strips (rails or busses), that provide common power and ground when connected to a power source (see Fig 3).

Paper circuits combine paper crafts and arts with circuitry and computer programming. Paper-based surfaces serve as

Fig. 3 Front and back views of solderless breadboard exposing power rail columns and metallic rows of clips



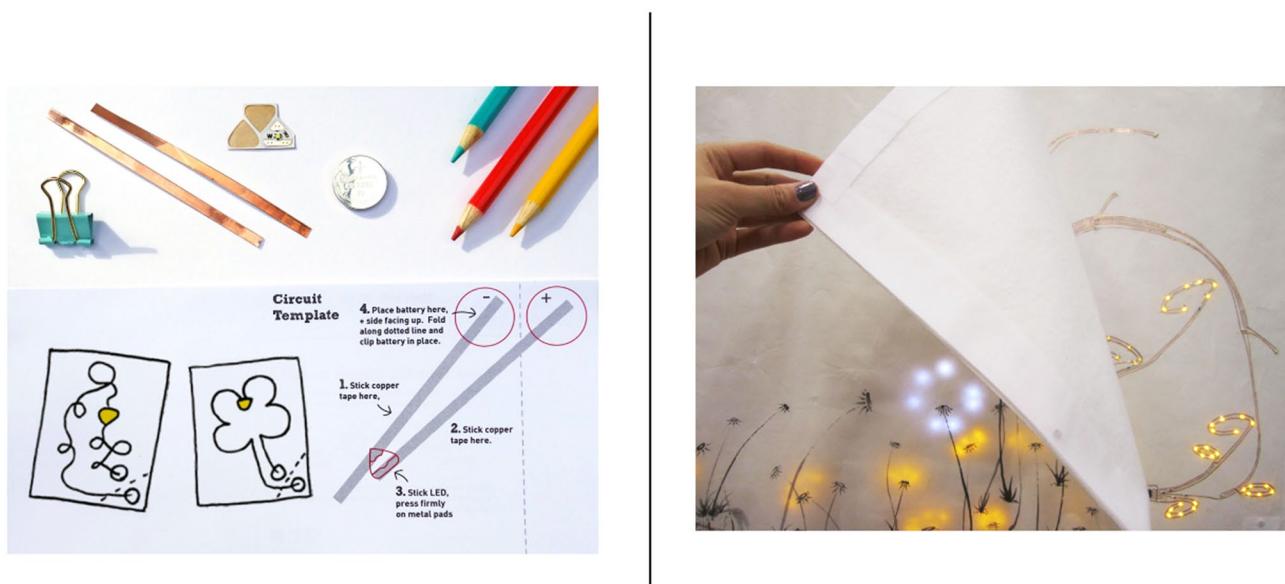


Fig. 4 Chibitronics™ materials with an introductory project (left); and Pu Gong Ying Tu (Dandelion Painting) by Jie Qi (right)

the foundation for circuit designs, upon which users place peel-sticker LEDs and copper tape to connect components to each other and to the power source. Paper circuitry is also solderless and the same fundamental circuit concepts apply to the components and circuit configurations to power the projects. However, while paper circuits can be used to prototype circuitry concepts and layout design principles, these materials are also designed to become more permanent forms of art-making. Paper circuit projects use copper tape to connect the circuit stickers to paper, which can then be surrounded by artistic elements with personal meaning (see Fig. 4). Paper electronics tend to appeal to people who already participate in crafting and who are willing to work with these circuit stickers regardless of the potential for complexity.

There are a couple of evident differences in circuitry design between the two toolkits (Table 3). The first difference has to do with space allocation due to the size of the work area. Paper circuit projects are not constrained by the small surface area of the breadboard to place and connect components, though multiple breadboards can be attached and multiple insulated wires can be used. The second difference is related to the placement of the components. Due to the space constraints of the connecting surface of the breadboard, components need to be connected to the metallic strips through the tiny openings which are already in close proximity. In addition, component orientation and alignment relative to each other is also constrained to the grid-like configuration of the breadboard. In contrast, sticker components of paper circuits can be placed throughout the paper-based surfaces. Finally, the third difference is related to the aspect of routing connections. Insulated

wires used for breadboard projects can touch and cross without causing short circuits. In contrast, connecting traces with copper tape cannot touch or cross because they will cause short circuits. Also, another distinct property of the position of the connecting elements (or routing) is that the copper tape in the paper circuits is positioned or routed on a 2-dimensional (2D) or flat surface making sure the traces do not touch. In the breadboard toolkit, the flexible insulated wires are placed on a 3-dimensional (3D) space on top, bottom, crossing, touching other wires. This 2D vs. 3D positioning of the connections facilitates or complicates (depending on the toolkit) accurate connections and troubleshooting actions. It can be easier to figure out accurate connections in the paper circuit projects.

Data Sources

The design of the pre- and post-circuit diagram assessments used in this study were used to assess circuitry understanding by creating working circuit diagrams of the power source and microcontroller boards in each question and stickers representing the switch and LEDs. As circuitry understanding is traditionally rooted in the tools and materials in which they are learned (e.g., Peppler & Glosson, 2013), pictures of the actual components were used to represent working circuit diagrams. We consulted with commercial kit designers, licensed teachers, historical examples found in textbooks, and licensed engineers over a period 18 months to refine the assessment, helping to ensure that the items and coding categories identified would have content validity. In constructing the rubric, we aimed to find alignment between what is valued by

Table 3 Comparison table of circuit components across the two toolkits

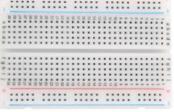
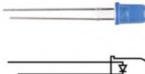
Workshop Materials	Breadboard	Paper Circuits (Chibitronics™)
Work Surface	 Solderless breadboards are rigid pieces of plastic with a pre-set grid. Thus, this work surface is neither flexible nor its size and form can be modified.	 The copper tape and LED stickers can stick to any type of paper-based material. One can use any color and size of paper material and change its form if desired (e.g., folding). The work surface may be incorporated into the final design of the artifact.
Power Source	 2 AA batteries used for a total of 3-Volts with a battery holder.	 3-Volt Coin cell for simple circuits and 2 AA batteries (3-Volts) in a battery holder to power the microcontroller board.
LED (load)	  The polarity is determined by the length of the leads. The longer lead (leg) is the positive terminal.	 The polarity is indicated by the + and - markings on the LED stickers. The "Y" on this image indicates the color of the light, yellow.
Switch	 Small commercial push-button switch.	 Switch made from conductive tape and folded paper.
Conductive connecting element	 Insulated wires with end-leads to insert into holes in the breadboard. These types of flexible wires are called "jumper wires."	 Conductive copper tape with conductive adhesive backing.
Microcontroller Board	 Microcontroller board from the open source Arduino hardware platform for quick prototyping. This circuit board can connect to sensors (input signals) and actuators (output actions) via the pins and jumper wires.	 Clipable microcontroller board with connecting pins on the clip's edges.

Table 4 Scoring criteria for basic circuit concepts and layout design principles per test

Concepts and principles	Scoring criteria	Points per question	No. of questions	Max score
Basic circuitry concepts				
Polarity (P)	Positive and negative sides of electrical components are correctly oriented to matching terminals of the power source (i.e., positive + terminal of the component connected to the positive + terminal of the power source)	0–1	8	8 (10*)
Current Flow (CF)	All components are connected in a loop with no redundant traces from the power source, to the output components, and back to the power source without gaps or short circuit-inducing overlaps	0–1	8	8 (10*)
Connections (C)	All traces representing wires or conductive material can be seen fully touching the conductive terminals of the power source and output components	0–1	8	8 (10*)
Subtotal				24 (30*)
Layout design principles				
Polarized component orientation (O)	Positive terminals of polarized components are consistently oriented toward the positive terminal or pin(s) of the microcontroller board. The consistent orientation among all polarized components decreases the chance opposite terminals or traces touch each other causing a short	0–3	4	12 (15*)
Trace-to-trace spacing (T)	The traces (wires or copper tape) for power and return-traces to ground do not touch. Also, positive traces connect to a pre-programmed pin without touching other positive traces	0–4	4	16 (20*)
Power distribution (PW)	Components connect to the positive terminal of the battery or to a microcontroller board pin without open gaps, and without redundant connections to components not needing power	0–3	4	12 (15*)
Ground distribution (G)	Components connect to the negative terminal of the power source or microcontroller board for the current to return without open gaps or redundant connections between component(s)	0–4	4	16 (20*)
Subtotal				56 (70*)
Total max. combined score per test				80 (100*)

*Standardized total scores in parentheses to compare scores between the different scales of basic concepts and layout design principles

industry and areas taught in the K-16 classrooms. Each assessment had four sections, one section corresponding to one circuitry toolkit: breadboard, paper circuits, little-Bits™ (Bdeir, 2009), and LilyPad Arduino (i.e., e-textiles) (Buechley et al., 2013). These sections of the assessment compared how youth formed working circuits using materials familiar to them (i.e., the kit they used during the workshop) against less familiar materials (i.e., the other three kits they did not use during the workshop), exposing general learning gains as well as indicators of preparedness for future learning (Bransford & Schwartz, 1999). Given that this is a new and exploratory area of research, this study aimed to check the utility and feasibility of this new instrument through a pre-post design to examine the extent to which the instrument could detect changes in overall understanding of circuitry and layout design over the course of the workshop.

To control for prior experience, each section asked participants if they had prior experience with each of the

presented four toolkits and asked them to use the provided stickers of electronics components and a pencil to diagram (A) a working circuit with one LED and a switch; and (B) a circuit where three LEDs in the circuit could perform a different function. This resulted in an eight-item assessment (two items for each of the targeted toolkits).

Analytical Techniques

In order to address our research questions, we used criteria presented in Table 4 to score each of the eight assessment diagrams according to the presence or not of understanding of the three basic circuitry concepts and layout design principles.

For questions on the basic circuitry concepts, we assigned a “0” if any of the three basic circuitry concepts were absent or a “1” if any were present. One of the authors and another research assistant coded 30 of the tests, randomly selected,

reaching a high interrater reliability of $\kappa=0.836$ (Cohen, 1960) before they split up the remaining assessments and coded the remaining data for basic circuitry concepts. Both raters were blind to the workshop condition, had backgrounds in engineering or robotics, and neither was an instructor during the workshop. To assess layout design, we assigned different values to the multi-function circuit diagrams (involving the three LEDs and a microcontroller) according to the presence of the four layout design principles. These codes were only applied to the four assessment items that asked learners to create working circuits with multiple LEDs. Two raters with experience with circuitry designs scored all tests together. Polarized component orientation was scored by assigning a 1 for each components' positive terminal oriented toward one of the microcontroller board's pins. Trace-to-trace spacing was scored by assigning one point for each line from each LED's positive terminal that did not touch any other positive and one more point if no positive line touched or crossed any negative lines. Power distribution was scored by assigning one point for each line that correctly connected each LED's positive terminal to a different pin in the microcontroller board to indicate proper connection to power. Finally, correct and effective ground distribution was scored with one point for each line that correctly connected each LED's negative terminal to the negative terminal of the microcontroller board and one more point for one shared line to the negative terminal.

Due to the fact that the scores for basic circuitry concepts and layout design principles have two different scales, maximum scores were multiplied by a factor of 5/4 (1.25) to standardize data and assist comparisons made between the two. See Table 5 for examples of coded items across pre- and post-tests.

Statistical Analysis

To determine how each of these toolkits impact the learning of simple circuitry and the practice of advanced circuitry design principles, we used SPSS to perform paired-samples *t*-tests to examine differences and changes between groups. We ran paired-samples *t*-tests for each of the seven constructs to compare groups at different points in time (i.e., within-subjects factor). We also ran independent-samples *t*-tests to compare the mean gain scores of basic and design layout constructs for the two independent workshop groups (i.e., between-subjects factor) to determine how each toolkit related to each of the seven constructs.

The unequal sample size ($n=12$ and $n=9$ for each of the groups) made this an unbalanced design. Therefore, we used the results of the Welch *t*-test to correct for these types of unbalanced designs (Howell, 2010). We checked all assumptions for the normal distribution of variables, homogeneity of variances, and identification of problematic extreme

outliers. The variables for connections, polarity, and ground violated the normality assumption with *p* values less than 0.05 in the Shapiro–Wilk test. However, considering the exploratory nature of this study, we proceeded performing the *t*-tests backed by previous findings from Boneau (1960), Posten (1984), and Schmider et al. (2010), confirming the robustness of *t*-test and ANOVA to violations of normality.

Findings

Overview of Combined or Total Scores

Both toolkit groups had statistically significant within-group differences, where learners in both groups performed better in the post-test than in the pre-test. However, when comparing pre- to post-test scores, youth had a higher gain mean score for paper circuits as compared to the breadboard workshop in terms of combined scores, basic concepts, and layout design principles. After running independent-samples *t*-tests of the total scores between groups (Fig. 5), we found two differences of total gain scores of breadboard and paper circuits to be statistically significant but at the $p < 0.10$ level using Welch's test for correction of unequal sample sizes, $t(16.050) = -2.096$, $p = 0.052$, with a large effect size of Hedges' $g = 0.9$.

This overview presented all *t*-tests with total scores, so we further breakdown these total scores by performing *t*-tests of each of the three basic concepts and four layout design principles.

Basic Circuitry Concepts

Participants in both groups performed better in the post-test for each of the three basic concepts with gains after the workshops. For the breadboard workshop condition, the highest gain score was for current flow ($M=20.8$, $SD=25.7$, $p < 0.05$), followed by polarity ($M=9.4$, $SD=22.7$) and connections ($M=7.3$, $SD=12.5$, $p < 0.1$). For the paper circuit workshop condition, the highest gain score was for polarity ($M=33.3$, $SD=21.7$, $p < 0.05$), followed by current flow ($M=15.3$, $SD=23.2$, $p < 0.10$) and connections ($M=11.1$, $SD=17.1$, $p < 0.10$). The only gain without significant difference between pre and post was the polarity score for the breadboard workshop.

When we ran independent-samples *t*-tests of the gain scores for the three basic concepts, current flow, connections, and polarity, the only mean gain score to achieve statistical significance at the $p < 0.05$ level (using Welch's test) was polarity, where the mean gain score in the paper circuits ($M=33.3$, $SD=21.7$) surpassed the breadboard group ($M=9.4$, $SD=22.7$). We believe the printed positive (+) and negative (-) signs on the corresponding terminals

Table 5 Example of pre- and post-test scoring of each test section (cases from Kiera and Eileen—both pseudonymous) from the papercircuit workshop

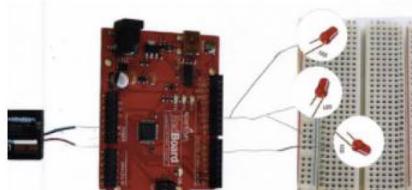
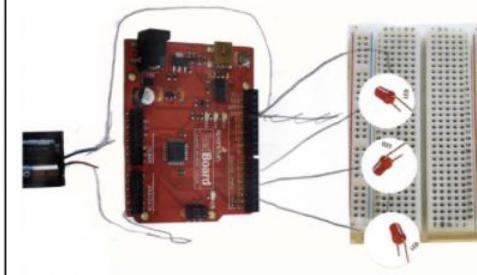
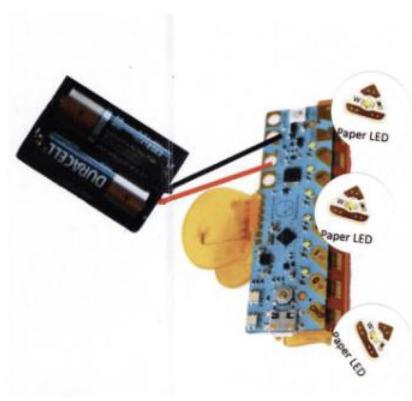
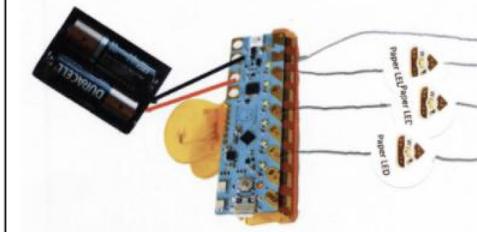
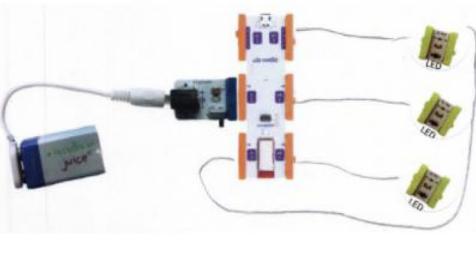
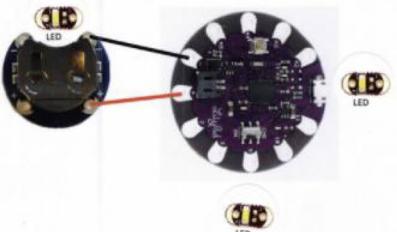
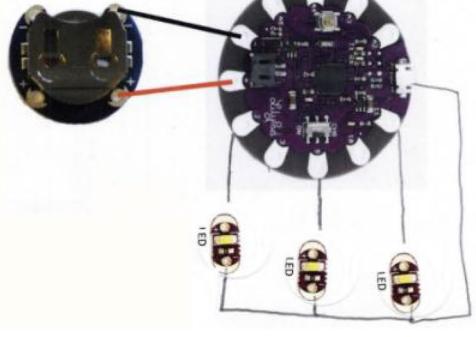
	PRE-test/Scores & Interpretation	POST-test/Scores & Interpretation	
Test Item	<u>Basic Circuitry:</u> Current Flow (CF), Connections (C) and Polarity (P) <u>Layout Design:</u> Polarized Component Orientation (O), Trace-to-Trace Spacing (T), Power Distribution (PW) and Ground Distribution (G)		
Breadboard Toolkit	 	<p>Eileen's pre-test diagram revealed a number of misconceptions: None of the LEDs have its own loop to the battery; two top LEDs are placed in the wrong section of the breadboard; two LEDs are aligned to each other and oriented in the same direction; and the three connecting traces are touching each other.</p> <p>Score = 4: CF0, C0, P1, O2, T0, PW1, G0</p> <p>Eileen's post-test diagram showed improvement: Each LED has its own loop to the microcontroller board; each positive trace from the 3 LEDs do not touch; Each LED connects to a power source; and all 3 LEDs are connected to the correct negative terminal of the board and redundant lines are removed.</p> <p>Score = 12: CF1, C1, P0, O0, T3, PW3, G4</p>	
Paper Circuits Toolkit			<p>In Kiera's diagram, none of the basic concepts were present: None of the LEDs had its own loop to the microcontroller board; there were no drawn lines connecting any of the components, including the board and the LED terminals; though the positive terminal of the 3 LEDs were correctly oriented towards the microcontroller board.</p> <p>Score = 3: CF0, C0, P0, O3, T0, PW0, G0</p> <p>Kiera's diagram showed improvement in her post test: Each LED has its own loop to the microcontroller board; drawn lines connect all components to the correct pin; each trace from the 3 LEDs do not touch or cross and 1 point for no crossing of positive and negative lines; Each LED connects to a power source; and negative terminals of all 3 LEDs are connected to the correct negative terminal of the board and all lines connect to only one line for common ground.</p> <p>Score = 17: CF1, C1, P1, O3, T4, PW3, G4</p>

Table 5 (continued)

littleBits Toolkit	 	<p>In Eileen's diagram, none of the basic concepts were present: None of the LEDs have its own loop to the power source; LEDs are placed on top of the microcontroller board, not adjacent to it; the positive terminal of the 3 LEDs are on top of the board; and no drawn lines connect the components. The LEDs are oriented correctly, however.</p> <p>Score = 1: CF0, C0, P1, O0, T0, PW0, G0</p>	<p>Eileen's diagram showed improvement in her post test: Each LED has its own loop to the microcontroller board; Drawn lines connect all components to the correct pin, as well as the microcontroller board and the positive terminals of the LEDs; Each positive terminal of the 3 LEDs is oriented toward a correct positive pin; Each trace from the 3 LEDs do not touch or cross and 1 point for no crossing of positive and negative lines; and none of the 3 LEDs is connected to the correct negative terminal of the board (but it has 1 point for removing redundant lines and connecting all lines to only one line to common ground).</p> <p>Score = 14: CF1, C1, P1, O3, T4, PW3, G1</p>
e-Textiles Toolkit	 	<p>In Kiera's diagram, none of the LEDs has its own loop to the microcontroller board, and there are no drawn lines connecting any of the components.</p> <p>Score = 1: CF0, C0, P0, O1, T0, PW0, G0</p>	<p>Kiera's post-test diagram showed improvement: Each LED has its own loop to the microcontroller board; drawn-lines connect all components; each positive terminal of the 3 LEDs is oriented toward the correct pin; and none of the 3 LEDs is connected to the correct negative terminal of the board (but it has 1 point for removing redundant lines and connecting all lines to only one line to common ground).</p> <p>Score = 13: CF1, C1, P1, O3, T4, PW3, G1</p>

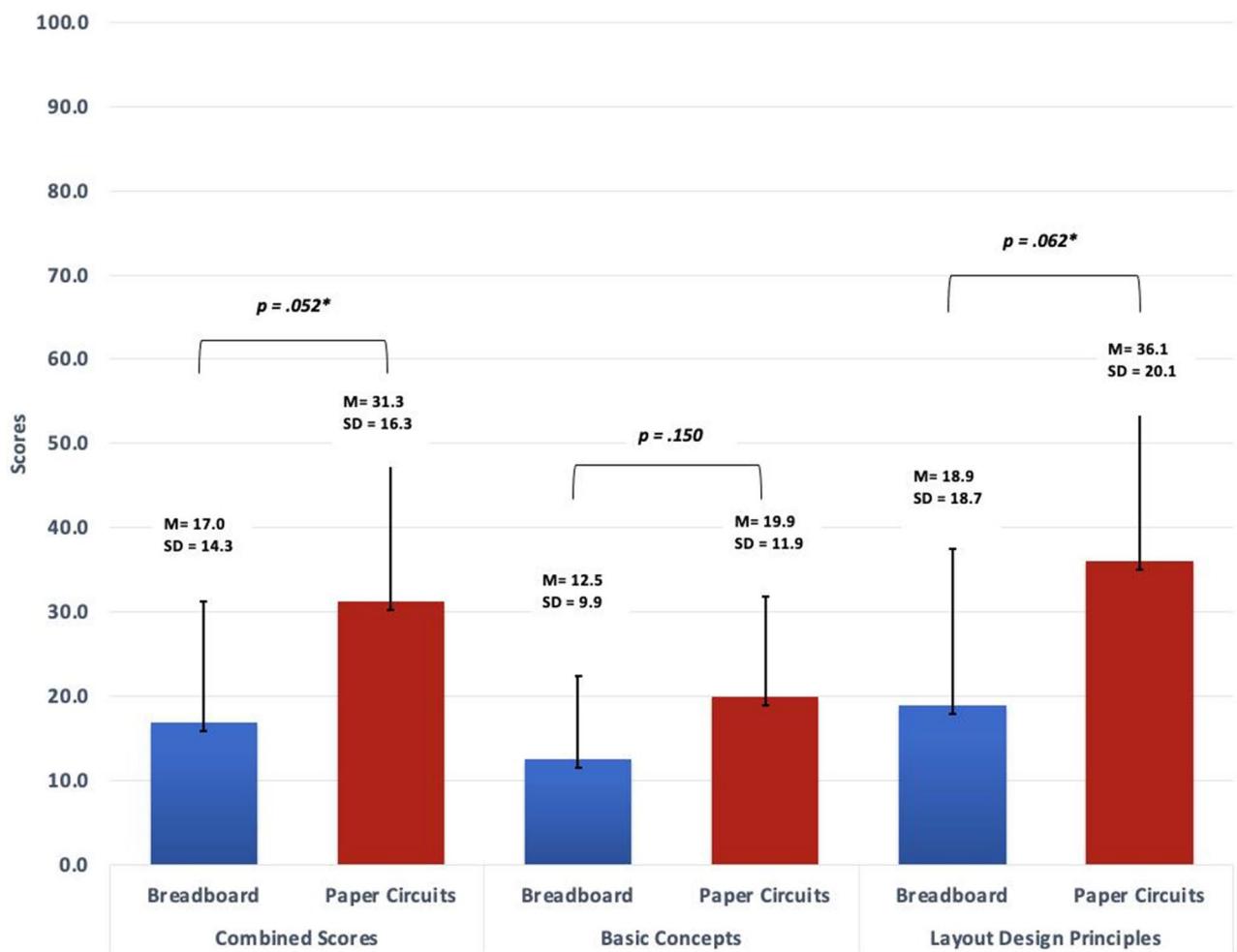


Fig. 5 Comparisons of combined or total mean gain scores between toolkits. Note. Mean (M), standard deviation (SD), and statistical significance (p) are displayed. *Significant difference at the $p < 0.10$ level

on the LED stickers used in the tests may have contributed to the higher gain scores for the paper circuit participants.

Design Layout Principles

Participants in both groups performed better for each of the four layout design principles with gains after the workshops (see Fig. 6). For the breadboard workshop condition, the highest gain scores were for ground distribution ($M = 28.6$, $SD = 28.4$) and power distribution ($M = 28.5$, $SD = 36.7$), both statistically significant at $p < 0.05$ level, followed by trace-to-trace spacing ($M = 9.4$, $SD = 25.8$) and orientation of polarized components ($M = 9.0$, $SD = 17.6$), none with statistically significant differences. In contrast, all gain scores for design layout principles from the paper circuit workshop condition were statistically significant at $p < 0.05$ level. The highest gain score was for power distribution ($M = 56.5$, $SD = 27.6$), followed by trace-to-trace spacing ($M = 31.9$, $SD = 28.2$), orientation of polarized components

($M = 30.6$, $SD = 31.7$), and ground distribution ($M = 29.2$, $SD = 22.3$).

Independent-samples t -tests that compared mean gain scores for the four layout design principles between toolkits (Fig. 7) revealed that power distribution gains were higher in the paper circuit group ($M = 56.5$, $SD = 27.6$) than the breadboard group ($M = 28.5$, $SD = 36.7$) and statistically significant at $p < 0.10$ level (using Welch's test). Similarly, the mean gain score for trace-to-trace spacing in the paper circuit group ($M = 31.9$, $SD = 28.2$) exceeded that of the breadboard group ($M = 9.4$, $SD = 25.8$), just as it did regarding orientation of polarized components (paper circuits: $M = 30.6$, $SD = 31.7$; breadboard: $M = 9.0$, $SD = 17.6$), both statistically significant at $p < 0.10$ level (using Welch's test). Finally, the mean gain score in the paper circuits for ground distribution ($M = 29.2$, $SD = 22.3$) was a bit higher than that of the breadboard group ($M = 28.6$, $SD = 28.4$) but not statistically significant ($p = 0.963$).

Fig. 6 Comparison of trace spacing (and routing) of a PCB and paper circuit and breadboard projects. (1) An example of a PCB showing parallel and non-crossing traces illustrating a proper trace-to-trace spacing. (2) Paper circuit project depicting a similar 2D configuration as an actual PCB. (3) Same circuitry project using a breadboard but with a convoluted 3D configuration with touching traces (wires)

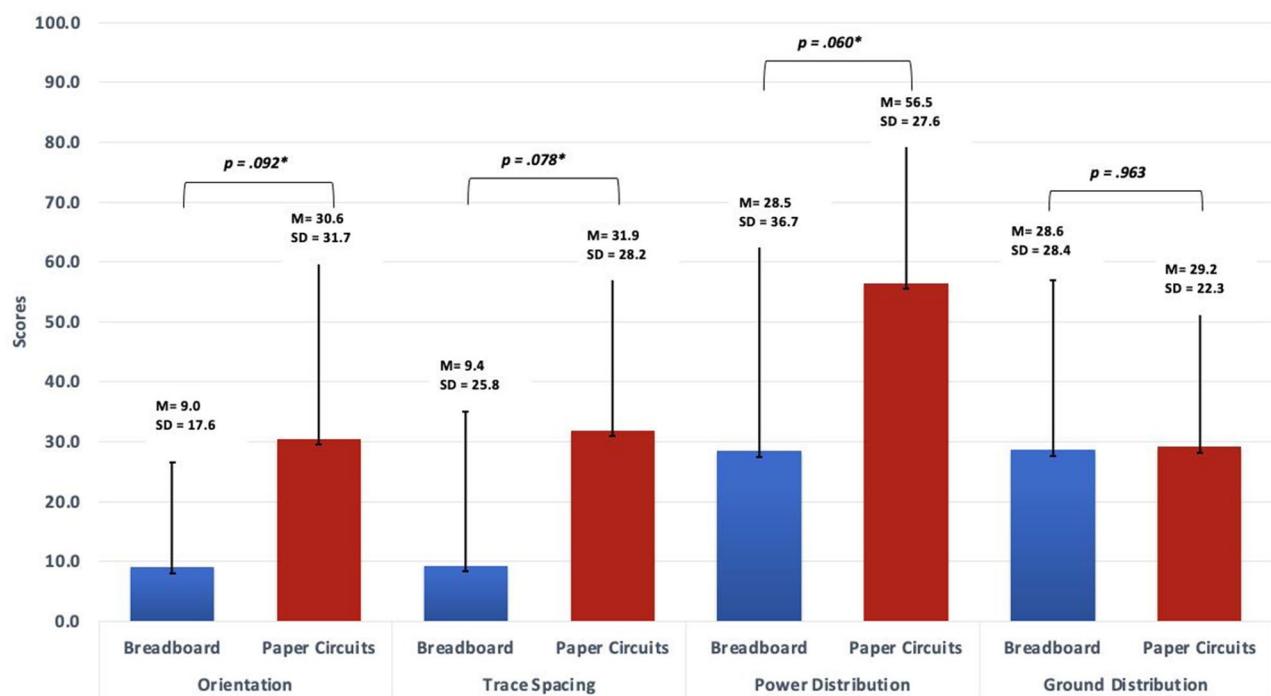
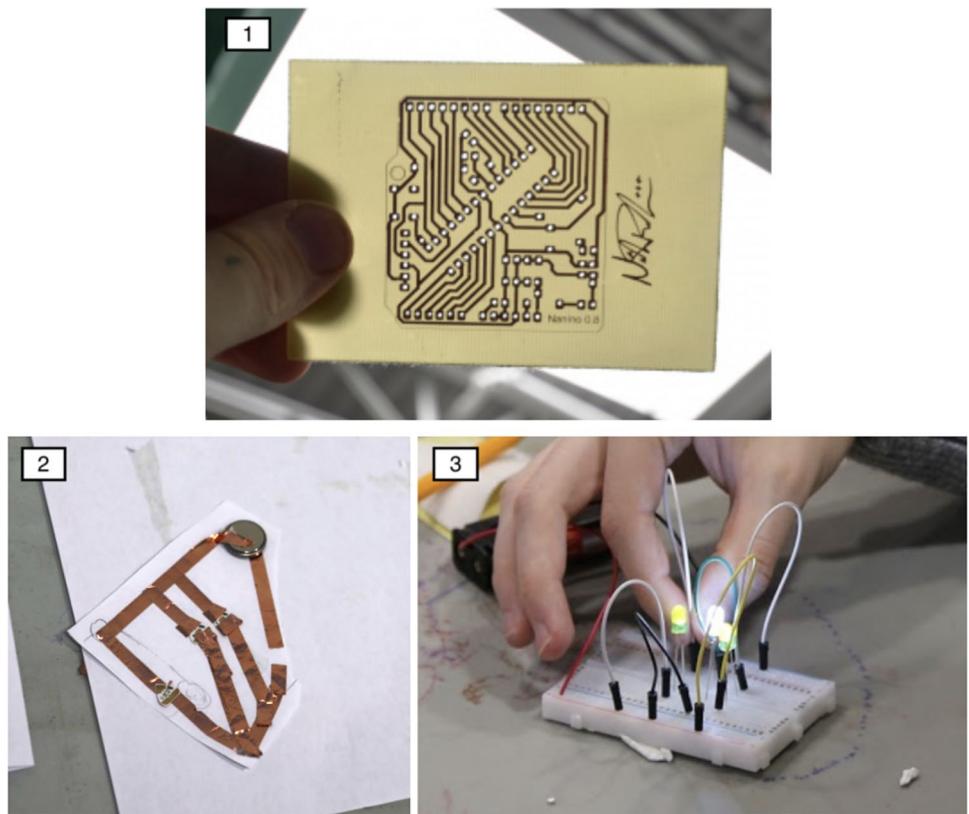


Fig. 7 Comparisons of mean gain scores of layout design principles between toolkits. Mean (M), Standard deviation (SD), and statistical significance (p) are displayed. *Significant difference at the $p < 0.10$ level

Table 6 Effect sizes within the breadboard group

Concepts and principles	Within group comparison pre- v. post-test: breadboard ($n=12$)			
	Pre-test sample mean score	Post-test sample mean score	Significance, p	Repeated measures effect size, Hedges'
	x_{Pre}	x_{Post}		g_{rm}
Current flow	33.3	54.2	0.017**	0.95 (large)
Connections	0.0	7.3	0.067*	0.77 (large)
Polarity	20.8	30.2	0.180	0.62 (medium)
Orientation of polarized components	64.6	73.6	0.103	0.35 (small)
Trace-to-trace spacing	46.9	56.3	0.234	0.36 (small)
Power distribution	43.1	71.5	0.021**	0.89 (large)
Ground distribution	4.7	33.3	0.005***	1.20 (very Large)

* $p<0.10$; ** $p<0.05$; *** $p<0.01$

Effect Sizes: Within and Between Groups

Effect sizes provide the actual magnitude of the differences of the mean scores (Coe, 2002; Sullivan & Feinn, 2012; Lakens, 2013; Cumming, 2014), but since experimental designs generally deal with sample effect sizes (not population effect sizes), they are influenced by sampling variability brought by the sample sizes. Thus, we also calculate confidence intervals for all sample effect sizes.³

Effect Sizes Within Groups

The repeated measures effect size Hedges' g_{rm} compares standardized effect sizes in order to illustrate the magnitude of the sample mean difference. For example, the effect size for connections between pre and post in the breadboard group was Hedges' $g_{rm}=0.77$, indicating that the magnitude of the sample mean difference between pre and post is 0.77 standard deviations. The breadboard toolkit also had large effects for the basic concept of current flow (Hedges' $g_{rm}=0.95$) and for the layout design principles, power ($g_{rm}=0.89$) and ground distribution ($g_{rm}=1.20$) (Table 6).

We can conclude that larger post-mean scores are evidence of learning for these concepts after the participants participated in the breadboard workshop. For the large effect sizes on current flow ($g_{rm}=0.95$), power ($g_{rm}=0.89$), and ground ($g_{rm}=1.20$) distribution, we conjecture that the marked power rails with the positive (in red) and negative (in blue) signs and lines along the rails (see Fig. 3) supported the learner to follow the direction of the current flow from the power source and back to ground. In contrast, the paper circuit toolkit had large effects in the basic concepts of connections (Hedges' $g_{rm}=0.83$) and

polarity ($g_{rm}=2.15$), and in all layout design principles, orientation of polarized components ($g_{rm}=1.02$), trace-to-trace spacing ($g_{rm}=1.18$), power distribution ($g_{rm}=2.02$), and ground distribution ($g_{rm}=1.73$) (Table 7).

Effect Sizes Between Groups

All large effect size differences favored the paper circuit group over the breadboard group. The only large effect for the basic concepts was polarity (Hedges' $g_{rm}=1.03$) but large effects were found in all of the layout design principles: orientation of polarized components ($g_{rm}=0.84$), trace-to-trace spacing ($g_{rm}=0.81$), and power distribution ($g_{rm}=0.81$) (see Table 8). We interpret the small effect sizes for current flow, connections, and ground distribution (in Table 8) as neither the paper circuits nor the breadboard toolkit performs higher than the other. In other words, both workshops seemed to positively impact higher scores (see medium to large effect sizes in Tables 6 and 7).

Discussion

In examining the outcomes of this study, we see that both toolkits advance understanding, yet the tools and materials used in the paper circuit toolkit vastly outperform the standard breadboard kit in terms of affording possibilities for learning targeted concepts and layout design principles. To explain these differences, we can turn to prior research that illuminates how the materials (e.g., metal, plastic), properties (e.g., transparent, hard, flexible, weight), and forms (e.g., shape, size) of our STEM educational toolkits impact learning outcomes (Peppler & Glosson 2013; Peppler et al., 2018). Viewing these findings through the constructionist notions of body syntonicity and material syntonicity (Keune, 2022), we start to understand how tools and actions that mirror and mimic the embedded concepts may lead to stronger outcomes in learning and understanding.

³ Hedges' g effect size (refer to the “Methods” section for rationale).

Table 7 Effect sizes within the paper circuit group

Concepts and principles	Within group comparison pre- v. post-test: paper circuits (<i>n</i> = 9)			
	Pre-test sample mean score	Post-test sample mean score	Significance, <i>p</i>	Repeated measures effect size, Hedges' <i>g_{rm}</i>
	<i>x_{Pre}</i>	<i>x_{Post}</i>		
Current flow	37.5	52.8	0.084*	0.68 (medium)
Connections	0.0	11.1	0.086*	0.83 (large)
Polarity	27.8	61.1	0.002***	2.15 (huge)
Orientation of polarized components	45.4	75.9	0.020**	1.02 (large)
Trace-to-trace spacing	35.4	67.4	0.009***	1.18 (very Large)
Power distribution	29.6	86.1	<0.001***	2.02 (huge)
Ground distribution	4.2	33.3	0.004***	1.73 (very large)

p* < 0.10; *p* < 0.05; ****p* < 0.01

In this instance, we can hypothesize that human-material interactions create concept-clarifying parallels between the body and the objects being manipulated.

Furthermore, we also see that paper circuits promote arts integration with STEM, leading artistic exploration into STEM engagement. In this case, the comparatively prescribed design options for a breadboard are replaced by the “blank canvas” of paper and the addition of crafting supplies, encouraging learners in the paper circuit condition to imagine new possibilities for circuit design. Creating a circuit using copper-colored tape and paper provides flexibility and possibility for exploration with esthetics, color, shape, unexpected uses of circuits, and more. According to Papert, exploring concepts through personalized interaction and imagination forges the formation of powerful ideas of a domain. This is a similar pattern found in other toolkits that promote artistic engagement; in addition to a more artistic output, the process of crafting these types of circuits seems to deepen opportunities for applications of STEM concepts for greater learning.

Further, arts integration seems to demonstrate a broader applicability for transfer of circuitry concepts from one set of context and materials to another. With flexible materials that require deep embodied actions, such as pressing down copper tape along its entire trace, circuitry kits like paper circuits create a unique type of relationship between the materials and the elements that are necessary to build a working circuit. This leaves space for learners to apply parts of that close relationship to other toolkits and potentially learn the new materials more easily. This power of the more arts-based toolkits is echoed in studies where learners who used such kits outperformed their peers (Peppler et al., 2018). Maker toolkits and the integration of new materials bring about promising new ways to rethink how concepts are taught, and help educators and designers imagine new ways for electrical engineering to advance societal needs unmet by our current uses of electrical energy.

Table 8 Effect sizes of between group comparison

Concepts and principles	Between group comparison of breadboard v. paper circuits			
	Breadboard sample mean gain score	Paper circuit sample mean gain score	Significance, <i>p</i>	Effect size, Hedges' <i>g</i>
	<i>x_B</i>	<i>x_{PC}</i>		
Current flow	20.8	15.3	0.611	0.22 (small)
Connections	7.3	11.1	0.579	0.25 (small)
Polarity	9.4	33.3	0.024**	1.03 (large)
Orientation of polarized components	9.0	30.6	0.092*	0.84 (large)
Trace-to-trace spacing	9.4	31.9	0.078*	0.81 (large)
Power distribution	28.5	56.5	0.060*	0.81 (large)
Ground distribution	28.6	29.2	0.963	0.02 (very small)

p* < 0.10; *p* < 0.05

Table 9 Toolkit features that afford or obstruct learning of targeted basic circuitry concepts

Targeted basic circuitry concepts	Toolkit features	Chibtronics/paper circuits	Solderless breadboards
Current flow	Simpler configuration ✓ The (one-side sticky) copper tape affords its placement on a flat 2D surface and does not occupy 3D space. This avoids entanglement with other traces and generally affords perceiving the circuit loops where the current flows from/back to the power source (compare Figs. 2, 3, 4, 5, 6, 7 and 8 with Figs. 3, 4, 5, 6, 7, 8 and 9)	Complex 3D wire configuration ✗ The non-insulated ends of the jump wires get connected to the breadboard, but the rest of the insulated wires may touch other wires. This extra length of wires occupies 3D space and may entangle with other cables (compare Figs. 2, 3, 4, 5, 6, 7, 8 and 9 with Figs. 3, 4, 5, 6, 7, 8 and 9). This convoluted configuration makes it harder to perceive the circuit loops where the current flows from/back to the power source Marked power rails for energy supply ✓ + The vertical power rails are marked with positive and negative signs and color lines along the rails (positive red, negative blue; see Fig. 3). Both marked rails seem to help users to identify where the current flows “from” and “back” to the power source Insulated and hidden ✗ Connections between the components and the breadboards are hidden and not visible under the holes of the breadboard. While jump wires covered with insulating plastic can touch without risk of a short circuit, educators could not teach this phenomenon with insulated materials Weaker connections ✗ The connections between the LED stickers and the copper tape traces get weaker as the stickers lose their tack when users frequently move and manipulate their project. Components (e.g., LEDs) and tape are not reusable	The vertical power rails are marked with positive and negative signs and color lines along the rails (positive red, negative blue; see Fig. 3). Both marked rails seem to help users to identify where the current flows “from” and “back” to the power source Stronger connections ✓ + The connections between the breadboard, power source, and components are strong and do not easily break with movement during manipulation. Components connected to the breadboard are not soldered and can be reused Polarity unlabeled ✗ Through-hole LEDs do not have labels to indicate polarity. These small components depend on their shape configuration to be identified (e.g., longer LED leg = positive, flat side of the bulb = negative)
Connections	Exposed and visible ✓ + The connections between the copper tape traces and the components are exposed and visible. Also, copper tape traces connected to the positive and negative (ground) terminals had to be kept separated from each other to avoid short circuits and have a working circuit		
Polarity*	Shape and label redundancy ✓ + The triangular shape of the LED stickers (larger side = positive) and the + sign printed on the sticker provide two ways to recognize positive polarity		

Key:

✗ = feature obstructs learning.

✓ = feature positively affords learning.

✓ + = feature positively affords learning and with higher potential for it.

*The paper circuit toolkit afforded higher gain scores of this basic concept with larger effect sizes when compared to the breadboard toolkit (see Table 7)

Table 10 Toolkit features that afford or obstruct learning of targeted design layout principles

Targeted design layout principles	Toolkit features	
Oriented components*	Chibitronics (paper circuits)	Solderless breadboards
Orientation of polarized components*	Polarity easily identified ✓ + Redundancy of shape and labels on polarized components afford correct orientation and placement Not-reusable ✗	Polarity not easily identified ✗ Lack of redundancy of shape and labels on polarized components do not afford correct orientation and placement Reusable components ✓
Trace-to-trace spacing*	Not reusable stickers make corrections on orientation very hard to fix once they are placed on the paper and copper tape Flat 2D traces ✓ +	Generally, through-hole components for breadboards can be quickly inserted and removed in the breadboard quickly fixing their orientation Potential 3D wire entanglement ✗ Insulated wires afford connections in multiple directions and complex configurations, but they are difficult to follow and trace current flow. Entangled wires obstruct visual perception for troubleshooting connections of components (Fig. 9)
Power distribution*	Exposed and labeled positive terminal ✓ + The exposed and labeled positive terminal of the components (i.e., LEDs) afforded accurate connection to the positive terminal of the battery for proper power distribution	Labeled positive rail ✓ + The labeled and colored positive rail of the breadboard afforded accurate connection for proper power distribution
Ground distribution	Exposed and labeled negative terminal ✓ + The exposed and labeled negative terminal of the components (i.e., LEDs) afforded accurate connection to the negative terminal of the battery for proper grounding Consolidation of negative traces ✓ + All negative traces from multiple components could be consolidated into one trace when connecting to common ground and avoid unnecessary and redundant traces	Labeled negative rail ✓ + The labeled and colored negative rail of the breadboard afforded accurate connection for proper ground distribution Large negative rail for connecting to common ground ✓ + Multiple negative wires from all components could be connected to the negative rail for common ground. The negative rail could accommodate multiple connections

Key:

- ✗ = feature obstructs learning
- ✓ = feature positively affords learning
- ✓ + = feature positively affords learning and with higher potential for it

*The paper circuit toolkit afforded higher gain scores of this design principle with larger effect sizes when compared to the breadboard toolkit (see Table 7)

Implications for Teaching and Learning

While we have a good understanding of the features that promote basic circuitry learning, more work is needed to tightly tie design features to advanced STEM conceptual categories. In this effort, we explore design features of each toolkit in support of electrical engineering concepts, based on their relative strengths in cultivating these understandings. Based on our findings, we list relevant toolkit features and how they afford or obstruct learning of targeted circuitry concepts and design layout principles (Tables 9 and 10).

The design hypotheses included here build on a growing body of research on the materiality of learning (Peppler & Glosson 2013; Peppler et al., 2018), which urges for a new mapping of design features and theoretical content to be further tested. In combination with the findings presented in this study, such design recommendations encourage educators to be deliberate when considering using any type of educational toolkit and assess how the materiality and features of the toolkits can positively afford or obstruct possibilities for learning. Additionally, these observations can be used to empirically inform the design of future toolkits, inviting designers to better align their design choices to targeted conceptual content.

Implications for Assessment

This study presented an initial foray into addressing the need for new educational assessments and studies on circuitry and layout design. The above results demonstrated that the tested rubric is both reliable and valid for use in out-of-school electronics workshops: its content was validated by consulting with teaching artists and by aligning to standards and showed high inter-rater reliability.

A strength of the assessment is that it took place in the context of a short 3-day workshop activity in a low-stakes environment. As the activity captures learning over time, the rubric could be used at different time points to evaluate student development across the selected concepts measured by the instrument (sample items are in Table 4). This initial effort to create an unobtrusive, research-based assessment toward the support of program evaluation and other interested stakeholders shows promise in its reliability, validity, and ability to assess learning over time.

Conclusion, Limitations, and Further Work

By performing systematic studies on recent electronic tools and materials, this study sought to understand how more advanced circuitry and layout design principles can be materialized for future teaching and learning experiences. In the process, findings suggest illuminate design principles for future toolkits to effectively support learning. Further research should seek to test each of the design hypotheses listed here under controlled experiments and a broader range of participants and settings (see Table 11 for an emerging set of design principles specific to this work). To clarify the relationship between these design features and their learning outcomes, it would require that we provide opportunities for learners to engage with multiple types of materials and closely examine the actions and interactions that the materials prompt and discourage.

Additionally, further work is needed on convergent and discriminant validity of the circuitry and layout design assessment instrument. A limitation of the current design is that we did not employ other measures of reliability such as test-retest reliability and internal consistency. Test-retest reliability was not appropriate for the two treatment groups since we hypothesized that scores would change over time. Future research could add a control group to establish test-retest reliability and examine the internal consistency of the rubric, as another indicator of its reliability.

Appendix 1: Layout Design Principles Derived From the General PCB Design Principles

In order to operationalize the general design principles of space allocation, placement of components, and routing for this experimental and exploratory study, we consulted relevant literature and experts in the field to derive the following constructs: polarized component orientation, component spacing, trace-to-trace spacing, correct and efficient power distribution, and correct and efficient ground connection. The table below summarizes the general design principles and the five design constructs we call layout design principles for this study.

Table 11 Layout design principles derived from the general PCB design principles

General PCB design principles (Webb, 2016; Wilson, 2018; Kularatna, 2008; Mitzner et al., 2019)	Layout design principles for this study
<ul style="list-style-type: none"> I. Space allocation or floorplanning <ul style="list-style-type: none"> • Take into account size of materials, as larger surface areas increase costs • Aim for shorter and direct connections to improve circuit performance and speed of data transmission • Avoid small and complex geometric configurations that are harder to manufacture II. Placement of components <ul style="list-style-type: none"> • Organize components with proper spacing and alignment • Face polarized components the same way III. Routing or trace positioning <ul style="list-style-type: none"> • Avoid open circuits by properly connecting components • Avoid unwanted interactions such as short circuits • Directly connect between elements to avoid redundant connections and unnecessary trace or track's length • Connect each load to input power according to energy requirements • Connect each load to common ground avoiding redundant connections 	<ol style="list-style-type: none"> 1. Polarized component orientation 2. Component spacing* 3. Trace-to-trace spacing 4. Correct and efficient power distribution 5. Correct and efficient ground connection

*Based on pilot implementation and analysis, this design principle was not included in this study because it is relative to factors that were not relevant for our study context (i.e., material costs, heat avoidance, and signal interference). However, we may develop this component spacing construct in future studies

Appendix 2: 95% Confidence Intervals for Effect Sizes (Hedges' g)

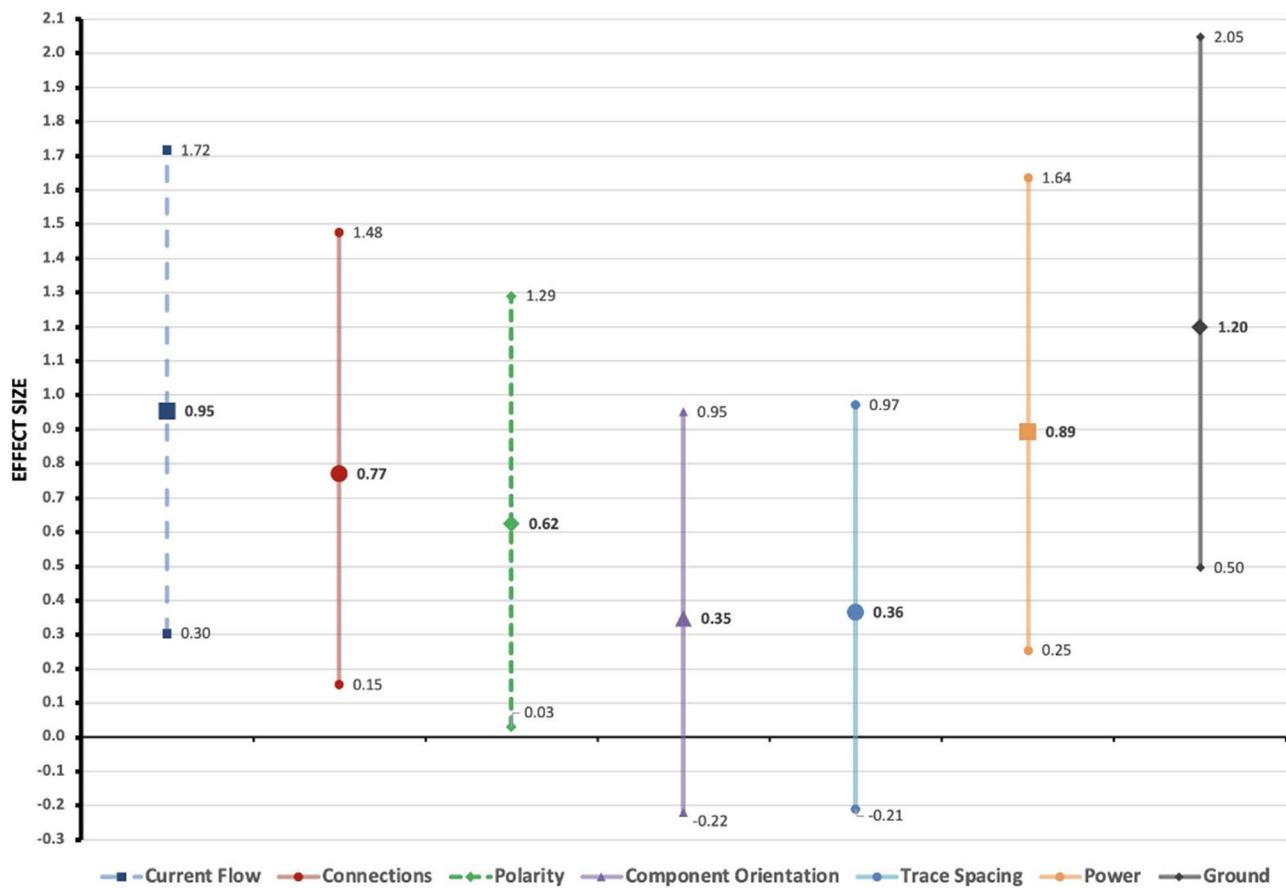


Fig. 8 Confidence intervals for basic concepts and layout design principle from comparison (pre vs. post) of mean gain scores within the paper circuit group

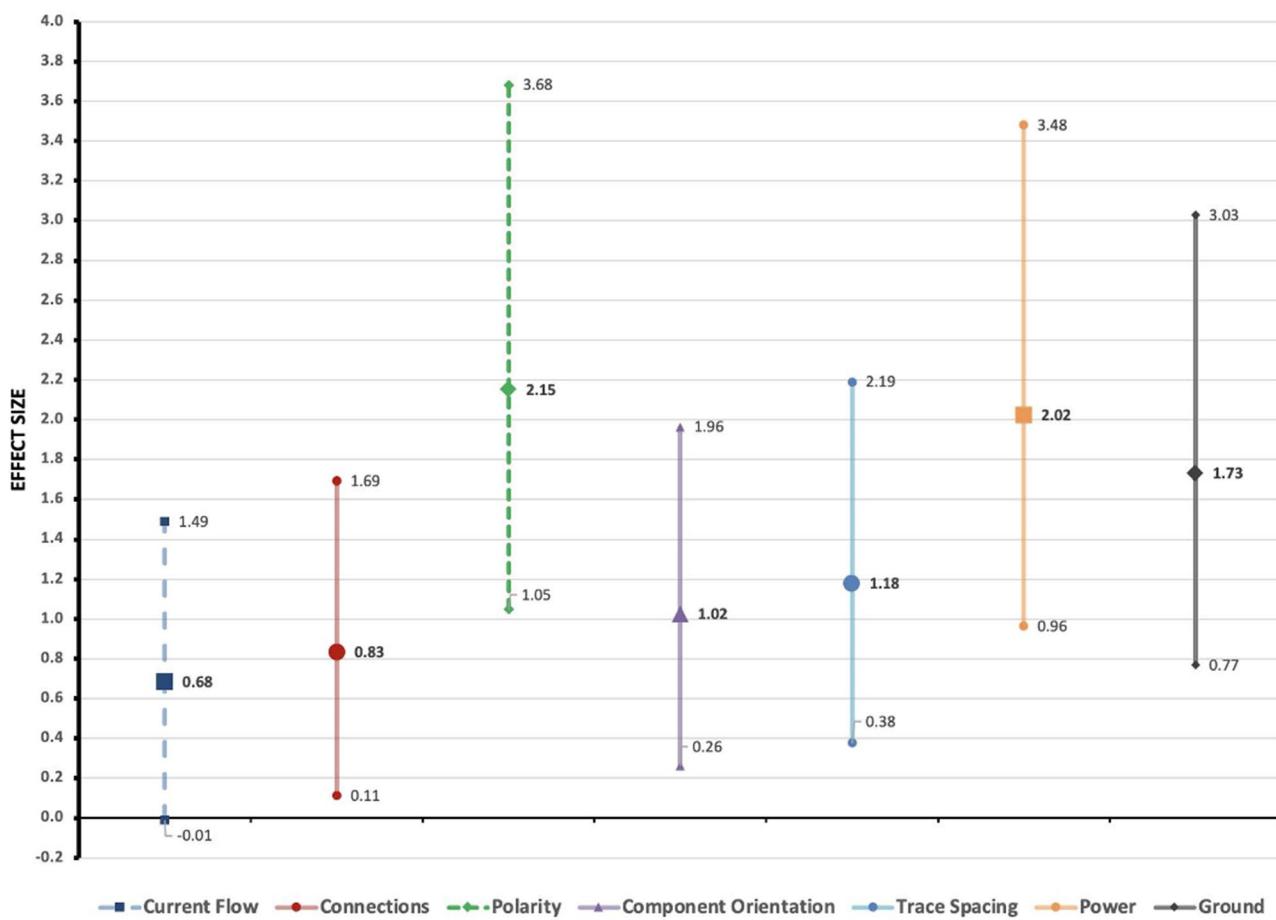


Fig. 9 Confidence intervals for basic concepts and layout design principle from comparison (pre vs. post) of mean gain scores within the breadboard group

Appendix 3: Curriculum Overview

Day 1.

Breadboard condition	Paper circuit condition
2 min in: introduction	
• Explain that the goal of the 3-day workshop is to learn basic principles of electricity and electronic circuit design	
30min: sticker activity (“pre-test”)	
• Have students answer questions about their experience with circuitry kits	
• Pre-test: place stickers of LEDs and switches in front of each student (the stickers are of LEDs and switches of 4 different kits: e-textiles, breadboard, paper circuits, littleBits)	

Breadboard condition	Paper circuit condition
Simple circuit: lighting 1 LED 2–3 min: introduction to activity	
<ul style="list-style-type: none"> Ask participants to mention 3–5 devices that use electricity to work. Mention each student will have the necessary materials to create something of their own and help each other 	
3–5 min: introduction to materials and key terms and definitions	
<ul style="list-style-type: none"> Explain to each individual the goal to light a LED with the new components they receive Batteries are the source of electrical energy. The ends of the battery are called terminals or poles. Batteries have very small “active” particles called electric charges that want to move from one terminal of the battery to the other To use the batteries, we commonly placed them in a holder. We put the positive end (or pole) of the battery marked with a plus sign (+) on the positive end of the battery holder Then we place the negative end (pole or terminal) of the battery marked with a negative sign (−) onto the negative side of the holder To know which wire is connected to which end of the battery, we commonly used two different colors. One wire of the battery holder becomes the positive wire, commonly in red, and the other wire is the negative one, in black Loads are devices that work and perform an action when the “active” electric charges from the energy source move or flow through them. For example, a load can be a light bulb, an electrical motor, an electric toy, or a computer The movement or flow of these active or charged particles is called current flow In a LED or light-emitting diode, the current moves or flows in one direction. The plus side is positive. The minus is negative. This means, the positive end of the LED has to touch or connect to the wire coming from the positive terminal of the battery and the negative end of the LED has to be connected to the wire going to the negative terminal of the battery Charged particles move easily through materials called conductors, such as metals: iron, silver, aluminum, gold, copper, or steel 	
Jumper wires are made out of metal but covered with plastic material because we do not want two conductors to touch and disrupt the current flow	Copper tape is made out of metal but has a sticky material on the bottom
Review:	
<ul style="list-style-type: none"> When the energy source is correctly connected to a load with conductors between them, the current will flow (or move) from the positive end (pole or terminal) of the battery holder, through the load making it work, and back to the negative terminal of the battery This pathway or loop is called a circuit. The current always has to have a loop to follow or none of the loads (or devices) will work! The current will only move if all components are connected really tight and securely. This is called connectivity The direction of the current flow in a circuit is called polarity. Conventionally, the current moves from the positive terminal or pole to the negative terminal or pole 	
Distribute 1 circuit kit per youth	
5 min: introduce tips and tricks of the tools	5 min: introduce tips and tricks of the tools
<ul style="list-style-type: none"> The breadboard is used as a common base to place and connect various loads or small electronics components to an energy source [Show one breadboard and take the tape off from the back of one to show metal strips. Take one of the metal strips off to show clips.] Metal strips with clips make connections with the different loads [insert one of the LEDs]. Rows on the breadboard share the same metal clips. Power rails or busses deliver current vertically The board is divided into two sections by a space down the middle. The two sections do not share the same power rail 	<ul style="list-style-type: none"> Place the copper tape as a continuous piece rather than separate pieces, even when turning corners. The adhesive on the bottom side of the foil makes a weak connection Fold a corner of the page for the battery to be placed. Have the flap over the battery and hold it in place with a binder clip Stick the LED stickers onto the foil, on top of the tape not underneath
15 min: simple circuit with 1 led	15 min: simple circuit with 1 led
<ul style="list-style-type: none"> Each participant should have all materials from the breadboard kit Have students light up 1 LED without showing them how to. Encourage exploration, collaboration, and persistence Encourage students to use jumper wires and not to place the LEDs right in the power rails Using your finger or a pencil, help participants to track the movement of the particles (electrical charges) with a finger from the battery holder (+), through the LED (load) and back to the battery holder (−) 	<ul style="list-style-type: none"> Distribute the rest of the Chibitronics kit per participant Have students light up 1 LED using the simple circuit template. Encourage students to connect the LEDs on top of the copper tape not on the bottom Help participants to track the movement of the particles from the battery holder, through the LED (load) and back to the battery holder After participants finish lighting up their 1 LED on the template, ask them to fold it in half so the LED shines through it. Ask them if they see something they could make with the light Ask the participants to draw a design to include the shining LED and make a greeting card or just a picture They can make a card by folding the paper in half first then creating the circuit on one side of the inside of the card. This makes the light shine through when they close it. Another way is to just have the lights on the outside

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Ethics Approval All procedures performed with human subjects were in accordance with the ethical standards of the University's IRB. The study received IRB institutional approval.

Consent to Participate Informed consent was obtained from all individual participants included in the study as stipulated in the IRB protocols.

Consent for Publication The authors affirm that participants provided informed consent for publication of their de-identified data from the pre- and post-tests and images of their assessment and projects (in Fig. 6 and Table 4).

Competing Interests The authors declare no competing interests.

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