Breadboards and Paper Circuits: Differences in Advanced Circuitry Learning and PCB Layout Design

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Abstract: Most electronic devices have complex circuitry systems embedded in flat and thin structures called printed-circuit boards (PCBs) traditionally to learn at the university level. We systematically compared how 21 youth (ages 15-16) learned basic circuitry concepts and PCB layout design principles using two educational circuitry toolkits, paper circuits or the traditional solderless breadboard for prototyping. Statistical tests of pre- and post-assessments showed large effect sizes (*Hedges' g*) of the score-gain differences favoring paper circuits.

Introduction

Electronic devices, ubiquitous in our fast-paced and interconnected world, are built with complex circuitry systems usually hidden from the users' view and embedded in flat, thin structures called printed-circuit boards (PCBs). PCBs resemble a matrix of layered highways that allow energy to flow in and out of multiple microelectronic components. The different ways learners interact with educational electronic toys and kits, actually do present opportunities to substantially shape learning and participation (Buchholz et al., 2014). However, little research exists on the toolkits' efficacy and how their design features, like the role of materiality, best support learning. In this exploratory study, we sought to explore how each of these toolkits impacted the learning of simple circuitry concepts and advanced PCB design principles by asking: *How do each of these toolkits impact the learning of simple circuitry and advanced PCB design principles? What are the design features of the kits that seem to best support learning?*

Theoretical foundations on learning and materiality in circuitry

This work builds on constructionist theories of learning (Papert, 1980) which perspective asserts that learners construct understandings based on hands-on experiences with tools and materials, particularly through activities that involve the iterative design of personally meaningful artifacts (Peppler & Glosson, 2013). Prior research has demonstrated that the teaching of electric circuitry frequently produces common conceptual misunderstandings, particularly in the areas of *current flow*, *connections*, and *polarity* (e.g., Shepardson & Moje, 1994). Moreover, materials and tools to teach early circuitry can also contribute to erroneous conceptual conceptions (e.g., nonpolar lights, insulated wires) that persist into university level courses (Fredette & Lochhead, 1980).

Methods

For this quantitative study, we held two circuitry workshops in a science museum introducing solderless breadboards and paper circuits (Chibitronics^{TM}). The solderless breadboard has been one of the most common toolkits for over 60 years for electrical circuit learning in electrical and computing engineering labs (Figure 1-3). Paper circuits (Figure 1-2) are a recent toolkit that combines paper crafts and arts with circuitry (coin batteries, paper, copper tape, and sticker lights). The workshop participants were 21 youth, ages 15-16 years old, 12 participants for the breadboard group and 9 participants for the paper circuits group. Informed by our prior work (Peppler & Glosson, 2013), we administered one pre- and post-test on basic circuitry concepts (*polarity, current flow, connections*). We performed t-tests using gain scores (post- minus pre-mean scores).

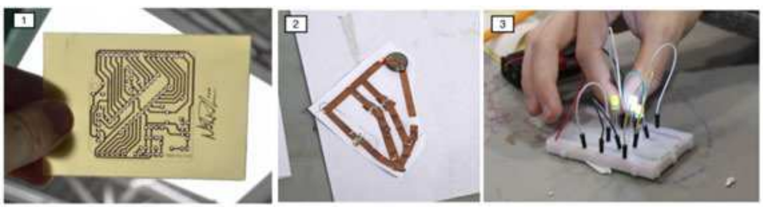

Figure 1. Similar parallel and non-crossing traces in PCB (1) and paper circuit (2) but not in breadboards (3).

For effect sizes, we calculated Cohen's *d* (Cohen, 1988) and its correction for small sample sizes, Hedges' *g* (Hedges & Olkin, 1985). We also analyzed and scored their tests for evidence of appropriate use of the four PCB (see Figure 1-1) layout design principles. Expert PCB designers consider three areas: (1) space allocation or floorplanning, (2) placement of components, and (3) routing or trace positioning (e.g., Wilson, 2018). We narrowed to *polarized component orientation, trace-to-trace spacing, power and ground distribution.*

Findings

We show the results of the comparison of mean gain scores *between* groups (i.e., independent-samples t-tests) in Figure 2. The only statistically significant difference at the .05 level was the mean gain score in the paper circuits for *polarity*, higher than of the breadboard group $t(17.817) = -2.458$, $p =$ **.024**, and a large effect size Hedges' **g = 1.03**. The mean gain scores were higher in all four principles in the paper circuit group, but only three statistically significant at $p < .10$ level (see Figure 2-*right*). The results of the independent-samples t-tests indicated the highest mean gain scores were for the paper circuit group for *power distribution*, *trace spacing* and *orientation of polarized components.* We also calculated effect sizes (Hedges' g) for the paper circuit group.

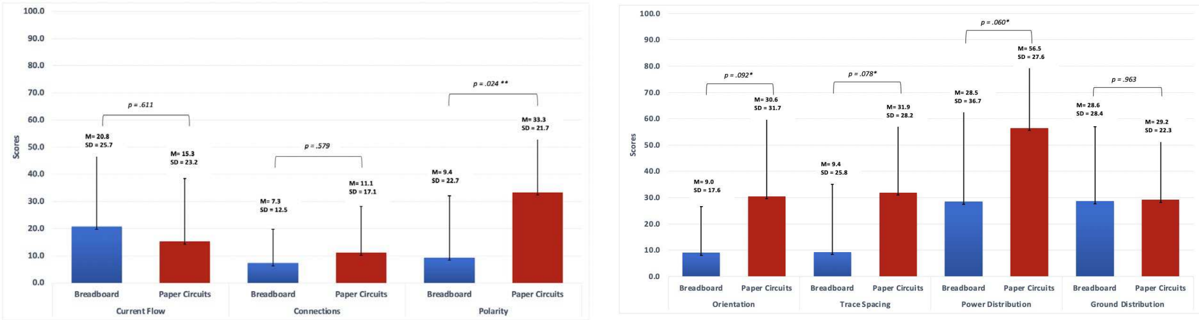

Figure 2. Comparisons of Mean Gain Scores of Basic Concepts (*Left*) and of Layout Design Principles (*Right*). Mean (M), Standard Deviation (SD) and statistical significance (p) at the $*p < .10$, $**p < .05$ levels.

Those effects sizes were large for the basic concept of **polarity** (g = **1.03**) and for the layout design principles of **orientation of polarized components** (**.84**), **trace-to-trace spacing** (**.81**), and **power distribution** (**.81**).

Discussion and implications

We encourage educators to carefully select educational toolkits considering the properties of their materials. Breadboards may be a traditional go-to toolkit, but in our study, paper circuits seemed to afford better understanding of some basic concepts, such as polarity, and PCB layout design principles. The familiar nature of the paper circuits materials and their placement in a 2D space offers similarities with the actual space and nature of a 'real' PCB (Fig. 1). Breadboards may cut out problems for novices, such as the use of insulated wires and a grid to temporarily and quickly place components, but also seem to prevent deeper learning opportunities.

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Acknowledgments

We thank the National Science Foundation (awards 1936098/ 1647150) and the Wellcome Trust (award 206202/Z/17/Z), the youth, and staff of our partner museum in Dublin, Ireland.