# ElectronicsAR: Design and Evaluation of a Mobile and Tangible High-Fidelity Augmented Electronics Toolkit

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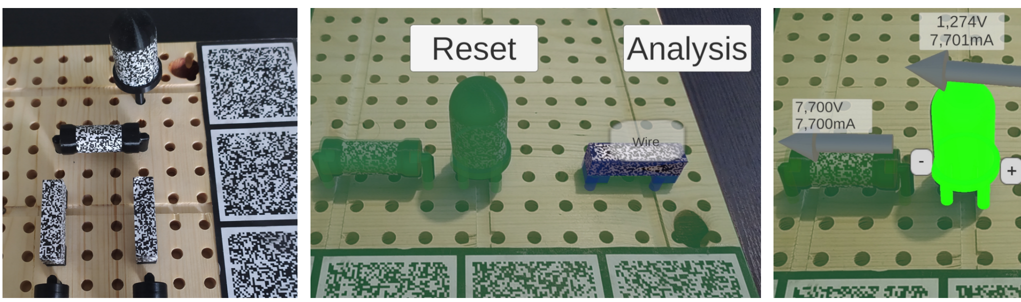


(a) (b) (c)

Fig. 1. Overview of ElectronicsAR, a high-fidelity mobile AR kit for electronics education. **(a):** The kit consists of a wooden breadboard and 3D-printed electronic components, including LEDs and resistors. While all elements are scaled, they resemble their functional counterparts both in form and proportion. This is a key difference in terms of fidelity as compared to related work on AR electronics support. **(b):** The ElectronicsAR mobile app detects the components and their positions on the breadboard. The user manually confirms or corrects detected component types. Here, the LED and resistor (both green) have already been confirmed, the blue jumper wire still needs confirmation. **(c):** The AR app analyses the detected circuit and shows that all conditions are met to turn on the LED. The app further depicts internal component processes related to voltage and current that would be observed in a functional circuit.

Exploring and interacting with electronics is challenging as the internal processes of components are not visible. Further barriers to engagement with electronics include fear of injury and hardware damage. In response, Augmented Reality (AR) applications address those challenges to make internal processes and the functionality of circuits visible. However, current apps are either limited to abstract low-fidelity applications or entirely virtual environments. We present ElectronicsAR, a tangible high-fidelity AR electronics kit with scaled hardware components representing the shape of real electronics. Our evaluation with 24 participants showed that users were more efficient and more effective at naming components, as well as building and debugging circuits. We discuss our findings in the context of ElectronicsAR's unique characteristics that we

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contrast with related work. Based on this, we discuss opportunities for future research to design functional mobile AR applications that meet the needs of beginners and experts.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Mixed / augmented reality**.

Additional Key Words and Phrases: Augmented Reality, Augmented Electronics, Electronics Learning Support, AR/MR Circuit Toolkit.

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## 1 INTRODUCTION

Electronics is an essential part of STEM[1] education. Yet, experimenting with electronics is subject to a series of unique challenges for beginners and advanced users of electronics [15, 31]. The inability to perceive internal processes of electronic components and circuits is a major barrier. Consequently, educators and technology developers explored analogies, such as ski lifts and bowling balls [32], as well as water pipes and bike chains displayed through augmented reality (AR) [26] to explain electronics and circuits. In general, AR becomes increasingly used in self-directed electronics exploration to convey complex phenomena that are otherwise invisible to the human eye. For example, projected AR was successfully used to interactively teach physics [16] and to simulate how environmental changes affect the surroundings in geography [35]. In the context of electronics, researchers designed a range of AR applications to support electronics education [7, 9, 14, 44]. Those solutions largely differ in terms of feedback, functionality, interactivity, and component fidelity. Existing commercial solutions rely on printed AR trackers placed next to each other [7, 9, 14, 44] that do not resemble the real shape of electronic parts and do not allow to tangibly interact with the parts. In contrast, tangible and functional components have been proposed in previous research [7, 44]. However, they do not represent the real shape of electronics. Rather, they use abstract presentations of the objects, possibly hindering the transition from virtually augmented to real electronic kits.

We present ElectronicsAR, an AR electronics toolkit that uses scaled 3D-printed electronic components that resemble their functional counterparts. Figure 1 provides an overview of the custom breadboard (see Figure 1a), the circuit identification process in the mobile AR app (see Figure 1b), and the AR display showing voltage and power consumption within two components, as well as the LED turning on (see Figure 1c). We decided to use non-functional components to address two additional key issues involved in self-directed explorative making: (1) the fear of injury and (2) concerns regarding hardware damage [11, 40]. In addition, the use of non-functional components allows to provide a unique AR experience by virtually parameterizing the characteristics and values of individual electronic components, thereby supporting electronics exploration [37]. In the example depicted in Figure 1, the user could, for example, change the value of the resistor or the power supply to explore the effects on the LED. In this paper, we report about the design of ElectronicsAR, as well as our mixed-method evaluation with 24 participants.

This paper is organized as follow. First, we provide a detailed reflection of challenges involved in electronics education and making, present an overview of technology-mediated support in general, and AR applications in particular. In this context, we provide a broad characterization of related AR work across the dimensions functionality, fidelity, feedback, and interactivity. We position the design of ElectronicsAR in relation to those characteristics. Next, we describe the system in detail, before presenting the methodology and results. Finally, we discuss our findings in the context

[1]Science, Technology, Engineering, and Mathematics

of ElectronicsAR's unique characteristics and describe future research challenges for mobile AR electronics support.

## CONTRIBUTION STATEMENT

This paper presents three main contributions: (1) We report on the design and development of ElectronicsAR, a mobile high-fidelity tangible AR electronics kit that supports self-directed explorative making. (2) We then present findings from a mixed-method study with 24 participants, instructed to name components as well as build and debug circuits. (3) Finally, we contrast ElectronicsAR and its unique characteristics with related mobile electronics AR kits to discuss avenues for future research that are expected to meet the needs of beginners and experts alike.

## 2 RELATED WORK

Internal processes of even the most basic electronic components such as resistors, LEDs, and transistors are completely hidden from observers. Users constructing an electrical circuit will evaluate visually whether or not the circuit demonstrate a predicated behavior. A common example is turning an LED on or off. In case a circuit does not function as expected, users must investigate issues with the help of tools, such as a multimeter, to measure the voltage and combine their observations with detailed knowledge about the components. This missing direct insight into circuit behavior, as well as fears of injury and hardware damage, represent some of the greatest barriers to electronics learning that concern both educators and developers of training tools [1, 31]. To visualize and teach a basic understanding of internal processes in circuits, Mogstad and Bungum [32] investigated four analogies across secondary students: ski lifts, bowling balls, pipe systems, and waterfalls. While their results showed that students were able to grasp the concept of electronics (i.e., current, voltage, resistance) through those analogies, the authors noted that "weaknesses in how the analogies are presented may cause major problems for students in building a fruitful understanding." [32] In contrast, a requirement of our work is to communicate real circuit behavior through AR, allowing to expand capabilities of visualizing and understanding internal processes of electronic circuits and components. This design strategy relates to the wider research on AR for learning [13, 33], and AR-supported education in STEM [19, 20]. One example is presented by Strzys et al. [43] and Knierim et al. [22, 23] who developed an AR application for physics teaching that visualizes heat conduction on a metal rod. Another example is HOBIT [16], demonstrating how projected AR can be used to interactively explore the Michelson interferometer experiment by observing changes in the spectroscopy when changing parameters in real-time. Finally, Kosch et al. showed how the creation of electrical circuits can be facilitated using in-situ projections on a worktable [24]. In their work, they recognize functional parts using optical depth sensing to project visual support onto the worktable. Other examples do not only use physical assembly and allow to simulate the function of electrical circuits on worktables [10]. Hence, the use of functional and non-functional tangibles as metaphors for abstract concepts enhances the understanding of students [30] and supports the learning process [3], resulting in taxonomy designs for tangible learning scenarios [2]. Consequently, a tangible approach of using AR for teaching geography was presented by Pantuwong et al. [35], showing how changes in a sandbox environment affect the shape of the surrounding areas.

In this section, we initially reflect on research around electronics education that is supported by a wide range of diverse interactive systems. Next, we specifically reflect on work related to AR support in electronics. We show how ElectronicsAR relates to and differs from previous research in the context of four design characteristics: functionality, fidelity, feedback type, and interactivity.

## 2.1 Technology-Mediated Electronics Support

The inability to visualize internal circuit processes, the fear of injury, and concerns to damage hardware, are three key barriers of education in basic electronics [11, 40]. Technology-mediated approaches and solutions to these problems are as diverse as the challenges they aim to address. This wide range of interactive systems designed to support electronics users in training and routine circuit building range from AccessibleCircuits [8], providing 3D-printed add-on circuit components to support persons with visual impairments in constructing circuits, to smart functional breadboards that detect, digitize, and analyze configurations [12, 47, 48]. Breadboards are plastic boards that allow rapid prototyping with functional elements across a matrix of inter-connected conductive rows and columns. Furthermore, 3D printing itself is becoming an accessible pipeline-driven process, enabling users without prior CAD knowledge to rapidly create customized objects [39] that can be embedded into everyday objects [28, 29, 38].

AutoFritz [27] is an example of a completely screen-based support system that helps users design circuits on a popular prototyping platform, Fritzing, through suggestions and autocompletion. AutoFritz provides suggestions based on an analysis of corresponding datasheets and a wide set of openly available community projects. In contrast, Proxino [46] is an example of a tool that bridges between entirely virtual screen-based circuits and physical components. Proxino enables interaction with virtual circuits through physical proxies and supports remote collaboration and learning. Similar, Simpoint [42] makes use of a tight coupling between real physical circuits and virtual counterparts. Here, Strasnick et al. created a system that juxtaposes live signals measured from a physical circuit with simulated data from this circuit's model to aid in debugging. Simpoint further allows to programmatically modify the signals and component parameters as advanced debugging features. Our own work takes inspiration from these approaches that blend the real with virtual information to allow for a most effective interaction with physical circuits. Our system further took inspiration from programmatic parameterization, as introduced in Simpoint, allowing for an interactive experimental interaction with an electronics AR app that does not pose risks to physical injury or hardware damage. In contrast to the research described in this paragraph, and Simpoint in particular, ElectronicsAR focuses on basic electronics exploration, rather than expert debugging.

On the other end of the spectrum, systems were developed that focus on the augmentation, analysis, and interaction with the physical instance, usually the breadboard, itself. Drew et al. [12] developed the Toastboard, a type of extended smart breadboard that measures the voltage of each row. An LED bar directly indicates one of three types of voltages detected: power, ground, or other voltages, enabling users to perform a first set of analyses on the breadboard. For further analysis, those measurements can be shared with a dedicated software application. SchemaBord [21] by Kim et al. makes use of LEDs to provide additional information. SchemaBoard is an LED-backlit functional breadboard that can highlight elements which are selected in a circuit schematic that is displayed on a connected computer. This augmented breadboard is expected to support makers in finding, placing, and debugging their real circuits. Another example is CurrentViz [47], a system similar to Toastboard, but measuring current instead of voltage. Finally, CircuitSense [48] is a smart breadboard that detects the locations of placed component and tries to automatically recognize the type of component. This way, users can quickly create virtual circuits by digitizing their physical counterparts. This is expected to benefit open sharing of circuit designs. Overall, previous research demonstrates the value of augmented physical breadboards as primary interaction material. Here, augmentations were limited to LED bars and computer-processed visual information. In contrast, our work directly augments the physical dashboard with detailed information to enable an interactive and tangible learning experience.

## 2.2 Augmented Electronics

There is a range of AR applications designed to support users at understanding internal processes of circuits and electronic components. ARBits [44], for example, is a toolkit consisting of large wooden components each representing and featuring functional components. The kit comes with wooden blocks and their functional components for eight element types. Each of the wooden blocks further features one printed AR marker used for object detection and recognition. The blocks are larger than the components they represent. This makes them suitable for interaction with students at an early age. Yet, their shape is abstract and barely related to the shape of the components represented. Aligned in a circuit, the electronic components are fully functional. At the same time, the users can visualize basic information, including component type and polarity, through a mobile AR app. Here, ElectronicsAR takes inspiration from ARBits as it also displays information about circuit components. In addition, we provide additional feedback by calculating and visualizing how voltage and current are affected within each component. Furthermore, users can adjust the component parameters (e.g., resistance, capacitance) using ElectronicsAR.

Chan et al. [7] developed LightUp, an electronics kit similar to ARBits. LightUp also makes use of functional, but enlarged and abstract, components. In addition, LightUp even provides functional bricks for the conductor paths and comes with a pre-mounted battery block. Yet, the visualizations provided through the mobile AR app are more limited and focus mainly on bubbles indicating the order in which the elements are configured within the circuit. In contrast, AR Circuits [14] is limited to printed paper cards with AR trackers representing a type of electronic component. Students align those cards to create a non-functional circuit which can be visualized and analyzed through a mobile AR app. Notably, some of the displayed components, for example the button, are interactive and impact the circuit behavior. We incorporate interactive features into ElectronicsAR to enable users to change parameters of components.

Kreienbühl et al. [26] designed AR Circuit Constructor (ARCC), a toolkit featuring abstract but functional electricity building blocks including basic components and a QR code used for AR tracking and identification. In contrast to ARBits, LightUp, and AR Circuits, the mobile AR application of ARCC focuses on providing detailed circuit feedback. Students can choose between three types of analogy-driven visualizations: bicycle chain, water pipes, and waterfalls. The *water pipe* visualization, for example, displays functional circuits as a closed water pipe system in which resistors are represented by pipes that are tighter (i.e., the diameter of the pipe reflects the resistance). The authors conducted a qualitative user study with eight science teachers and found that educators would use ARCC for self-directed explorative learning [37].

Reyes-Aviles and Aviles-Cruz [36] proposed a system that differs strongly from previously presented approaches in terms of the level of feedback provided. Their mobile app expects to receive a photo of a functional breadboard and a resistor circuit configuration, along with captured data about the voltages and currents measured at the nodes of installed resistors. The application performs image recognition for all resistors installed on the breadboard and adds information related to the calculated theoretical voltage and power consumption within each resistor node directly into this augmented image. This detailed feedback inspired our development of ElectronicsAR which is designed to show calculated voltage and power consumption of all identified components. Yet, in contrast, our system includes more types of functional components and supports a live view that we expect to support the interactive learning experience.

Wang and Cheung [45] explored a similar research direction that relies on electronic component recognition in images. The authors expect that their computer vision system will facilitate circuit building through step-by-step instructions in a mobile AR app. Similarly, Srivastava et al. [41] present an intelligent breadboard that senses errors including loose wiring or wrong connections. A mobile AR app provides visual feedback, instructions, and testing to the user. In contrast, Chatterjee et al. [9] explored how AR applications can be used to support experts in circuit debugging. They found that their proposed AR interaction techniques, called Augmented Silkscreen, can benefit experts in different ways, including the search for components and probe points on complex Printed Circuit Boards (PCBs) and element metadata. Yet, their evaluation has been limited to a PCB simulator and video sketches.

## 2.3 Summary and Research Questions

The reflections in this section showed that students and experts are confronted with various challenges around electronics learning, circuit building, and debugging. AR provides a strong opportunity to address those barriers by visualizing processes that are invisible and difficult to understand. This section also highlighted the diversity of approaches that can be characterized across a set of different features, including:

- **Functionality**. While some applications like AR Circuit Constructor [26] and ARBits [44] make use of functional components and circuits, others focus on non-functional toolkits that are easy to setup and safe, or even entirely image-based. Examples include AR Circuits [14] and the computer vision system presented by Wang and Cheung [45].
- **Fidelity**. Related work used a wide range of approaches in terms of component fidelity. The spectrum ranges from simple paper-based trackers in AR Circuits [14], abstract blocks in ARBits [44], AR Circuit Constructor [26], and LightUp [7], to image-based augmentations of real circuits, as presented by Reyes-Aviles and Aviles-Cruz [36].
- **Feedback Type**. The feedback provided through AR applications ranges from abstract visualizations to detailed calculations. For example, LightUp [7] is limited to bubbles highlighting the overall circuit configuration. In contrast, AR Circuit Constructor [26] provides three analogy-driven visualizations that are expected to support students understanding of voltage and current. At the other end of the spectrum, Reyes-Aviles and Aviles-Cruz [36] combine real measurements and component recognition to display accurate voltage and power usage.
- **Interactivity.** Most AR electronics apps presented in this section do not forsee user interaction with the virtual objects. Almost all applications focus on displaying information. Exceptions include AR Circuits [14], allowing users, for example, to interact with virtual switches, thereby changing the state of the circuit.

While this summary does not intend to provide a systematic description of characteristics in AR electronics, it helps to understand how ElectronicsAR differentiates from related work. ElectronicsAR aims to create a toolkit that is suitable for electronics learners at all ages and levels of experience. Hence, we decided for safe and **non-functional** components. While enlarged in size, we created 3D-printed components that precisely resemble real components (**high fidelity**). This is a key difference to related work that designed more abstract solutions [7, 14, 26, 44]. Another major difference is the **detailed feedback** provided by ElectronicsAR, showing how components consume voltage and power. Finally, our toolkit leverages the potential of non-functional components to adapt component parameters, thereby making the AR and circuit experience **interactive**. Users can set, change, and experiment with a wide range of values. For example, students can virtually change the value of a resistor to see the effect on an LED. We expect that this feature will help both young and inexperienced learners through self-directed explorative learning [37], as well as support advanced learners in understanding the effects of individual electronic parameters. Our evaluation of ElectronicsAR is guided by two key research questions:

**RQ1: How effective is ElectronicsAR at supporting interaction with electronics?**


Fig. 2. 3D printed proxies with an embedded QR code. ElectronicsAR can detect **(a)** resistors, **(b)** LEDs, **(c)** capacitors, **(d)** transistors, and **(e)** (jumper) wires. The QR code can either be glued to existing models or printed with a multi-material 3D printer.

We evaluate ElectronicsAR across three typical tasks that differ in complexity: (1) naming electronic components; (2) debugging a circuit; and (3) creating a circuit. We aim to study user experience and effectiveness of the interaction with such a novel system by including a set of participants that are diverse in age and personal electronics experience.

**RQ2: What are the implications for the design of future AR electronics assistants?** We expect that findings from this multi-task evaluation across a diverse participant pool help to map design implications for future augmented electronics assistants. This reflection on future design should place particular emphasis on the unique characteristics of ElectronicsAR.

## 3 ELECTRONICSAR: AN AR ELECTRONICS PROTOTYPING TOOLKIT

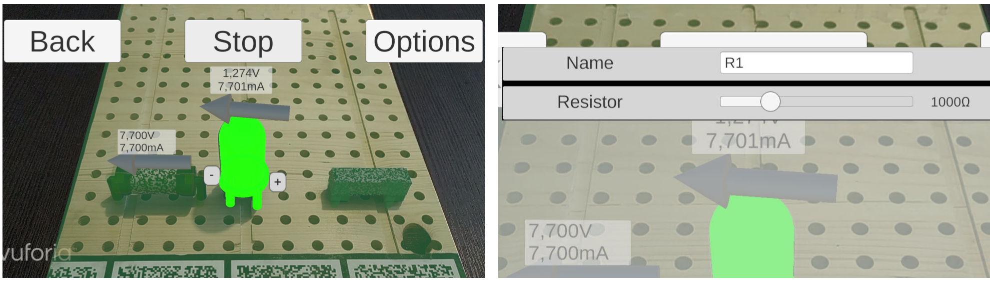
This section describes the architecture, functionality, and implementation of ElectronicsAR.

### 3.1 Component Detection and Parameterization

ElectronicsAR detects non-functional 3D printed objects that resemble their real counterparts. We used Vuforia[2] to detect the QR codes through the smartphone rear camera and projected interactive holograms on the circuit components (see Figure 1). We successfully deployed and tested the application on Android phones and tablets, as well as iPhones and iPads. The QR codes can either be glued or printed alongside the electronic part using a multi-material printer (see Figure 2). By design, the parts were printed in a larger size to improve the tangibility and detection accuracy of the electronic components. We used a scale factor of six compared to the original size of the electronic parts.

The AR user interface consists of three principal views: the component detection and confirmation screen, the circuit analysis screen, and the component parameterization views. When the users start the application, they are first asked to scan the visual markers fixed to the breadboard itself. After placing the circuit components on the breadboard (see Figure 1a), the user will see a blue overlay over all detected components together with the corresponding component type. The user confirms the placement by pressing on the corresponding item. At this point, the placement is confirmed and turns green (see Figure 1b). Once the user confirms that the circuit is correctly placed and detected, they can start the analysis. In this main view, users can observe voltage and current and visually see the outcome of the circuit. For example, an LED might turn on or remain off (see Figure 3a). From this screen, users have access to the third view: the component parameterization view. Pressing on a customizable component like a resistor opens a corresponding view. Figure 3b shows

[2] https://developer.vuforia.com




(a) (b)

Fig. 3. ElectronicsAR detected three electronic components on the board: a resistor, an LED, and a (jumper) wire. In addition, the system detected the polarity of the LED. After confirming the configuration, in (a), the users can review calculated voltage and current for each individual component. These values can only be calculated and displayed for functional closed circuits. In this example, ElectronicsAR further shows that the circuit and parameters of the components meet the conditions to light up the green LED. (b) The user selected a resistor to change either its name or value, i.e. the resistance in Ohm. Changes are applied immediately and result in adjusted calculations. For example, selecting a high resistance would turn off the LED.

the screen that appears when pressing on a resistor. Here, the user can change the resistor value and observe how this change affects the overall circuit.

### 3.2 Circuit Analysis

ElectronicsAR uses SpiceSharp[3] to simulate the detected circuit. SpiceSharp is an open source implementation of the Simulation Program with Integrated Circuit Emphasis (SPICE) [34]. Circuit simulations can be created on-the-fly and enriched by supported electronic components. These components entail values that can be changed when users touch the components on the mobile phone screen. A pop-up is displayed where the user can enter custom parameters (e.g., resistance or capacity). The parameter boundaries of all parts presented in this paper follow the specification of the according data sheet. We make the source code, 3D printed parts, and markers available on our GitHub repository[4].

## 4 USER STUDY

We conducted a user study to investigate the interaction experience and performance of ElectronicsAR. We facilitated a between-subject design with two groups, where the use of ElectronicsAR was the between subject factor. Each group was assigned to a condition with and without support through ElectronicsAR respectively, meaning half of the participants were working with real electronic components and the other half of the participants with ElectronicsAR. Inspired by the work from Booth et al. [5], we defined three tasks concerning recognition of electronic components, circuit debugging, and construction of electronic circuits. Figure 4 provides an overview of the study procedure, including the three tasks, key metrics, and the final interview.

### 4.1 Independent Variables

We utilize the assistance modality as only factor in our study design. The assistance modality consists of two levels, where participants use either ElectronicsAR or functional components during

[3]https://spicesharp.github.io/SpiceSharp
[4]https://github.com/sefeg/ElectronicsAR_ISS22

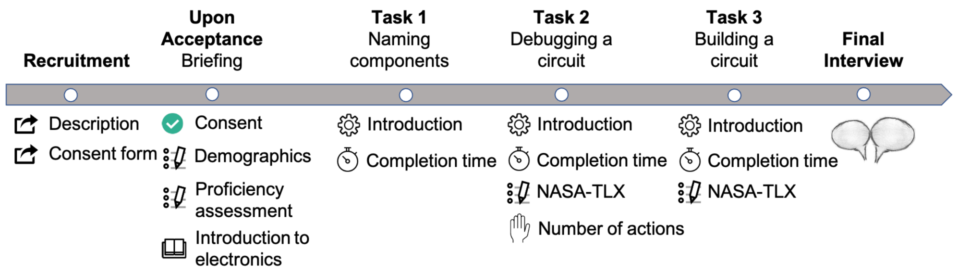



Fig. 4. An overview of the study procedure. The participants completed three tasks in a between-subjects study: naming components, debugging a circuit, and creating a circuit. Half of the participants used real components, the other half used ElectronicsAR.

the study. When assigned to ElectronicsAR, participants used the mobile AR app to address three predefined tasks with the help of the augmented electronics prototyping kit. The other group of participants used real functional components.

## 4.2 Tasks and Measures

Our study consists of three tasks that participants solve using either ElectronicsAR or functional electronic components. We describe the tasks and the measures in the following. They were designed to increase the difficulty as users gained experience interacting with either the real components or the ElectronicsAR kit.

*4.2.1* ***Task One:*** *Naming Electronic Components.* We asked our participants to name electronic components. This task assesses the participant's ability to find and recognize electronic parts. Four real electronic components were put on a table in the real electronics condition, consisting of a capacitor, transistor, LED, and resistor. The participants received a sheet of paper where they should write down the names of the components. Participants were allowed to use the internet to search for the components (e.g., model number). Figure 5a depicts the naming condition with real electronic parts. In the AR condition, the participants were using ElectronicsAR to obtain the component names. Instead of real components, participants were using the 3D printed proxies for the electronic components. The participants were asked to use the app and write the names on a sheet of paper. Figure 5b shows the setup when using ElectronicsAR. We measured the time participants took to identify and name the components.

*4.2.2* ***Task Two:*** *Debugging a Circuit.* In the second task, participants received a schematic of a circuit accompanied by either a functional version of the circuit or a prepared version using ElectronicsAR. We created a bridge circuit with an LED acting as the bridge (see Figure 6). However, the LED is installed the wrong way in both circuits (polarity). The task is to find and correct the error. Participants had several tools at their disposal, including a resistor color diagram, a multimeter, the internet, and a schematic to debug the circuit in the real electronics condition. In the augmented condition, participants were provided with a schematic and ElectronicsAR. We measured the time that participants took to find and correct the error. We also counted the number of actions from each participant until they found the error. We asked participants to fill in a NASA-TLX questionnaire [17, 18] at the end of the task.

*4.2.3* ***Task Three:*** *Building a Circuit.* In the third task, participants were asked to construct a circuit from scratch using a schematic. The circuit consists of three resistors, connected in parallel and in series (see Figure 7). Afterward, participants were instructed to report the current and voltage of a resistor. In the real electronics condition, participants received the schematic, a multimeter, a color table, and the internet as support tools (see Figure 7a). In the augmented condition, participants received the schematic and the ElectronicsAR kit (see Figure 7b). We measured the task completion time and further asked the participants to fill in a NASA-TLX questionnaire at the end of the task.

We note that the experimenter monitored the circuit building process the entire time. In case that this person, a skilled electronics expert, had realized that the circuit is not behaving as expected, even though it was configured correctly, this person would have intervened. This is the case if a component was actually damaged. However, we also note that this did not happen in the study.

### 4.3 Protocol

We first introduced the participants to the goals of the project. The participants then provided informed consent. Afterward, we provided a short introduction to electronics where we explained a circuit with a functional LED and a resistor mounted on a breadboard. This was carefully explained to ensure that participants understood the basic principles of electrical circuits. We then randomly assigned the participants to a group (i.e., using ElectronicsAR or real electrical components). Participants assigned into the group using ElectronicsAR received an explanation how the app works, how objects can be scanned, and how the parameters of electric components can be manipulated. Similar, the group using real components received an introduction into measuring voltages and currents using a multimeter, how to interpret a circuit diagram, and how to decode the resistor sheet. The participants executed tasks one to three sequentially.

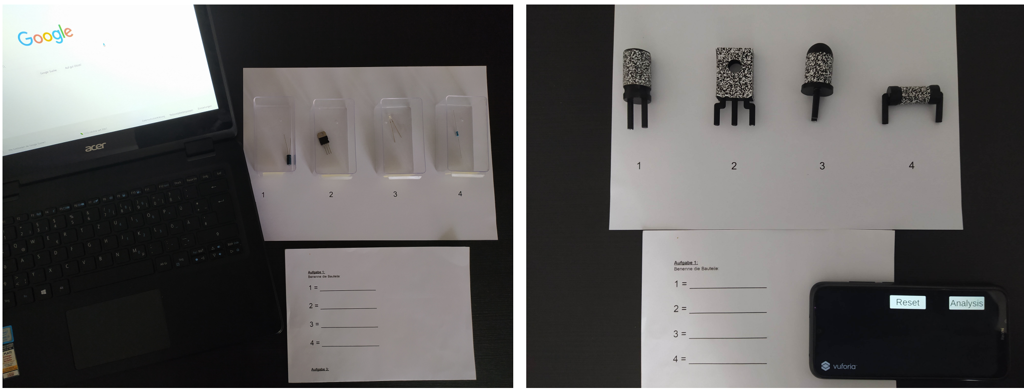
We measured the task completion time for each task. We probed the subjectively perceived task workload in the tasks two and task three using the NASA-TLX questionnaire [18]. The NASA-TLX is an established questionnaire to probe the task load after an interaction [17] in terms of mental, physical, and temporal workload. Thus, the NASA-TLX questionnaire provides a measure to compare the task load between both interfaces (i.e., functional components and ElectronicsAR.)

Additionally, we measured the number of errors in task one and number of actions in task two. We conducted brief semi-structured interviews with the participants to learn about perceived benefits and downsides of the provided tools.

### 4.4 Participants

We recruited 24 volunteers via university mailing lists and through personal networks. Ten volunteers self-identified themselves as female and 14 as male with a mean age of 34.5 years (SD = 18.22). We divided the participants into two groups: one was using ElectronicsAR to solve the tasks while the other group was using the previously described functional tools, resulting in twelve participants per group. We asked the participants to rate their proficiency in prototyping with electronics on a scale from one to ten[5]. Here, the participants rated their proficiency with 3.92 on average (SD = 2.36). We consider the diversity in our sample, characterized by the standard deviation, regarding age and electronics proficiency, a strength of our study. Most of the augmented electronics tools presented in related work have not been systematically evaluated. Therefore, we consider the mapping of interaction experiences from a diverse participant pool a requirement and strength that helps provide a fundamental understanding of how AR tools can support a larger part of society gain access to electronics.

[5] 1: Not proficient at all; 10: Very proficient.




(a) (b)

Fig. 5. The first task comprised of an electronics naming task. Participants were invited to identify and name the components. **(a):** Participants were invited to use a regular internet search in the condition dealing with real electronics. **(b):** Condition using ElectronicsAR. Participants were asked to scan the objects and name the components.

## 5 RESULTS

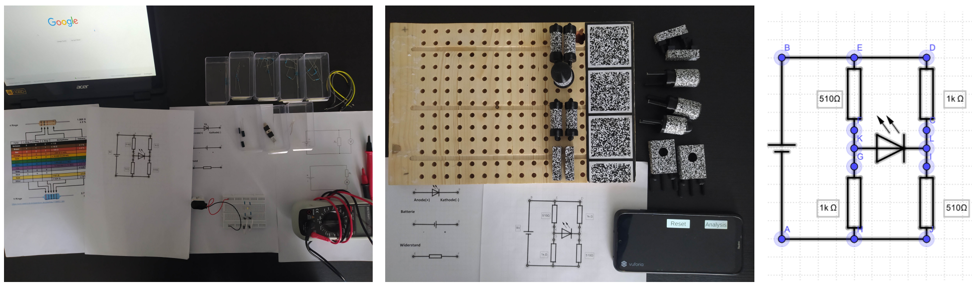
We present the results of our study in the following. We tested our results for statistical significance. We ran a Shapiro-Wilk test to check the normality of the data and performed a one-way ANOVA or a Kruskal-Wallis test to check for statistical significance, depending on the results of the Shapiro-Wilk test.

We transcribed the entire audio material verbatim. The total length of the audio recordings is 46 minutes. Three authors analyzed the data using thematic analysis as described by Blandford et al. [4]. Due to the exploratory nature of our study and the commonly found interpretative practice in HCI research, we found an open-ended thematic analysis most suitable to analyze the collected data. We conducted an initial coding round where three analysts open-coded data from six randomly chosen participants (i.e., three participants of the group using ElectronicsAR and real electronics respectively). We held a code comparison and adjustment session afterward, where we discussed the initial coding tree and equally distributed the remaining interviews among the three coders. We iteratively discussed the entire data set where we refined the final coding tree and identified commonalities in the data.

### 5.1 Task One

In task one, we asked participant to recognize electronic components and write their names down on a sheet of paper. Six out of twelve participants named all components successfully in the real electronics condition. In contrast, all participants using ElectronicsAR named all components correctly.

A Shapiro-Wilk test did not reveal a deviation of normality for both groups, $p > .05$. A one-way ANOVA revealed a significant effect between both groups, $F(1, 22) = 21.25$, $p = .001$. The group using ElectronicsAR achieved a faster mean completion time (M = 67.75s, SD = 26.42s) compared to the real group (M = 329.42s, SD = 186.40s). Figure 8a shows the mean time for task one.




(a) (b) (c)

Fig. 6. The second task of the study: circuit debugging. The participants were asked to find an error in the circuit. **(a) real condition:** Participants received access to various tools, including a color diagram, a multimeter, the internet, and a schematic. **(b) augmented condition:** Participants used a schematic and/or ElectronicsAR. **(c):** The schematic used in this task.

## 5.2 Task Two

In task two, we asked participants to debug a circuit where an LED was inserted in the wrong direction. Ten out of twelve participants solved task two using ElectronicsAR while three out of twelve solved this task in the real components group within the given time frame of ten minutes.

We analyzed the task completion time and number of actions participants took to solve task two. A Shapiro-Wilk test did not reveal a deviation from normality for the the task completion times in both groups, $p > .05$. However, a deviation from normality was found for the number of actions, $p < .05$.

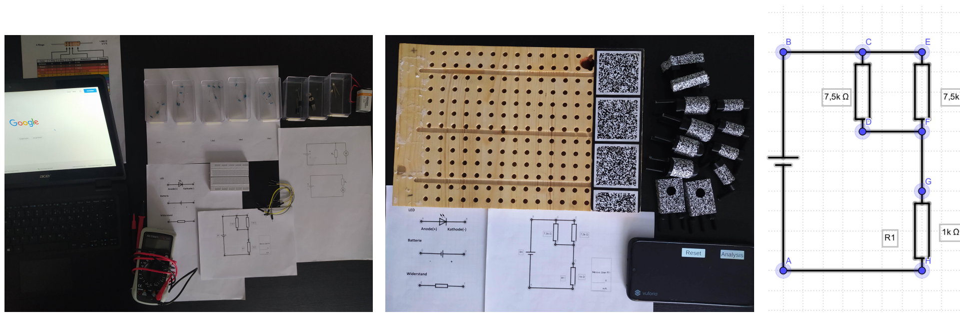
A one-way ANOVA showed a significant difference for the task completion time between both groups, $F(1, 22) = 6.05$, $p = .022$. Again, participants using ElectronicsAR solved the task faster (M = 415.00s, SD = 121.60s) compared to the real components group (M = 591.00s, SD = 203.92s) (see Figure 8b). A Kruskal-Wallis test did not show a significant effect for the number of actions, $H(1) = 0.76$, $p = .38$ (see Figure 9a), and for the NASA-TLX questionnaires, $H(1) = 0.85$, $p = .35$ (see Figure 9b).

## 5.3 Task Three

In task three, participants were asked to build a circuit from scratch using a schematic as reference. All participants managed to construct the circuit correctly using ElectronicsAR. Three out of twelve participants failed to build the circuit correctly with real components within the given time frame of ten minutes. A Shapiro-Wilk test revealed a violation of normality for both groups , $p < .05$. A Kruskal-Wallis test shows a significant difference between participants using ElectronicsAR and real components, $H(1) = 5.88$, $p = 0.02$. Participants using ElectronicsAR were faster (M = 301.75s, SD = 139.29s) compared to the real electronics group (M = 410.83s, SD = 128.43s) (see Figure 8c). Again, no significant effect was found in the NASA-TLX questionnaire, $H(1) = 0.10$, $p = .75$ (see Figure 9c).

## 5.4 Interview Findings

After completing all tasks, participants were asked about the usability and user experience of the tools, as well as general challenges they encountered while completing their tasks. Our thematic analysis revealed three themes: *Challenges*, *Tools*, and *Augmentation*.




(a) (b) (c)

Fig. 7. The third task: the participants were asked to create a complete circuit from scratch. Participants were then asked to report the current and voltage. **(a):** Participants received access to various tools, including a color diagram, a multimeter, the internet, and a schematic. **(b):** Participants used a schematic and/or ElectronicsAR. **(c):** The schematic used in this task.

*5.4.1 Challenges.* This theme describes the challenges our participants encountered when working with real electronics and ElectronicsAR. Many participants had difficulties remembering the electronic parts, requiring them to relearn electrical engineering principles and problems. This prevented participants from interacting with electronics at first:

> *"My main problem was that I first had to find my way back into the subject matter of physics."* (P4, ElectronicsAR)

Many participants had issues with handling the breadboard and correctly plugging components in. Several participants reported issues understanding the internal connections of the breadboard. Despite our previous explanation, we observed that users created short-circuits or circuits that were not properly closed.

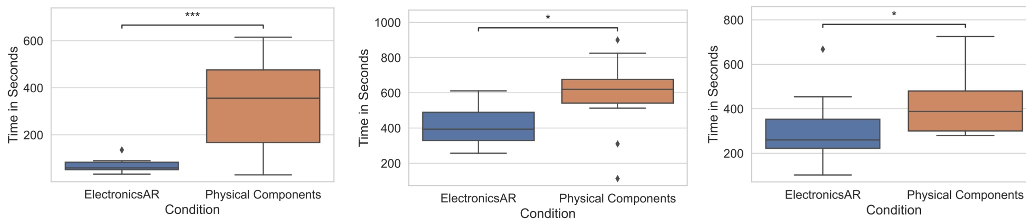
> *"In Task 3, I had a little difficulty recognizing the circuitry in the board."* (P2, ElectronicsAR)

The real electronic components also posed a physical challenge for some participants. This was mainly due to the size of the parts and the difficulty to distinguish colors on the resistors:

> *"Well, the color coding of the individual resistors is a bit difficult to read, so that delayed me a bit."* (P6, Real Components)

A multimeter was available for all participants throughout all tasks. However, using it was considered a challenge for the participants. Three participants observed that the contacts of the multimeter were not properly connected to the electronic components when measuring. For example, an attempt was made to measure at the insulation of a cable. In addition, the difference between current and voltage measurement (i.e., measuring in series vs. parallel) confused some participants.

*5.4.2 Tools.* This theme describes how participants were handling the provided tools. In task one, all participants in the real components group used the internet for the task. In contrast, participants did not use the internet in tasks two and three. The feeling of assistance provided by the internet was mixed since participants had issues searching for the names of the components:




(a) (b) (c)

Fig. 8. Mean task completion times for **(a)** task one, **(b)** task two, and **(c)** task three, for the augmented and real conditions.

> *"For task one, I found it difficult to figure out the terms. Although I haven't heard them yet, so accordingly I did not know what to google for. And then just had to use pictures to somehow figure out what the things could possibly be called."* (P1, Real Components)

ElectronicsAR was described as helpful. Beginners with little knowledge about electronics perceived it as supportive tool. One participant stated they would not be able to solve the task without ElectronicsAR:

> *"I didn't thought that such an app can be so helpful, because without the app I would not have been able to solve it. For people with no knowledge of electronics or no knowledge of physics at all, it really was all solvable through the app."* (P4, ElectronicsAR)

The participants in the real electronics group stressed that a more detailed introduction into electronics could have improved the task performance:

> *"Bit more basic knowledge, but otherwise it should fit so far."* (P6, Real Components)

> *"No I had everything, I had a schematic, had the app, that was all ok."* (P7, ElectronicsAR)

*5.4.3 Augmentation.* This theme describes how the augmentation of electronics using ElectronicsAR supported the participants. For most of the participants, it was the first time to work on such problems with the help of an app:

> *"It was a new experience for me to solve a task with the help of an augmented reality application in reality."* (P16, ElectronicsAR)

Most participants found the app easy to use once the controls were understood. In addition, many participants perceived the app's controls as intuitive and easy to understand:

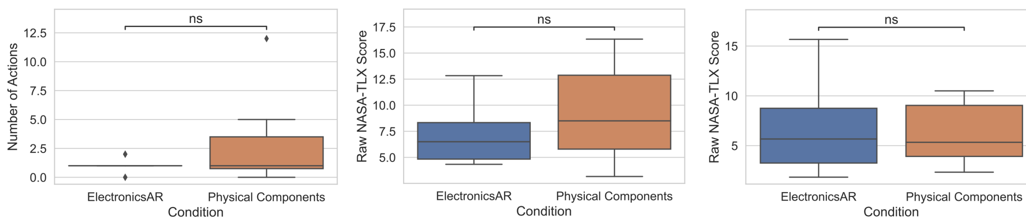
> *"What I liked very much is that it is very clear. It is actually very easy to control, once you have understood the system briefly, then it is really easy to understand [. . . ]"* (P10, ElectronicsAR)

One point of criticism that was raised frequently relates to the scanning process. Some participants found it too complex and too time-consuming. They also emphasized that the scanning process must become more reliable to account for external factors like light conditions.

> *"What I find improvable is the visual recognition of the parts, [. . . ]"* (P6, ElectronicsAR)

> ‘*'It was a little bit difficult to scan things sometimes, so because of the lighting conditions it took a little bit longer, or sometimes it shifted a little bit around a position, but otherwise it actually worked out well overall."* (P15, ElectronicsAR)

Overall, ElectronicsAR was very well received. The possibility of displaying the current flow and being able to read out the currents and voltages was echoed frequently in our interviews:




(a) (b) (c)

Fig. 9. **(a):** Average number of actions for task two. Mean raw NASA-TLX scores for **(b)** task two and **(c)** task three.

> *"Well, I especially liked the animations of how the electrons flow, because then you could imagine a bit visually how the current really flows through the parts [...]"* (P15, ElectronicsAR)

## 6 DISCUSSION

We presented ElectronicsAR, an electronics prototyping toolkit that visually augments electronic mock-ups to support users who prototype with electronics. We conducted a between-subject study to investigate the feasibility, efficiency, and usability of ElectronicsAR. In this section, we discuss our findings, their design implications, and opportunities for future research through the lenses of our two research questions.

### 6.1 RQ1: How effective is ElectronicsAR at supporting interaction with electronics?

Our results show that the participants solved the tasks more efficiently compared to the use of traditional methods. While this entails a significant effect for the task completion times and number of actions, we do not find a significant effect for the perceived task load. In contrast, participants using ElectronicsAR were more likely to solve a given task as compared to participants who used functional components. The user feedback revealed a number of advantages of ElectronicsAR for circuit sketching, as compared to functional components. Here, participants described several barriers when sketching with functional real components, such as not knowing the names, the constraints of specific parts, or debugging potential errors in the circuit. Our evaluation further shows that the small size and flexible nature of real components led to issues in placing and rearranging electronic parts. This is likely to represent major issues in electronics learning among children and the elderly. One common approach to deal with such challenges are web-based circuit simulators. They are easy-to-access and allow for a safe exploration with a large number of electronic components. While the availability and component diversity are advantages of such simulators, they cannot provide the tangible experience provided by ElectronicsAR. Based on our findings, we expect that the interaction with tangible proxies that closely resemble their real counterparts will lower the barriers of electronics learners to actually place real components on a functional circuit. Yet, we note that a formal comparison between tangible AR-supported circuit building and debugging and web-based simulators can be of great interest for future work in the context of broader domain learning.

Most participants positively acknowledged the support provided by ElectronicsAR. As a result of the lack of functional components in the augmented condition, the participants expressed more confidence in changing the circuit parts and exploring the effects of changes. In contrast, participants in the real electronics group expressed a fear of contact with the functional components. AR-driven systems, such as ElectronicsAR, can help users gain a fundamental understanding of electronics and circuit engineering, hence lowering the entry barrier into electronics. Thus, we are confident that ElectronicsAR can act as an entry tool for beginners who want to become familiar and comfortable with electronics. Yet, we also understand that beginners require more support than ElectronicsAR currently provides. For example, several participants asked for an augmentation layer that depicts the connections between the pins (i.e., horizontal lanes for the power pins and vertical lanes for all other pins).

We further note that ten out of twelve ElectronicsAR users debugged their circuits successfully. In contrast, only three out of twelve participants found the error in the circuit using functional components. The participants remarked that ElectronicsAR compensates for the lack of perceiving internal processes. In fact, most participants stressed that they would want to first self-explore a circuit through ElectronicsAR before building it with real components. Finally, we note that external factors like changes in the light conditions affected the ElectronicsAR users in their interaction with the circuits. The participants asked for more reliable detection mechanisms that could further benefit the construction of more complex circuits in which components may overlap and partly cover each other.

### 6.2 RQ2: What are the implications for the design of future AR electronics assistants?

Considering ElectronicsAR's characteristics, the mobile AR toolkit represents a different class of augmented applications for electronics learning and support. This has implications for the future development of AR tools for electronics in particular and tangible AR research in general. To support this discussion, we scored ElectronicsAR and key related work on a scale from 0 (not at all applicable) to 5 (fully applicable) across five characteristics: *functionality*, *fidelity*, *feedback type*, *interactivity*, and supported *circuit complexity*. While the assigned scores are the result of extensive discussions between the authors, we note that they are not grounded in any systematic review, neither are they supposed to represent a contribution in itself. Rather, we aim to support the discussion of how ElectronicsAR's characteristics differ from related work and how these differences inform use cases and interaction scenarios of future AR-based electronic tools. Figure 10 visualizes the scoring of characteristics of ElectronicsAR, as well as AR Circuits [14], AR Circuit Constructor [26], and ARbits [44].

One key difference between the various mobile AR applications lies in the functionality of electronic components. Here, our scoring was limited to 0 (i.e., non-functional virtual objects) and 5 (i.e., use of real and functional electronic components). Although ElectronicsAR does not make use of functional components, unlike ARbits [44] and AR Circuit Constructor [26], the components that users interact with closely resemble their real electronic counterparts. Therefore, we scored *fidelity* higher for ElectronicsAR, creating a contrast to the abstract components used by related work. Our system further differs in terms of *feedback type*, as it provides both, instant feedback on component behavior of the virtual objects, and detailed information on each component's voltage and current consumption. We also considered *interactivity* stronger in comparison to related work, as ElectronicsAR allows to parameterize components. Still, we see an opportunity to further increase interactivity by integrating interaction features similar to ARbits' [44] interactive virtual push buttons. Making, for example, rotary potentiometers interactive would allow for a more intuitive parameterization of certain components. Finally, we note that while our toolkit allows to create realistic circuits on a breadboard, the scaled size of the components and the rigid wires introduce limitations to circuit complexity.

Based on these observations and scores, we note the contrast between the detailed *feedback* that offers an opportunity to support even advanced and expert electronics users, and the limited circuit

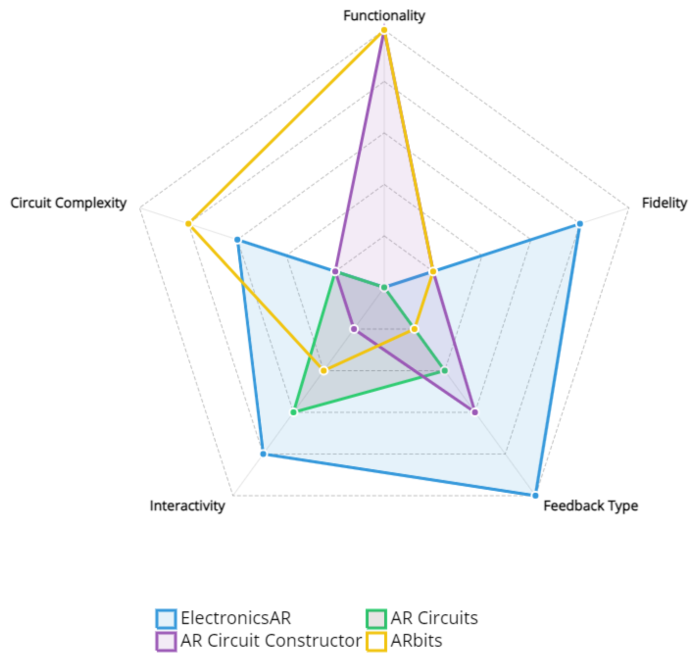



Fig. 10. An overview of ElectronicsAR's characteristics as compared to related work on mobile augmented electronics. While our toolkit advances fidelity, feedback types, and interactivity of mobile augmented electronics, further research on component and circuit recognition is needed to incorporate functional components and to increase circuit complexity.

complexity and functionality of the components. Contrasting our toolkit with related work, in particular ARbits [44] and AR Circuit Constructor [26], we note that adding functional components for complex circuits impacts component fidelity. The main reason for this lies in limitations related to image-based detection and recognition of electronic components. After experimenting with different image recognition strategies based on trained models of images and 3D models of our printed components, we found that marker detection, glued or printed, worked best. Reducing the size of the electronic components, or even using only the real components, renders recognition more challenging. Therefore, we note that future research attempting to increase circuit complexity and to integrate functional components into AR applications, while maintaining component fidelity, will need to explore new forms of tangible toolkits. Even a mix of functional and non-functional components within the same toolkit could be possible. For example, a real LED could be inserted into our 3D-printed scaled LED model. Wiring the breadboard could then enable the development of a functional future ElectronicsAR toolkit that profits from augmented circuit information for both functional circuits and non-functional ones. This could be controlled entirely by the user who decides whether or not they want to power the breadboard. Going further, smart breadboards like Toastboard [12], CurrentViz [47], and CircuitSense [48] might provide valuable starting points for research to explore toolkits that self-identify their configuration and that communicate retrieved information to mobile AR applications. Resulting mobile AR toolkits could accommodate the needs of diverse users, from beginners experimenting with simple components, to experts who need to understand intricate details about circuit issues and the behavior of electronic components. These efforts might further open new avenues for research beyond electronics to explore how AR image recognition can be complemented by smart objects that self-detect and communicate user configurations.

### 6.3 Limitations and Future Work

We note four key study limitations and opportunities for future work. First, the computer vision approach that we used for component detection and recognition is subject to certain conditions. For example, overlapping components on the breadboard can decrease detection performance. This limits the maximum circuit complexity and therefore the supported use cases of ElectronicsAR. In the discussion, we contrasted these limitations with the unique benefits of ElectronicsAR. Further, we described how future mobile AR toolkits could overcome these limitations by developing and integrating smart breadboards that sense and communicate the user configuration. This would enable the development of augmented electronic toolkits that do not rely on image recognition and that would be able to support complex circuits. However, we also note that the system in its current state is suitable to support the interaction with electronics on a basic level. Detailed feedback and component parameterization are likely to benefit even more advanced electronics learners. In addition, removing the markers presents an opportunity to even more closely match the visual features of the proxies with their real counterparts. Yet, we also note that it might remain difficult to represent intricate details of components that are very difficult to distinguish. One example are resistors and axial type inductors that are generally highly difficult to distinguish. However, we note that the need to distinguish such components likely goes hand in hand with applications that are out of scope of AR electronics learning toolkits.

Second, we note that the recruitment for the evaluation study was not limited to specific target groups. Rather, we recruited participants who were generally interested in exploring electronics and improving their knowledge about circuit building. This recruitment strategy impacted our control over participants' electronics experience or their motor skills/age. In this context, we want to stress that we perceive diversity in our sample as a strength of the study. Most of the related augmented electronics tools have not been systematically evaluated. Therefore, we consider the mapping of interaction experiences from a diverse participant pool a requirement and strength that helps provide a fundamental understanding of how AR tools can support a larger part of society gain access to electronics and making. This includes the use of didactic methods to evaluate potential learning effects of using ElectronicsAR in the long term [6]. Yet, we also note that future research should systematically explore interaction experiences and performance development of specific groups. Based on our findings, we discussed that the enlarged 3D printed toolkit components could be particularly suitable for children and the elderly. Supporting a wide range of society in learning electronics can greatly benefit participatory digital making.

Third, we note that most of our study participants were unfamiliar with AR technologies. Using AR for the first time might lead to a novelty effect and subsequent increased user expectations that can bias the results of the study [25]. Thus, a long-term field study will need to show the efficacy of AR technologies as tool facilitating electronics education. In this context, we also stress opportunities to explore and compare different AR technologies. In our work, we used hand-held mobile devices, common smartphones, due to their wide distribution in the society and even across many student populations. Exploring head mounted displays like the HoloLens in future work might open up new opportunities for tangible interaction with the circuit as the user does not require to hold any AR capable device. This might become particularly useful in future iterations that support more complex circuits.

Fourth, we highlight the tension between broader domain learning versus learning to use the system itself. While our work showed that the ElectronicsAR users performed overall better at the various tasks, this does not prove that the tool is effective at supporting to learn electronics on a broader scale. Rather, it demonstrates that users are able to interact with basic circuits more effectively and efficiently with the help of the system. While we argue that this applied skill set will substantially lower the barriers to the interaction with electronic circuits, it does not constitute a proof around larger domain learning. Therefore, we advocate for future work that investigates the long-term effect of using ElectronicsAR in formal educational settings and in the context of really learning and understanding electronics and key components.

## 7 CONCLUSION

This paper presents ElectronicsAR, a mobile and tangible Augmented Reality (AR) prototyping toolkit that assists users in sketching, understanding, and debugging electronics. ElectronicsAR detects 3D printed and enlarged components that act as proxies for functional electronic parts. We decided to use non-functional enlarged components to address two key barriers to electronic learning: fear of physical harm and fear of component damage. ElectronicsAR leverages the benefits of AR to address these concerns through a layer of interactive feedback that even provides insight into circuit processes that are normally not visible. To evaluate ElectronicsAR, we ran a between-subject study with 24 participants who completed three tasks: naming electronic components, debugging a circuit, and creating a new circuit. Participants using ElectronicsAR were more time efficient compared to study participants who used functional components. While the subjectively perceived task load did not show a significant difference between ElectronicsAR and functional components, participants acknowledged the strengths of ElectronicsAR. Based on our findings, we expect ElectronicsAR to lower the entry barrier for beginners and support advanced users in their circuit sketching process. We further contrast ElectronicsAR's characteristics with related work on mobile augmented electronics and discuss possible avenues for future research to include functional and complex components into the toolkit, while maintaining the high fidelity, feedback, and interactivity of the system. We publish the source code of ElectronicsAR as well as the 3D models on GitHub[6] to foster and encourage future research in this direction.

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