From Theory to Touch: Using Haptic Feedback to Support Students' Understanding of Voltage and Current

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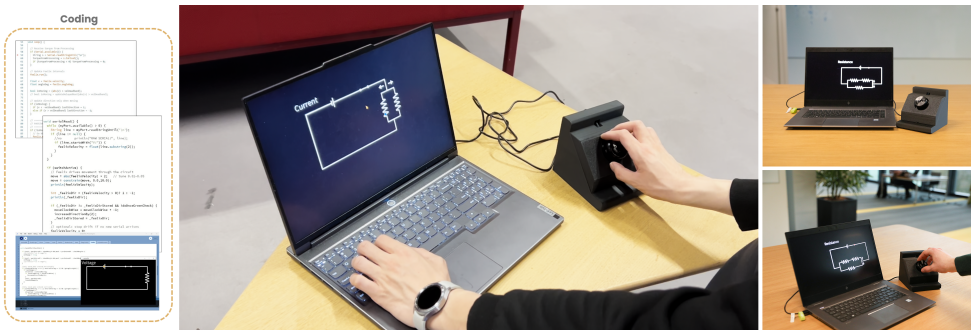


Fig. 1. Haptic-based System with Feelix

Learning basic electric circuits is a foundational yet challenging topic for beginners, as core concepts such as voltage, current, and resistance are typically introduced through abstract and symbolic representations. These quantities cannot be directly perceived, making it difficult for learners to build an intuitive understanding of circuit behavior. In this paper, we present From Theory to Touch, a Feelix-based haptic and visual learning tool that explores how multisensory interaction can support the understanding of basic electric circuits. The system combines a real-time visual circuit simulation with a haptic interface that provides torque feedback mapped to circuit properties. By allowing learners to both see and feel changes in circuit behavior while actively interacting with the system, the tool aims to bridge the gap between theoretical knowledge and embodied intuition. We describe the design rationale, system concept, and interaction principles behind the prototype, and discuss its potential, limitations, and future directions for multisensory circuit education.

Additional Key Words and Phrases: Circuit Education, Haptic Interaction, Tangible User Interfaces, Embodied Interaction, Force Feedback, Multisensory Learning, Feelix

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1 INTRODUCTION

1.1 Background

Understanding basic electric circuits is a fundamental learning objective in physics and engineering education. Concepts such as voltage, current, and resistance form the basis for more advanced topics, yet they are often difficult for beginners to grasp. Traditional circuit education relies heavily on visual and symbolic representations, including schematic diagrams, mathematical formulas, textual explanations, and static physical demonstrations. While these approaches are effective for communicating formal knowledge, they provide limited support for developing an intuitive understanding of how circuit parameters interact dynamically.

One core challenge is that electrical quantities are inherently invisible and intangible. Learners cannot directly observe current flow or physically feel changes in resistance or voltage, which can result in fragmented or purely theoretical mental models. Prior work in physics education has highlighted that this lack of perceptual grounding makes it difficult for beginners to meaningfully connect equations such as Ohm's law to observed circuit behavior, particularly in early learning stages [13].

Recent research in learning sciences and human–computer interaction increasingly demonstrates the value of multisensory learning environments. A recent meta-analysis of tangible and graphical user interfaces for teaching electric circuits reports consistent benefits of multimodal interaction for learning performance and conceptual clarity, especially for novice learners [10]. In parallel, recent reviews of haptic technology in education emphasize that touch-based interaction can enhance learning by transforming abstract concepts into physically perceivable experiences, particularly for children and beginners [6]. Together, these findings suggest that multisensory approaches can play a meaningful role in supporting the understanding of complex, invisible phenomena such as electrical behavior.

1.2 Research Aim

Building on this perspective, this project explores how haptic interaction can complement visual representations in circuit education. We investigate whether a Feelix-based haptic natural user interface, combined with a real-time visual simulation, can help beginners better understand the relationships between voltage, current, and resistance in basic electric circuits. Rather than replacing traditional teaching methods, the proposed system aims to augment visual learning with embodied, hands-on experience grounded in physical interaction and continuous feedback.

2 RELATED WORK

Prior research has explored a variety of approaches to make abstract electrical concepts more accessible to learners. Visual augmentation techniques are commonly used to represent invisible quantities such as voltage, current, and resistance through color coding, animation, and spatial metaphors. For example, augmented reality systems have been applied to support the understanding of Ohm's law by visually externalizing circuit behavior, enabling learners to better relate mathematical relationships to observable effects [8]. While such approaches improve perceptibility, they remain limited to a single sensory modality.

More recently, immersive technologies such as virtual reality have been introduced into circuit education. VR-based classroom systems allow learners to explore circuit behavior in interactive three-dimensional environments and have shown promising results in terms of engagement and conceptual understanding [3]. However, these systems often require head-mounted displays and complex technical setups, which may limit their accessibility and scalability in everyday educational contexts.

To address these limitations, researchers have investigated tangible and haptic interfaces as a means of supporting embodied learning. Tangible systems such as TouchWire enable children to learn circuit concepts through direct physical interaction, demonstrating how touch-based interfaces can support engagement and comprehension[9]. TangibleCircuits further extends this approach by enabling learners with visual impairments to construct and explore circuits using 3D-printed components, highlighting the critical role of touch in understanding electrical systems beyond purely visual representations [4]. While these systems effectively support discrete tangible interaction, they typically focus on component-level manipulation rather than continuous, real-time feedback linked to circuit dynamics.
In parallel, recent work in human–computer interaction has explored the design of flexible force feedback using the Feelix platform. Feelix supports continuous, programmable torque feedback and has been shown to enable a wide range of haptic and embodied interaction designs [**?**]. Design guidelines and tutorials further emphasize its suitability for prototyping haptic interfaces that require fine-grained control and real-time feedback [12]. Building on this body of work, our project explores how Feelix [11] can be applied in an educational context to provide continuous haptic feedback directly mapped to circuit behavior, tightly coupled with a visual simulation in a closed interaction loop.

3 DESIGN

3.1 Design Concept and Learning Goals

The core design concept of this project is to support students' understanding of basic electric circuits by transforming abstract electrical phenomena into perceptible and interactive experiences. Instead of focusing on numerical accuracy or symbolic equations, the system is designed to help learners develop qualitative intuition about how current, voltage, and resistance behave within a circuit.

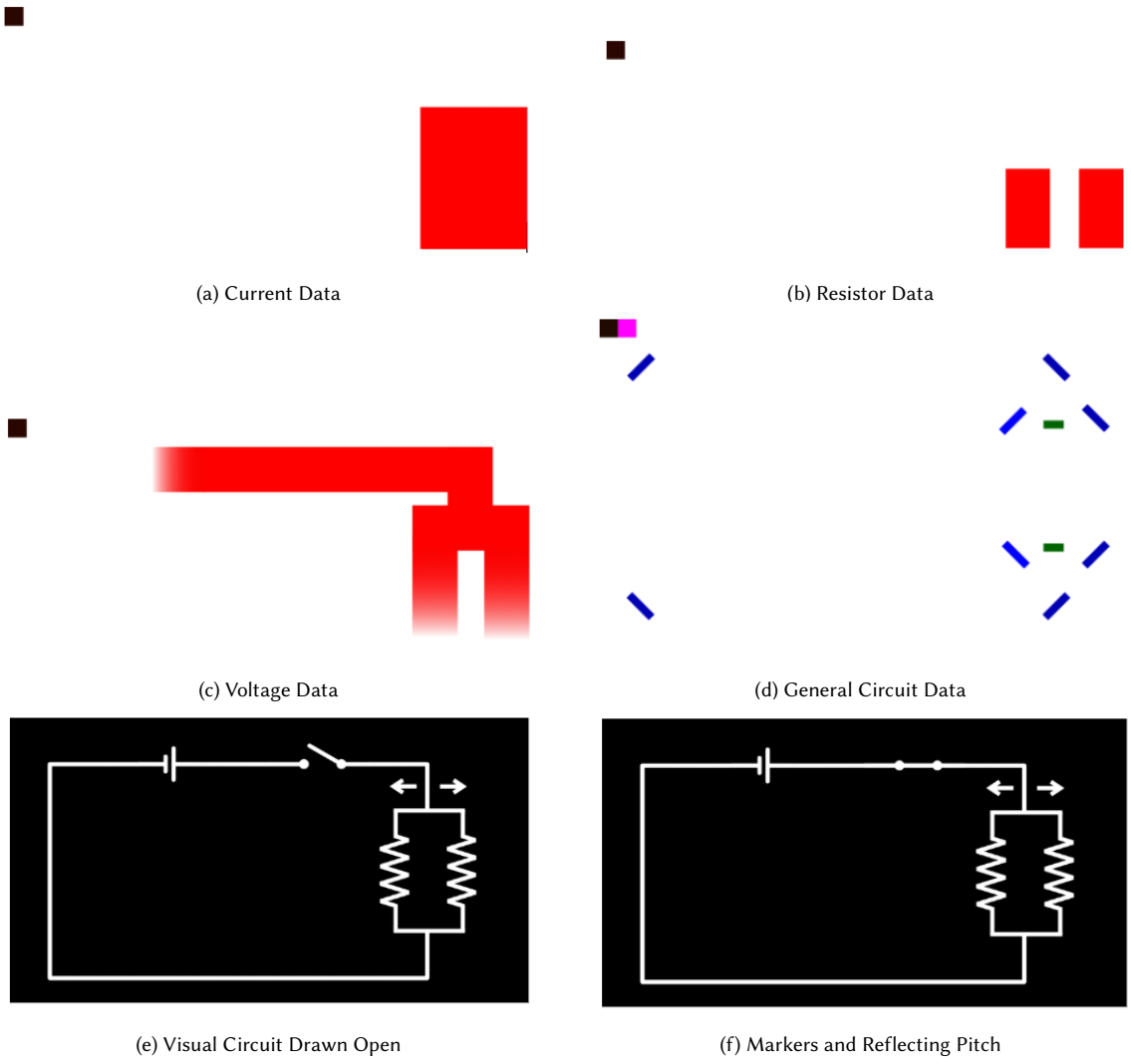
To achieve this, the interaction is centered around continuous exploration rather than discrete actions. Learners move through a circuit by physically rotating a haptic interface, while simultaneously seeing changes in circuit behavior and feeling resistance through force feedback. This design emphasizes embodied interaction, where understanding emerges through the coupling of action, perception, and system response.

The system is intentionally constrained to a small set of predefined circuits and interaction modes. This limitation allows learners to focus on perceiving relationships—such as how resistance affects effort and flow—without being overwhelmed by complexity. By tightly coupling visual feedback with haptic resistance, the design aims to bridge the gap between theoretical knowledge and experiential understanding of electric circuits.

3.2 Image-Based Interaction Model for Circuit Exploration

In Processing[2], an app is created to display and track nine different electronic circuits. One circuit is loaded at a time and a tracker moves along it. The tracker's position determines the torque value sent to Processing. Processing reads the color values of multiple images to know which values or actions to take at certain positions. In order, Processing renders and overlays the following circuits images: current torque data (either current, voltage, or resistance data), general circuit data, and visual circuit drawing (with switch either open or closed). Before rendering the final image, the visual circuit drawing, Processing reads the color value at the tracker's position. Each color represents a different action; Red values (0-255) represent the torque sent to Arduino. The value is mapped from 0-255 (value r) to 0-1 (value torque), so R = 0 is no torque, and R = 255 is high torque. Blue represents corners in the circuit; a blue value of 180 means clockwise rotation, and 255 means counterclockwise rotation. Green indicates a junction point: a value of 100 represents a T-section, and 150 represents a three-way junction. At a junction point, the tracker stops, and the user can

select a direction using the arrow keys. The purple square, as seen in the top left corner of figure X, informs Processing that there is a switch in the circuit. The number keys 1-9 are used to switch between different circuits. The TAB key is used to switch between experiencing haptic feedback of the current, voltage, or resistance. The spacebar is used to toggle switches.



(a) Current Data

(b) Resistor Data

(c) Voltage Data

(d) General Circuit Data

(e) Visual Circuit Drawn Open

(f) Markers and Reflecting Pitch

Fig. 2. Figure Details

3.3 Feelix to interface communication

The Feelix [1] motor communicates with the Processing interface through a serial link. When turning the motor, the rotating velocity (positive or negative) gets sent to Processing through Arduino, determining in which direction and by how much the tracking point on the circuit should move. At the same time, Processing continuously sends a single

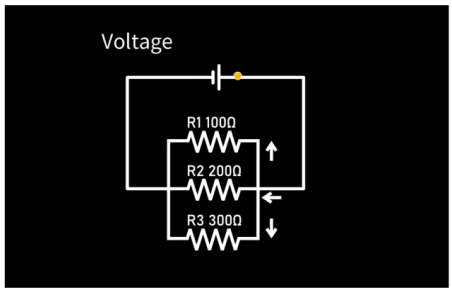


Fig. 3. Final Visual For The User

float value between 0 and 1 depending on where the tracking point is located in the circuit, representing how much torque should be applied on the Feelix. By updating the zero angle of the Feelix every time velocity falls below a certain threshold, the prototype can be let go without it returning to the starting position. When velocity is negative, torque direction also gets flipped. This results in users being able to move through the circuit freely in both directions and without being under constant pressure when not rotating the motor.

3.4 IMPLEMENTATION

This project explores how haptic interaction can complement visual representations in circuit education. The vision is to implement it in junior high school classrooms, where teachers can create custom circuits for the students to explore and experience. Through haptic feedback, students can better understand what happens within an electronic circuit. In future versions, it will be easier to create circuits, so that students can design and experience their own circuit drawings.

4 EVALUATION METHOD

In order to explore how haptic interaction can help users understand basic electronic concepts [7], we used feelix to make a circuit experience system and carried out a qualitative user study. The evaluation focuses on the user's understanding of circuit concepts and the experience of using feelix system.

4.1 Study Setup

The study was conducted at the Eindhoven University of Technology. The physical feelix system was placed next to the computer displaying the circuit diagram. Appendix x shows the study setup. We recruited five participants with different levels of circuit theory knowledge. This variety of performance helps us explore the operation of feelix system under different learning background. Each test lasts about 30-40 minutes. There are three sessions with 1-2 participants in each test. Participants need to interact with feelix system. The system integrates tangible interaction and haptoc feedback to simulate the circuit.

4.2 Study Protocol

The study took an average of 35 minutes and was divided into four parts. First, participants answered short questions to introduce their knowledge and confidence in electrical concepts such as current and voltage. Secondly, participants freely explore the interaction through the feelix system. Observe their intuitive understanding of the system, exploration strategies, and interpretation of tactile feedback. Subsequently, participants experienced two core tasks based on the

system. Task A is to modify different circuit modes (such as voltage and resistance modes) to feel tactile feedback. Task B is to compare different circuit diagrams to identify perceived current and voltage differences.
Finally, the participants accepted a semi-structured interview, answered the Likert scale questions, elaborated their understanding of the relationship between circuit and tactile perception, and compared feelix with traditional learning methods such as textbooks and circuit diagrams.

4.3 Data Collection and Analysis

Data collection methods include observing the interaction between user experience circuit and feelix system, and interviews based on different key points. After summarizing all the above qualitative answers, extract the high-frequency topics in the data. In addition, users' quantitative score responses were collected in the interview. The analysis focuses on how participants establish a connection with the circuit from tactile feedback, how tactile interaction affects conceptual understanding, and how the system affects user participation and learning motivation.
This hybrid qualitative method enables us to correlate circuit understanding and feelix experience, so as to deeply understand the potential of entity and tactile interfaces in learning abstract scientific concepts.

5 RESULTS

These implementations resulted in a haptic-based feelix system, focusing on how participants perceive and interpret haptic interactions, and how these interactions affect their understanding of electrical concepts. The experience site provides users with computer equipment and physical equipment which keeps feelix. The circuit diagram is visually displayed on the laptop screen running code as the laptop is horizontally placed on the desktop. Users can press shortcut keys to adjust the circuit diagram and different modes. The physical device is connected to the computer and also placed horizontally on the desktop. When the user turns feelix clockwise, the colored charge in the circuit diagram begins to move along the circuit, and feelix generates torque. Users can gain more in-depth knowledge and understanding of the circuit through tactile interaction.
Our test was made to communicate and validate this concept. The code is written by Processing. Map () function is used to map the circuit data to haptic feedback, constraint() function is used to limit the range of feelix speed and torque to avoid wild interaction caused by excessive values. And translate() function is used to adjust the coordinate system so that the charge position is aligned with the circuit image. The calculated torque is sent back to feelix in real time, enabling users to perceive the changes of circuit elements when adjusting the circuit.

- In the free exploration phase, most participants control the keyboard with one hand and feelix with the other. Participants with circuit knowledge tend to explore the system more systematically. For example, a participant directly and quickly tried different circuits and experienced different torques. In the process, they tried to connect haptic perception with known electrical concepts. While for participants with limited background knowledge, they were more inclined to intuitive exploration. Initially, they would try to switch the circuit mode and twist feelix at a slower pace, and understand how haptic feedback reflected charge mobility through repeated experiments. They paid more attention to sensory differences than the theoretical explanation of the circuit. In all experimental parts, participants can quickly master the basic interaction logic of the system. Observation results show that feelix supports exploratory learning through users' sensory interaction, and also reveals the need for a clearer mapping relationship between haptic cues and conceptual representation.
- Many participants interpreted haptic feedback as the resistance or difficulty of current flow. In tasks, participants adjust circuits to change haptic feedback. This shows that feelix has successfully transformed the invisible

electrical phenomenon into tactile experience, which may serve as a bridge between sensory experience and concept learning. However, when asked to compare two circuit configurations, some participants were difficult to distinguish the differences only through tactile feedback, such as comparing the voltage, which indicates that the system has limitations in the mapping between specific electrical concepts and tactile.

- In addition to concept understanding, according to Likert scale score, feelix significantly affected the participants' engagement and made abstract concepts more specific. Participants said that the system was more interesting, novel and perceptive than traditional learning methods such as textbooks or circuit diagrams. The high availability score shows that tactile interaction provides an easier way to understand the concept of circuit.

6 DISCUSSIONS

The study explored to what extend tangible haptic interaction, implemented with the Feelix prototype, can support students in understanding the basic concepts of electrical circuits such as voltage, current and resistance. [5]The results indicate that the prototype shows potential in translating abstract circuit behaviour into more concrete and experientially accessible information, particularly for users with limited prior knowledge of electronics. However, several limitations and opportunities for future work were also identified.

Across participants, the free exploration section of the study revealed that users began to match the haptic feedback with the intended circuit behaviour quickly. The participants often started off relatively hesitant, particularly by students that were not familiar with the Feelix, but followed by increasingly confident and exploratory behaviour. Especially for participants that were not experienced, the system encouraged trial-and-error interaction rather than relying on formal instructions. Most participants alternated between manipulating the Feelix and visually inspecting the laptop interface, suggesting an attempt to link physical input with changes in the circuit layout. Once participants experienced a notable change in haptic feedback, they began forming hypotheses about cause-effect relationships, such as associating stronger torque with a higher unit value and vice versa. This supports the suggestion that tangible interfaces can support the sense-making of abstract concepts by allowing users to actively experience system dynamics rather than only reasoning about them through text, numbers and schematics.

The results also highlighted a contrast between novice and experienced users of electronic circuits. Participants with a stronger electronic background reported that the system added limited new insights for them. One experienced participant stated that "with or without tactile feedback, I already understand the circuit diagram itself; it doesn't have much impact on the overall circuit" (#P2). This was also reflected by lower Likert scores for conceptual understanding, with the same participant rating the statement "The haptic feedback helped me understand current and voltage" as low as 2/7. In contrast, novice users consistently reported higher engagement and perceived learning. One participant rated engagement as high as a 7/7 and described the system as "more personal and detailed; understanding abstract concepts through touch" (#P3). This suggests that the system may be particularly well-suited as an introductory or supplementary learning tool when understanding about circuit dynamics is relatively low, rather than a replacement for traditional instructions, especially when circuits get more complex.

A recurring theme across all participants was difficulty in clearly distinguishing between representations of current, voltage and resistance at first. Even though most participants generally understood the fact that more torque from the Feelix translated to more 'difficulty' in moving through the circuit, the mapping between the different quantities and haptic feedback was not always clear. Some participants (state which ones), stated that voltage and resistance felt similar, while others needed either visual cues on the laptop or prior knowledge to interpret what the haptic feedback

was communicating. This indicates that while haptic feedback can support learning and understanding, it may require complementary cues or prior instructions to avoid confusion.

6.1 Limitations

Several limitations of the current prototype emerged across the user studies. First, the limited number of circuits constrain exploration. Participants noticed that while the system was engaging at first, it lacked complexity or extent to move beyond basic or short-term use. Secondly, as mentioned above, the current setup made it difficult for some participants to distinguish between voltage, current and resistance purely through haptic feedback. Switching between modes could feel too ambiguous or subtle.
Additionally, this version of the prototype still relied heavily on keyboard input for mode switching and navigation. This partly interrupted the tangible interaction and made it more complex and difficult for participants to get into a workflow, by constantly having to switch between inputs. Technical issues were also present, such as the Feelix vibrating while turning, resulting in hesitation and unwanted outputs that could feel confusing, and bugs in the laptop interface resulting in resets that interrupted interpretation of the feedback.

6.2 Future Work

Future iterations of the system could address the current limitations in several ways. Expanding the number of available circuits would support further experimentation and deeper exploration of possible changes of the quantities. Another way to achieve this is to allow users to build their own circuits using available elements with different characteristics, to essentially allow users to build an infinite amount of possibilities. To facilitate this, more complex elements such as diodes, capacitors or transistors could be integrated. Reducing reliance on keyboard input would also greatly enhance user experience. Integrating tangible controls or on-device interactions for mode switching would better align with the embodied learning goals of the system. The biggest challenge here is, of course, to come up with an intuitive interaction architecture that does not unnecessarily complicate the system. Finally, performing a longitudinal study with a larger sample group where learning outcomes between traditional methods and the haptic system are compared would help clarify its educational value.

7 CONCLUSION

The aim of this project was to explore how haptic interaction can support the understanding of the flow of different electrical properties by making abstract behaviour physically interpretable. Through the prototype, quantities such as voltage, current and resistance were translated into haptic feedback, allowing users to explore circuits through touch and torque rather than relying solely on visual input on a screen or paper. The user study has demonstrated that this embodied approach shows promising opportunities for supporting learning, especially for beginners. Participants with a higher level of prior knowledge consistently reported that the tool helped them understand concepts that otherwise seemed abstract, describing the experience as more intuitive, concrete, and engaging than traditional learning materials. By physically feeling intuitive changes in the circuit, participants were able to make links between the feedback and circuit structure, supporting exploratory and self-guided learning.
At the same time, the results also highlight that the tool is not equally beneficial for all users. Participants with a stronger electronic background found the prototype to be less informative, or at least to have less added value. This suggests that its current design is perhaps better suited as an introductory or complementary learning tool rather than a replacement for traditional learning methods. Additionally, limitations of the current prototype in circuit variety and several bugs constrained deeper exploration that could be improved upon with future iterations.

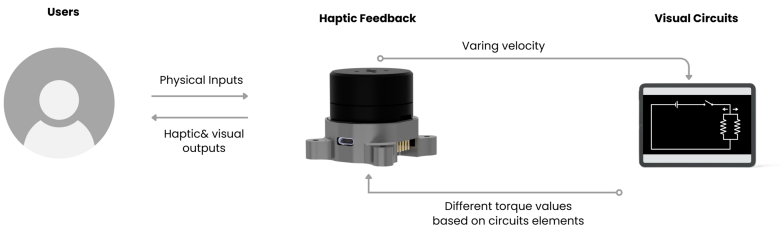
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A USER SYSTEM



B VIDEO DEMO

Here is the video link: https://youtu.be/xJZ0TRuqTiA

C AI USAGE STATEMENT

We acknowledge the use of ChatGPT to assist in the translation and grammar polishing of certain content. All other design research content is original.

D USER STUDY SCRIPT

1. Introduction and Consent

Hello, thank you for participating in this study.

Today you will be interacting with an educational prototype that uses the Feelix tangible haptic hardware toolkit to support learning about basic electrical concepts such as current and voltage. This prototype is designed to make abstract circuit behavior physically perceivable through touch and tangible interaction. The goal of this study is to understand how tangible and haptic interaction can support learning, not to evaluate your performance.

This is not a test of you, but a test of the system. There are no right or wrong answers. We are interested in your thoughts, feelings, and experiences while using the prototype. The session will take approximately 20–30 minutes. Your participation is voluntary, and you may stop at any time. We will not collect any personal identifying information.

Before we begin, please take a moment to read the Consent Form provided to you. The form explains the purpose of the study, what you will be asked to do, and how your data will be handled. Please read the form carefully. If anything is unclear, feel free to ask questions at any time. If you agree to participate, please complete the required fields on the Consent Form and sign your name at the bottom to indicate your consent. Once you have signed the form, we can begin the study.

Do you have any questions before we start?

2. Background & Baseline Questions

Purpose: Understand prior knowledge and learning background.

1.1 Have you studied basic electricity or circuits before? 1.2 How confident do you feel about understanding electric current and voltage?

(1 = not confident at all, 5 = very confident) 1.3 In your own words: What do you think electric current is? 1.4 What do you think voltage means? 1.5 Do you usually find circuit diagrams easy or difficult to understand? Why?

3. Free Exploration with Feelix

You can now explore Feelix freely. Please try touching, connecting, or modifying the circuit in any way you like. Think aloud if possible — say what you think is happening.

(Observe: Hesitation or confidence Exploration strategies Whether the participant links sensation to circuit changes)

Follow-up Questions

(1) What do you think is happening when you interact with Feelix?

(2) What do you think the haptic feedback represents?

(3) Was anything confusing at first?

(4) Did you feel like you needed instructions, or could you figure it out by yourself?

4. Task-Based Learning Activities (Core Study) (I might will change it according to the updated design)

Task A : Understanding Change in the Circuit

Task Instruction: Please try to change the circuit so that the haptic feedback becomes stronger.

Questions:

What did you change to make that happen?

Why do you think that change affected the feedback?

Did the haptic feedback help you understand what changed in the circuit?

Task B – Comparing Two Circuit Configurations

Task Instruction: Now please compare these two circuits. Try to feel how they are different.

Questions:

How do these two circuits feel different?

Which one do you think has higher current or voltage? Why?

Would you be able to tell the difference without looking at a diagram?

5. Reflection & Comparison

Purpose: Compare with traditional learning methods.

5.1 Compared to learning from textbooks or diagrams, how was this experience different?

5.2 Did the haptic feedback make abstract concepts more concrete? How?

5.3 Did you feel more engaged than in a typical electronics lesson?

5.4 What did you like most about using Feelix?

5.5 What would you improve or change?

6. Likert-Scale Evaluation

Ask participant to rate from 1 (strongly disagree) to 10 (strongly agree):

I could understand the relationship between the circuit and the haptic feedback.

The haptic feedback helped me understand current and voltage.

The system was intuitive to use.

I felt more engaged than with traditional learning materials.

I would like to use this system again to learn electronics.

7. Closing Questions

Do you think this system would be helpful for beginners learning electronics?

In what situations do you think Feelix would be most useful?

Is there anything else you would like to share?