ColabAR: A Toolkit for Remote Collaboration in Tangible Augmented Reality Laboratories

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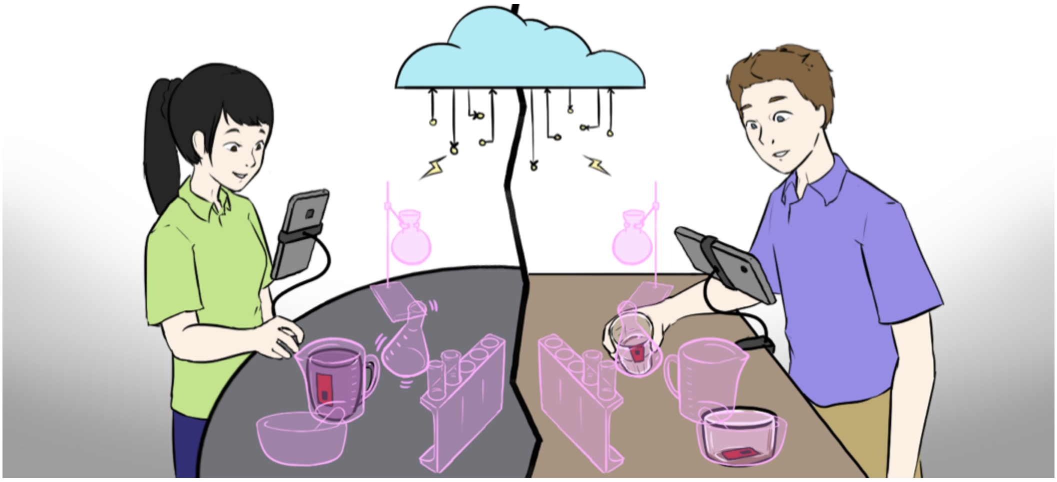

Fig. 1. Overview of the usability of our toolkit to enable remote collaboration in a TAR laboratory. Each module includes a fiducial marker, Arduino Nano, and a haptic driver for customizable haptic feedback. Students collaborate remotely by using tangibles that are proxies to virtual objects.

Current times are accelerating new technologies to provide high-quality education for remote collaboration, as well as hands-on learning. This is particularly important in the case of laboratory-based classes, which

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play an essential role in STEM education. In this paper, we introduce ColabAR, a toolkit that uses physical proxies to manipulate virtual objects in Tangible Augmented Reality (TAR) laboratories. ColabAR introduces haptic-based customizable interaction techniques to promote remote collaboration between students. Our toolkit provides hardware and software that enable haptic feedback to improve user experience and promote collaboration during learning. Also, we present the architecture of our cloud platform for haptic interaction that supports information sharing between students in a TAR laboratory. We performed two user studies (N=40) to test the effect of our toolkit in enriching local and remote collaborative experiences. Finally, we demonstrated that our TAR laboratory enables students' performance (i.e., lab completion rate, lab scores) to be similar to their performance in an in-person laboratory.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Interactive systems and tools*; User interface toolkits; *Interaction devices*; Haptic devices.

Additional Key Words and Phrases: Augmented Reality; tangibles; haptics; remote; collaboration; laboratory; STEM; distance; learning; education

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1 INTRODUCTION

Current unprecedented times with the spread of COVID-19, have led to the cancellation of in-person classes, suddenly introducing the majority of students into remote learning, and leaving instructors and students scrambling to figure out how to continue with their lessons given the diversity of subjects at universities [57]. In particular, remote learning has to accelerate new technologies that provide high-quality education while maintaining a sense of immersion and community, as well as hands-on learning. This is especially true in the case of laboratory-based classes, which play an essential role in STEM education [29].

Laboratory-based classes provide students with hands-on experimentation into real systems and processes. However, they typically require high costs from equipment, space, maintenance [24]. These physical laboratories also require on-campus residency for students; which limits accessibility for distance learners [51, 54]. Accordingly, there is a push for new types of laboratories that offer students hands-on distance learning and that enable remote collaboration between students [14].

New technologies, such as Augmented Reality (AR), overlay virtual information into the physical world [6], while Tangible User Interfaces (TUIs) allow the manipulation of this virtual information by using objects from the physical world [40]. TUIs are powerful because the physical props are typically obtained by re-purposing objects, which have familiar properties, physical constraints, and affordances [30, 61]. Similarly, AR interfaces can benefit from physical props such as input devices to enhance usability, direct manipulation, and overlay information [86]. Thus, combining both technologies in the form of Tangible AR (TAR) provides users with everyday physical objects as proxies for their virtual counterparts [9]. This interaction enables users to directly manipulate an AR object by handling its physical representation [49]. Building TAR applications and prototyping haptic feedback for users in immersive environments remains challenging due to several requirements: (1) registration of physical props in the AR scene; (2) leveraging these physical props to provide haptic feedback; (3) enabling spontaneous and direct manipulation of virtual objects using physical props.

Past work has shown that participants have more realistic remote collaboration on physical tasks using AR as compared to typical video conferencing [26, 27]. Thus, an AR system that enables remote collaboration shows a promising solution in a multi-user educational context. However, while AR systems have been evaluated on their transmission of virtual annotation between users, little work has been done to understand how haptic feedback–obtained from the physical props–can be shared in the AR scene.

We propose combining AR with the capabilities of TUIs to leverage haptic feedback, improve local and remote user experience, and provide a sense of presence to spatially distributed users. In this work, we propose the hardware and architecture to facilitate remote collaboration between students. We aim to enrich the local and remote user experience by providing users with customizable and shared haptic feedback, and enabling the coordination in both the AR content and procedure of the laboratory. We consider it timely to propose the toolkit to enable AR and haptic-based remote collaboration in TAR laboratories. Thus, we design, develop, and assess ColabAR (Fig. 1), and present the following contributions:

1. **An approach to introduce customizable haptic feedback interaction techniques for remote collaboration in TAR laboratories**.
2. **A toolkit for prototyping of TAR laboratory experiences.** The physical props are made from everyday objects and the hardware enables direct manipulation of the virtual world. We include a remote collaboration architecture to support sharing of AR content and haptic information.
3. **User studies** to explore the role of haptic feedback in supporting peer-to-peer guidance distance laboratories and in enhancing the tangible experience when interacting with the system.

2 RELATED WORK

2.1 Mixed Reality Remote Collaboration

In recent years, much focus has been placed on remote collaboration in mixed reality (MR) technologies [20]. The purpose of MR remote collaboration is to enhance interaction between users, usually through non-verbal cues, such as haptic feedback, visual cues, annotations, and avatars [81]. Non-verbal cues, in the form of a hand avatar or a pointer [11, 44, 77], have been shown to improve collaboration and performance; while haptic feedback can improve user experience and awareness [81].

Other remote interactions include drawings and annotations, that allow users to look at the content from multiple viewpoints [3, 21, 45, 64], head pointing [4, 23, 82], shared video [5, 21, 26], shared gaze [17, 25, 66], and shared gestures [35, 83]. Another alternative has been to use 3D models to facilitate explanations [19, 65] between users.

Multi-modal interactions are meant to enhance collaboration between remote participants and resemble face-to-face scenarios as close as possible. However, these interactions are typically parts of systems that require significant setups, such as projectors, headsets, skeleton tracking [81]. These are each individual technologies and integrating them is complex, which is why a TAR remote access has not been successfully developed. Our toolkit provides end-to-end integrated technology setup for the laboratory to be deployed in students' own mobile phones. Our work focuses on implementing and testing haptic feedback for phone-based AR [8].

2.2 Haptic Feedback

Many TUIs utilize physical objects to provide haptic interaction with mixed reality interfaces [10, 38, 39]. Combining AR with TUIs creates a Tangible Augmented Reality (TAR) setup, which can use haptic feedback from physical objects and uses AR as the virtual interface to the physical world. Physical objects, which act as proxies to virtual counterparts, have familiar properties and physical constraints. Thus, these objects are easier to use as input devices [39, 74].

We use haptic feedback to enhance peer-to-peer collaboration in TAR laboratories. Thus, our setup aims to resemble physical laboratories and their real-life experiments [14]. Haptic feedback for collaborative work has been extensively explored in successful interaction and collaboration between humans and robots [53]. Similarly, it has been used to enable interaction between human participants [43, 56, 73], although to a lesser extent.

Currently, the tactile approach is one of the most commonly used haptic feedback techniques [8]. For example, vibration on our smartphones or game controllers enables the cutaneous perception of a text message or a car crash in a video game. Vibration motors have become easily accessible given their miniaturization and simple design, which allows for their implementation as a haptic technique. Past work has evaluated the benefits of audio and tactile feedback to facilitate communication [55, 79]. They have also been used to deliver different feedback such as confirmations of received messages, error warnings, and download progress reports [32]. Vibrotactile feedback provides a wide range of sensory information, which enable informing intentions and actions in cooperative tasks [60, 73]. In some cases, vibrotactile feedback has been shown to transmit instructions at a faster rate than using verbal communication [56, 69]. However, participants have reported that there is a challenge to understand the specific meaning behind this feedback [56]. One technique to solve this confusion can be achieved through changes in the vibration pattern. Different vibration patterns, such as rate, duration, and strength, have improved the resolution for haptic information transmission [13, 50, 79], the vibrohaptic experience [68], and user immersion by providing an appropriate intensity and roughness [48].

Typically, haptic techniques for AR had the vibrotactile feedback contained into the AR-based device, e.g., smartphone, wristband, headband, etc [8]. Self-contained haptic devices impede direct object manipulation of tangibles in the scene. Audio feedback is innate to an AR-compatible device since it can be obtained from the phone's speakers [8]. However, haptic feedback responsive to an AR environment is an add-on feature. In our toolkit, we decouple the feedback modules from the phone, instead placing a module on the surface of each tangible. We hypothesize that combining inertial measurement unit (IMU) sensors and vibration feedback into a single module will enable a richer haptic experience. Thus, we leverage readings from the IMUs–during users' direct manipulation with the physical props–to generate customizable vibrotactile feedback.

2.3 Virtual Laboratories

Virtual labs have the potential to lower costs of equipment and maintenance of in-person labs while leveraging students' tech-savvy intuitiveness [51, 54]. Empirical results have reported that virtual labs provide comparable academic performance and curiosity. Past work has shown that properly planned and delivered virtual labs can increase students' knowledge, skills, and performance in examinations; while facilitating distance learning, promoting health and safety, and reducing performance cost to traditional in-person labs if the content is carefully curated [12, 28, 47, 52, 58, 59, 75, 76, 80, 85]. Some other benefits cited by these authors include the availability of these labs at any time, unlike physical labs which are typically only available for short periods of time due to logistic accommodations. Also, scientific inquiry usually requires iteration of an experiment [31, 46], which is simplified by virtual labs.

Virtual labs, which take place in the digital world, support a wide range of subjects involving thermodynamics [15], chemistry [7], electricity [41, 42], physics [18], biology [33, 34], fluid mechanics [85]. Virtual labs are also useful tools to facilitate pre-laboratory preparation and make sure that students get exposition to how to handle equipment and perform an experiment [2, 16], which is an essential part of the laboratory learning experience [70, 72].

Our toolkit for AR-based labs aims to use the best features of virtual labs: TAR experience provides hands-on learning by adding virtual information overlaid on the physical objects in the scene and enables students to practice as often as they like, without taking up resources. Additionally, we focus on providing a cloud architecture to share virtual information and haptic feedback to enrich collaboration.

As we implement TAR laboratories, we imitate the principles of in-person and virtual laboratories, which have extensively explored how to best provide inquiry-based science education [22]. Laboratories should supply hands-on testing to arouse interest; provide a diversity of hardware, instruments, demonstrations, and assets; yield similar outcomes to real-world materials and experiments; supply real-world data and estimations to approach genuine frameworks; provide an interface that enables data collection through analog and digital signals or perform complex calculations [14]. When it comes to virtual laboratories, our main challenge is enabling haptics for peer-to-peer learning. We apply haptics—vibrotactile feedback—to accelerate non-visual cues between participants and promote spatial awareness [56]. Thus, we hypothesize on the usefulness of haptics for learning. Haptic feedback offers an additional layer of sensorimotor input, which in turn contributes to a mental representation of the physical object [37]. Previous work has shown that object handling and haptic feedback contribute to enhancing learning experience and outcomes [62, 63]. However, there is still a research gap to answer the role of haptics in a TAR remote laboratory by directly linking the experience to learning outcomes.

3 ELICITATION REQUIREMENTS

In order to enable TAR laboratories for STEM distance learning, we need to find out what unique challenges we have to overcome to deploy a laboratory at home–in particular–using AR. We interviewed 3 laboratory instructors and 10 students who had at least one year of experience in laboratory courses in Chemistry and Physics. Two instructors had at least 2 semesters of experience teaching Chemistry for Engineers and the other instructor had 3 semesters of experience teaching Circuits and Electronics. We prepared a semi-structured interview with the instructors to understand what valuable experiences needed to be mimicked from the physical world and what to leverage from the augmented setup to enrich students' experience. Each interview was individual and lasted from 30 minutes-1 hour. Students responded to a survey completed voluntarily.

3.1 Findings

Instructors were mostly concerned with recreating the practical aspect of handling science equipment. There was a consensus that concepts taught during a lecture were better understood through scientific experimentation. Also, instructors considered that this type of exploration was the closest experience to the real-world situation they could provide for their students (e.g., chemical reactions, current flow, collision). Students were more concerned with a flexible setup that is simple to implement while providing enough room to change and tune parameters within the experiments and obtain different results. Although students had little experience with virtual laboratories, they were excited by the prospect of freely exploring a laboratory setting without the fear of breaking or damaging any equipment. Thus, based on these observations, we decided on design goals for our toolkit.

D1. A need to support a complex environment. A toolkit for TAR laboratories needs to support equipment that matches the complexity and variety of real-life physical laboratories.

D2. A need for new techniques for communication. A TAR system needs to generate techniques to successfully share non-verbal cues between participants.

D3. A need for empathetic collaboration. While laboratory partners are interacting remotely, we need to make sure that help and instructions are shared organically between them, with a focus on the audiovisual and tactile sensory channels.

D4. A need for augmentation beyond physical limits. We need to successfully correlate physical proxies and their virtual counterparts, and also extend their functionalities beyond what is possible in the real world. Instructors were interested in utilizing fewer resources while allowing students to engage in more versions (i.e., different conditions) of the same experiment. Students were

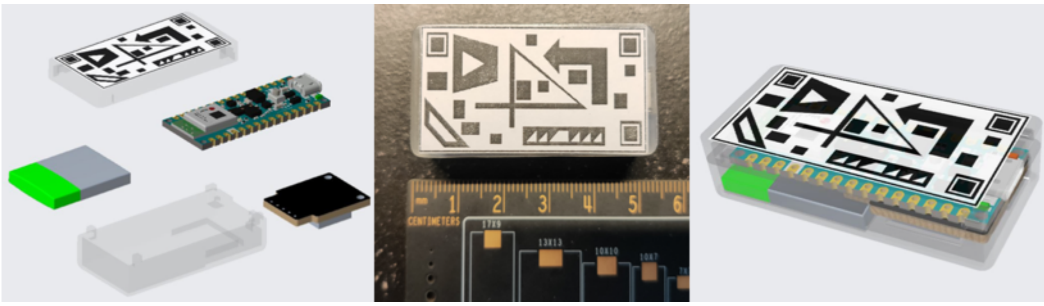

Fig. 2. *Left*: Explosion CAD view from haptic module of ColabAR, includes: encasing with fiducial marker, Arduino Nano, haptic driver, and battery. *Middle*: Tag and ruler(cm) for scale. *Right*: Tag Assembly.

optimistic about the possibility of engaging in augmented laboratory work but were apprehensive as to how their performance could be maintained in completing experiments.

D5. A need for a scalable architecture. We need to leverage cloud capabilities to enable multiple users to simultaneously take part in a laboratory, even if these are split into pairs. Instructors indicated that any lab session they create for their students should be accessible and easily implemented by students.

4 SYSTEM OVERVIEW

4.1 Hardware

4.1.1 Haptic Module. The haptic module is shown in Figure 2. We used the DRV2605L haptic driver breakout with a linear resonant actuator (LRA), to render fine-grain tactile vibration. The small range of resonant frequencies of LRA guarantees stable vibration at various amplitudes. The low haptic response time allows the LRA to be sensible to the input signal (start-up time is around 0.75ms and typical rise time is around 10ms), which is the key to generate authentic haptic feedback. The Arduino Nano 33 BLE Sense board includes an nRF52840 processor and a 9-axis Inertial Measurement Unit (IMU). The nRF52840 processor contains a powerful Cortex M4F and integrated Bluetooth Low Energy (BLE) Radio. The BLE protocol allows us to connect the toolkit with the phone at low power consumption. The connection latency has a minimum of 5ms. The IMU–which measures the angular velocity and acceleration–has an update frequency of 952Hz. It captures the module's movement constantly in real-time, so as to enable more responsive feedback to be provided accordingly. We used a 150mAh Lithium Polymeter battery which allows the toolkit to work continuously for about two hours without recharging. All these components are encapsulated in a (48mm*23.5mm*13mm) sized 3D-printed case. On the external surface, an AR fiducial marker–used for camera tracking was attached. The whole haptic module weighs 19.8g and costs around $30. The modules were attached to the real-world objects through double-sided tape, which proved to be sufficiently stable.

4.1.2 Smart Phone. In our setup, Android phones are used both to render/display AR content and to control haptic modules. The use of the Android phones is optional as they could be replaced by students' own smartphones, as long as these were AR-compatible.

4.2 Software

4.2.1 Unity Package. We provide a *Unity Package* for content designers to easily author varied types of haptic module behaviors and integrate them seamlessly into an existing AR application. The interface of the package is shown in Figure 3 (Left). Each haptic module with an AR marker attached

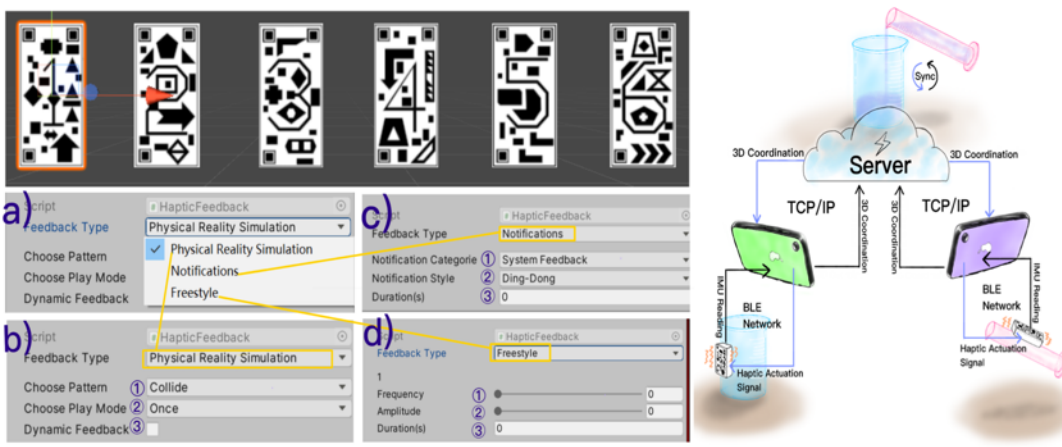

Fig. 3. *Left:* Unity package interface. *Right:* System diagram of the multi-tier network.

is in one-to-one correspondence with an *Unity Prefab* (see Figure 3: Top-Left). The authoring process begins with clicking on one of these prefabs, after which users are prompted to choose from three types of haptic feedback (see Figure 3a). Each haptic feedback comes with customizable options (see Figure 3a-c) to meet with diversified demand. Details on these types of haptic feedback will be illustrated in the next section.

4.2.2 Network Architecture. We adopted a tree topology, as shown in Figure 3 (Right) to construct the multi-tier network architecture which connects the haptic modules, phones and the remote server together. On the lower tier, haptic modules are linked to the phone through the Bluetooth Low Energy (BLE) network. The BLE network can operate with low energy consumption which is crucial for our self-contained module. On the upper tier, phones from different users are connected to each other through an intermediate server. The TCP/IP protocol is used in this tier to ensure reliable data transmission between phones. After connecting a module to the phone, it starts sending periodical IMU sensor data, while receiving haptic actuation signal simultaneously. Meanwhile, the phone sends the real-time 3D coordination of the local module to the server to be synced and forwarded to its remote counterpart.

5 HAPTIC FEEDBACK

Haptic feedback has been shown to be effective in conveying information to the user when used in conjunction with visual feedback [84]. We leveraged haptic feedback for the following categories:

5.1 Physical Reality Simulation

We utilized haptic feedback to provide a more realistic user experience inside the TAR laboratory. The goal is to provide the illusion as if physical properties and constraints still persist when interacting with virtual objects. To this end, we took from the suggestions of the experts in *Elicitation Requirements* section. Thus, we designed physical events which occur frequently during lab sessions and generalized seven physical built-in patterns (see Figure 4a-g)–"Collide", "Dock", "Switch", "Knob", "Electric Current", "Chemical Reaction", and "Liquid Flow". We sampled the sounds of each event in real world, analyzed the sound wave spectrum, and tuned a similar shape vibration waveform accordingly through altering the amplitude of LRA. By doing so, we derived high fidelity feedback to represent those patterns. Figure 4 (Bottom-Left) shows an example of how we encode "Dock" from sound to a haptic signal.

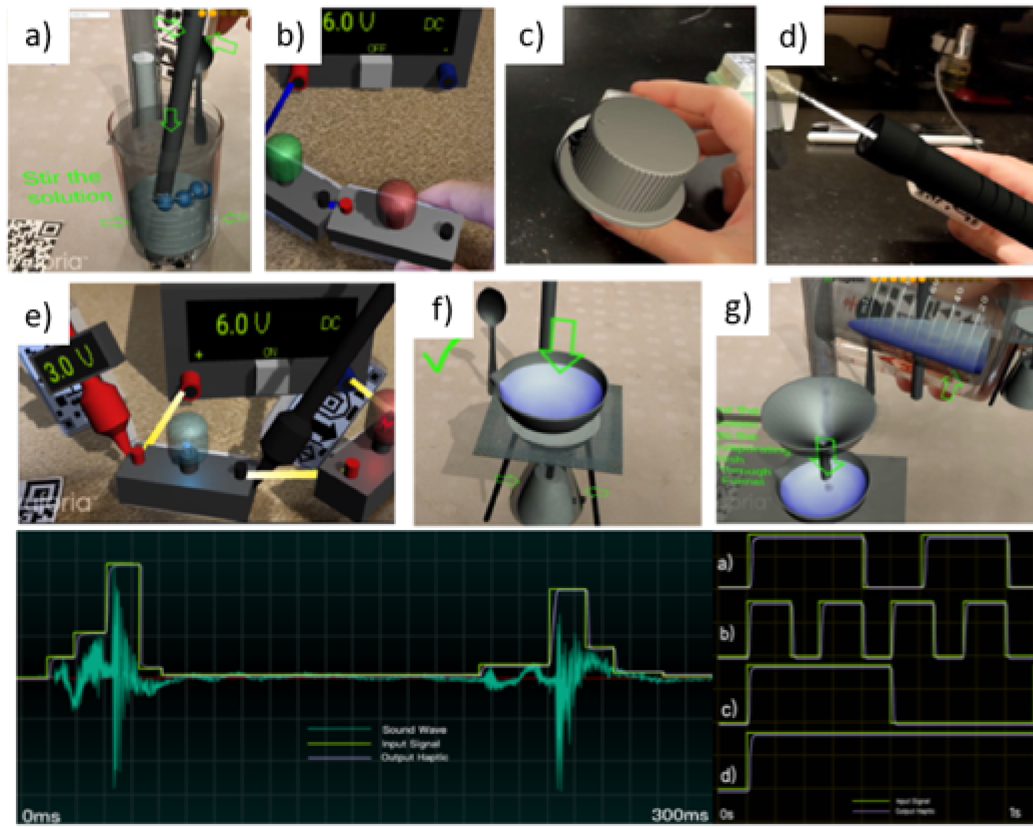

Fig. 4. *Top:* Haptic feedback triggered in various situations:(a) "Collide", (b) "Dock", (c) "Switch", (d) "Knob", (e) "Electric Current", (f) "Chemical Reaction", (g) "Liquid Flow". *Bottom-Left:* Conversion from sound to haptic signal. *Bottom-Right:* Vibration waveform spectrum of notifications feedback: (a) "Ding-Dong", (b) "Beep", (c) "Interval", (d) "Non-Stop"

These converted feedback will be triggered under specific circumstances to provide users with better perception of the environment. For instance, during remote collaboration, both parties are constantly interacting with virtual objects, which are proxies of the physical module on the other side. Past work has shown that users who experience AR on their phones often find it hard to tell exactly how close or how far the virtual object is which makes the interaction process difficult [71]. This lack of depth perception can be mitigated by adopting "Collide" feedback whenever the module makes contact with a virtual object. Users now can both see and feel where the virtual objects are. To further achieve a higher level of realism, the magnitude of the haptic feedback can be dynamically altered according to user's action intensity. The angular velocity and acceleration readings from the IMU are leveraged for calculating the gain value for the dynamic adjustment. For instance, when a rod is used to stir liquid, the corresponding module triggers the "Collide" feedback, as if the rod is hitting the wall of the beaker. To make the vibration dynamic, We let the vibration gain to be: λa, where a is the acceleration obtained from IMU and λ is a constant scaling factor. This mimics physical world circumstances, in which the force is proportional to acceleration.

Fig. 5. User study overview: (*Left*) (Top) Example of physical props used for Organic Chemistry TAR laboratory. (Bottom) AR superimposed on the tangibles. (*Middle, Right*) Students collaborate remotely and send each other feedback.

5.2 Notification Feedback

Haptic feedback can also serve as notifications, which augment users' awareness of hints and cues in the virtual world. We establish two categories of notification feedback–*System* and *Partner*. They share four haptic notification style –"Ding-Dong", "Beep", "Interval", and "Non-Stop". The vibration waveforms spectrum can be find in Figure 4 (Bottom-Right).

5.2.1 System feedback. Notifications which convey positive, negative, or suggestive haptic feedback based on user's inputs are defined as system feedback. System feedback is pre-defined by the content designers, with in-built hints and warnings. The duration of the feedback is chosen as per designers' preferences.

5.2.2 Partner feedback. Synchronous collaborative tasks require participants to maintain an awareness of their partner's cues and activities, as a necessity for effective inter-personal communication. Spatial tactile feedback can reduce the overload of information visual and audio space. Partner feedback is actuated by one user to inform his or her partner. In our case, vibration conveys the message of a notification, which is used by a student to help his or her partner in finding the correct object. The duration of the feedback is set by users' preferences.

5.3 Freestyle Feedback

We enable content designers to create their own sequential haptic feedback as the means to open the door for more creativity. They can design up to five different haptic patterns in sequence. For each pattern, there are three variables for adjustment: frequency, amplitude, and duration Figure 3d. Frequency represents the interval between every single vibration and can be set from no vibration (0Hz) to continuous vibration (around 300Hz). Amplitude represents the magnitude of vibration in a range from 0g to 1.4g. Duration represents the time length of the pattern. Both frequency and amplitude are fitted into a hundred percent scale for better perception.

To create the AR environment, the color of AR visual cues are entirely similar in both collaborators' interfaces. Any visual pointers–such as arrows or annotations–are anchored to the haptic modules. Any spatial sound effects have to be delivered through the smartphone. Also, the smartphone which delivers the AR, is mounted to a phone holder and placed directly in from of the students as seen in Figure 8 (middle).

6 AR-ONLY VS. COLABAR EVALUATION

We performed a within-subjects user study to determine the validity and effectiveness of our toolkit, which supports hands-on learning through a TAR framework. As we previously explained, audio and visual cues are innate to AR, while our haptic feedback requires the implementation of a hardware module (external). Thus, our experimentation exposes participants to two conditions: (a) AR only, (b) AR with haptic feedback (ColabAR implementation). The order by which we provided conditions (a) and (b) was randomized for participants. Half of the participants started with the AR-only condition and the other half started with the AR+Haptics condition. ColabAR aims to facilitate the remote collaboration experience by providing haptic feedback during direct manipulation of tangibles in a TAR laboratory. The purpose of this evaluation was made to analyze students' reactions to the technology and gain knowledge into how the toolkit facilitated collaboration between laboratory partners.

6.1 Setup

For this experiment, we chose a Chemistry laboratory (Fig. 5) for our implementation. We wanted the laboratory to be based on an advanced curriculum for undergraduate students, so we implemented an Organic Chemistry Laboratory on *Purification of Solids by Recrystallization* (as an example, see [1]). We selected this particular laboratory for the following reasons: (a) Chemistry laboratory equipment conveniently aligns with the use of tangibles in AR for hands-on learning; (b) Chemistry laboratories are typically performed collaboratively.

Each participant was in a separate room, but the laboratory was done in pairs. This laboratory took about 65 minutes: 15 mins. for pre-lab, 20 mins. per condition, and there was a short break (5-10 mins.) in between. There was at least one researcher physically present with one participant, while each participant had a full view of the virtual world (i.e., collaborative laboratory) of the other's environment through the phone (Fig. 5, left). Researchers provided three daily objects (e.g., a glass, a battery charger, a spoon) for one user and three objects (e.g., an Apple pencil, eye cream bottle, toothpick container) for the other, because this laboratory required 6 pieces of lab equipment and these objects were proxies for the lab equipment. We attached one module to an object using double-sided tape and then connected via Bluetooth. The dynamics of collaboration were as follows: if a participant has the physical object required for a step, then he or she completes the step. For example, one step is to pour the solution into the beaker: participant A has the flask with the solution while participant B has the beaker; participant A completes the physical action of pouring the solution.

The study began with a pre-lab session, which included an interactive tutorial to learn the capabilities of the AR and the haptic feedback from the tangibles in the scene. After this initial pre-lab session, participants were able to understand the basics of AR and direct manipulation using tangible devices as input.

For AR-only condition (AR), participants were able to communicate and observe each other's movement inside the AR scene, i.e., shared audio/voice and visual environment. Participants did not see each other's faces. For AR with haptics condition (AR+H), participants had the same setup as the AR-only condition, with haptic feedback added from the vibration motors. For participants to go from one condition to another, we turned the Bluetooth connection from the modules on or off.

The lab session included users working through the experiment's procedure. Instructions for each step of the lab were shown on the phone's screen. These instructions were taken word-for-word from the undergraduate curriculum.

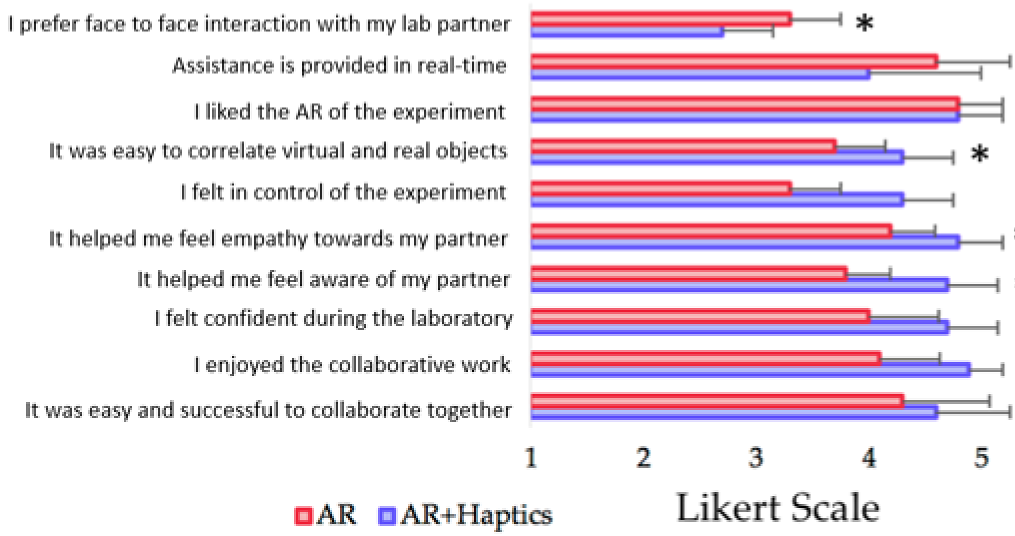

Fig. 6. Results from average scores on the usability of AR, haptic feedback, and collaboration experience for all participants. Blue: AR+Haptic feedback condition, Red: AR-only condition. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree). (*: $p<0.05$)

6.2 Participants

We recruited 20 participants (8 male, 12 female) ranging from 20 to 28 years old (M=21.7, SD=1.9), based on background and experience. All of our participants were undergraduates at our university and had a STEM major. Each pair of participants working together already knew each other. We did not have access to a real laboratory; however, we made sure that our participants had previous experience with physical laboratories so that their answers and comments could compare our TAR laboratory to their real-world experience. All of our subjects had considerable experience with STEM physical laboratories (M=4.6 years, SD=1.9). 11 participants had prior experience with smartphone AR systems, but none had any experience with direct manipulation of tangibles in an AR scene.

6.3 Results

Following the laboratory session which was successfully completed by all participants, we presented the students with a 5-point Likert scale (1-strongly disagree, 5-strongly agree). The survey evaluated the usability of AR, haptic feedback, and collaboration experience. Figure 6 shows the average scores reported by students. We collected the results for the following questions: Q1: "*It was easy and successful to collaborate together*"; Q2: "*I enjoyed the collaborative work*"; Q3: "*I felt confident during the laboratory*"; Q4: "*It helped me feel aware of my partner*"; Q5: "*It helped me feel empathy towards my partner*"; Q6: "*I felt in control of the experiment*"; Q7: "*It was easy to correlate virtual and real objects*"; Q8: "*I liked the AR of the experiment*"; Q9: "*Assistance is provided in real-time*"; Q10: "*I prefer face to face interaction with my lab partner*".

As we explained previously, our study compares participants under two conditions: AR-only vs. AR with haptics. We started with a Shapiro-Wilk normality test to verify that the normal assumption was not met. Then, we performed the Wilcoxon-signed rank test, the equivalent of the nonparametric paired t-test (Fig. 6). When comparing both conditions, we found several questions for which differences between conditions were statistically significant ($p<0.05$). The haptics (M=4.9,

Fig. 7. User study overview: (*Left*) Equipment used for Electrical Circuitry laboratory. (*Right*) AR superimposed on the tangible modules.

SD=0.3) provoked greater enjoyment in the distant work than AR-only (M=4.1, SD=0.54) [Z=-2.53, p=0.01]. The haptics (M=4.7, SD=0.46) produced greater confidence in the laboratory procedure than AR-only (M=4.0, SD=0.63) [Z=-2.33, p=0.02]. Similarly, the haptics (M=4.7, SD=0.46) enabled greater awareness of the partner than AR-only (M=3.8, SD=0.4) [Z=-2.46, p=0.01]. Also, haptics (M=4.8, SD=0.4) produced more empathy with the partner than AR-only (M=4.2, SD=0.4) [Z=-2.49, p=0.01]. As for specific interactions enabled by the system, the haptics condition (M=4.3, SD=0.46) made it easier to correlate virtual objects and their physical counterparts than the AR-only (M=3.7, SD=0.46) [Z=-2.43, p=0.01]. Finally, with the AR-only condition (M=3.3, SD=0.46), we found that more participants tended to voice a preference for face-to-face interaction than when the AR+Haptics (M=2.7, SD=0.46) condition was introduced [Z=-2.449, p=0.01]. For the remaining questions, we found no statistically significant differences between conditions (p>0.05).

We also interviewed students on their experience. We had the advantage that they all had considerable exposure to physical laboratories, so they could compare them to the hands-on TAR experience we provided. In the discussion section, we will explain the criteria behind the survey's responses, based on students' comments and experiences.

7 ZOOM LAB VS. COLABAR EVALUATION

We conducted a between-subjects user study to measure performance, time, and usability of a TAR laboratory implemented using our toolkit. For this user study, we decided on a more realistic approach following the way laboratories have been continued at a distance in some universities. Thus, we expose our participants to two conditions: (a) *AR with haptic feedback*, full implementation of our ColabAR toolkit; (b) *Zoom videoconference*, including physical components of the laboratory. In both instances, the technology (AR or Zoom) was used to enable collaboration between laboratory partners.

7.1 Setup

We borrowed from the curriculum of a *Circuits and Programming* class to test our implementation for a laboratory session. We selected this laboratory due to the following logic: (a) circuitry has been one of the few laboratories that did not get canceled and were able to be continued at a distance; (b) some instructors provided their students with circuitry kits, so they could keep working on the lessons with these physical components; (c) we had access to the curriculum, instructor, and physical components that made up the class. In our case, the instructor/developer implemented the laboratory in Unity using our toolkit. The instructor reported that creating the AR environment (assets and animations) took approximately 7 hours while implementing the haptics using our toolkit only took him approximately *30 minutes*.

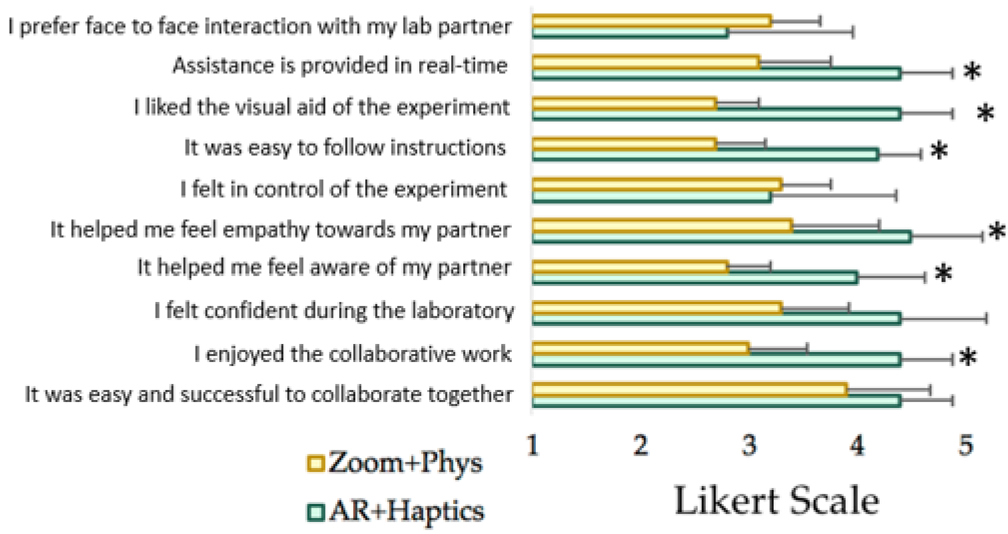

Fig. 8. Results from average scores on the usability and collaboration experience for all participants. Green: AR+Haptic feedback condition, Yellow: Zoom+Physical components. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree.) (*: p<0.05)

During our laboratory session on *DC Circuits* we introduced and then tested our students to the following concepts: (a) *circuit components, connections, and measuring tools*; (b) *connections in series and parallel*; (c) *power supplied and dissipated*. For the Zoom condition, we provided the physical equipment required for the laboratory and the phone for videoconferencing (Fig. 7, left); while for the AR with haptics condition the setup was similar to our first user study (Fig. 7, right). Since Zoom condition had no AR to deliver the instructions, we provided participants with written instructions. The session split was as follows: pre-lab and lab session. The 20 participants were divided into pairs, but each pair only completed one condition, since this was a between-subjects study.

In this user study, we wanted to focus on students' performance at the laboratory session. Students had a more exploratory setup in which to *understand voltage and current*, *make several circuitry connections*, *take multiple measurements*, *add variations to those connections*, *draw diagrams*. For the Zoom condition, the only visual aid was the laboratory instructions and drawings on paper. For both conditions, we provided a lab worksheet with questions and exercises, which participants had to complete and turn in for grading. Also, for both conditions, we provided a questionnaire similar to the previous experiment.

7.2 Participants

We recruited 20 undergraduate students (10 male, 10 female) ranging from 20 to 25 years old (M=21.65, SD=1.62). This set of participants were different from our previous user study. All but two participants did not have a background in electrical circuitry and were not majoring in a STEM career. Each pair of participants working together already knew each other before the experiment. The instructor in charge of content creation and grading had more than 2 years of experience in electrical circuitry classes and workshops.

7.3 Results

In this section, we compare two conditions: Zoom+Physical Components vs. AR+Haptics. We performed the Shapiro-Wilk test to validate the normality of our data. Since this assumption was violated, we evaluated our data using Mann-Whitney U Test.

After the lab session was completed and the lab manual was turned in by participants, the instructor graded the worksheets from both groups. The grades of the lab manuals provided by the instructor are our reported performances scores. The instructor scored each answer with a 0 if incorrect, +0.5 if the answer had some substance, or a +1 point if correct. Then, the total points were normalized to fit into the 1-point scale. The instructor was the primary coder and reviewed all lab worksheets. Inter-rater reliability on scoring was validated by having a second person grade over 25% of the data. From our rubric, the instructor and the researcher in charge of grading had a Cohen's Kappa of 0.68. The results showed that for AR+Haptics (M=0.85, SD=0.05) and Zoom+Physical Components (M=0.87, SD=0.07) there was no statistically significant difference between grades (U=39, p>0.05); however, both groups were scored highly by the instructor and were able to perform the laboratory satisfactorily.

In terms of time to complete the experiment: AR+Haptics (M=60.8 mins, SD=4.26), Zoom+Physical Components (M=81.2 mins, SD=4.71). The decrease in time (25.2%) was statistically significant between conditions (p<0.05).

With respect to the usability questions (Fig. 8), several had differences between conditions that were statistically significant (p<0.05). The haptics (M=4.1, SD=0.7) provoked greater enjoyment in the lab experience than Zoom (M=3, SD=0.54) [U=15, p=0.007]. The haptics (M=3.9, SD=0.7) produced greater awareness of the partner than Zoom (M=2.8, SD=0.4) [U=17, p=0.011]. As for specific interactions enabled by the system, the haptics condition (M=4.2, SD=0.6) made it easier to follow instructions than Zoom (M=2.7, SD=0.46) [U=15, p=0.007]. Visual aid was also preferred under the haptics condition (M=4.2, SD=0.75) than Zoom (M=2.7, SD=0.4) [U=10, p=0.002]. The quality of assistance was considered better with haptics (M=4.1, SD=0.54) instead of Zoom (M=3.1, SD=0.66) [U=13, p=0.004]. Finally, the haptics (M=3.4, SD=0.66) produced more empathy for the partner than Zoom (M=4.5, SD=0.81) [U=19.5, p=0.019]. For the remaining questions, we found no statistically significant differences between conditions (p>0.05).

8 FINDINGS

8.1 AR-only vs. ColabAR

Our experiment aimed to understand whether haptic feedback in a TAR laboratory enriched the collaboration experience. To this end, we chose to replicate an Organic Chemistry Laboratory. We begin by explaining students' first impressions on the setup under both AR-only (AR) condition and the AR with haptic interaction (AR+H) condition. AR-only allowed users to view the same AR content to see what their partners were doing from their end. For example, if user A moves a beaker, student B watches the beaker being moved in the AR scene. Also, participants could listen to each other's voices. AR+H provided the same functionality as AR-only condition, but also included haptic feedback from the vibration driver attached to the physical props.

The consensus among participants was that they preferred the combination of AR (visual cues and voice) with haptic feedback (AR+H). Using our toolkit, we provided participants with 3 types of haptic feedback: Physical-reality simulation feedback, Notification feedback, Freestyle Feedback. This means that each module present in the scene was capable of producing the 3 types of feedback. The user study is designed to have users activate each feedback at least once per module. However, the number of times each feedback can be activated is arbitrary and depends on the user. Both conditions (AR and AR+H) scored highly for successful collaboration overall, and participants commented that some types of haptic feedback were more intuitive than others; while visual cues, in general, were easier to process.

Notifications feedback gave warnings or hints and was already pre-defined for the AR scene, so it was provided to the participants as they moved along with their experiment. Subjects liked this feedback because it stopped them from making mistakes, especially as they were considering how it would translate to keep them from choosing the wrong apparatus or substances in a real-world scenario. This type of feedback seems to have increased the confidence within participants regarding the control of laboratory work.

The add-in haptics made the collaboration smooth, but above that I can always find the items and objects I am looking for.–P17, 22 years, male, statistics major.

Added system haptic feedback was perceived as a positive complementary feature to the shared audio of participants. This feedback was used by participants for specific hands-on help when participants were not verbally responding or were stuck at any part of the experiment. As explained, voice communication was the go-to, intuitive method of communication, but participants reported that the haptic feedback added *"another dimension"* (*P16, 26 years, female, food science major*) to the collaborative process. For example, it could be used by students to softly let their partners know that they were done working with a certain apparatus.

The vibration is useful and I really liked using that feedback to signal to [my partner] by clicking on the screen decreased confusion.–P4, 23 years, male, physics major.

Physical-reality simulation type of feedback was considered as the most *"enjoyable and realistic"* (*P8, 21 years, male, biology major*) feature in the TAR system. As we previously explained, we leveraged readings from the IMU modules to provide customizable feedback in terms of frequency vibration based on tangibles manipulated by participants. This type of feedback improved the individual's experience and awareness of his or her partner in using the TAR laboratory.

I liked the real-life mimicking of the actual thing because it wasn't that different from the real lab experience.–P5, 21 years, male, biology major.

I've done some virtual labs before, but this is my first time actually involved in a hands-on [TAR] lab. You can do the motion of picking things up, stir the solution, pour water. It feels very real!–P14, 21 years, male, pre-med major.

I knew it wasn't the real thing, but I felt like I was doing the real thing.–P9, 20 years, female, math major.

System feedback–a category under Notification feedback and pre-defined–was considered useful for the collaborative experience but not intuitive towards the individual experience. It usually had to be coupled with Partner feedback–a category under Notification feedback but with duration control by the partner–or verbal communication. The purpose of this feedback was to allow students to correlate a physical object with its virtual counterpart. For example, if a participant was not sure of which physical object was the proxy of a virtual object, he or she could simply tap on the virtual object and receive a vibration from the physical object. Participants typically reminded their partners of this feature, but it was difficult for their partners to remember this functionality while they were manipulating objects in the scene.

This [system feedback] haptic functionality is useful, but sometimes I would forget to use it, until [my partner] would make it vibrate, and I would be like "Oh, this is the wrong [beaker]!"–P1, 21 years, female, math major.

We consider that a multi-session exposure to our system could possibly make system feedback a stand-alone or, as one participant suggested, we could add a feature to change the opacity of the virtual object superimposed to make the physical object more realistic. This suggestion, however, could take away from the immersion of the scene.

I liked the haptic feedback but I think I'd prefer for the opacity to be adjusted so models don't overlap with each other.–P12, 22 years, female, engineering major.

Participants considered our TAR laboratory to be a better alternative to the AR only, especially to share information. Several students liked the option of being able to perform laboratory sessions from home. Most students referred to scheduling conflicts and safety as important reasons to work using remote collaboration. A few participants commented on a short lag in the virtual environment but reported that it was not significant enough to take away from the experience.

AR content lacks some physical information but haptics is a great addition to the physical information.–P7, 21 years, male, video-game design major.

8.2 Zoom vs. ColabAR

As we previously mentioned, we focused on the performance of the students in the laboratory.

In terms of remote work, one of these options (AR+H) offers the possibility of different experimental setups, as well as a cheaper alternative including avoiding the purchase of the physical equipment. However, our main concern was whether handling these proxies (AR+H) would have comparable results to the physical elements (Zoom+Phys). Our results demonstrated that students' performance was positively comparable for both conditions. However, in terms of time to complete the experiment, AR with haptics required considerably less time to complete all exercises when compared to Zoom videoconferencing with physical elements. It seems like this is due to the *physical-reality simulation* feedback mimicking and amplifying real-world responses between components (e.g., bulbs making contact with the power source and with each other). Also, *notification* feedback enabled users to know whether they had connected the bulbs in the wrong direction. Similarly, this feedback was used for partners to send warnings to each other (e.g., when a bulb was missing from the circuit; when a bulb had been added in series rather than parallel as the manual requested; when the setting in the multimeter was on measuring current rather than voltage and vice versa as the exercise requested; when measuring probes of the multimeter were being used to measure mistaken points on the circuit).

The AR coupled with the haptic feedback allowed for an improvement in working collaboratively in less time than the Zoom videoconferencing. Similarly, in terms of user experience, the immersion of AR with haptics provided significant improvement in getting and providing help between partners. As students worked in the laboratory, participants can use videoconferencing (Zoom+Phys) to demonstrate or point to their circuitry work; however, there were several problems with focusing and moving the phone camera around to show the scene, and even then, help with problem-solving was mostly descriptive between participants. One benefit of haptics (AR+H) is that the help is in-situ, so students do not have to find the right camera angle to show their work; instead, all they have to do is send *notification* feedback to lead students to the correct area in the circuit. This feedback coupled with their shared AR environment is used to provide hands-on help. As for videoconferencing (Zoom+Phys), students would change between the front and the back camera, so that it would sometimes focus on the workspace and other times on their own faces, and this did seem to have a positive effect on empathy during collaboration. Camera switching may not be a stable idea to include in an AR environment due to loss of tracking; however, it may be interesting to explore a cohesive way to implement it as a future option.

Finally, as the performance evaluation between physical objects and proxies seems to be comparable, we see great potential in deploying our toolkit for designers and instructors to create their own TAR laboratories. Our approach creates a rich experience by combining haptic feedback into a learning environment for remote collaboration. This scenario requires interaction techniques that supplement in-person laboratories (e.g., as a tool to create pre-labs) and partnership.

9 DISCUSSION

9.1 Strength of Haptics in Collaboration

The first research question in this paper was to analyze whether the implementation of haptics improves the user experience of distant collaboration. Based on our results, haptics received significantly more positive feedback than non-haptic conditions due to the following reasons.

9.1.1 State of Interaction. When going about the laboratory process, one of the main challenges for the participant is to establish engagement with his/her partner. Physical presence will always be the gold standard of interaction; about half of participants reported that vibrotactile patterns were too smooth to be human-like, but they appreciated the variety of the patterns and the awareness they provided with the knowledge that it was activated by a human on the other side. This 'activation' of the feedback provides an additional layer of interaction that seems to enable a 'negotiation' through this non-verbal information, in which a participant is highly in-sync with the status of the other and what new information needs to be provided. This agrees with previous research that to create full interaction between partners, partners have to react to users' actions by using haptic feedback through the physical embodiment of their online avatars [36, 78]. Then, in the case of semester-long recurring lab partners, we would strongly recommend instructors give students the flexibility and choice for which haptic patterns will be established between partners.

9.1.2 Control Trade. Setting up this collaborative experience makes sense if we can ensure a superior joint efficiency of the partners. Similar to a physical laboratory in which a participant tends to guide the other, haptic feedback provides the illusion that a participant is helping the other with the execution of a task. This illusion works as long as one participant is not providing too much help or receiving too many cumbersome stimuli. This provides an answer to the hypothesis that 'haptic limbs' could be used for guided assistance or as a didactic device[78]. In our experiments, the roles of the partners were almost evenly distributed, such that the haptic feedback was perceived as positive. However, when it comes to different lab scenarios, designers should consider introducing limits to the number of haptic interactions; perhaps a UI in which each partner determines the class, amount, and frequency of interactions one is comfortable with.

9.1.3 Effective Combination of Haptic Cues. We provided haptic feedback with a combination of patterns, intensity, and frequency. While all of these combinations can target diverse contexts and experiences, these decisions should not be arbitrary. For example, if a pattern is considered so passive that it can be easily ignored or confused with another, instructors have to consider what modifications would be appropriate to call the attention of a participant. These settings should be altered based on students' feedback and are also dependent on the learning material. This follows previous research done in using different vibration patterns, which found that changes in rate, duration, and strength, can improve the resolution for haptic information transmission [13, 50, 79].

9.2 Effect of ColabAR in TAR laboratories

The second question in this paper addresses how to optimize a distant laboratory such that performance and user experience improved based on our toolkit. In this paper, we analyzed qualitative, quantitative, and semi-structured interviews to understand how our toolkit had an effect in the laboratory. From our results, we observe that TAR laboratories show a promising solution to distance learning; but their efficacy is dependent on the use of multimodal feedback as outlined below.

9.2.1 Visual, Voice, and Vibrotactile Feedback. Visual cues are inherent to an AR environment; thus, in a TAR laboratory, they should be leveraged to provide spatial and temporal guidance to participants, e.g., arrows, text, diagrams, etc [81]. However, participants reported on the importance of voice sharing alongside haptic feedback in order to clear confusion and simplify the information process and transfer. This is backed by our results, in which the AR+Haptics condition resulted in increased performance, as well as a decrease in the overall time that it took participants to complete the laboratory. We consider that this improvement in performance is partially due to the use of haptics + voice (ColabAR) as opposed to voice-only (Zoom). These two features are complementary to each other and are useful for successful interaction. We also found that not aligning this multisensory feedback leads to confusion and should be avoided if possible when designing a TAR laboratory.

9.2.2 Role Emphasis. The TAR laboratory designer/instructor is capable of determining whether each participant will play a specific role and what equipment each will handle. Clear goals or outcomes from the experiment are important for students to successfully understand their own roles within the laboratory [67]. This should be leveraged to target weak spots of any participant, to give him/her more responsibilities that include more practice in a particular role (e.g., pipetting, handling the multimeter, etc.).

10 LIMITATIONS

We included 40 participants to test the initial implementation of our toolkit in a TAR laboratory environment. The subject areas we chose were *Organic Chemistry* with participants with experience of physical labs in STEM areas; and *Circuitry and Electronics* with participants without a STEM background. However, given the diversity of courses in an undergraduate curriculum, we would need more testing of laboratories and equipment. A semester-long evaluation would also provide deeper insights into the adoption of the system. Similarly, our user studies had a limited focus on the learning and peer learning experience, which should be investigated more extensively in future work.

Also, we emphasized that our work meant for remote students to set up their laboratories based on what they had available at hand. This was the reason to use smartphones and any physical objects that students already had. However, using the smartphone provided students with a limited point of view (PoV) and a limited range of motion due to the constraints of the phone holder. While these were not reported as considerably distracting or discomforting, it may be convenient to recommend students to use tablets with larger PoVs if they had those available. Similarly, given the need to attach the haptic modules to the physical objects, these objects need to be solid and at least be of the same size as the haptic modules. This is to avoid interfering with the vibration strength and to ensure that the modules are properly attached to the objects.

Finally, while we provide room for different customization options using our toolkit, we may realize that more suggested types of feedback need to be added to the library of interactions.

11 CONCLUSION

This paper introduced a toolkit to facilitate and improve collaboration in TAR laboratories, more specifically, for STEM courses. We showcase a prototype system and two user studies to demonstrate the capabilities and value of our toolkit. By adding haptics to a TAR system, we enabled students to feel awareness and empathy towards their remote partners, feel confident and share information about the experiment, successfully navigate the physical and virtual world, and have an overall enjoyable collaborative experience. We also demonstrated that our TAR laboratory provided comparable performance results to a laboratory with physical components. Additionally, our TAR laboratory decreased students' completion time by 25%. These results are a preliminary step towards the creation and integration of TAR laboratories into classroom environments. Some of these classes can include: machine design, dispersion of light, artistic sculpting. We expect that laboratories of this kind will be seen as a promising step towards more natural interactions with distance technology. Thus, designers and instructors can use these collaborative technologies, which provide useful and enjoyable learning environments.

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