# “BoulderPlay”: Exploring AR and Vibrotactile Integration for Novel Bouldering Experiences

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## Abstract

Bouldering has become a popular sport, and HCI has been increasingly interested in augmenting bouldering, in particular, through wall projections or using mixed reality. However, further integration of interactive elements in bouldering, like the combination of AR and vibrotactile feedback with bouldering, has yet to be explored. We present BoulderPlay: an interactive experience where the boulderer wears vibrotactile feedback devices on their forearms, and an AR headset, which is used to render 3D plants onto the bouldering wall, placed by a virtual competitor. When a plant is touched, the boulderer feels vibrotactile feedback on their forearm. From a user study with five participants, we learned that BoulderPlay created a novel dynamic climbing experience, with virtual obstacles that blocked holds visually and changed the topology of the wall virtually. Through our work, we aim to inspire designers and researchers to combine AR and vibrotactile feedback to create novel bouldering experiences.


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## CCS Concepts

• **Human-centered computing**; • **Human computer interaction (HCI); Interactive systems and tools**;

## Keywords

Bouldering, climbing, augmented reality

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## 1 Introduction

Bouldering as a sport has gained popularity in recent years, even becoming an Olympic sports discipline in 2020 [10]. Bouldering differentiates itself from other forms of climbing through the lack of safety equipment that boulderers have to wear: the artificial climbing walls are not taller than 4m and are equipped with thick sports matting to break any falls [1].

The lack of equipment worn on the body provides unique opportunities for bouldering augmentation using body-worn technologies. Within industry and HCI research, we see many examples of augmenting the bouldering experience, either by using interactive

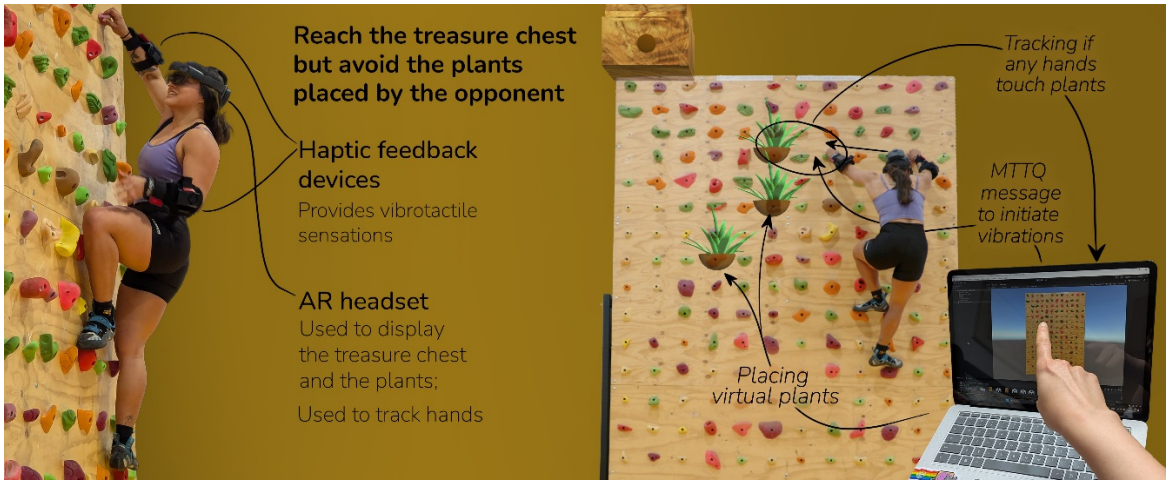


**Figure 1: BoulderPlay in a nutshell. Left: The boulderer showcasing the devices worn while climbing. Right: A representation of the gameplay, with the virtual plants and treasure superimposed on the wall.**

holds [7, 8, 13], projections [11, 12, 14], augmented reality (AR) [2] or virtual reality (VR) headsets [4, 5]. Interestingly, we observe that AR combined with haptic feedback provides novel opportunities: dynamically changing the topology of the physical climbing wall through virtual visuals, and using AR to create a competitive climbing experience.

BoulderPlay (Figure 1) explores these opportunities: Using an AR headset and haptic feedback devices worn on the forearms, the boulderer plays a game where they have to climb to reach a virtual treasure chest, but are increasingly hindered by suddenly appearing virtual plants that "sting" (expressed through vibrotactile feedback), placed by a virtual opponent. From five participants that experienced BoulderPlay we learned that AR and haptic feedback have the ability to dynamically change the topology of the bouldering wall, creating novel bouldering challenges. BoulderPlay provides an early example of how AR combined with haptics can create dynamic bouldering experiences, thus providing opportunities to develop novel playful bouldering challenges that extend beyond the traditional bouldering experience.

In this paper, we will first outline existing work on bouldering augmentation and bouldering together, followed by a description of the BoulderPlay prototype. Then, we use the results of our user study to perform thematic analysis, which resulted in 4 themes. These themes were used to inform 3 design strategies. With our work, we aim to support designers and researchers in the development of future dynamic augmented bouldering experiences.

## 2 Related Work

In this section, we discuss what we learned from the prior work that aimed to augment the bouldering experience using technology, including extended reality (XR) and other input/output technologies such as haptics and sensing.

### 2.1 Augmented bouldering

In the very early HCI work that aimed to augment the bouldering experience, they mainly focused on attaching sensors and lights to climbing holds [5]. However, later, we see several works that utilise full body tracking to provide real time feedback and interaction with projected graphics. For example, Kajastila et al. [2], designed "The Augmented Climbing Wall", by projecting visuals to a bouldering wall and making visuals interactive by using a Kinect V2 depth and camera. While the setup helped researchers to design three movement-based games, they identified that it is difficult to see the projected content when the climber is too close to the wall. In our work, we avoid this by utilising an AR headset.

With the advancement of XR technologies, immersive games and environments were built for bouldering. Some of them are mobile phone based and some of them are built for VR headsets [13]. Many of the early immersive environments only offered audio and visual feedback. One of the first to incorporating haptic feedback into VR bouldering is Kosmalla et al. [4], who explored rock climbing in a mixed reality environment leveraging the tactile sensation of a real climbing wall. In this experience the climbing height was limited to the size of the physical bouldering wall, limiting the experience of the virtual world. As a solution, the InfinityWall [3] has investigated how VR can be made useful to perform "continuous climbing". The authors have achieved this by using a rotating treadmill bouldering setup inside an immersive VR environment, offering physical variations in angle and speed of the treadmill.

Utilising Augmented Reality (AR) in bouldering experience was first explored by Daiber et al. [1]. The authors developed a mobile AR application to support collaborative training. The work mainly focuses on predefining, new problems and goals using an AR map and sharing those problems with fellow boulderers. However, there is an opportunity to utilise AR HMDs in bouldering enabling more dynamic and richer bouldering experiences. Hence, in our work we utilise an AR HMD device and developed a dynamic bouldering application, better utilising the advantages of AR HMDs. Also, the

better tracking capabilities of AR HMDs avoid inherent tracking issues of mobile AR.

## 2.2 Bouldering together

The concept of collaborative bouldering is explored in various researches, but research performed by Daiber et al. [1] determines a concept of combining mobile technology with augmented reality applications for boulder training. The main motivation behind the concept is to train beginners and those who have not performed bouldering before. Although bouldering can be performed individually, collaborating, and working in groups is seen to demonstrate higher effectiveness in learning bouldering. One of the common training techniques is called "send me" and is a skill practice, where, "[the] teammate [points out] the climber to random holds" and this motivates the "climbing partners to socialise" [1]. One of the aims of our work also is to provide users with a fun social experience.

Furthermore, there are several games designed using mixed reality bouldering walls to create activities. One of the games that currently exists is mentioned and studied by Kajastila et al. [2] and it includes the user "avoiding moving electricity lines" which acts as obstacles, where the main aim of the game is to touch a stop button without touching the lines. Additionally, another application game developed is a "whack-a-Bat" concept, where users "touch a bat sitting on the holds before a timer runs out" [2]. While these games are goal oriented and can be played together, they cannot be considered collaborative or competitive games. The researchers also performed a user study for which one of the questions was focused on what the users enjoyed the most - this was answered by describing the experience as "versatile and different", "was climbing more in a short time", and "panic and laugh" [2]. The researchers concluded that this information indicated that the overall climbers' experience made them "[forget] one's fear of heights". Later utilising the same technology researchers developed a Pong game on a climbing wall that can be played by two players competing against each other [2]. Inspired by prior work on gamification of bouldering experience, in our work we aim to design a remote social bouldering experience by adding competitive gaming elements to it.

# 3 BOULDERPLAY

In this section, we describe the design of BoulderPlay as well as the setup of the user study.

## 3.1 Design

BoulderPlay (Figure 1) uses a Microsoft HoloLens2 [6] as the AR headset, and Tactosy haptic feedback devices [14], which were fitted on the forearm. The participant's objective is to reach the treasure chest, which is projected at the top of the bouldering wall, before their virtual competitor does, or before their three-minute timer runs out (Figure 1, right). The gameplay is as following: The participant starts the game with no plants on the wall, and the treasure chest at the top. The timer starts running. The participant starts climbing, and is presented with a pop-up after 15 seconds: they have to wait 15 seconds so their virtual competitor can "climb" and place plants on the wall. These plants show up as virtual 3D plants that cover part of the holds on the wall. Once the pop-up disappears, the participant can continue climbing. However, every time they touch a plant, they experience vibrotactile feedback on their forearms. This is to resemble the plant "stinging" them, encouraging the participant to avoid the plant. When the participant touches the treasure chest, they hear a victory sound, while running out of time or losing to the opponent triggers a losing sound. The experience is concluded with a pop-up detailing the results of the game (win/loss, time left).

To emulate the virtual opponent, a researcher used a Unity-based app on a laptop (connected via WiFi with the AR headset) to place plants. Then, using the AR headset's hand tracking capabilities, a signal was sent to the laptop every time a plant was touched. This prompted a signal via an MTTQ server to a smartphone that used a Bluetooth connection with the vibrotactile feedback devices, resulting in the feedback devices vibrating (Figure 1).

## 3.2 User study

We performed a user study with five participants. We asked the participants to play BoulderPlay on a small bouldering wall, which is located at the Exertion Games Lab. Each participant had at least 25 sessions of bouldering experience and ranged from V3/V4 to V7/V8 in Vermin-scale levels [8]. The participants had an average age of 24.5 years (SD=3.61), with three participants identifying as female, and two as male (Table 1). For safety, each participant used their own bouldering shoes. A first aider was on site during the sessions, and the climbing wall was outfitted with professional sports matting compliant with local regulations. Our research was approved by our institute's ethics board.

Each session involved one participant. The participant was first interviewed about their bouldering experience and level, their experiences with AR and VR, and with different forms of AR bouldering (Table 1). After the pre-interview, the participant had the opportunity to change into their climbing gear and to warm up off the wall, followed by an instruction on safe falling technique and a warmup on the wall as guided by the participant. Once warmed up, the researchers helped the participant with putting on the AR headset and the vibrotactile devices, which are placed on the forearms using elastics and Velcro. The participant played multiple rounds of BoulderPlay, first one round without plants appearing, and then several rounds with a virtual opponent (played by a researcher) placing plants. Each participant experienced BoulderPlay for 15-20 minutes, or 4-5 rounds with plants appearing, with regular climbing breaks. Halfway through experiencing BoulderPlay, the participant was asked to share three words that describe their emotions while experiencing BoulderPlay. We ask this question to elicit in-the-moment responses to their ongoing experience with BoulderPlay. Asking this question happens when the participant is resting between bouldering attempts - a common practice during bouldering and supports recovering strength between attempts. After experiencing BoulderPlay, the participant was interviewed in-depth about their experience, including comparing their BoulderPlay experience with unaugmented bouldering.

All interviews were audio and video recorded, and later transcribed. The participant's time on the wall experiencing BoulderPlay was also video recorded. Four researchers performed reflexive thematic analysis using the transcripts of the interviews, along with

**Table 1: Participant demographics.**

| Pseudonym | Age | Gender | Number ofbouldering sessions | Bouldering level per Vermin-scale [8] | AR/VR experience |
|---|---|---|---|---|---|
| Aline | 24 | Female | ~200 | V3/V4 | Workplace training in VR |
| Bruno | 25 | Male | ~30 | V3/V4 | Playing a VR game, AR on hand-held console, Pokémon GO [15], projection augmented squash |
| Clara | 25 | Female | ~280 | V4/V5 | Pokémon Go [15] |
| Dave | 32 | Male | ~150 | V5 | None, but has seen it |
| Elspeth | 21 | Female | ~200 | V7/V8 | Pokémon Go, racing games in VR with interactive chair, playing a VR game |

videos of experiencing BoulderPlay as data input. The first author took the lead with the thematic analysis, and has ~300 climbing sessions of experience (level V3/V4) at the time of the study. The first author is an industrial designer with experience developing AR applications. One researcher has ~40 sessions of climbing experience (level V2/V3) and is a software engineering student, and the other two researchers climb sporadically (less than 10 sessions, level V1) and are lecturer in HCI specialising in bodily augmentations, and a software engineering student, respectively.

## 4 Results

The thematic analysis resulted in 451 codes, which were used to construct four themes. These themes describe the different ways in which BoulderPlay changed the bouldering experience.

### 4.1 Dynamic changes resulting in dynamic challenges

The appearing plants created a dynamic challenge for the participants, which they would not encounter in regular bouldering. Because of the plants appearing, the participants were unable to analyse the route from the ground beforehand, which came as a surprise to the participants. Bruno reflected: "Because I guess a big part of bouldering, especially when I'm not too sure about it, is, like, legit just, like, solve it from the bottom while you're here and then attempt it. So I'm not used to it being very surprising in the middle." Not being able to see the route at the start was "challenging" (Dave, Clara, Aline), at times "frustrating in a sense of a good frustration like competition." (Dave), and "interesting" (Dave, Aline). As Dave explained about his "frustration": "Not being able to read a route beforehand was difficult but it did bring a factor of enjoyment, like the difficulty changes once you are on the board and you don't know what to expect. I think that is kind of a novel experience that you get." Aline enjoyed the continuous analysis of the route: "[With] regular bouldering, you don't get obstacles stuck in your way as you go on. [...] In that sense, it sort of forces you to keep updating your analysis as you're climbing." The dynamic changes on the wall required participants to be flexible in their route planning, at every stage of the climb.

### 4.2 Adapting the climbing style to the dynamic changes

BoulderPlay changed the temporal qualities of bouldering with the wait timer and the appearance of plants on the wall. The participants felt that the wait time created an endurance challenge: they had to hold an, at times uncomfortable, position on the wall, while they waited for their opponent. To Elspeth, the novel endurance challenge was motivating: "[...] such as waiting for your teammate in, like, what could be an uncomfortable position that was like motivating because it's, like, testing and challenging yourself." Similarly, Bruno described the endurance challenge as putting him out of his comfort zone: "This is definitely more of an endurance challenge than I thought, which generally contradicts how I usually boulder because I'm not great for endurance. Like, if I get stuck for X amount of time or we get to a point where, like, I can maintain it, but I can't reach for anything anymore, so I'm just, like, I'm done. Whereas this, maybe it's probably because the route was a bit easier and the holds are a bit nicer." It appears that the endurance challenge was appreciated as a personal challenge, and because the holds on the bouldering wall were comfortable enough to actually engage in the challenge.

Additionally, the appearing plants required the participants to rethink their route, which added to the endurance challenge. Bruno described: "That's probably the biggest thing that I wasn't expecting is having to readjust my plan in the middle of the climb. Which partially to do with the field of vision. And made it a bit more of an endurance battle than I thought." Clara highlighted how she focused less on her technique: "I'm more just thinking about where I can go. In this game, I feel like, well, cause usually I'm, like, trying to have good technique and make sure, like, my body rotates in and everything, but I feel like maybe this one. I lost a lot of technique because I was so focused on trying to avoid the plants, and get to the chest. So, I'm just, like, grabbing whatever I could." The appearing plants and resulting dynamic route changes slowed the participants down, as they had to take time to replan their route, as Dave described: "I had to change my style a bit to reach the chest because everything was blocked off, so it was interesting. It definitely brought a more intellectual aspect to it, because suddenly things are changing." The route changes resulted in participants having to take time to rethink their next moves, and in adding that time to replan, their activity became more of an endurance

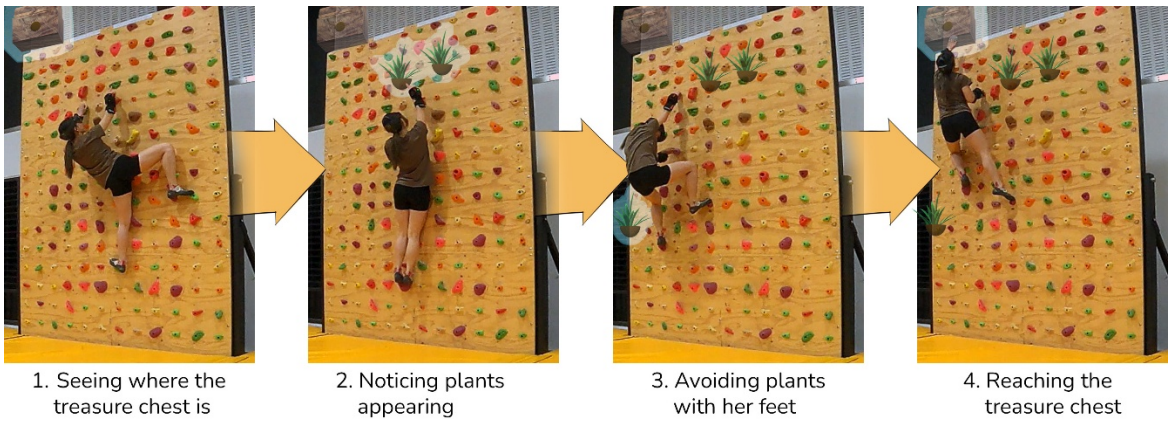


**Figure 2: Participant Clara figuring out her route. The AR projections are superimposed to represent what Clara would be seeing while climbing, minus the glow, which is used for emphasis in the image.**

challenge. Additionally, the loss of technique appeared to result in the participants reverting to simpler climbing moves.

### 4.3 The challenge of climbing differently around virtual obstacles

The topological qualities were changed by the displaying of plants onto the wall through the AR headset, which caused the participants to change their climbing moves (Figure 2). The participants identified the plants as 3D obstacles they had to avoid, as Clara described: "It does make it interesting that you just have to go around stuff and I think like, yeah, the plants actually do kind of block your vision of the holds. Yeah, so, it did definitely made it more challenging, which is cool." Aline's experience also emphasised the impact of having 3D obstacles: "I guess it's because I imagined it as physical things that protruded outwards, so if I was going into it, that means my body was also going into the plants? So that to me meant, 'oh, I can't do that."' Clara's and Aline's experiences highlight how the participants had to change their movements to avoid the plants. In fact, both Clara and Aline also avoided plants with their feet (Figure 2). Aline described: "Yeah, no touching. And even though there weren't any sensors for my feet, I still felt like I had to avoid my feet, too, because of that visual." Clara's experience was similar: "I could see my feet. But I feel like it just took more effort to look at them and figure out where my next foot placement would be, yeah." The participants appeared to extend the rule of avoiding plants with their hands to their feet, despite their awareness that they did not receive feedback on their feet.

To communicate the fact that the participants should avoid the plants, the vibrotactile feedback appeared to be effective. Clara exclaimed while climbing: "Whaah! There is spiky things everywhere!! [. . .] I don't know [what] to do with the spiky things. So I just tried to avoid them." Aline reflected: "Well, once it vibrated, I immediately knew that 'Oh yeah, OK, maybe this was not it. I'll have to find another way."' However, due to the size of the projected plants, the limited field of view of the AR headset and the fact that the participants had to look at their hands to properly let the AR headset track their hands, it was at times unclear to the participants which plant triggered the vibrotactile feedback. This led Elspeth to just ignore the feedback while climbing: "How can I avoid the grass? I will just cheat." In the interview afterwards, Elspeth reflected: "Your view is, like, limited. Yeah, so it's a little harder to tell what you will grab, but, it looks really cool and sounds really cool." Clara described how the tactile sensations, including its limitations, impacted her motivation: "At the start I was probably more motivated to get to the chest without touching the plants. And then I struggled. Like, it was really hard to not touch the plants at all because they're so big and even if I'm a couple holds away [. . .] I lost motivation of trying to not touch the plants I was still wanting to get to the chest. But then I was just ignoring the plants." Though the participants appreciated that the vibrotactile sensations emphasised that the plant blocks holds, the fact that they were not always able to identify the cause of the actuation lowered their motivation to uphold the proposed obstacle.

### 4.4 Theme: The gamified experience of AR bouldering

Overall, it appeared that the participants were delighted, describing the experience as "cool" (Clara, Aline, Elspeth), "fun" (Aline, Clara, Bruno, Dave, Elspeth), "weird in a good way" (Elspeth) and "annoying in a fun way" (Clara) or "a good frustration, like competition" (Dave). Elspeth shared about her experience: "[It] felt pretty strange, the projections looked really weird. Like looking around and seeing projections sort of felt strange. The vibrations, that was really unexpected." BoulderPlay appears to have provided an experience that was overall fun and interesting to the participants.

All participants were aware of the definition we used for AR bouldering, that being the rendering of virtual visuals on the physical world. Thus, all participants expected visual feedback, but not the integration of the visuals with sound and vibrations. Discovering these modalities was mostly delightful, though the vibrations were at times "annoying" (Bruno, Clara) due to difficulty identifying which plant triggered the actuation. Elspeth highlighted her surprise: "The vibration surprised me and the type of game it is. Just like how it looks as well." Bruno described: "It did make me very engaged. [...] It was definitely much more involved than what I thought it would be in regards to the plants, in regards to the

sounds, the haptics there was a lot more than I was expecting. [...] I was happy that it wasn't as light as I expected it to be. I think it definitely added to the experience" The added modalities appeared to support the experience of BoulderPlay.

The participants felt that using BoulderPlay had a steep learning curve, about which Aline commented: *"Probably the only thing I would add is an AR tutorial."* Bruno emphasised the need for support, by mentioning the *"lack of instructions"* while using BoulderPlay, noting that he felt "a little bit of apprehension. Definitely in regards to what I should and shouldn't be doing." When the participants were climbing, the researchers provided instructions, for example to Elspeth while she was using BoulderPlay: "So when you reach the holds, try and look at the hold first and then grab it and then make sure it's always a clear line of sight and then directly look at it when you grab it." Yet, even with the instructions, the AR experience caused confusion at times, as Aline pointed out: "Well, at first I was very confused because I kept losing what I was looking at. Especially if I was to go for my next hold, I keep forgetting that I need to look at it. But then I had completely forgotten about the timer while playing because it's so high up there." The participants' experiences highlight how technical limitations, such as the AR headset's limited field of view, can affect participants' bouldering style.

In the end, the participants concluded that BoulderPlay offers a novel experience of bouldering, as it is less serious, more gamified and more interactive. Elspeth reflected that BoulderPlay was less satisfying than unaugmented bouldering: "It feels a little less serious, which it is I feel, you know, like you're trying to reach a treasure chest but, yeah, not the same level of satisfaction." The participants described the experience as a game that involves bouldering, rather than bouldering that involves a game, like Clara described: "Where it more felt like that the main activity felt like a game with climbing involved rather than climbing, with the game involved." This is emphasised by Elspeth, who expressed that they prefer regular bouldering, as they get more satisfaction from completing the boulder. Meanwhile, Elspeth sees an implementation of BoulderPlay in the form of an arcade game, where people can experience a low-entry version of bouldering. "It made it seem like a little more of a game than regular bouldering, it feels like something pretty different to regular bouldering. Something you could go to an arcade and have this there, something like that."

## 5 Discussion

For the design of future AR bouldering experiences, we propose considering the following design strategies:

- **Use AR and vibrotactile sensations to create a dynamic augmented 3D experience that encourages different ways of climbing (derived from 4.1, 4.2, 4.3 and 4.4):** Participants enjoyed that the climbing experience turned into a more augmented experience thanks to the protruding virtual plants as they had to now find new routes to reach the treasure chest, and move in a way that would let them avoid the plants. Traditional projections with projectors provide a 2D overlay, which might mark holds as unavailable, but does not add 3D volumes to the bouldering wall, as was shown in Waterfall Climber [9]. VR, on the other hand, would require a more time- and effort-intensive implementation, because the virtually available holds must exactly match that of the physical wall, as we see in work by Kosmalla et al. [3] and Diaber et al. [4]. Hence, we recommend to designers to consider using AR's ability to overlay 3D objects to turn the topology of the wall into a more augmented 3D experience to encourage finding new bouldering moves.
- **Use wait times to create an endurance challenge (derived from 4.2 and 4.4):** The participants experienced the time waiting on the opponent as an endurance challenge, which they appreciated. In BoulderPlay, the implementation of a wait time was to resemble a virtual opponent. However, such a wait timer could be used as an endurance challenge all in itself: having to hold a strenuous position is in itself a bouldering challenge. AR could support the use of such timers, by visually blocking the entire wall and therefore making it temporarily difficult to continue, or using hand tracking to apply penalties when the boulderer is still climbing.
- **Use dynamic AR obstacles to create an endurance challenge (derived from 4.3 and 4.4): The** appearing plants created a dynamic challenge that required the participants to replan their route. The time needed for replanning added to the endurance challenge of the experience. AR offers a way of adding dynamically changing environmental elements without physically changing a bouldering wall, which would otherwise be difficult to (safely) implement on a physical wall.

## 6 Limitations and Future Work

Our work is limited by having a limited participant group. However, within this group we had a variety of bouldering experiences, and different levels of experience with AR. These differences provided us with rich feedback on BoulderPlay, allowing us to formulate the three design strategies that could be used for the future development of AR bouldering experiences. Additionally, our participants only experienced BoulderPlay once, using the protoype for about 20 minutes with the assistance of a researcher. Though this was plenty to offer us initial insight into the impact of AR and vibrotactile feedback on bouldering, we would strive for a use scenario in a commercial climbing gym, where the participants could experience BoulderPlay in multiple sessions over a longer period of time.

Another limitation is that our current prototype used a virtual opponent instead of a real opponent. A future prototype would focus on creating a game where the boulderers have equal roles – placing and seeing plants – and testing this with a larger group of participants. With this prototype, we can also implement ways to make the opponent more visible.

## 7 Conclusion

We presented BoulderPlay: an AR and vibrotactile experience where boulderers try to avoid virtual plants while trying to reach a virtual treasure chest on top. From our participants using BoulderPlay we learned that AR can be used to change the topological and temporal aspects of bouldering. Based on these findings, we propose three design strategies, which could be used by designers interested in augmenting bouldering in novel and engaging ways.

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