SoniBould: Towards understanding the design of sonified expressions for bouldering

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Abstract

Previous research has shown that enhancing the sports experience can increase engagement and motivation. However, the design of interactive systems for bouldering has mostly focused on enhancing athletic performance, overlooking the opportunity to support the experiential aspects. This paper focuses on using sonification to enhance the boulderers' experience during bouldering. We designed a novel system that uses capacitive sensing on climbing holds to enable the creation of sonified expressions of bouldering movements. Using this system called SoniBould, we conducted a user study, consisting of four workshops with eight sound experts and four boulderers, to explore the design strategies that can be used to create sonified expressions of bouldering. We present our findings from these workshops in the form of three approaches, for the use of sonification in bouldering. Additionally, based on our experience developing this system and the insights gathered during the workshops, we identified three themes for sonification in bouldering. With these findings, we hope to contribute to the growing body of SportsHCI and movement sonification research by opening new avenues for designing sonification in sports.

CCS Concepts

• **Human-centered computing** → **Empirical studies in interaction design**; *Sound-based input / output*.

Keywords

Movement Sonification, SportsHCI, Bouldering, Sound Design

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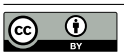
1 Introduction

The subjective experience of athletes has become increasingly recognized as an essential factor in enhancing sports performance and fostering long-term participation [28, 35]. This factor is often linked to an athlete's ability to immerse themselves in the experience, enter flow states, and maintain enthusiasm over time [12]. One of the various ways that sports-related human-computer interaction (often called "SportsHCI" [14]) research utilizes to enhance the sports experience is using sonification [37, 39, 42].

Sonification is defined as the use of sound to facilitate communication or interpretation of data [20] by "transforming data into non-speech audio signals" [29]. Within the SportsHCI, sonification is generally used to provide two key benefits in sports settings. First, it can offer sportspeople rapid, intuitive feedback that allows for more informed decision-making and improved performance [13, 18, 48]. Second, it has the potential to enrich the overall experience by addressing emotional and aesthetic preferences, subtly influencing motivation and engagement [40, 44]. Previous research has demonstrated that sound can evoke specific emotional responses, such as energizing or calming effects, which have a direct impact on an athlete's perception of effort and performance [32, 42, 46]. While this subconscious influence of sound in other sports has been explored in various manners [4, 6, 13, 16, 19, 22, 24, 25, 31, 37, 38, 43, 45, 47, 49, 52], designing sonified expressions for bouldering seems underexplored [33, 41].

Bouldering is a discipline of indoor climbing that emphasizes short bursts of intense physical exertion combined with strategic problem-solving. Each boulderer approaches and solves the bouldering problems, also known as routes, in their unique way based on factors such as physical ability, mental ability, and past experiences [30, 36]. In return, each boulderer's experience while performing a route wildly varies based on the physical and mental exertion they have [9, 23]. With all these characteristics, bouldering could be an appropriate case for exploring the potential of sonified expressions for enhancing sports experience.

To explore the use of sonification in bouldering, we designed SoniBould system that augments climbing holds (Fig. 1) with capacitive sensing. The system sonifies the interactions of boulderers with the holds by detecting when, for how long, and which limb (hands or feet) is touching them. These data are then used to create different "sonified expressions of bouldering," which we define as sound-based representations of the routes, actions, and climbing holds. To understand the design of sonified expressions in bouldering, we conducted four workshops with eight sound experts (musicians, music producers, and sound designers) and four boulderers. Based on their initial feedback on SoniBould and the sonified expressions they created, we derived three sonification approaches around the design of sonified bouldering experiences. With these findings, we hope to contribute to the growing body of SportsHCI and movement sonification research by opening new avenues for designing sonification in sports. Our work features the following contributions:



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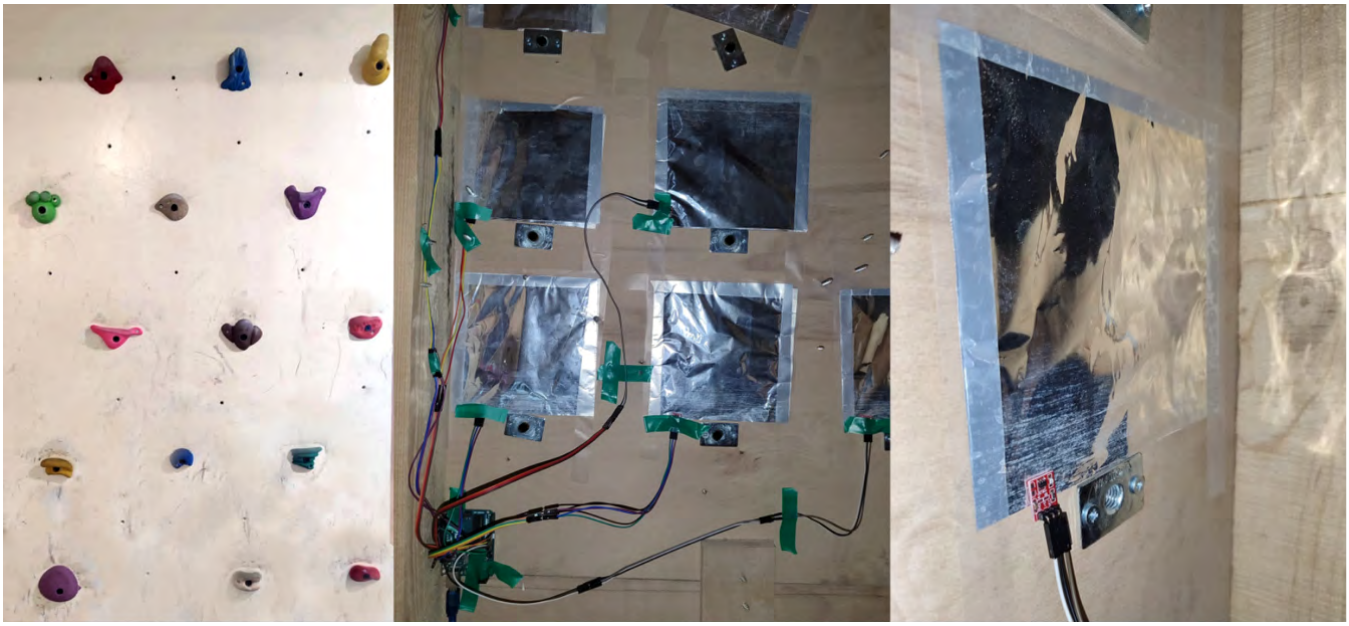

Figure 1: a) SoniBould setup b) conductive strips behind the wall setup c) view during assembly of sensors

- SoniBould: We present SoniBould, a novel system that augments the climbing holds on a climbing wall using capacitive sensors embedded behind each hold. This system contribution can be useful for bouldering equipment industry practitioners and bouldering gyms, as inspiration for creating new interactive systems aimed towards bouldering gyms and individuals.
- Approaches in creating sonifications: We describe three distinct sonification approaches that define different inspirations and sources for sonification from the bouldering sport and how each one would influence the boulderers' experience. These approaches are aimed at interaction designers and HCI researchers working with sports. They can be used in future SportsHCI research, in addition to the growing body of climbing and bouldering-related HCI works.
- Themes for sonification: Additionally, we present three design themes derived from the study: the interviews during our workshop and our craft knowledge having designed SoniBould. These sound design themes define choices regarding mapping while creating sounds, specific dimensions of sound, and the interaction between sonification and sportspeople. We frame these themes for sound experts working in sports context, as inspiration for design of sound in both research and commercial works.

2 Related Work

We investigated prior works that use sonification to influence sportspeople's experiences. Initially we looked at works that focus on comparing the use and impact of different sonification strategies. These strategies ranged from sonification for performance [5] to use sonification to enhance experiential aspects of the motion, such as aesthetic perception [17]. We examined works from various sports settings like running [19, 43, 49], speed-skating [45], rowing [11, 39], cycling [25] and dancing [3, 6]. Additionally, we identified two studies that used sound and sonification in climbing-related sports [33, 41]. Based on these studies, we framed three key areas of influence for our research: use of sound for enhanced performance in sports, interacting with sound during sports, and use of sound in climbing. We used these to guide our investigation towards the use of sonification for bouldering.

2.1 Use of sound for enhanced performance in sports

Van Rheden et al. [49] explored the use of different sound instructions during running to improve breathing techniques. Their study tested five distinct sounds, with varying information depth, all of which were aimed to help stabilize breathing. Sounds were grouped in two, single tone sounds that only trigger at either breathing in or out, and two tone sounds that use both single tones sounds and have various transitions between them. They found that sounds with two tones were easier for users to follow and caused less mental load than simpler single tone sounds. Additionally, they noted that while user experience was generally low due to the rudimentary sound design, offering multiple sound options and allowing users to switch sounds based on their specific needs could enhance the overall experience. Siriaraya et al. [43] explored the use of Spatialized Audio Augmented Reality (AAR) to allow users to compete against the sonic ghost of their past performances, resulting in improved running performance. A key challenge the authors outlined regarding the design of the sound was to convey progress and performance through sound effectively. As they used footstep sounds and sound volume to represent the proximity of the ghost opponent, once they were more than a certain range away, the absence or low volume of

footsteps made it difficult to assess their progress. To address this, they had to add periodic voice clips indicating whether users were winning or losing, and pre-recorded voice messages were played at intervals to inform users of their progression throughout the course. Similar to van Rheden et al. [49], their insights outlined the importance of sound perception and information depth change based on the specific needs of sportspeople. Together, these two studies showcase that there are benefits of using different sonification styles, based on the needs and aims of the sportspeople. When representing immediate actions and checkpoints, the design of the sonification should also reflect the directness of the action, however comparative and analogous information required more in-depth and gradual sonification outcomes. Based on these learnings, we aimed to further investigate which kind of actions exhibit themselves and which sonification strategies should be used to represent them, in the context of bouldering sport. Work of Dubus and Bresin, focused on use of different sound feedback, discreet sounds in comparison to continuous sounds, with elite rowers [11]. They implemented a speaker system to the rowing boats, which played four different sonification models in a randomized order for rowers to explore. The sonification models were, Pure tone (Velocity to Pitch), Wind (Velocity to Loudness), Car engine (Acceleration to Spectral centroid), and a combined model, Wind + Car engine. This approach translated rowing parameters into sound feedback, providing varied sonic representations of the participant's actions. Recruiting eight elite rowers and two coaches, they gathered insights on how rowers interacted with different sonification models. Their insights showed that rowers preferred sounds that allowed easy cognitive mapping to the actions for performance feedback. They drew metaphors between the sounds and the rowing actions, such as relating wind sound to the interaction between paddles and the water. Their participants also expressed the importance of similarity between actual sounds of the rowing sport and the performance sounds created, as they claimed it impacted understandability. Hug and Ketelhut [19] created a system for the "shuttle run test" that is used to assess aerobic fitness, they investigate the use of sound cues to increase motivation to exert maximal effort. They created three different sounds; the "Standard Beep", "Chime Swell" percussive sounds, and "Game Wobble" five-note motif and wobbling sound to frame the test as game-like experience. By trying these stimuli in both isolated online settings and a real shuttle run trial, they were able to emphasize the importance of designing engaging audio stimuli that not only improve user experiences but also enhance task performance. While digital beep sounds scored best in terms of understandability, they suffered in terms of being fun or interesting, thus having low engagement. On the other hand, Game Wobble was perceived more interesting and pleasant, but suffering in terms of understandability. Chime Swell performed best as a middle ground between these two opposites. In a similar effort, SoundBike [25], the authors created melodic and rhythmic sound patterns, matching the frequency to the motion, based on the rhythmic motion of the pedals. By trying different patterns, such as beeps, melody and drums, they were able to show the impact of various sound techniques in terms of subconscious auditory-motor synchronization. Their discussion highlights the potential benefits of each type of sound, while smaller and direct sounds can be useful for giving quick feedback during action, melodic patterns provide more opportunities for communicating more complex information. These studies highlight the interplay between informational depth, understandability, and user experience in sonification. Different sonification approaches, like simple digital sounds were easier to react to, however, their user experience and sound quality suffered in return. During our workshops, as we focused on the experiential aspects of the bouldering as well, we investigated the perception of sonification from the user experience perspective. In addition, we aimed to find the balance between these points, by including the perspectives of both sound experts with the aim of communicating information clearly, and boulderers with their perspective on usability and hedonistic values of sonified expressions.

2.2 Interacting with sound during sports

In order to create a sonification system that can be used to create a wide variety of sonified expressions, and can be applicable to variety of routes and boulders, we looked at the works that create sonification systems that focus on bi-directional interaction between sonification and sportspeople. Starting with Stienstra et al. [45], authors focused on the potential of movement sonification in professional speed-skating. Their research focused on the process of learning and recognizing the sonification provided by their system to the speed-skaters. They created a sonification system that directly translated the changes on speed-skater's movements. By presenting this to a professional speed-skater in a real-life setting, they aimed to investigate the mechanisms of learning and adapting to the sonification. They observed that within a short period of eight hours, speed-skater was able to learn the meaning behind the changes in the sonification, and achieve autonomous integration for subconscious interaction based on sound. Their findings showed that sonification of speed-skaters actions can offer informative, and easy-to-learn feedback. However, they lacked explorations of the design criteria for sonification, such as the aesthetics and musical quality of the feedback, due to having a single participant. Extending on this, Bergsman and Sabarwal [3] investigated the influence of electroacoustic music on movement by spontaneously arranged dance phrases. In order to communicate movement with sound, they created a set of 15 sound phrases, which were presented to two dancers. Dancers were then asked to create and test choreographic ideas they had based on the sound phrases, thus giving meaning to these individual sound phrases. They then analyzed these phrases, based on overlaps in movement analysis and audio peaks. Their study outlines the selection criteria for the phrases, duration, complexity, and range, and how these are perceived and synchronized with the movement patterns of the dancers. However, their study lacks details regarding the perception and experiential aspects of auditory stimuli, which is mentioned as desirable in their future work section. Together, these studies showed us that design of a sonification framework, that can be learned and acted-on by the sportspeople, can be achieved with positive impact on both performance and experience of the individual sportspeople. In our case, bouldering, we designed SoniBould using climbing holds as a reference for sonification. We expected that this would allow the creation of replicable and adaptable sounds by the sound experts, thus creating a language of bouldering sounds. Working in a similar vein, Schaffert et al. [39] investigated the case of a boat's motion in

a rowing sport. In order to accurately reflect the intensity, duration, and rhythm of the boats' movement, they created unique "sound prints" that match up with the movement sequences of the boat. While their sound prints solely focus on the rhythm of the boat's movement, they also outline the potential for fostering a "group flow" state, where athletes become highly attuned to the collective rhythm. This collective reflection on sonification guided us in creating "sonified expressions", similar to sound prints, which are sounds that are generalizable, shareable, and can be used as a way of communicating the boulderer's actions. Clay et al. [6] further explored how physical movement can be transformed into sound and perceived by others, focusing on enhancing dancers' understanding of their own movements through interactive sound and visuals. Focusing on the interpretive and open-ended nature of the dance, they emphasize fostering social and emotional connections between the dancer, choreographer, and the audience. They outline the importance of including multiple stakeholders involved in the creation of these sounds, which are main boulderer, route-setters and other people in the gym in our case. Both Schaffert et al. [39] and Clay et al. [6] showcase the importance of designing sounds in a way that provides a common ground of communication between multiple people involved in the sports settings. This common sounds, or sound prints of certain actions can allow intuitive and communicable framework to be used in sport settings. In our study we identified them as sonified expressions, as our focus was on the subjective experience of the boulderers and how these experiences can be represented. To investigate the creation of these sonified expressions, we decided to involve both sound experts and boulderers in our workshops. We believed that sound experts had an extensive library of terminology to express themselves through sound, while boulderers were limited to their inherent knowledge and past experiences with sound. Therefore, bringing them together in our workshop setting aimed to create a common sound expression of bouldering. Taken together, we saw that implementation of sound could benefit bouldering sport, both in terms of increased performance and enhanced engagement. However, while studies explored the use of different sonification strategies, for both performance and creating interactions around the sound, there was a lack of expert insights on how to design individual sound to create combined sonified expressions.

2.3 Use of sound in climbing

Bouldering also provides its unique challenges for sonification. We identified two works that used sound in bouldering settings to guide our design process of SoniBould. Starting with Ramsay and Chang [33], authors focused on creating an auditory aid blind rock climbers. They used optical tracking systems to track the body of climbers on a Moonboard [27]. As a grid-based climbing training tool, Moonboard allowed the creating and trying various routes, each using a different combination of its 142 holds. Based on the Moonboard system, authors created verbal cues to guide blind climbers towards the next hold on their selected routes. Additionally, they implemented non-verbal signals to indicate the direction and proximity of climbers' limbs to the holds. Their work provides user insights on using climbing holds as triggers for sound, allowing climbers to easily associate hold-sound matchings based on their previous experiences in using systems that focus on hold-based interactions like Moonboard App. As they focus on the creation of the tracking system, their study does not highlight any feedback from climbers regarding how to design individual sound prints. In their work, Simone and Galatolo [41] shed some light on the use of different kinds of sounds and how they are perceived, again aimed toward visually impaired climbers. In their case, visually impaired climbers were assigned trainers who provided verbal cues about the next move or hold. While they specifically used verbal cues for sound, their work highlights the sequential nature of climbing and how these sounds or verbal cues should align with it. Unlike many sports mentioned above, climbing and bouldering involve target-oriented physical movements that connect to create routes. While the intended solution of a route, also known as beta, may be universal, each attempt by a boulderer will feature variations and differences that require slightly adjusted sounds to guide them. In their case, the authors called these sounds assistance instructions, emphasizing the importance of the trainer's continuous and detailed analysis of the climber's movements to modify their verbal cues as needed. These two studies were influential in designing both our system and workshops. We designed SoniBould to create sounds based on boulderer's interactions with holds, similar to the approach of Ramsay and Chang [33]. However, as we focused on the design of the sounds and the inclusion of sound experts, we chose to use an active climbing wall in a bouldering gym instead of a preexisting wall like Moonboard. This approach afforded us a more flexible workshop setting, allowing sound experts to observe different types of bouldering moves, such as balance moves or dynamic jumps, that could not be represented on a Moonboard. By conducting the studies in an active gym environment, sound experts had the chance to observe the interactions between boulderers and the wall, in addition to the social dynamics of a bouldering gym. Additionally, creating our own wall allowed us to provide first-hand experience to the sound experts, in return allowing them to reflect on their newfound personal experiences with the bouldering for inspiration of sound. Taken together, we found that existing literature showcases the benefits of sonification in sports, however, there are not many examples of sonification for bouldering. Hence, our knowledge of how to design sonified expressions for bouldering is limited. To begin filling this gap, we ask the research question: how do we design sonified expressions for bouldering?

3 Method

To address our research question, we developed "SoniBould," an interactive system that utilizes capacitive sensors embedded in climbing holds to generate baseline sonified expressions of bouldering movements (Fig. 1). SoniBould was designed as an open-ended platform, providing sound experts with a foundation for exploring sound within the bouldering context. Through workshops with sound experts and boulderers, we aimed to explore the design of sonified expressions for bouldering. During these workshops we gave a preliminary introduction to bouldering, followed by our participants experiencing the SoniBould system, observing the baseline sonifications produced by different hold interactions. Post-interaction interviews explored the potential of sound in bouldering, sound creation strategies, and system usability. Based on

these insights, participants were tasked with creating their own distinct sonified expressions of bouldering routes, using SoniBould's baseline sonifications as inspiration rather than direct sound design tools. We employed qualitative coding [26] using thematic analysis to analyze emerging themes in their insights. After the coding, we focused on identifying significant points of interest that emerged from the coded data.

3.1 SoniBould

The SoniBould system consists of a bouldering wall measuring 220 x 340 cm, equipped with 15 climbing holds. The wall allows for the creation of multiple bouldering routes using the embedded T-nuts. These T-nuts, which are threaded inserts placed in a grid pattern across the panels, provide anchor points for attaching climbing holds. We placed conductive strips behind these anchor points to function as capacitive sensors that can detect touch behind the 18mm thick bouldering wall panels. The strips are then connected to an MPR121 [1] chip and interfaced with an Arduino Uno [2] and Raspberry Pi 4 [34]. Data from the Raspberry Pi 4 is later relayed to TouchDesigner software [8] on a PC, which maps the capacitive sensor input to sound triggers. By leveraging TouchDesigner, we created a flexible environment that facilitates the assignment of sounds to individual holds and the adjustment or change of these sounds by sound experts.

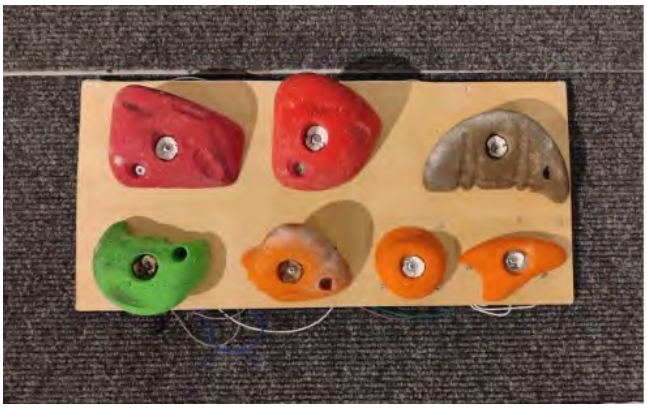

Figure 2: Small-scale portable version of the SoniBould

This setup allows the production of sonification based on touching the holds while bouldering, using the natural conductivity and capacitance of the body. For tracking hands, the natural capacitance of the boulderers were sufficient to trigger the capacitive sensors. However, extra layers of Vibram [50] plastic used in climbing shoes for grip prevented the tracking of feet placement. To solve this, we placed a thin layer of conductive strip inside the rental climbing shoes provided in the gym, enabling our system to detect feet placement. The capacitive triggers from sensors were used as boolean triggers for playing sounds in the system, which continued playing the assigned sound as long as climbing holds were held or stepped on. We aimed to use non-intrusive and inconspicuous sensors in our system for two reasons: to prevent any changes in the textural qualities of the holds that might interfere with grip, and to demonstrate the potential of our system to be applicable to different routes and walls gym. For the sound design, we assigned each hold unique sounds, allowing the sound experts and boulderers to recognize and map their initial tries easily. Taking inspiration from the work of Stienstra et al. [44], we limited the initial sounds to be easily learnable in terms of complexity within the timeframe of our workshops. The system had two different presets to represent both the instrumental and digital sonification [7] potentials of the system:

- Piano mode: This mode utilized a different random note assigned to each climbing hold. This mode was inspired by considering the boulderer to be a pianist. We chose this musical approach as we believed that piano sounds would allow for an easy learning process. This in return, would allow boulderers to reflect on their climbs and provide insights with ease.
- Soundboard mode: This mode had different sound effects assigned to each hold, inspired by a sound effect soundboard, which is used to allow sound experts to get inspired regarding non-instrumental sounds as well. These non-instrumental sound effects ranged from a "fall whistle" to a "drum roll" effect, showcasing the potential of using digital and fabricated sounds within the system.

3.2 Sound design workshops

Using the SoniBould system, we conducted three workshops with eight sound experts and four boulderers, where sound experts were paired up and collaborated with one boulderer (randomly assigned). The workshops were structured to facilitate hands-on engagement with the system and foster collaboration between sound experts and boulderers, to promote discussion amongst sound experts, and to introduce insights from boulderers as users. Additionally, we aimed to allow participant groups to experiment with different sound mappings on a real climbing wall and explore how sound could enhance bouldering. Participants were encouraged to explore various combinations of climbing holds, generating a wide range of sonified experiences.

Table 1: Frequency of Special Characters

Sound Expert #	Profession	Years of Expertise
S1	Musician	10
S2	Digital Sound / DJ	6
S3	Musician	7
S4	Sound Designer	5
S5	Digital Sound / DJ	3
S6	Sound Designer / Musician	10
S7	Sound Designer	4
S8	Sound Designer / Music Producer	6

3.2.1 Participants. As outlined in the related work section, designing sound for movement is a complex task. It benefits from specialized expertise; therefore, we recruited eight sound experts from a wide variety of backgrounds, ranging from sound design for the digital game industry to folk music. We initially used word of

mouth for recruiting our participants and later employed snowball sampling to reach out. Each sound expert had a minimum of three years of experience in their profession. While we did not require any prior knowledge of movement sonification and bouldering, two of our participants (S2, S3) were previously engaged in bouldering as a hobby. Regarding boulderers, we recruited them from the climbing gym where the study was conducted. We utilized our personal contacts and word-of-mouth to find participants during the workshops. Our aim was to gather insights from boulderers with a solid understanding of various climbing techniques. We assessed expertise levels based on the difficulty scale employed in the gym. The climbing gym used colored markers to indicate the difficulty of the routes, with technical moves and solutions typically occurring around the blue (5c+/6a+) and grey (6a+/6b) markers. We considered their ability to consistently climb grey routes as the criterion for recruitment.

Table 2: Frequency of Special Characters

Bouldering Expert #	Climbing Experience	Bouldering Grade
B1	Bouldering / Sport Climbing	7c
B2	Bouldering	7b
B3	Bouldering / Sport Climbing	7a+
B4	Bouldering / Sport Climbing	7b

3.2.2 Structure. The workshops began with a 15-minute introduction, providing an overview of bouldering as a sport and discussing the use of sonification in the context of bouldering. As we did not expect our sound experts to have prior bouldering experience, we included a small introduction to the rules and safety during bouldering. Following this, participants had two hours to interact with the SoniBould system. They were invited to discuss how different sounds could support the bouldering experience. Participants were also free to explore other routes in the gym to engage with different moves details in exertion and expression (without any sound output). We also provided them with a small-scale portable version of our system (Fig. 2) to aid exploration. During this time, they were limited to the two presets defined above. Finally, we asked the groups to choose from a set of climbing routes we established in the climbing gym (Fig. 3) and discuss the potential inspirations for designing the sonified expressions. We video-recorded the boulderer's attempts while climbing these routes and provided them to the sound experts. Based on these video recordings, we asked our sound experts to create sonified expressions of these routes, with an explanatory text to outline the sound design choices they have made while creating these sonified expressions. In their own sonified expressions, we asked them to propose their own sonification triggers and methods, as both sources of inspiration and technical exploration, that can be used in the future versions of SoniBould.

4 Findings

Here we present the findings of our study, reflecting on both the comments we received during the workshops, and the sonified expressions that sound experts created. Participants' overall comments on the use of sonification revealed various perspectives that go beyond mere data representation. For the sound experts, integrating sound into the bouldering experience was a novel concept, although some participants (S1, S2, S3, S5) understood the interplay between sound and sport. Their insights stemmed from personal experiences in other sports and their preferences for incorporating music during activities. Sound was described as a playful agent with the potential to enrich the climbing experience with an element of fun and engagement. Moreover, it was noted to significantly influence attention, subtly guiding climbers through routes and highlighting critical moments. This led to discussions on the potential for music and sound to reflect the dynamics and challenges of different climbing routes.

4.1 Approaches to create sounds for sonified bouldering expressions

We identified three distinct approaches that can be followed when creating sounds for sonified bouldering expressions: musical approach, sound design approach, and source inspiration.

4.1.1 Creating sounds inspired by musical approach. In the beginning, all sound experts observed similarities between the music played in the bouldering gym and sonification. As we conducted our workshops at various times throughout the day, the gym's music varied accordingly. While the overall theme leaned towards fast-paced rock, some participants (S1, S2, S3, and B1, B2) pointed out that the pacing and rhythmic qualities of the rock genre do not necessarily best represent bouldering. In particular, inspired by this ambient music, musicians (S1, S3, S6) noted that different music styles could highlight various routes. For instance, S3 expressed interest in exploring alternative styles due to their background in folk music and instruments. They stated that while the music in the gym can effectively set the mood, boulderers may prefer different styles or genres for their sonified expressions. Boulderers (B1, B2) further expanded on this, discussing the specific styles associated with different sections within the bouldering gym. Each wall in the gym was assigned a name that suggested the style of its routes (Figure 3). For example, the "slab wall," which typically featured calm and balanced routes, was named "Zen," while the inclined wall that hosted strength routes was referred to as "Ape." B1 drew a comparison to these, saying; "The name of the slab wall is already Zen, for example, and when I'm about to enter a route there, I take a deep breath and calm myself. If it (the system) were there, it might play things like a traditional Japanese garden."

The use of distinct musical instruments to represent different climbing actions was also discussed, allowing for an intuitive auditory representation of the boulderer's progress. Two experts, S6 and S3, mentioned the use of harmony and melody. S6 explored the idea of using harmony to denote the vertical movement of the boulderer, building it up, hold by hold, similar to musical harmony. This idea stemmed from their belief that each hold in a bouldering route could build upon the others. In this context, they defined harmony as the outcome of multiple sounds coming from different sources that combine meaningfully. This would allow the final sonified expression to incorporate impressions from every hold of the route. While these chords could effectively represent each

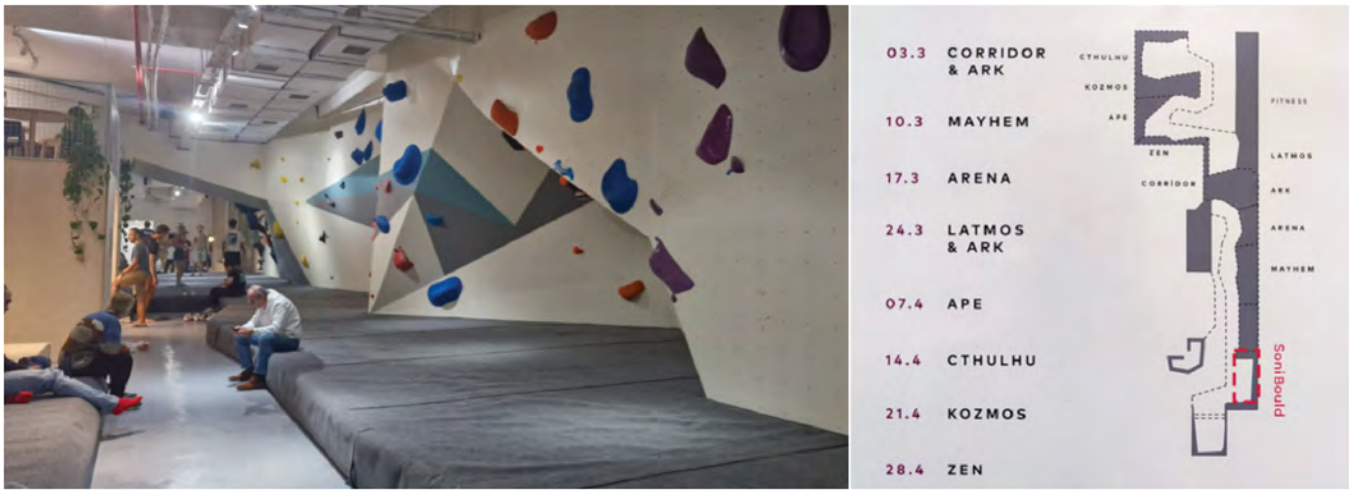

Figure 3: a) Overall view of the bouldering gym, b) map showing layout and placement of our SoniBould system

individual part of the route, they would not convey information on the sequence or flow between them. They explained this concept as: "It can work just like a chord, or a scale. The harmony and meaning are already pre-established in the chords, like AMajor, based on the notes it has. So the route can have a complex chord, maybe 6 or 7 notes tops, and each hold can be one of the single notes in it."

S3 mentioned the melody approach to create unique expressions. While harmony is built additively in parallel, melody can be constructed in a serial manner. Each note and hold would still relate to the preceding and following ones; however, the overall impact of each movement would lessen as the boulderer progressed through the route. They stated that this would serve as a means of depicting the sequential nature of the route and allow the boulderer to alter the melody by playing with the flow between the notes through their movement. They also referred to the differences in the concept of melody in Eastern and Western cultural music. " Western music has the vertical approach, adding sound on top of each, but the eastern approach can also be interesting here (bouldering). It (the Eastern approach) also has a structure that is not uniform like Western music. The non-uniform long notes, ups and downs can match better to bouldering. The routes are not as one-way up as Western music."

Another method mentioned by the sound experts was correlating the building process of music to the climb of the routes. Based on their previous experience in music production, S8 proposed that a direct mapping of the user interface of music design software can be used in bouldering. They stated that their workflow starts with base sounds, namely drum kick, to establish the beat, and then each new instrument layer would get higher and higher, with most treble sounds added last. "The root of the music is actually the kick, then I add basses (guitar), if I am making rock or pop, then other guitars, etc. to the final point of vocals. And the vocals also follow same stuff. Maybe the route can also build up vertically, just like I see it on a sheet music or in my screen, so I can have layering."

4.1.2 Creating sounds inspired by sound design approach. Experts in digital sound and sound design (S2, S4, S5) held differing opinions on sound styles. The digital sound approach was favored for its capacity to provide direct guidance, with specific sound effects corresponding to individual holds, which enhanced the climber's awareness. S2, who has experience in foley sound design, remarked that a sonified expression approach might be the most effective by amplifying the existing sound prints of the bouldering moves. They noted that this method could involve recording the naturally occurring sounds during bouldering, such as climbing shoes hitting the wall or a climber's hand slapping a hold. This could also create certain gaps in sound, which might be filled with "expected sounds." S2 referred to them as; "Actually, there is an expectation of sound while you're (waiting) on the wall. Because even if you're stationary, you're still exerting effort. This can be conveyed not only with the sound of the holds but also with the preparation sound before the sound itself."

S4 referred to the same phenomenon through sound fading. They noted that, similar to bouldering moves, each sound requires a build-up or fade-in, followed by the main sound and then a fade-out. When this principle was applied to bouldering, they indicated that fade-ins and fade-outs could enhance sound perception by providing mental preparation time. While a musical approach can also feature transitions, such as an instrument fading away in a composition, they stated that flow and time signatures would limit the extent of these transitions. They proposed that not all bouldering routes have a uniform rhythm; thus, trying to fit the boulderer's analogous movements into a fixed common time (also known as 4/4) would be restrictive. In such cases, sound designers said that they can fit the sound to the boulderer, rather than fitting boulderer to the sound (S7). This in return would allow more room for creativity while creating the sonified expressions. This was also supported by B4: "I feel that when there is a rhythm to it, it is a good route. But I can not exactly do it on the clock, it may not even matter, as I feel it takes longer when I am exerting."

A point made about sound style was the design of success and failure situations in bouldering. While some sound experts (S1, S3, S4, S6) asserted that the overall harmony achieved at the end is

sufficient to convey the success of a completed route, others (S2, S5) suggested using specific success sounds. Boulderers also concurred with the use of success sounds, as it drew parallel to the social aspect of bouldering. Quoting B3: "When I post it (on Instagram), I mute the audio to add the music, and all of the claps and "bravos" disappear. The sound can also show this (success)."

At this point, sound experts coming from sound design backgrounds suggested that a sound design approach can be more beneficial in terms of representing bouldering actions. They stated that while musical approach allows for more emphasis on flow and taste, sound design approach can afford greater thematic freedom. One of the thematic approaches they mentioned was the use of comedic elements and sounds, exemplified by the fall-effect whistle, which was proposed to increase engagement (S2). Since these thematic approaches stem from existing sound effects or metaphors, they are regarded as universally understandable. S2 elaborated on this by stating: "Instead of the sound when you hit the pad, you can have something like a loud WHAM. The surprise effect due to the difference of sounds, serious during climb and shocker at fall, can also amplify the impact. Maybe it can even make it fun."

B1 also acknowledged the potential of this notion, particularly highlighting the social environment of the bouldering gym. However, they noted that excessive repetition of such comedic sounds can become frustrating. While occasional falls and slips were expected during regular climbs, boulderers often failed during their "projecting" attempts. These projecting sessions are when a boulderer tries to learn and solve a route that challenges their physical or mental limits. During such sessions, the consecutive repetition of these exaggerated failure sounds can become annoying or even disheartening.

4.2 Sources of inspiration for sonified bouldering expressions

While the two distinct approaches discussed in the previous section focus more on the inspiration for type of sonification, we also identified two distinct approaches regarding to the source of the sonification. These are, hold-specific sounds, route-solution sonification. The first method establishes a direct correlation between hold attributes and sonic outputs, turning holds into instruments and leveraging natural bouldering sounds for intuitive feedback. Sound experts defined this approach based on the existing method we used in our prototype. Regarding this method, sound experts (S4, S5, S8) referred each hold as a different instrument, or sound source. This was deemed helpful for beginners especially, as they may miss holds while on the wall due to exertion. They reflected on this using their recent experience with bouldering, saying that: "It can be good for guiding me where the hold is, maybe the sound can be spatial to make me match the hold to the sound better, as I'll be holding multiple (holds) at the same time." (S8)

The second method translates the route's overall movement into sound, capturing rhythm and energy, ideal for guiding boulderers through complex sequences. Reflecting on the experiences and insights of the boulderer participants, several sound experts (S1, S6, S7) stated they would prefer this method as it would allow for more creative freedom. They stated that their understanding regarding different movements in bouldering was lacking to relate details of each route. However, observing the boulderer participants, they were able to get enough insights to relate to the boulderers. Extending on this method, S2 and S3 proposed that different solutions of the boulderers can be reflected on the sonifications. Based on their own knowledge, and observing the boulderers, they stated that intention of the route and the boulderer may not match perfectly. They claimed that, from a sound design perspective, this could offer room for "artistic preferences" similar to personal preferences and inclinations boulderers have while performing a route. "Others (sound experts) will have different choices when it comes to sound, just like different boulderers having different choices during bouldering. And in bouldering, these are observable, like the height of a boulderer." (S2)

5 Discussion

Based on our findings, we defined three themes for sonification in bouldering. These themes combine insights from the workshops with the sonified expressions created by the sound experts. These themes related to the approaches for creating the sound, context of sound in the sport and the interaction between sound and sportspeople.

5.1 Sonification approaches

First theme emerged when analyzing the workshops was regarding the different sonification approaches that sound experts suggested during workshops, and they applied during their creation of sonified expressions. When focusing on the route, aspects of sound correlate with specific elements of the route, such as holds. This approach benefits from directly mapping the physical attributes of the holds to the physical or sonified correlations of music and sound. The primary method proposed by our sound experts involves using direct correlations, where the holds function like individual instruments that produce sound. As also outlined in the example by Clay et al. [6], the interactive elements in the sport and performance can serve as triggers or instruments for audio or visual output. This concept of interactivity is essential, as it bridges the gap between physical action and sensory feedback, transforming the bouldering experience into a more immersive and responsive process. While utilizing these existing elements in the sport, one of the primary strategies is to incorporate the actual sounds of the elements. In the case of bouldering, sound experts drew inspiration from the naturally occurring sounds during the boulderers' interactions. For instance, the sound produced when a climber grips a hold or shifts their weight can be amplified or sonified to create a more dynamic auditory landscape, enhancing the sense of connection between the climber and the route. By leveraging existing elements and sounds, this approach facilitates easy and intuitive learning for boulderers. In situations requiring a reaction from the audience, whether from the bouldering trainer or the crowd in the bouldering gym, such direct methods allow for effective communication too. Conversely, another approach is the mapping of the boulderer's direct performance to the sound. This approach is the one that tunes most to the sonified expression, as it aims to enhance what is visible to the outside eye using sound. Incorporating sound as a dynamic reflection of a climber's actions adds another sensory layer to the experience, amplifying the excitement and emotional engagement

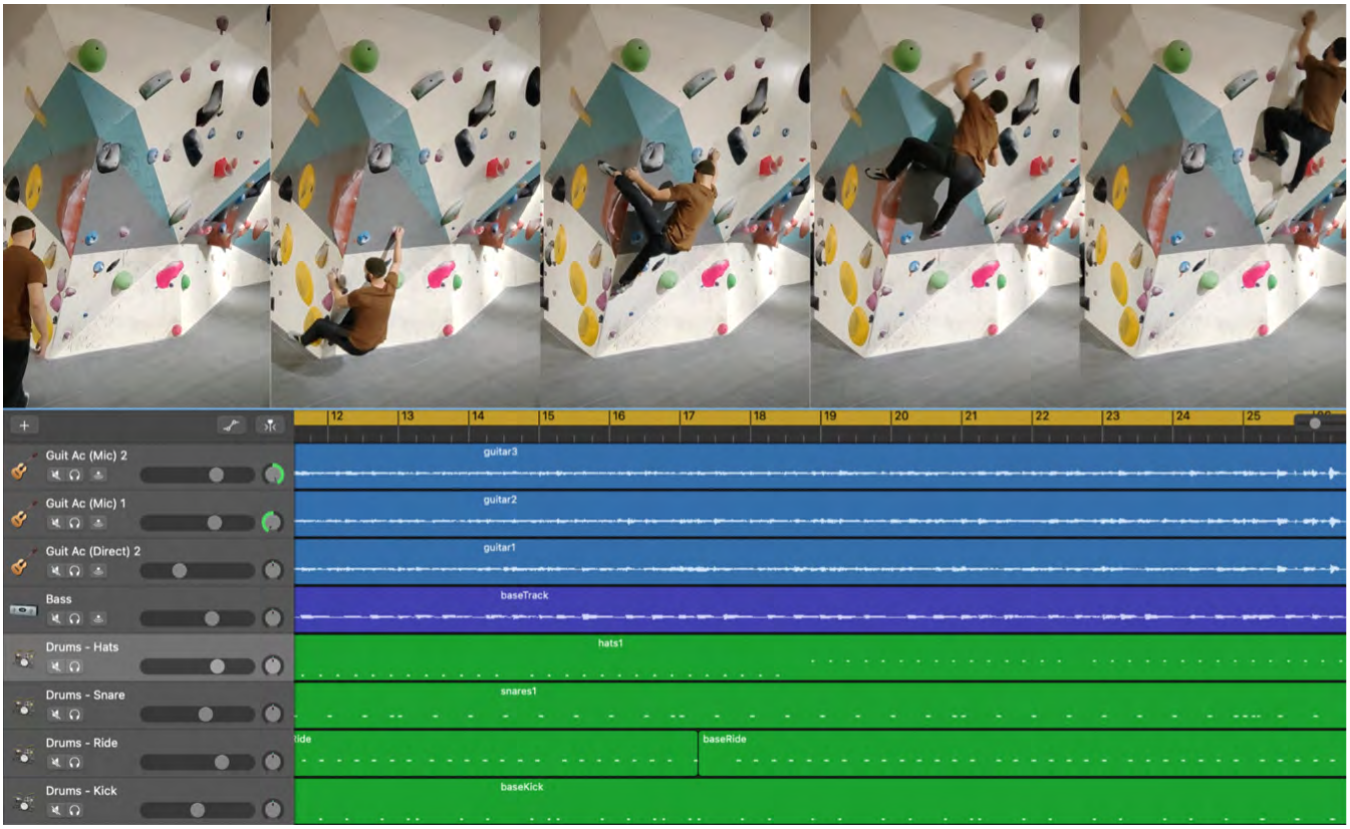

Figure 4: Sound design experts' example sonification of a bouldering route

of the climber. Mostly expressed by the sound experts with sound design backgrounds, this method employs sound as a broader, more abstract indicator. Instead of just tracking individual actions, the sonified sound embodies the climber's journey, offering auditory feedback that complements and elevates the physical and mental challenges faced during the climb. This method also prioritizes a less intrusive experience due to the lower number of triggers for sound, allowing boulderers to focus on the physical and mental challenge without being forced to follow up with detailed sound cues. This less intrusive approach gives the boulderer the freedom to engage with the climb without distraction, while still benefiting from the subtle integration of sound that enhances the enjoyment and engagement. Such implicit approaches to using sound as a trainer of guidance have been explored in previous work for performance gains [21, 51]. Such sonification approaches should not only focus on functionality but also taps into the emotional and experiential aspects of climbing, creating a system that resonates with the climber on a deeper level, leading to a richer and more enjoyable overall experience [53]. In the middle of this spectrum, we have the sonification on the route or the solution, which utilizes the general movements and actions of the route. These can range from the crux moves, the hardest moves in the route that define the whole route, to the overall style or "feel" of the route. In this method, sound is not just a representation of individual holds but rather an embodiment of the entire climbing sequence, reflecting the broader rhythm, pacing, and energy of the route. It is still influenced by the physical elements of the route, while allowing room for interpretation by boulderers. While each route has a definitive solution, these adjustments and interpretations from boulderers introduce diversity, thus this approach can be used best in the case of guiding boulderers. Similar approaches to use sonification in sports, such as the work of Schaffert et al. [36], used direct mapping strategies to the performance of a sportsperson. However, open-ended nature of bouldering sport diminishes the impact of such approaches. One possible method is to map the sounds to key movement phases, effectively dissecting the intended solution into smaller sound phrases, or sound prints [39]. These smaller sound phrases can have their own preset structures, allowing boulderers to focus on parts of the whole solution, while allowing flexibility in unique cases of "beta break". These beta breaks are rare cases in which boulderer finds an unexpected approach to a route that allows solving the route in an easier way. While creating each sound phrase, metaphors are used to convey specific feelings or characteristics of that segment route. For example, faster rhythms might represent a quick, intense part, while slower, more drawn-out beats could be associated with more strategic, calculated moves. While this method offers great flexibility, it also requires careful attention to ensure that the metaphorical sound cues align with the climber's experience and the intended challenge of the route, as a mismatch could reduce the effectiveness of the sonification.

5.2 Boulderer's control over sound

A theme that emerged from the workshops was regarding the amount of control the boulderer can exert over the creation or manipulation of the sound. As each route had set holds and a predetermined intended solution, one of the approaches taken by the sound experts was the use of sound as a guidance. This way, a single sonification would be created for the entire route, and the main aim of the boulderer is to perform it perfectly. The boulderer has limited control over the sonification, as they can only manipulate the sounds based on their movements. This approach limits the control of the boulderer, and as the lower control offers a more passive experience, it also decreases personalized engagement. This lower control on the outcome of the sonification effectively puts the boulderer in a spot similar to a performer of a musical instrument. They can still express their own variations and minute expressions on the overall sonification. While this may seem like a limitation on the boulderer, it could also help boulderers to focus on more precise control and internal dialog. This guidance and passive agency have been used in various other works, such as SoundBike [24], which utilizes an external sound to guide and influence the pedal cadence of the cyclist. In their case, the sounds were designed specifically to indulge cyclists to a certain cadence, using time signature or rhythm, to which cyclists responded by achieving an "audio-motor synchronization". In the context of bouldering, this constrained control could help focus the climber's efforts on perfecting technique, reinforcing the connection between their body and the soundscape without being distracted by excessive control over the sound itself. On the other end of the spectrum, granting higher control to the boulderers creates more opportunities for exploration and motivation. By allowing climbers greater freedom in how they interact with the sonified elements, this approach taps into the climber's creativity and personal expression, offering an experience where sound is not just a passive reflection of movement, but a tool for active engagement. Higher control over sound fosters a deeply engaging and personalized experience, enabling boulderers to express themselves creatively and reflect on their movements through sonified expressions. For instance, both auditory preferences (such as genre preference) and bouldering preferences (such as climbing styles like dynamic or static) of a boulderer can be represented in high control scenarios. This level of control enhances immersion and encourages experimentation, transforming the climb into a reactive performance. However, this approach comes at the cost of informational depth and fidelity. While lower control sound manipulation allows for precise relay of critical information, open-endedness can create messier sounds that are expressive yet open to interpretation. Works such as those by Bergsland and Sabharwal [3] and Françoise et al. [15] employed similar open-ended sonification in the context of dancing. They highlight the complexity of using sound to convey meaning, as individual interpretations and emotional responses to certain sounds can vary widely. In bouldering, while high control offers more expressive freedom, it also requires careful consideration of how sound is used to ensure that it remains meaningful and motivating, balancing creativity with clarity to create an enjoyable yet informative experience. The mapping of urban and natural sounds to dancers' movements illustrates this, but their findings also discuss the importance and subjectivity of interpretation connotations.

5.3 Using sonification versus musification

Another theme emerging from the discussions was the use of sound-based approaches in comparison to music-based approaches. In our study, we noticed the different approaches taken by sound designers and musicians in terms of shaping the experience, as different sound strategies can dramatically affect how climbers interact with the environment and perceive their performance. When considering a musical approach, the goal was often to create organized sound with elements like rhythm, melody, harmony, and dynamics. This approach can evoke specific emotions or tell stories, making it particularly suited for crafting aesthetic experiences [17]. In the case of bouldering sonification, a musical approach might use rhythms or melodies to enhance the climber's emotional connection to the activity or reflect the progression of their movement, creating a deeper, almost narrative-like experience as they climb. This approach can heighten the climber's sense of immersion, making the experience not just about completing a physical task, but also about engaging with the environment in an emotional way. On the other hand, sound design, especially in the form of foley or sound effects, aims to create a sense of realism by emphasizing physical actions and adding layers of immersion to the environment. Our participants coming from this background used sound to highlight the climber's movements, the pressure on the holds, or even the climber's physical exertion through detailed sound effects like the click of a foot finding a hold or the scrape of skin against rock. This kind of sound design provides immediate, action-driven auditory feedback, helping climbers connect more directly with the environment while aiding their decision-making process as they climb. We can observe similar mappings, regarding real-life sounds of the sport and the added sonification, in the work of Dubus and Bresin [10] with rowing and wind sounds. The distinction between these two approaches becomes particularly evident when we consider the communicative aspect of sound. While music tends to communicate in a more abstract and emotional way, sound design has a more direct, functional communicative purpose, closely tied to the task at hand. In essence, the sonification of bouldering, when approached through either music or sound design, has a significant impact on the user experience. The challenge lies in aligning the expert's design intention with the non-expert's subjective interpretation, ensuring that the sounds effectively communicate the intended emotional or functional cues while resonating with the boulderer's personal experience. These differing strategies underscore the importance of considering both the functional and emotional potential of sonification when designing soundscapes for bouldering.

6 Conclusion

In this paper, we expand upon the exploration of sonification in SportsHCI, within the context of bouldering. We present "SoniBould", a novel system that augments the climbing holds on a climbing wall using capacitive sensors embedded behind each hold. Using this system, we aimed to investigate the interactions between boulderers and sonified data. By inviting experts from the field of

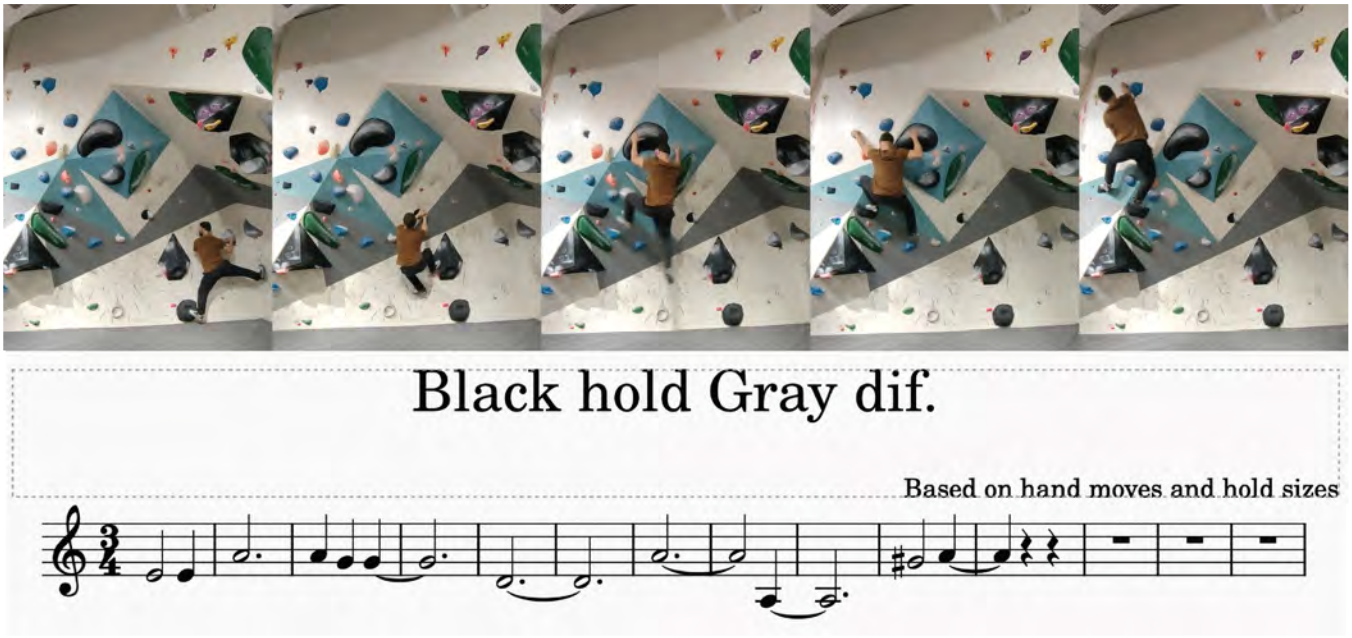

Figure 5: Musician experts' example sonification of a bouldering route

sound design, and boulderers, we outline three sonification approaches and three sound design themes tailored for future designers working at the intersection of sound and bouldering. Beyond the primary user group, we defined in our study, as intermediate-level boulderers, these insights can be adapted to serve diverse user groups within the bouldering community, such as children seeking enhanced motivation. We believe that our insights can be applied to various other cases based on the specific needs and expectations of the sportspeople involved. In the future, we aim to analyze the sonified expressions created by the sound experts, based on auditory user experience and their impact on boulderer's experience. Based on this analysis, we aim to create a final iteration of SoniBould, for real-world testing of an open-ended sonification system for bouldering. With these findings, we hope to contribute to the growing body of SportsHCI and movement sonification research by opening new avenues for designing sonification in sports.

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