ClimbAware - Investigating Perception and Acceptance of Wearables in Rock Climbing

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ABSTRACT

Wearable sports devices like GPS watches and heart rate monitors are ubiquitous in sports like running or road cycling and enable the users to receive real-time performance feedback. Although rock climbing is a trending sport, there is little to no consumer electronics available to support rock climbing training during exercise. In this paper we investigated the acceptance and appropriateness of wearables in climbing on different body parts. Based on an online survey with 54 climber we designed a wearable devices and conducted a perception study with 12 participants in a climbing gym. Using vibro-tactile, audible, and visual cues while climbing an easy route and a hard route, requiring high physical and cognitive load, we found that the most suited notification channel is sound, directly followed by vitro-tactile output. Light has been found to be inappropriate for the use in the sport of climbing.

Author Keywords

Climbing; sports technologies; wearable computing; ambient information; perception; visual alerts; tactile alerts, audible alerts.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Rock climbing in its original form was only practiced by smaller, more adventurous groups of people who have gained expertise in handing the necessary protection equipment such as ropes and bolts whilst climbing outdoors. In the last several years, a new style of climbing emerged which generally focuses on the athletic aspect and the physical exercise of the climbing activity. The latter is today known as *sport climbing*, differentiating itself from *traditional climbing*. Sport climbing can be performed both, indoors and outdoors. Climbing outdoors usually requires the climbers to bring their own ropes, which are clipped into either predrilled bolts or self set protection. Examples for that are nuts, which are a small piece of metal that is sticked in cracks of the rock to hold the climber in case of a fall. In contrast to that indoor climbing requires only little material. Artificial climbing walls (see Figure 1) are equipped with colored holds for hands and feet. Although the amount of holds mounted to the wall is large, only a few are part of a specific route and are allowed to be used. Holds which belong to the same route can be identified by either their color, or colored strips which are taped next to the holds. Routes can be setup in different difficulties. These can be influenced by the distance, the size, and the orientation of the holds, resulting in body positions which require a lot of grip or body core strength.

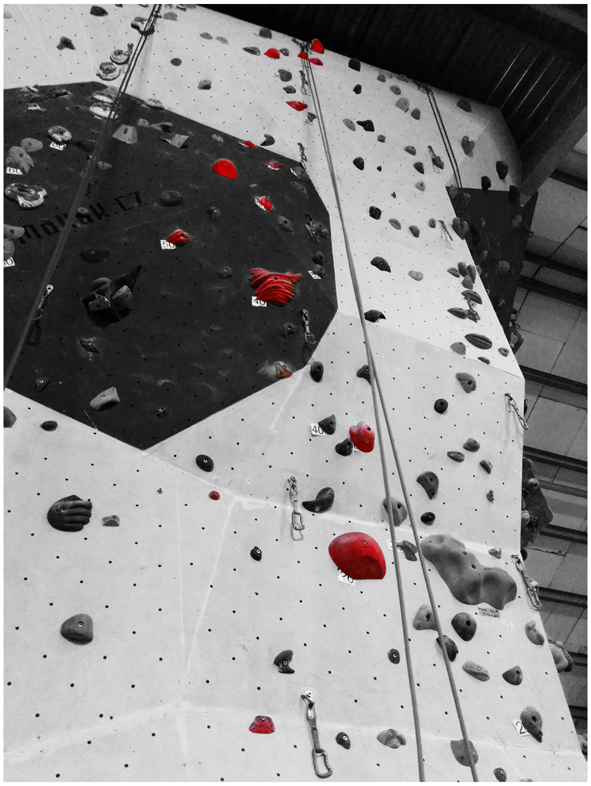


Figure 1: A climbing route is composed of a number of different holds (often of the same color, or marked with colored tape). Only these holds are allowed to be used.

The climber may still bring her own rope and do what is called *lead climbing*, i.e. carrying the rope from the bottom of the wall to the top but the usual and more accessible option is so called *top-roping*. In this activity the climber uses ropes which are already hanging from the top of the wall, while one end is attached to the climber and the other end is attached to a belaying device, operated by the belayer during the ascend.

When climbing indoors, the risk of injury is reduced by allowing for permanent bolts and anchors in the walls, and thus requiring less expertise while performing lead climbing, but it also makes the sport much more accessible as it requires less experience and only a small set of equipment when climbing top-rope.

The increased accessibility is one reason why sport climbing, outdoors or indoors in a gym, became more and more popular. In the US there are now 353 climbing and bouldering gyms, including 29 new ones which where built in 2014 [6]. Even though indoor climbing on artificial walls and plastic was initially thought as a form of training for climbing outdoors, many people only engage in this form of climbing, as for example, it is easily accessible and does not depend on weather conditions.

High security standards [**?**] of the walls and the equipment, as also mandatory introductory courses do their share in providing a safe exercise environment for all age groups. Furthermore, climbing is a sport which demands, but also fosters both, physiological and psychological strength. During a climb, the climber uses a large number of muscles in her body while simultaneously concentrating on her next move, grabbing a tiny hold, paying particular attention where to place her feet, in which direction to shift her center of mass, and how to balance on a tiny ledge serving as a hold for her feet.

All these factors discussed above outline how different climbing is from other sports such as running or cycling. It represents a more holistic activity that besides muscle force and technique, especially requires attention throughout the climb. Green and Helton explored the influence of a memory task on climbing efficiency [4]. They found that climbing efficiency was significantly impaired through the memory task. This hints at the cognitive demands of climbing. If we now consider a climbing training system that aims at giving the climber feedback in-situ as proposed as future work of, e.g. ClimbAX [10], we need to take the cognitive capabilities of the climber in mind. If we want to give feedback to the climber about her performance or how he should adapt her technique during a climb such a system needs to be well tailored to these capabilities. Finding suited notification channels and positions for devices to deliver the feedback is crucial point. For example Roumen et al. [15] showed that a simple task like walking has a significant influence on the perceivably of different feedback channels. We expect these effects to be even more prominent for a complex activity such as climbing.

In this work, we investigated whether and how a climber can perceive and distinguish notifications, which are sent out from a device worn on her body, even with the high cognitive load described above. Existing interaction concepts that are widely used in other fields, such as sport watches, do not necessarily meet the specific requirements of climbing. We conducted an online survey in which we assessed appropriate body parts to place a wearable device and possible notification channels. Based on these results we developed a wrist worn device which was able to notify the user with either vibration or visual cues. In addition to that, we used bone conducting headphones for audible cues and tested all three notification channels in a user study in a local indoor climbing gym and top-rope routes. We propose exemplary use cases for different communication channels, based on the findings of the user study.

Figure 2: The notification device which is worn on the wrist. It is powered by an RFDuino equipped with three RGB LEDs and a vibration motor.

While parts of the study described below are very specific to rock climbing, we believe that it can inform the design of wearables for activities where high physical and mental demand come together, like white water kayaking or windsurfing.

RELATED WORK

Our work is related to previous studies on (1) wearable devices, (2) influence of mobility and (3) climbing research in HCI.

Wearable Devices

A variety of different wearable devices have been investigated by today, at this point we will briefly discuss a subset of these that have the potential to be used during climbing. So far most of the related work in this area focused on input techniques and only few investigated the output capabilities in depth. When it comes to interaction with wearable devices, Profita et al. [**?**] found the wrist and the forearm to be the most socially acceptable area to position for such devices. While their study mainly focused on interaction, Harrison et al. [**?**] investigated reaction time to visual alerts. They found that reaction time performance is not only influenced by the location but also dependent on outside factors, such as occlusion. In a climbing scenario these factors will be very likely even more prevalent compared to every day interaction with wearable devices.

While most of the prior work did mainly focus on input on such devices, the limited size makes output as complicated as well. One of the earliest interactive wrist-worn devices has been developed by Hansson and Ljungstrand [?]. Their Reminder Bracelet allowed a connected PDA to notify the user using integrated LED. With Damage, Williams et al. presented a wearable ambient display that allowed for semi-public notifications using LEDs as well [?]. Pasquero et al. investigated tactile output on a smartwatch [?]. Besides for notifications they found it to be suitable for obtaining numerical data as well. All these works have only been tested in well structured lab settings.

The multiple display segments of the Facet system [?] were able to overcome the problems that arise from the small display size of current devices. On the one side, the multiple viewing angles allowed for different relative head positions and on the other side, the ability to stretch applications over multiple display segments reduced the effect of the small display size. Nevertheless, the system not only requires a high amount of hardware and relied on manual adaption which might not be possible during climbing.

Influence of mobility

When interacting with mobile devices, the mobility is an important factor and often neglected in favor of non-mobile lab studies. For example when walking users can only keep stable interaction performance at 74% of their preferred walking speed [?]. Furthermore the effect of encumbrance on interaction - carrying an object in one hand and interacting with the other - while for example walking has a significant influence in task performance for target acquisition on a touchscreen mobile phone [?]. During climbing people are not only carrying an object but usually have no free hand.

Roumen et al. [15] investigated wearable interactive rings regarding the perceivably of different notification channels (light, vibration, sound, poke, thermal) during five levels of physical activity (laying down, sitting, standing, walking, and running). According to their results vibration is the most reliable and fastest notification channel, followed by poke and sound independent of level of physical activity. The other two channels, light and thermal, were less noticeable and were affected by the level of physical activity.

Notifications on a wearable add a secondary task to the main task of climbing. This relates to cognitive aspects how such a secondary task might influence the climbing performance. Green and Helton explored the influence of a memory task on climbing efficiency [4]. They found that climbing efficiency was significantly impaired through the memory task. Helton et al. [7] followed up these results and their findings indicate that climbing is highly cognitively demanding. Based on their results and memory resource theory, they suggested the need for communication equipment that augments the climbers memory. They suggest to use visual or tactile modalities but did not investigate their effectiveness. So far, to the best of our knowledge the effects of climbing on the perception of different output modalities have not been investigated. We are following up on the work of Helton et al. and investigate these in a real world setting.

Climbing and Human-Computer Interaction

Climbing is a complex activity that is determined by a variety of physiological and anthropometric factors. Mermier et al. [12] found that the variance in climbing performance can be mainly explained by a set of trainable variables and less by specific anthropometric characteristics. While the physiological factors of climbing have gained some research attention, there has also been research on the cognitive factors of climbing [13].

In wearable computing and HCI, climbing received little attention so far. Some related work exists regarding instrumented climbing walls, automated skill assessment and route recognition using a wearable device, and augmented reality [11, 14, 1, 3, 10, 9, 2, 8].

There are various possibilities to track a climber such as body-worn sensors, image processing, or instrumented climbing walls. Liljedahl et al. [11] proposed Digiwall, which consists of holds that can sense the climber's position with built-in capacitive sensors and provide subtle feedback with LEDs. The focus of their work is gaming, competitions, and challenges that can be rather used for playful activities than rigorous training. A very similar instrumentation was done by Ouchi et al. [14] whereas the goal of their work was to model play behavior of children. They used climbing holds that incorporated a LED and a strain gauge. Their work aims to improve the design of age-appropriate and safer playground equipment. Aladdin and Kry [1] proposed an instrumented climbing wall for static pose reconstruction. They use holds equipped with 6-axis force torque sensors that were used to reconstruct the climber's pose during an ascent. An evaluation showed that dynamic motions and higher errors coincide. Fuss and Niegl [3] also used torque sensors in instrumented climbing holds to measure the performance of a climber. Data collected on three climbing events was be segmented into the three phases of contact: set-up phase, crank phase, and lock off.

While the previous methods required an instrumented climbing wall, Ladha et al. [10] used wrist worn accelerometer sensors to assess climbing performance. An evaluation of the system during a climbing competition resulted in a positive correlation between the predicted and the actual score of the participants. Kosmalla et al. [9] introduced ClimbSense, a system to record and automatically recognize successfully climbed routes. In their approach the climber is equipped with wrist-worn Inertia Measurement Units (IMUs). The IMUs were used to collect a corpus of climbing data and train a classifier that is able to recognize different routes.

Daiber et al. [2] investigated handheld augmented reality for collaborative boulder training. They present a mobile augmented reality application to define, document and share boulder problems. Kajastila and Hämäläinen [8] also explored augmented reality for climbing walls but they directly augmented the wall with a projector. A preliminary Wizard-of-Oz study with six interaction prototypes and structured interviews showed that users liked the system. These two examples can be used in another potential scenario where the climber is guided by a coach or friend using an app that pushes notifications to a wearable device.

ONLINE SURVEY

To gain a first insight into possible locations of wearables we conducted an online survey. The participants were asked a set of general questions like age, sex, climbing experience and habits, followed by an assessment of body parts concerning appropriateness and perceptibility.

General Questions

54 climbers participated in the survey, of which 11 were female. When asked about their climbing skill, 29 considered themselves beginners, 18 intermediates, and 7 expert climbers. The age of the participants ranged from 18 to 49 with an average age of 27.87 years ($SD = 7.7$). We asked the participants to state whether they would rather boulder (1) or do classic rope climbing (5) on a 5-point likert scale. In average the participants answered 2.7 ($SD = 1.05$), which means that the participants rather boulder than climb. For both disciplines the participants had to state whether they train outdoors (1) or indoors (5). In average the participants answered with 1.89 ($SD = 1.66$) for bouldering and 1.63 ($SD = 1.36$) for climbing. This shows a tendency for practicing both, climbing and bouldering, outside on a real rock.

Assessment of Body Positions

To get a first insight about possible locations on the body for wearable devices, we investigated eleven body parts for their appropriateness and estimated perceptibility for vibro-tactile, audible, and visual notifications. Appropriateness and perceptibility were questioned after each other by providing the user with an interface, displaying a silhouette of a human with markers placed over the eleven body parts. The participant was guided from top to bottom via a wizard on the website.

Appropriateness

In the second part of the questionnaire, which assessed the appropriateness, the participant was asked to state how appropriate or inappropriate a device would be when worn during a climbing session. For this, the participants were shown a silhouette of a human body. We selected 11 points on the body to be assessed: head area, shoulder, chest, upper arm, lower arm, wrist, waist, upper leg, knee, and ankle (see Figure 3a). Except for the head, chest, and belt area all points where located on the right body half for the sake of simplicity.

For each body part, the participant could choose a value from *(1) not appropriate at all* to *(5) fully appropriate*. A generated heatmap of the fixed body parts and their cumulated values for the appropriateness can be seen in Figure 3a. As it can be observed, the wrist, upper arm, and ankle are stated as the most appropriate places on the body. Table 1a gives detailed information about the placements at each body part. For this, we summed up all the answers given by the participants for the given body parts. Especially the feed, lower leg, and shoulder area were perceived as least appropriate.

After the assessment of the appropriateness per point basis, the participants were asked which of the body parts they would consider most suitable for which kind of device and if they could think of concrete examples. The wrist (named 20 times) was clearly in the top position for appropriateness, followed by the upper arm (8), chest (7), ankle (6), head (6) and waist (4). When asked for inappropriate positions, the joints in general (named 8 times), head (7), feet (5), legs (4), hands (4), and shoulders (2) were mentioned as unfavorable position choices.

Some participants also mentioned preconditions for possible body worn devices. The most important requirement for such devices was that it would not hinder the climbing movements and the climbers flexibility at all. Especially the joints and the areas around it were rated as very inappropriate. Another concern of the participants was the risk of injury. The participants feared that devices placed on exposed body parts like knees, elbows or legs, are prune to get tangled somewhere on the rock or the artificial climbing wall and either damage the device or lead to injuries on the climber herself. A common understanding was that a device worn on the wrist would be the most appropriate, since people are already accustomed to smartwatches, classic watches, or bracelets in general. The device should be thin and neither limiting motion nor being uncomfortable.

Followed by the assessment of appropriateness, the participants were asked to estimate the perception quality of the three output channels, vibration, light, and sound. For this, the participants had to state for each channel how perceptible a notification triggered from a device, worn at a specific body position, would be. The participants could answer this question by selecting a point from a five-point scale ranging from *(1) not perceivable at all* to *(5) very perceivable*.

Perception of Tactile Notifications

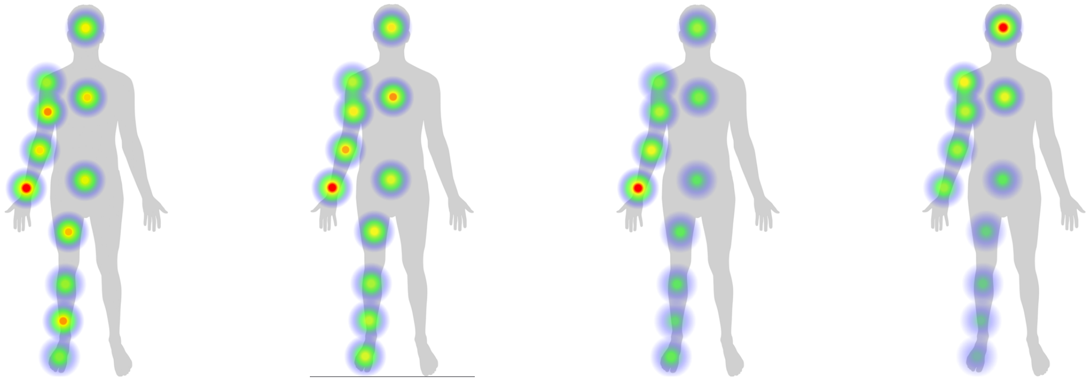
We asked the participants to state how perceivable a vibro-tactile notification would be when triggered during climbing at the given body positions. Figure 3b shows a visual interpretation of the results. It can be seen that the perceptiveness of vibro-tactile notifications is estimated slightly higher in the upper body half than in the area below the waist. Table 1b summarizes the answers for tactile notifications; While the wrist, chest, and lower leg area were estimated as the most perceivable areas, the lower leg, shoulder, and ankle were estimated as the least perceivable points to place a tactile notification device.

Perception of Visual Notifications

As in the question for the perception of tactile notifications, we additionally asked the participants how they think visual notifications would be perceived at each of the eleven body parts during climbing.

As it can be seen in Table 1c and Figure 3c, the body areas with the highest estimated perception of visual notifications are all located on the arm (wrist, lower arm, upper arm), while the area with the least estimated perception are the ankle, lower leg, waist, and upper leg.

Perception of Audible Notifications



(a) appropriateness (b) vibro-tactile (c) light (d) sound

Figure 3: Cumulated values for the different classifications of body positions. The redder the point, the more appropriate, or perceivable it was considered.

Position	Score
Wrist	193
Upper Arm	178
Ankle	176
Upper Leg	172
Chest	169
Lower Arm	167
Head	165
Waist	158
Shoulder	138
Lower Leg	136
Foot	129

(a) Appropriateness of body position in descending order.

Position	Score
Wrist	221
Chest	203
Lower arm	199
Head	191
Upper Arm	190
Upper Leg	187
Waist	180
Foot	178
Ankle	170
Shoulder	167
Lower Leg	162

(b) Estimated perception of tactile notifications when induced at different body positions.

Position	Score
Wrist	210
Lower arm	175
Upper Arm	157
Head	151
Chest	138
Shoulder	136
Foot	123
Upper Leg	118
Lower Leg	114
Waist	114
Ankle	106

(c) Estimated visibility of devices placed at various body positions.

Position	Score
Head	225
Shoulder	192
Chest	186
Upper Arm	172
Lower arm2	164
Wrist	158
Waist	126
Upper Leg	111
Lower Leg	108
Ankle	99
Foot	90

(d) Estimated perception of audio notifications when induced at different body positions.

Table 1: Cumulated values for the different classifications of body positions. The redder the point, the more appropriate, or perceivable it was considered.

In contrast to the output channels vibro-tactile and light, audible notifications are clearly estimated the highest around the head area (see Figure 3d). Body parts located more distant to the body are scored with a low perception of audible notifications. Looking at Table 1d reveals a descending order of body parts, beginning at the head and ending at the foot, confirming the observation made on the heatmap.

Qualitative Feedback to the Output Modalities

As in the *appropriateness* part of the questionnaire, the assessment of the estimated perception of notifications at the different body position was followed by a summarizing questions. We asked the participants which body positions would be easier perceivable than others. The wrist with 19 mentions leads the list of positions which are guessed as good places to trigger notifications, followed by the head (9), and arms (8). In contrast to that, the feet (7), legs (4), and ankles (2) are estimated as places with a low perception.

In general, the participants agreed that the head is the most suitable position for audible notifications, since the distance between the audio source and the ears is the shortest when used, for example, with smart glasses. Additionally, most of the participants stated that both, visual and vibro-tactile notifications would be most useful at positions on the arms, especially on the wrist. Concerning the visual feedback, the participant stated that the device has to be in the line of sight, thus, on the arms. *"The arms and hand are closest to the ear and eyes since I am mostly looking upwards when climbing rather than downwards." (P13)* In contrast to that, all participants agreed that areas in the lower body half are, with exception for some tactile notifications, not very suitable for any kind of notification.

Preliminary Design Implications

The feedback of the participants can be generalized as follows:

- Audio feedback is most suitable around the head area
- Tactile feedback is most suitable on the arms
- Visual feedback should be in the line of sight
- The wrist is most suitable for a device that combines the channels light and vibration
- A body worn device should be durable, not obstructive, and not entail any risk of injury

These results are in accordance with former studies that identified the wrist as the body location, at which notifications were perceived the fastest. In particular this has been shown for the notification with visual cues during other motor activities in which the wrist was located in the immediate field of view, such as reading, writing, typing, and conversational gesturing [5].

PERCEPTION STUDY

To get a deeper insight on the findings gained from the online survey, we conducted a user study in a local climbing gym. Our goal was to test whether climbers would perceive visual, audio, and tactile notifications differently when climbing an easy route, versus climbing a hard route.

Method

Participants

12 climbers (1 female) participated in our user study. Their age ranged from 13 to 60 years, with an average of 34.58 ($SD = 11.74$) years. For participants under the age of 18 we got written permission of their parental authority that they were allowed to participate in our experiment. When asked for their climbing skills, seven participants stated to climb *not harder than 5.11*, and five claimed to climb routes rated *5.12 and up*. The difficulties used in the results above are reported in the *Yosemite Decimal System*[1]. As an example, climbing beginners should be able to climb a route graded with 5.4, while competitive climbers succeed in routes graded with 5.15. None of the climbers of the perception study participated in the online survey.

Conditions

We tested three different notifications channels which could be perceived by the participants (light, vibration, sound). The first condition consisted of a visual cue, emitted from three RGB LEDs in the colors *red*, *orange*, and *green* for four-seconds. A vibro-tactile cue in form of a one-second long vibration pattern was used as the second condition. The vibrational pattern consisted of either one vibration for one-second, two vibrations within one-second, or three vibrations within one-second. The third cue was an audio signal which also lasted for one-second and consisted of a tone, either played once, twice, or three times. *TODO: describe, mention mario?* All notifications were manually triggered with the help of a smartphone app, operated by the experimenter.

Tasks

When climbing, the climber undergoes both, physical and psychological stress. The difficulty of a route depends on how hard the holds are to grab, which body positions are enforced, how hard it is to balance, and depending on the climbers attitude, the fear of falling. To investigate the perception in the presence and absence of stress, we selected two different routes. Route *R1* had a difficulty of 5.7 and was equipped with holds which where relatively easy to grab. The second Route *R2* was picked as the hard route with a difficulty of 5.10c, was slightly slanted, and consisted of many holds with a large slope, thus making them hard to grab.

The task for the participants was to climb both routes *R1* and *R2*, and to report notifications and their levels as soon as they noticed them (e.g. saying "red when testing the visual channel).

Design

We designed the experiment so that (1) each order of routes (easy route first, then hard route and vice versa) was climbed by the same number of participants, and (2) each of the 6 possible orders of notification channels was tested. For two consecutive climbs (easy and hard), only one channel was tested. This resulted in six climbs which each participant had to ascent. To avoid ordering effects, the order of each condition of the tasks was latin square counterbalanced between participants.

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[1] `http://climber.org/data/decimal.html`

Figure 4: Bone conducting headphones which were used during the study.

Procedure

First the participant was given an explanation of the experiment and was asked to sign an informed consent to record the data and video capture the study. In case of participants under 18, we asked their parental authority for consent. Then, we demonstrated the different notification channels and their different levels of notifications. Before the first climb, we asked the participant to fill out an initial questionnaire asking for her age and climbing experience. Depending on the current mode, the participant started with the easy or hard route and with one of the three notification channels. During the climb we triggered three notifications in three different levels, where each level was triggered once and in a random order per route. We chose three distinct holds in each route which the participant necessarily had to use during the ascent. For the hard route, we picked the first hold so that the resulting body position was especially strenuous. We did the same for the easy route, but in this case it was the last hold. As soon as the participant touched the hold, we triggered the specific notification and recorded her response by pressing the designated button within the smartphone app.

After the first climb, the participant directly climbed the second route, which was either the hard route if she started with the easy route or vice versa. When the participant finished the second route, we asked her to fill out a user experience questionnaire, asking how she perceived the notification for this specific channel. This procedure was repeated two more times, testing the two remaining channels, while maintaining the order of the routes. A final questionnaire was handed to the participant which assessed the overall experience and how hard she perceived the individual routes. All trials were video recorded.

In summary the experimental design was: 12 participants ×3 conditions ×6 trials = 216 data points. Overall the study took roughly 30 minutes and the participants were compensated for their time with 10 Euros.

Apparatus

We conducted the study in a local climbing gym, utilizing two selected top-rope routes. This kind of route ensures the safety of the climber, since the rope runs through a fixed pair of carabiners at the top of the route and does not require any additional self-protection except for tying herself in properly. Both routes were approximately 12 meters high.

Based on the guidelines presented above, we designed a wrist worn device which consists of an RFDuino with integrated bluetooth capability and three RGB LED, which were able to emit *red*, *orange*, and *green* light. We used LEDs of the type WS2812 which emitted light which could be perceived well in even light conditions. Furthermore a battery and a vibration motor were built in to provide vibro-tactile feedback to the user. An off the shelf 3V vibration motor was used to, which resulted in vibration intensities comparable to smart watches like the Samsung Gear. We used the approach of a custom designed device as opposed to a smart watch because it should give the user a feeling of a more abstract device. A potential bias which could occur when using a smartphone is therefore counteracted. To meet the need for safety and injury prevention, which arose during the online study, we equipped the wrist band with a magnetic latch. The latch is strong enough to hold the device in place, but is sufficiently fragile to open if the wrist band got caught during the climb, preventing serious injury by the wristband in case of a sudden, unlucky fall.

In addition to this device, we used a pair of AfterShokz BLUEZ 2 bone conducting headphones[2] for audio notifications (see Figure 4). We did chose these headphones because they do not cancel out the climber from her surrounding, enabling her to hear both, the audio notifications and commands from her belayer. The latter is a crucial prerequisite for a safe execution of sports climbing.

To control both notification devices, an Android application was developed to trigger notifications to either the wrist-worn device or the headphones. The application was also used to manually record and store response times and the duration of a climb. It furthermore managed the order of routes and notification channels during each individual experiment. When the participant started climbing, a button press started the stopwatch to record the duration of the individual climb. Whenever one of the three designated holds was reached by the climber, a press on the notification button triggered the appropriate notification. As soon as the participant stated the perception of a notification, a stop button was pressed and the response time was saved. The answer given by the participant was transcribed via a dialog within the application.

Results

Response Times

To evaluate the response times, we first averaged the response times for the easy route, the hard route, and both routes, for all channels (see Figure 5). As it can be observed, the *light* channel has a slightly higher mean response time than *vibration* and *sound*. A test of normal distribution followed by a pairwise T-test showed no significant difference of the means between the categories. However, the standard deviation of the *light* (1323.61) channel is notably higher for both, *vibration* (575.82) and *sound* (600.37).

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[2] `http://aftershokz.com/collections/wireless/products/bluez-2`

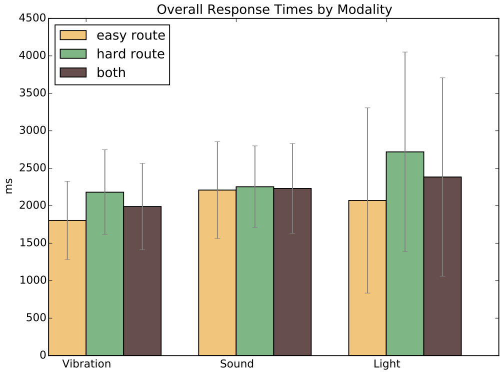

Figure 5: Response times of the participants, ordered by notification channel and climbed route.

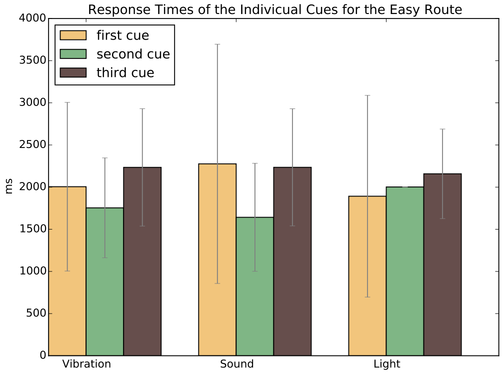

Figure 6: Response times ordered by the time of occurrence and grouped by notification channel for the easy route.

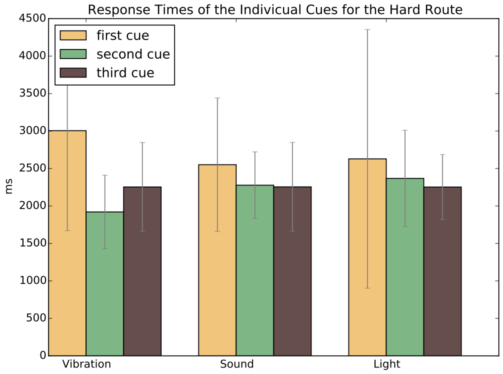

Figure 7: Response times ordered by the time of occurrence and grouped by notification channel for the hard route.

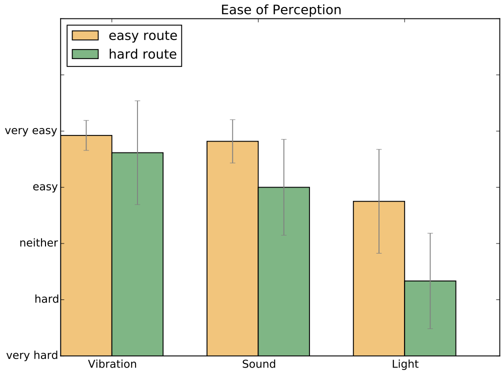

Figure 8: Ease of perception for the three channels, for both, the easy and the hard route.

We triggered three notifications at three distinct holds for each of the two routes, to ensure comparability. Since each hold or position within the route incorporates a different difficulty of the climbing move, we investigated the response times for each position (cue) within a channel and for both routes. As shown in Figure 6 (easy route) and Figure 7 (hard route) the response times differ for each position. In case of the easy route, the second cue for vibration and sound have a slightly lower response time as for the light channel.

Quality of Responses and Missed Notifications

For each notification the participant had verbally report the level of the notification by either the number from *one* to *three*, for vibration and sound, or one of the colors *green, yellow,* or *red*, for the visual notifications. Of a total of 216 notifications, 14 notifications were missed, and 4 answers where given incorrectly. We could observe that three of the 14 missed notifications were missed in the *vibro-tactile* channel, while the remaining eleven notifications were missed in the *light* condition. Four notifications were missed in the easy route and ten notifications were missed in the hard route. The four notification which were given incorrectly occurred solely in the hard route, while two of them occurred during the visual and two in the vibro-tactile channel. No notifications were either missed or wrong in the sound condition.

Participant Feedback

After each channel we asked the participant to fill out a short user experience questionnaire. We wanted to know how the participant felt about the different channels. For this, we asked them how easy they could perceive the notification itself and the different levels of it. Furthermore, we asked how comfortable they conceived the notification and how they judged the efficiency of the specific channel. As a final question, the participants were asked how they liked the channel in general.

The participants stated for both, the easy and the hard route that visual notifications are less easy to perceive than audio notifications, and audio notifications are less easy perceivable than tactile notifications (see Figure 8).

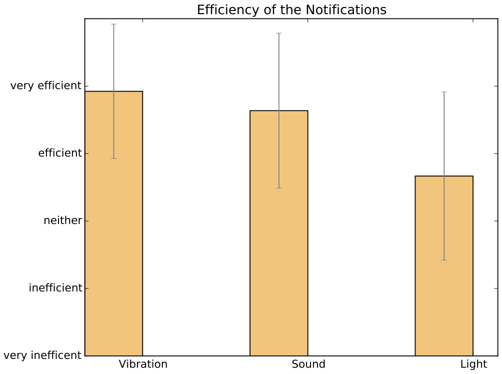

Figure 9: Answers of the questions *How efficient do you think this notification is?*

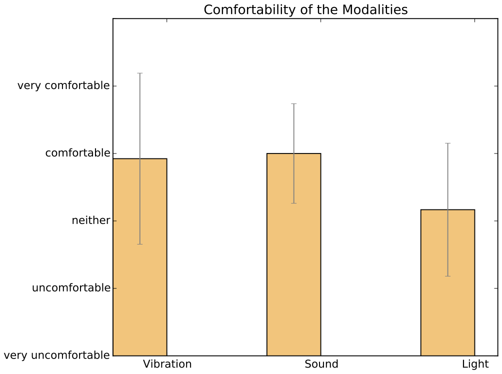

Figure 10: Answers of the questions *How comfortable did you perceive this notification?*

We asked the participants how efficient they judged the perceived notification on a five-point scale, ranging from *(1) very inefficient* to *(5) very efficient* (see Figure 9). The light channel was judged as the least efficient with an average of 3.67 (*SD=1.24*), followed by sound with an average of 4.64 (*SD=1.14*). Vibration was rated as most efficient with an average of 4.92 (*SD=0.99*).

When asking how comfortable the participants perceived the notification on a five-point scale with *(1) very uncomfortable* and *(5) very comfortable*, sound was perceived as most comfortable (*avg=4.0, (SD=0.73)*), followed by vibration (*avg=3.92 (SD=1.26)*), and light *(avg=3.27 (SD=0.98))*

In a final questionnaire we asked the participants how hard or easy they perceived both, the hard route and the easy route (see Figure 8). While all the participants perceived the easy route as either *very easy* or *easy*, seven participants perceived the hard route as *hard*, one as *easy* and four participants perceived it as *neither easy nor hard*. As the last task, we asked the participants to order the channels ascending by their priority. When scoring the channels with *three* for the first place, *two* for the second and *one* for the last place we could observe the following ordering: vibration (29), sound (26), light (11).

This feedback is also reflected by the comments the participants gave during and after the study. Most of the participants (10) stated, that the visual notification was the most distracting. They stated that this was due to the fact that when climbing during the light channel test, they felt the urge to always keep an eye on their wrist. One participant stated that he even chose his next hand hold so that he could keep the device in sight. Another participant stated that he felt forced to look at the device constantly which hindered him in focusing on the climbing itself. The fact that he missed some of the visual notifications was explained by the features of the selected routes. He reported that due to the slant of the route he needed to keep his feet in sight so that he could place them on small foot holds. This lead to not having the device in sight.

Two participants stated that audible notification were more easily perceivable. They claimed that one is more receptive for audible cues than tactile or visual ones.

After the final questionnaire we asked the participants if they could remember the positions where they received the notifications, which were always the same for each route and notification channel. Most of the participants stated that they could not recall all of the positions, but only the ones where they had the most struggle in climbing. Some participant claimed that they did not even notice that there were always three notifications and that these were always triggered at the same positions.

Observed Behavior

In addition to the subjective feedback, we also observed the participants during the experiments and did a video analysis post hoc. When testing the light channel, we could notice that some participants stopped during the climb to check if the wristband lit up during a move. Additionally, there was a large difference in response times for the light channel, since some participants responded very fast, while other participants reacted notably slower (see Figure 5). For all channels, we could observe, that most of the participants responded *after* they completed their move to the next hold and very seldomly during a move.

Another observation that surprised us happened during a participant's ascent of the hard route while testing the light channel. We could witness that he had the wristband in sight during the notifications but he was so focused that he did not perceive one of the three notifications. After climbing we asked him if he actually perceived the notification but forgot to report it, but he claimed that he, in fact, did not perceive the visual notification at all.

DISCUSSION

The results of both studies lead to promising results that can inform the future design of climbing technology. After discussing the results, we explore potential application areas to support climbing and address the validity of the perception study.

Online Survey

TODO: extend the Discussionsection accordingly and incorporate firstly the online survey more rigorous

Evaluation of the Light Condition

Although, in a variety of sports, watches with graphical displays are well established, visual output seems not to be suited for climbing, as we observed several disadvantages that do not outweigh its advantages. The wristband prototype created simple visual cues, which did not require the participant to read text or interpret graphics. However, the visual output of a plain green, yellow, or red light can be understood as a very simple form of a display. Despite its visual simplicity, the majority of the participants (10 out of 12) stated that they felt the urge to always keep the device in sight, which could explain the similarity in response time to the other notification channels, since they were explicitly informed before each climb that they will receive visual cues. The same group of participants also reported a decrease of their climbing performance as they felt distracted by the need to constantly watch their wrist, even in periods when there was no notification.

These observations stay in accordance with objective measures we gathered: light was the slowest channel with an average response time that was 1.2 times higher compared to sound and vibration, during the hard climb (see Figure 5). In the easy as well as in the hard climb, the average response times and the standard deviation of the *light* channel is notably higher for both, *vibration* and *sound*. Although there was no significant difference, we still think that this is an important finding, which is strongly reinforced by the subjective user feedback. The high standard deviation can be explained by personal strategies of the participants that were revealed by the subjective comments and observations. They either periodically stopped their primary task (climbing) and checked the device, or only occasionally glanced at it.

Furthermore, $78,57\%$ (11 out of 14) of complete notification misses occurred during the light condition. It was also subject of the highest standard deviation in terms of response time, which indicates that some climbers reported notification exceptionally slow, while others responded normally. If we regard the per move analysis in Figure 6 and 7 the light channel can be identified as a clear outlier, while the participants responded similarly to vibration and sound notifications.

Perceptual Differences of Routes

We analyzed the individual moves at which we triggered the notifications in the video footage. Figure 7 shows the average response for each moves with the corresponding channels. The hard route was physically demanding right from the start, after which the first notification was directly triggered. The grade of exhaustion and cognitive load also becomes evident in the average response times throughout all modalities. Compared to the other holds where notifications were triggered, the response times of the first hold in the hard route was considerably larger. One explanation for the higher standard deviation in the first as well as in the last move is that some climbers experienced this specific move as easy, for example, due to their reach, and others struggled at this specific part. At the last route, some of the climbers were already exhausted, which accounts for the higher standard deviation but similar response time. This explanation is in line with the video recording of the individual climbs. No climber struggled at the middle part of the route which lead to a small standard deviation and smaller response times compared to the starting move in all channels. The individual moves of the easy route can be explained analogously and also stay in accordance to the observation we made in the video (see Figure 6). It is possible that a low standard deviation and low response time are an indication for a move that was perceived as easy by all climbers and vice versa. When comparing the average response times of the easy and hard route, we noted that the climbers response time was notably slower for the hard route in the vibration and light channel whereas there was only a negligible difference for the sound channel. The error rates and the number of missed notifications in the hard route imply that notifications are more difficult to perceive towards the upper limit of the climber's difficulty spectrum (see Figure 5).

Evaluating the Performance of Vibration and Sound

When looking at the ease of perception in Figure 8, it can be observed that both, vibration and sound outperform the light channel. This also applies to the subjectively assessed efficiency and comfortability of the channels. Both channels, vibration and sound were ranked between very high and high for all three categories (*ease of perception, comfortability*, and *efficiency*). This is also reflected in the evaluation of the final questionnaire where both channels are close to each other on the first (vibration) and second (sound) rank.

However, the audio channel outperformed the vibration channel in terms of the average the response time. This is due to the fact that this is the only channel in which only a negligible performance difference could be observed in terms of response time between the hard and the easy route. Moreover, the participants subjectively rated sound as being the most comfortable of all channels (see Figure 10). For climbing outdoors, the pair of wireless bone conducting headphones could also be integrated into a climbing helmet.

We did not consider Google Glass as an output methodology as something attached to the forehead could lead to severe injuries in case of a fall. Even though we found the light channel to be less suited when attached to the wrist, it might still be useful when it is located on the top part of a helmet where it could act as a cue in the peripheral view.

The technology we used for audio output, the bone conducting headphones, is well suited for being integrated into a climbing helmet. Also, it provides eyes-free notifications while climbing, which has shown to be important as it also creates less distraction. For the visual cues, the majority of the participants reported to feel the need to constantly watch and observe the armband, even if there were no incoming notifications.

Validity

TODO: Additionally we will add a short paragraph that addresses the problem of the validity of the study. As R2, R3 and R5 point out the study has limitations that need to be discussed.

Application Scenarios

Real time on-body notifications in climbing could be used in a variety of situations and systems. We identified two main areas: (1) skill assessment and technique monitoring, and (2) climbing assistance. The successful ascent of a route depends on both of these areas. A good climbing technique plays an important role in sports climbing. Examples for that are the efficient use of grip power, the placement of the climber's body's center of mass below the arms, and to keep the elbows unbent whenever possible, to save power.

Another important factor is an efficient flow of movements. It is good practice to leave hard parts of a route behind as fast as possible to find a more suitable position to rest the arms. This is only possible if the climber knows which hold to use next, if a placement of a foot could make her reach a hold which is seemingly far above her, or twist herself in a position which optimizes her center of mass.

An experienced climber or trainer can be of great help to assist the climber, but only if both are in immediate hearing distance. A notification system as described and tested above could either facilitate the communication with both parties, or in case of an autonomous climbing assistance system, be used as an output medium.

We think that each channel has its advantages and disadvantages for communicating different information. The results mentioned above suggest that visual notifications are not ideal for time-critical and immediate notifications. In contrast to that, a gauge that communicates to the climber how much power she has left would be an example of a good use of visual notifications. The climber could glance on the device every now and then to decide whether she should take a break to ensure that her muscles will not harden, so that she can continue to climb later in her climbing session. As opposed to the visual notifications, vibro-tactile or audible notifications could be used in an autonomous system to give the climber an immediate hint to stretch the arms again, if the systems detects a lasting contraction of the biceps.

CONCLUSION

In a preliminary online study, we determined the most appropriate body parts for wearables to trigger notifications during climbing. In general, the wrist was found to be most appropriate body part, at which we triggered light and vibro-tactile notifications.

The perceptional study revealed that both, audible and vibrotactile feedback are suited for ambient notifications during climbing. Overall, sound was rated slightly better than vibration. Further, in accordance with related work, our results indicate that light is inappropriate as a real-time notification channel during climbing (slowest response times, highest error rates, and the most missed notifications).

To conclude, we investigated the acceptance and appropriateness of wearables in climbing with their corresponding body parts. Using these insights we conducted perceptional study by triggering vibro-tactile, audible, and visual cues while climbing an easy route and a hard route, requiring high physical and cognitive load. We found that the most suited notification channel is sound, directly followed by vitro-tactile output. Light has been found to be inappropriate for the use in the sport of climbing.

In future, we plan to cooperate with a competitive climbing team. Training in a professional climbing team is very rigorous. This allows the study of the perception in different states of exhaustion and on a broad variety of difficulties in highly-controlled experimental conditions. Furthermore more varying levels of notifications could be tested, or even secondary tasks like solving a math problem. Finally, testing the output modalities in actual applications and not like in this study just with a wizard-of-oz type of setting would reveal the real-world applicability of applications mentioned in the discussion.

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