ClimbVis — Investigating In-situ Visualizations for Understanding Climbing Movements by Demonstration

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ABSTRACT
Rock climbing involves complex movements and therefore requires guidance when acquiring a new technique. The classic approach is mimicking the movements of a more experienced climber. However, the trainee has to remember every nuance of the climb, since the sequence of movements cannot be performed in parallel to the experienced climber. As a solution to this problem, we present a video recording and replay system for climbing. The replay component allows for different in-situ video feedback methods. We investigated the video feedback component of the system by studying two example visualization techniques, i.e. a life-sized in-place projection and a real-time third-person view of the climber, augmented by a video showing a successful ascent. The latter is presented to the user on both Google Glass and a projected display. The results indicate that a life-sized projection was perceived as easiest to follow, while most of the climbers had problems with the context switches between the augmented video and the climbing wall. These findings can aid in the design of assistance systems that teach complex movements.

Author Keywords
Climbing; sports technologies; augmented reality; projection; video feedback; expert modeling.

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Figure 1. The trainee sees himself from a third-person perspective and can use the augmented video stream of the experienced climber to adjust his body position.

INTRODUCTION
Climbing is a complex activity that is determined by a variety of physiological and anthropometric factors. Although rock climbing, especially indoor rock climbing, is a trending sport, learning basic climbing techniques is still a challenging task for beginners. This is especially true for bouldering, which is a variant of rock climbing that is done at low heights and without ropes but instead thick mats that prevent the climber from serious injuries in case of a sudden fall. Typically, bouldering gyms consist of artificial blocks or walls of various shapes on which climbing holds are mounted. The objective of the climber is to ascend the walls while using only a predefined set of holds (a *route* or *problem*) to grab and step on. Often these routes require the climber to use a certain set of climbing techniques to not only reach the top but also do this in a graceful and energy-efficient way.

The classic approach to understanding these techniques is applying them on a specific problem. Usually this is done in pairs of the trainee and a more experienced climber (instructor) demonstrating the route. As opposed to other sports

Scenario
Sarah and Paul meet up in a local climbing gym. Paul has just started climbing while Sarah is an experienced climber willing to show Paul some moves. They find an interesting climbing problem that Paul has some trouble with. To help explain the problem to Paul, they roll the camera projection unit in front of the bouldering wall and start the calibration process by pressing a button. A smartphone app remotely connects to the unit and controls the video recording function.
Paul starts the recording and Sarah demonstrates the ascent of the route. Now Paul can pick a visualization method which suits him and the problem the best. By following the movements of Sarah in the recording, Paul can more easily ascend the route.

which involve complex movements like martial arts or ballet, the trainee cannot mimic the instructor in parallel, since the instructor is using the climbing wall (i.e. the specific route) while demonstrating. This bears the disadvantage that the trainee has to remember every nuance of the movements, including how to shift her body weight, how to grab a certain hold, where to hook her foot, and the dynamics of a move, i.e. how to use the inertia that is building up throughout the ascent.

To overcome this issue, we propose a system for visualizing climbing movements in an indoor climbing gym. The system allows the trainee to see herself in parallel to the trainer's movements. This is accomplished by using a movable camera projection unit, as described in [25], filming both the trainee and instructor from behind during a climb. The resulting augmented real-time video footage can be presented to the trainee via different visualization methods: a Google Glass, a projected display, or a life-size in-place projection of the instructor on the climbing wall. We envision the use of the system as described in the scenario above.

All three methods were evaluated during a lab study with 12 participants who either have never climbed or are early beginners who have not engaged in climbing technique training before. The results showed that the life-size projection was the easiest to follow while most of the participants had problems switching context between the augmented third-person video and the climbing wall.

In this paper, we provide three main contributions: first, we propose a flexible system which uses a Kinect, a projector, and a Google Glass for instant climbing movement visualization for interactive climbing spaces. Second, we introduce three visualization methods for understanding climbing movements by demonstration. Finally, as a third contribution, we identified a number of issues that are critical for the design of in-situ video feedback methods. In order to address these issues, we suggest an in-situ hybrid video feedback approach.

RELATED WORK

Climbing is a sport that is determined by a variety of physiological and anthropometric factors. Mermier et al. [18] found that the variance in climbing performance can be mainly explained by a set of trainable variables and less by specific anthropometric characteristics. Lopera et al. [15] investigated the effect of indoor climbing on strength, endurance, and flexibility in novice climbers. Their study reveals that novice climbers quickly improve their climbing performance, but they do not significantly gain more muscular strength and endurance compared to experienced climbers. This indicates that improving climbing technique, over strength and stamina training, should be focused on when introducing climbing to beginners. In this work, we explore ways to assist novice climbers in this respect.

Video Feedback and Expert Modeling

In sports psychology and motor learning research, some work exists that investigates video feedback (e.g. soccer coaching [5, 6]) as well as expert modeling as training tools. In video feedback, positive as well as corrective feedback is given to the athlete based on video recordings of her performance. Conflicting studies on the efficiency of video feedback in sports training have been published: Studies on video feedback in golf [7] and tennis [26] found no significant differences compared to traditional feedback methods, while others presented promising findings that may inform the design of future video feedback systems (e.g. for soccer [5, 6] and ice hockey amateur coaching [19]). Expert modeling uses videos of an elite athlete that present the correct execution of a specific skill and show the performance to the trainee.

Some approaches aim to improve complex athletic performance by combining expert modeling with video feedback (e.g. [3, 20]). This approach enables the athlete to compare video recordings of her performance with videos of an elite athlete correctly executing the task. In this work, we go beyond existing video feedback and expert modeling techniques by applying an approach that provides in-situ feedback during rock climbing.

Augmented Movement Guidance

Performing the correct movement in sports is important to achieve a certain goal. When it comes to rehabilitation exercises or physiotherapy, it is even more crucial that the movement is executed correctly. There has been some research in the human-computer interaction (HCI) community that addresses this problem.

In *physio@home* [24], the authors developed a system for guided physiotherapy at home. For this, they used a high precision tracking system to track the user's limbs. A screen in front of them guided the user through different exercises while showing a mirrored live image of the user, augmented with visual guidance on how to move. In *SleeveAR* Sousa et al. [23] presented a system that gives real-time feedback for rehabilitation exercises by projecting guidance and performance feedback on the user's sleeve and the floor around her. Sodhi et al. [22] proposed *LightGuide*, a guidance system that projects guidance hints directly on the user's hands. In a user study, the authors could show that with their real-time guidance system, the participants could perform movements nearly 85% more accurat than when guided solely by a video recording. In line with prior research, we used augmentation on both the surrounding and body of the climber to guide her during the ascent via video feedback and expert modeling.

Human Computer Interaction and Sports

In [21] Sigrist et al. give a an extensive review about augmented visual, auditory, haptic and multimodal feedback in motor learning. They claim that especially for complex tasks, concurrent visual feedback has predominantly been reported to be effective. However, the performance gain which is build up in the acquisition phase is lost in retention test. This is explained by the *guidance effect* [1] which states that continuous feedback during a learning task builds up a dependency to the feedback. One example for video feedback for sports is the interactive video mirror [8], a training system for martial arts. Large displays enable the athlete to review her performance with a mirror metaphor that extends the capabilities of a real mirror (e.g. spin kicks). Super Mirror is a similar approach for ballet dancers [16]. The Super Mirror uses the Kinect to analyze the dancer's motions and augments the dancer in the video replay with the correct poses. Similar to that, *YouMove* by Anderson et al. [2] provides the user with a large scale augmented reality mirror with graphic overlays for guidance and feedback.

In climbing, augmentation has been envisioned to teach climbing movements [10, 25] and to collaboratively explore climbing problems [4]. With *The Augmented Climbing Wall* Kajastila et al. [10] presented a climbing installation which projected interactive climbing games on a climbing wall. Wiehr et al. [25] introduced the *betaCube*, a movable, self-calibrating camera-projection unit which allowed for video recording of climbing moves and in-place, life-size replay directly on the climbing wall. In this work we investigated the effectiveness of continuous video feedback with one condition being life-size video feedback as in [25].

Wearables have been used to track performance of the user and offer a seamless way to provide notifications to her while climbing. Ladha et al. [14] used wrist-worn accelerometer sensors to assess the climbing performance of the user. In *ClimbSense* Kosmalla et al. [11] presented a wearable system for automatic climbing route recognition using wrist-worn inertial measurement units. Mencarini et al. [17] explored emotions in novice climbers. From interviews with beginner climbers, they conclude that haptic feedback can improve communication between climbing partners to manage negative emotions. Kosmalla et al. [12] investigated the perception of notifications through wearables in order to provide in-situ feedback while climbing. In a perception study with 12 participants in a climbing gym, they found that audible feedback is the most suitable notification channel while climbing, directly followed by vibro-tactile output. For wearables, visual feedback has been found to be inappropriate.

This work is inspired by research from sports psychology and motor learning and contributes to the design and evaluation of video feedback techniques in HCI and sports. In particular, the proposed approach goes beyond existing video feedback and expert modeling techniques by investigating an in-situ feedback mechanism while actually performing complex (climbing) movements.

Figure 2. During the ascent, the trainee sees himself from a third-person perspective through the Google Glass.

IN-SITU VIDEO FEEDBACK

The classic approach of presenting a particular climbing technique or a solution to a climbing problem is the demonstration of the sequence of movements by a more experienced climber ("instructor"). Followed by the demonstration, the trainee tries to mimic the instructor's movements. This has the disadvantage that the trainee has to remember every nuance of the instructor's ascent. To overcome this issue, we propose two different visualization techniques on three different mediums which allow the novice to climb a route while getting in-situ video feedback and expert modeling.

Life-Size Shadow View

We provide the trainee with a life-size projection (*Life-Size*) of the instructor, which is displayed in-place on the climbing wall with a very precise spatial matching from recording to projection. For this, we use the technique of the betaCube [25], a self-calibrating camera-projection unit. The unit comprises a Kinect v2, a 6000 lumen short-throw projector and a laptop. After an automatic calibration phase, it is possible to record a video and play it back at the exact same position where it was recorded, making it possible to project a detailed representation of the climber back onto the climbing wall.

Augmented Third-Person View

The trainee is provided with a video stream of herself from a third-person perspective that is augmented by a video recording of the experienced climber while ascending the route. Due to the fact that both video streams are recorded from the same camera and point of view, an exact match of both videos is guaranteed. For this method, we chose a projected display (*Display*) (see Figure 1) and Google Glass (*Glass*) (see Figure 2) as the display. Both videos were recorded in Full HD and streamed with a delay of approximately 250 ms. The video stream was cropped so that only climber and video of the expert were visible and scaled in respect to the replay medium (640x360 pixels for Google Glass and 1024x768 pixels for the projected display).

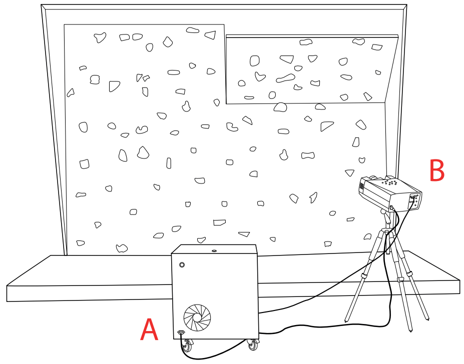

Figure 3. The setup of the experiment: (A) the betaCube camera projection unit consisting of a projector and a Kinect V2 camera, and (B) a second projector for local, high DPI projections. Projector B could be omitted when using a 4K projector.

The choice favored a projected display as opposed to a conventional flat screen display since the projected display can be placed on every position on the climbing wall without the danger of breaking or injuries. When choosing the head mounted display, we had the option of a) Epson BT 200 b) a Recon Jet, or c) Google Glass. Despite their binocular vision, we dismissed the Epson BT 200 augmented reality glasses because of their heaviness and the fact that they included a wired processing unit, which would have constrained the climber. While the Recon Jet, a monocular heads-up display including polarized lenses, has a smaller form factor, we found that the video quality with a resolution of 428x240 pixels was not sufficient to recognize details of both climbers on the wall. Our final decision went in favor of the Google Glass. The video displayed in the Google Glass was easier to see and provided the climber with a higher resolution video (640x360 pixels). Furthermore the Google Glass is lighter in weight than the other options.During the trainee's climb, only a part of the complete ascent of the instructor is displayed to the trainee, while looping continuously. As soon as the climber mimics the movements of the instructor, the next sequence is displayed. These sequences lasted 3.1 s in average ($SD = 1.3$ s).

STUDY

To assess the effectiveness and user experience of the proposed visual feedback methods, we ran a controlled laboratory experiment to compare the classical, in-person demonstration approach to the three in-situ visualizations of climbing techniques described above.

Participants

We recruited 12 participants (4 female, 8 male) by posting on university mailing lists and social networks. The only requirement was that the participant has neither climbed nor engaged in climbing technique training before. As an incentive, we offered 10 EUR for their participation. The ages ranged from 22 to 32 years (M = 26.5 years, SD = 3.6 years). The participants pursued 1 to 10 workouts per week ($M = 3,5$, $SD = 2.7$), including fitness (3), triathlon split training (2), mountain biking (1), riding (1), martial arts (1), and running (2). One participant was wearing prescription glasses throughout the experiment. Informed consent was obtained from all participants.

Conditions

In this study, we investigated four feedback methods: 1) video feedback through projection at life size (*Life-Size*, see Figure 8), 2) climbing with the augmented third-person view displayed in Google Glass (*Glass*, see Figure 2), 3) climbing with the augmented third-person view using a projected display on the climbing wall (*Display*, see Figure 1), and 4) the classical approach of getting a demonstration by an experienced climber as a baseline (*Human)*. For the third condition the position of the projected display was fixed and chosen so that the participant had a clear view on the projection (see Figures 6 to 9).

Study Setup

The study was conducted around a small climbing wall (4m in width, 3m in height) in our lab. Due to the short height of the climbing wall, a thick mat sufficed as protection in case of possible falls.

The setup consisted of (A) a camera projection unit (as in [25]), which was used for the life-size projection, capture of the video stream, and the highlighting of the climbing holds, and also (B) a second projector mounted on a tripod. The latter was used to display a higher resolution image at specific locations on the climbing wall. This projector could be omitted when using a projector with a higher-resolution (e.g. 4K). A sketch of the apparatus, including the climbing wall, can be seen in Figure 3.

Tasks

During the experiment, the participants were asked to climb four routes. Each route entailed a specific climbing technique which was demonstrated to the participants.

Flagging

is a static method to keep the climber near to the wall when using hands and feet on only one side (e.g. only the left or right side). When moving upward from this position, the opposite leg (in this case the right one) swings around the center of the body (a.k.a. barn door), leading to an unbalanced body position. To overcome this, the right leg is put in front of the left leg, pointing away from the body. This prevents the swinging of the whole body to the right (see Figure 4).

Outside Edge

is a power saving technique. While ascending, the goal is to rotate the hips so that the side of the body is parallel to the wall. This very stable position allows the climber to step up with her free leg (see Figure 7) .

The Rockover

is a technique for slabs or easy-angled routes. The climber is shifting her body over so it is directly above the hold that she is stepping onto. The movement goes to the side and not upwards (see Figure 5) .

Twistlock

The twistlock is usually used when trying to grab a hold on an overhanging part of the climbing wall. By rotating around the climber's body axis and simulataneously locking the grabbing arm, she can reach a high hold more easily (see Figure 6).

All climbing techniques were selected so that they are not overly complex but challenging enough for a novice to make room for improvements.

Training Task
Before climbing, the participant was given an introduction to the visualization used for the upcoming route. After that, the participant was asked to do a trial-run with the current visualization: she had to copy a sequence of movements which were displayed to her. The sequence started with the instructor standing on the ground grabbing two holds to his left and right. After touching a different hold with his left hand, he moved his left hand back to the initial hold and did the same with his right hand and then both feet, one after another. In the case of the *Human* condition, the experimenter demonstrated the sequence in person. The participant was asked to position herself on the same spot as the instructor and to copy each movement. Whenever she touched the right hold, the experimenter proceeded to the next movement by pressing a button on a remote control.

Procedure
After a brief introduction to the experiment, the participant was asked to sign an informed consent form, whereupon video and audio recording was started. Before beginning with the actual experiment, the participant was asked for her demographic data, whether she was wearing glasses, and what and how many sporting activities she does per week. Followed by that, four routes were climbed by the participant, each using a different visualization.

Usually in a climbing gym, colored holds are mounted on artificial climbing walls. Holds of the same color define a route and only the holds of one route are allowed to be touched or stepped on. In our study setup, only black and gray holds were mounted on the climbing wall. However, we highlighted the holds that belonged to the relevant task via the projector (see Figure 3).

After performing the training task as described above, the participant was asked to climb the route three times. (1) In the first try she was allowed to climb the route in any way she liked, except for the restriction to only use the holds that were highlighted. (2) In the second try, she was asked to copy the technique of the climber as closely as possible. Depending on the condition, she was shown one of the visualizations one step at a time. As soon as the participant progressed in the ascent, the visualization showed the subsequent step. (3) For the last trial, she was asked to repeat the technique, if possible.

This procedure was conducted for each of the four visualization methods on the four different routes. While the order of the visualizations were alternated in a latin-square, the order of the routes stayed the same. This resulted in a total of 4x3 trials per participant. The climbing session was followed by a semi structured interview. Overall, the study took around 45 min. per participant; they were compensated with 10 EUR each.

Semi-Structured Interviews
After the participants completed the trials, we conducted semi-structured interviews with them. The questions mainly concerned the different visualization techniques: a) How easy or hard did you perceive the matching from *Display* or *Glass* to the climbing wall? b) Could you imagine using one the visualizations in a climbing gym and if so, do you think that you could learn to climb better with one of them? c) Could you imagine that one of the visualizations could be an alternative to a human coach? d) Where do you see the advantages and disadvantages of the live feedback as opposed to demonstration via a human coach? e) *Final Conclusion*: Please rank the visualizations from best to worst and explain why.

Limitations
Since in the *Life-Size* condition we used a projection from behind the climber, it was possible that the participant occluded parts of the projection with her body. While the use of a transparent climbing wall would have allowed for back-projection, we used a camera projection unit which can be easily placed in front of any climbing or bouldering wall, allowing one to practice not only one specific technique, but also a specific movement on an arbitrary part of a climbing wall.

In the current version of the system, the next one of the video sequences is manually triggered as soon as the climber progresses in the ascent in a Wizard-of-Oz manner. Although we are using a Kinect, which suggests that tracking of the climber is easily possible, the climber almost disappears in the depth video stream when close to the wall. This results in faulty skeletons returned by the Kinect software (see also [9]). The solution to this problem is out of the scope of this paper.

RESULTS

Human Feedback vs. Video Feedback
The participants were asked to compare the classic approach using human feedback to video feedback in general.

In general, human feedback was acknowledged for its in-person communication possibilities*"You have someone who can give you tips in person and whom you can check back with"* (P7); *"With auditive instructions, I can focus on the climbing and do not have to look at other parts of the wall"* (P8). However, mimicking the demonstration was criticized since it requires the novice to recall the whole climbing sequence: *"The expert can explain it to you but you cannot directly repeat it without remembering what to do"* (P3); *"I need to remember the things and cannot do the movements at the same time as the instructor. With harder routes, that is probably challenging"* (P7); *"When [the instructor] did it, it is much better but only in small demonstrations. With very long routes, I would definitely forget what [she] did. So I could remember one or two steps. Otherwise I would have to look at the Google Glass or whatever was helping me"* (P5). P1 doubts that human feedback during the climb is effective: *"During the climb, the trainer can't give enough feedback. The trainee has to do a matching from speech to action"*.

Video feedback was positively valued for its in-situ, in-place, visual guidance: *"I see what needs to be done, so I don't have*

Figure 4. Flagging is a climbing technique that helps the climber to keep her balance when only having holds for one side of the body. The red rectangle depicts the fixed position of the projected display.

Figure 5. Rockover is a climbing technique in which the climber rocks onto a hold by moving sideways instead of upwards. The red rectangle depicts the fixed position of the projected display.

Figure 6. Twistlock. By rotating around the climber's body axis and simultaneously locking the grabbing arm, she can reach a high hold more easily. The red rectangle depicts the fixed position of the projected display.

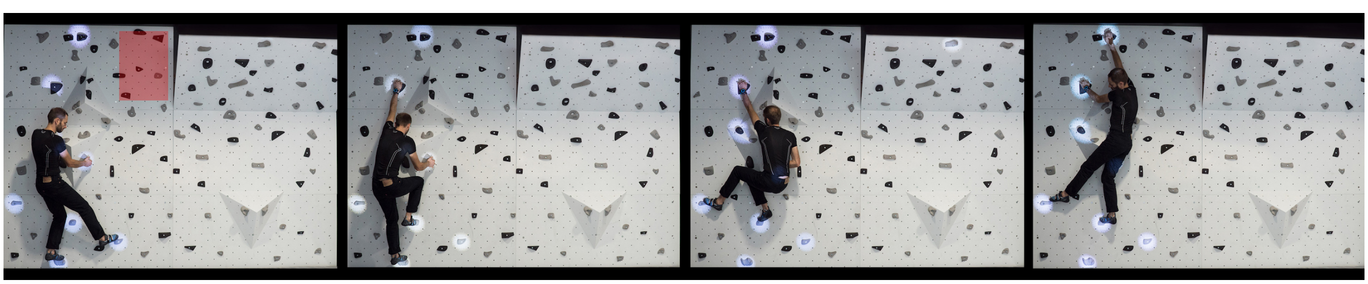

Figure 7. Outside Edge. The climber rotates the hips so that the hip opposite the pulling hand is turned into the wall. The red rectangle depicts the fixed position of the projected display.

Figure 8. A full-size video of the instructor is projected in-place on the climbing wall. The trainee has to mimic the body posture of the projection.

to understand what the trainer is saying" (P1); *"Seeing yourself is very helpful. It's the same thing when doing ballet in front of a mirror"* (P2); *"The video feedback is better because I understood faster what to do"* (P7); and for its independence from the availability of an instructor: *"You do not need an expert at hand"* (P3); *"I could do this whenever I wanted without an expert by hand"* (P4); *"You don't depend on an expert"* (P8). Social aspects also play a role *"Maybe some people would feel more comfortable with video feedback because they don't want to embarrass themselves in front of a trainer"* (P10); *"I can climb it my own pace and don't feel stressed because I am being watched"* (P12). A drawback of the video feedback was that some participants mentioned problems in correctly perceiving the demonstration of the expert: *"I need to understand the visualization. I see the visualization, I think to know what I need to do, but this might be totally wrong"* (P2); *"I think the video feedback is not suited for real novices but beginners who already have a rough understanding of how to move on the wall"* (P6). Another problem with the video feedback techniques was the quality of the visualization: *"Body rotations were hard to recognize because of missing contrast"* (P2); *"Missing depth perception"* (P4).

Video feedback

The participants were asked to comment on the video feedback techniques and the matching between the video and the real world.

Video Feedback Techniques

The participants were asked to vote for their favorite video feedback technique and justify their choice. Life-size was voted highest, directly followed by the Display condition, while Glass and Human condition placed a distant third (see Figure 9).

The Life-Size video feedback was appreciated because it was easy to understand and follow: *"Very easy to understand and copy."* (P4); *"Very good, it would be even better with back-projection"* (P5). On the other hand, the occlusion of the projection was seen as a problem by P2, P5, and P6.

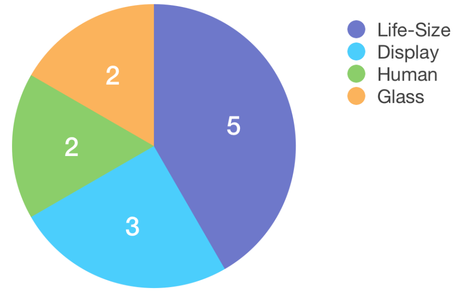

Figure 9. Votes for the Individual Visualizations

The Display condition was favored because of its constant position and unambiguity: *"I could recognize everything and it was unambiguous"* (P6); *"You can fit yourself in the image and it's alway there at the same spot"* (P4). However, P5 did not like that he had to look at different part of the wall to see the visualization.

P2 found that the use of the Glass display had the advantage of being inconspicuous, as opposed to projection, which could be seen by other climbers in his surroundings. P5 commended the fact that for the Glass he did not have to look around him but rather just switch focus onto the display of the Google Glass. However, P1 and P7 complained about the image quality and size of the video *"Display too small"* (P1); *"Too small, I could not recognize the holds"* (P7).

Matching

Another dimension of the semi-structured interview addressed the matching of video content and real-world objects, i.e. which is the next hold the participant should put her hand or foot on, or where to shift her center of mass.

In the Life-Size video feedback, the matching was perceived very well and unambiguously: *"The matching was very easy"* (P2); *"The Life-Size projection was the easiest because it's the same thing"* (P4); *"Matching was very fast and easy"* (P8); *"With the life-size projection, the danger of confusion was much lower"* (P9); *"The Life-Size projection was easier to understand"* (P11). Occlusion was identified as a common issue *"Some minor issues arose when occluding the projection with my body"* P2, *"It was hard to see holds that are close by"* P5, *"For the projection it was unambiguous, but sometimes it was hard to keep track of every movement that was displayed"* P6, while P3 describes occlusion as a feature *"I occluded the projection sometimes, but then I felt safe because I knew that I am in accordance with the expert"*.

Display was also rated very well with respect to matching and the most preferred technique by some participants, because the expert modeling was well perceivable *"The Display was the most comfortable since you could always see yourself in reference to the expert"* P6 and the display was located at a fixed position which allowed for easy focus switches *"Display was better than Google Glass because the image was larger and more in my field of view"* P8. One participant had problems with the matching in third-person view *"It was unfamiliar when seeing myself from behind. You have to orient *yourself in the video image and then you have to transfer that back to the wall to recognize which hold to grab"* P11.

In addition to the aforementioned problems with the Glass, it was also criticized regarding matching. Besides the general problem with image quality and size (P1: *"Extremely hard because the image was too small"* P6: *"I couldn't recognize details in the video"* P12: "It was hard because the image was blurry"), the main issue here was the context switches between wall and Glass *"Hard because I could not focus on the display of the Google Glass while looking in the direction of the wall"* (P2); *"Google Glass was the most challenging. Because I had to look at the Glass first, then at the wall, and then back to the Glass to verify my movements"* (P8); *"I had problems getting the focus right"* (P9); *"It was hard to concentrate on both the Google Glass and the climbing. Another problem was focusing."* P10.

Analysis of Video Recordings

In addition to the semi-structured interviews, we (two experienced climbers) visually analyzed the video recordings. We examined both the first and the third ascent of the participant. Both ascents were executed without any assistance, as opposed to the second ascent, which was performed with the help of one of the three visualizations or the human instructor. When comparing the two ascents, we assessed how well the participant adopted the technique demonstrated by the system or the human instructor respectively on a three point scale ranging from *(1) no improvement* to *(3) significant improvement*. We distinguished the three possible values as follows:

1. **no improvement** – no improvement could be observed
2. **slight improvement** – the participant showed some improvement, for example the right orientation or placement of the feet or the right sequence of arm movements
3. **significant improvement** – the participant fully applied the technique, sometimes with loss of neglectable detail (e.g. slight deviations of timing)

Afterwards, critical ascents were assessed by a third expert and discussed, in order to agree on a mutual rating. The improvements of the participants by technique and by visualization methods are depicted in the tables below.

Technique	Improvement
Flagging	M=2.0 (*SD=0.81*)
Outside Edge	M=1.41 (*SD= 0.64*)
The Rockover	M=2.20 (*SD=0.60*)
Twistlock	M=1.58 (*SD=0.64*)

Table 1. Improvements by Climbing Technique

Visualization	Improvement
Human	M= 2.09 (SD=0.90)
Life-Size	M=1.45 (SD=0.50)
Glass	M=1.58 (SD=0.76)
Display	M=2.00 (SD=0.58)

Table 2. Improvements by Visualization

When looking at the improvements by climbing technique, it can be seen that *The Rockover* has the highest *MIS* while *Outside Edge* scored the lowest. The improvements by visualization technique show that the techniques utilized with the *Human* condition have the highest MIS, closely followed by *Display*. For the *Life-Size* condition we could observe the lowest improvement.

DISCUSSION

Human Feedback vs. Video Feedback

The participants' feedback indicates that the proposed approach cannot replace the human instructor in its entirety. This is mostly due to the instructor's ability to recognize the mistakes of the novice and to give instant, correcting feedback. To integrate such a feature into an automated system, it would be necessary to recognize the postures of both the video-recorded instructor and the novice while simultaneously converting the deviations into instructions, whether visually as in [16] or as spoken instruction derived from the recognized pose (e.g. "Drop your right knee"). However, this goes beyond the scope of this work.

The participants confirmed our assumption that in-situ visual feedback obviates the need for remembering every nuance of the instructor demonstrating an ascent. An interesting point of view on social aspects was also given by the participants: the use of (automated) visual feedback allows the novice to train in solitude, which also might be a desired feature.

Video Feedback

The rating of the video feedback methods by the participants confirmed our assumption that the life-size projection was rated best since it was easy to understand and to follow. This is due to the exact match between the recording and in-place replay.

While displaying a third-person view of the climber in the Google Glass initially seemed promising, since the display is fixed in the field of view of the climber, the feedback of the participants proved us wrong. Many participants found the image quality of the Google Glass not good enough because they could not recognize holds that were close by.

Matching

When using the augmented third-person view, the matching between video and the real world is the largest problem. For the Google Glass as the display medium, some of the participants had a very hard time switching context and focus between the display and the climbing wall. These problems result in an uncomfortable and exhausting climbing experience. While future head-mounted displays might resolve the technical restrictions (higher-resolution screen, more powerful processing unit), we think that the context switch issue will persist.

Using the projected display as a medium seems to be a good alternative to the Google Glass. Despite the fact that the climber still has to focus on a different part of the climbing wall during the ascent, the technique had a high user acceptance. We think that this is due to the fixed position and larger size of the projected display.

Finally, the life-size projection beat the third-person view in terms of ease of perception and reproducibility. While there is an obvious occlusion problem, the participants favored the unambiguity of the in-place projection. The observations indicated that the life-size projection was most useful when guiding the climber to the next hold.

Improvements

To quantify the improvements of the participants, we calculated the mean of the improvement rating, which we defined as the *mean improvement score (MIS)*. As it can be seen in Table 1, *The Rockover* has the highest *MIS*. This could be due to the fact that this specific technique gives the most advantage during an ascent when applied correctly. The *Outside Edge* technique, however, is mostly used to conserve power; thus it's not as vital to use this technique for a successful ascent. When looking at the improvements by visualization technique (see Table 2), it can be seen that the *Human* condition has the highest MIS. This indicates that the help of a personal coach is still preferable when it comes to copying a certain climbing move, which is also in line with the results of the interviews. Although the participants rated the *Life-Size* projection the best, we could still observe a higher MIS for both third-person view visualizations (*Display* (MIS=2.0) and *Glass* (MIS=1.58)) than the *Life-Size* condition with a MIS of 1.45. Due to the low sample size, we could not show a significant difference between the different MIS; the results still suggest that from the implemented visualizations, the *Display* condition is beneficial for reconstructing climbing movements.

Hybrid Feedback

The main key finding of our study is that none of the proposed visualization techniques is alone an ideal solution to the problem. While displaying the third-person view inside Google Glass seemed to be a viable solution, the participants' feedback suggested that both the context switch and also the need to refocus continuously, proved that assumption wrong.

Another key finding was that the life-size projected video worked best for most of the users. However, a common problem was the blocking of the projection when standing in front of the wall. A context-sensitive hybrid approach could combine the benefits of the life-size projection as well as the projected display: During the approach of the user, the projected display is placed in a way so that it is not blocked by the climber. After the climber reached the wall, the visualization switches to the life-size projection. While the projected display bears the challenge of matching the augmented video to the real world, it could be a good alternative for the starting phase of the climb. At this point in time the load for the climber is still low, since she is not fully engaged in the climb yet because she is still standing on the ground.

During the climb, the participants stated that the life-size projection was the easiest to follow, since the matching problem is nonexistent. However, some participants mentioned that they lost track of their surroundings. An intelligent system could recognize these times of confusion and provide the climber again with the projected display, automatically adjusting its position to the user's field of view. This recognition could be achieved by observing the user's behavior, such as moving her head in a searching pattern, or by knowing the characteristics of the route, e.g. overhangs or volumes that stick out and might block the view of the climber. The advantages of both visual feedback methods could be combined while overcoming their disadvantages.

CONCLUSION AND FUTURE WORK

In this work, we investigated different feedback methods for demonstrating climbing techniques: We propose an augmented third-person view in which the climber sees herself with a video overlay of an experienced climber. This view is displayed on a Google Glass worn by the climber or a projected display on the climbing wall. Furthermore, we provide the novice with a full-size video of the instructor which is projected in-place on the climbing wall. These approaches give a solution to the problem that a novice cannot mimic the instructor's ascent in parallel since the instructor is using the wall while demonstrating.

To assess the advantages and disadvantages of each feedback method, we conducted a lab study with 12 participants which entailed a semi-structured interview after the tasks and a manual video analysis of the respective ascents. One of our key findings was that none of the visual feedback methods can provide an overall solution for in-situ video feedback by themselves. For this we proposed a hybrid approach which combines the benefits of both, the life-size projection and projected displays. The Google Glass was not seen as viable solution by any participant. In addition, we identified a number of issues that are critical for the design of in-situ video feedback, which can be applied to fields other than rock climbing.

For future work, it would be interesting to see how the system could be improved by adding a semantic layer which recognizes the detailed variations between the climbing style of the novices compared to the instructor. These variations could be converted to meaningful real-time instructions for the novice. In addition, the use of virtual reality could leverage the process of explaining a specific climbing problem. An avatar performing prerecorded movements could be observed in a virtual environment which reflects the actual climbing wall, similar to [13].

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