

# Remote Guidance for Machine Maintenance Supported by Physical LEDs and Virtual Reality

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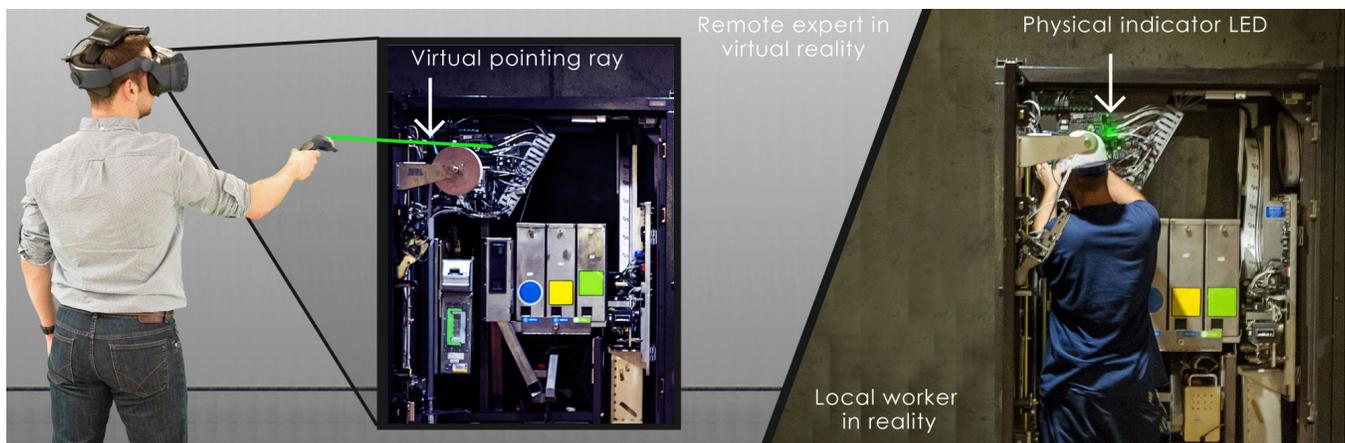
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**Figure 1: Collaboration between a remote expert in virtual reality (left) and a local worker in reality (right). The remote expert uses a virtual laser ray to indicate certain parts of the machine, which are then highlighted by LEDs (light emitting diodes) on the local worker's side. Parts of the image by Eric Ourcell [CC BY-NC 2.0] via Flickr [5].**

## ABSTRACT

Machines that are used in industry often require dedicated technicians to fix them in case of defects. This involves travel expenses and certain amount of time, both of which may be significantly reduced by installing small extensions on a machine as we describe in this paper. The goal is that an authorized local worker, guided by a remote expert, can fix

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the problem on the real machine himself. Our approach is to equip a machine with multiple inexpensive LEDs (light-emitting diodes) and a simple micro controller, which is connected to the internet, to remotely light up certain LEDs, that are close to machine parts of interest. The blinking of an LED can be induced on a virtual 3D model (digital twin) of the machine by a remote expert using a virtual reality application to draw the local worker's attention to certain areas. We conducted an initial user study on this concept with 36 participants and found significantly shorter completion times and less errors for our approach compared to only voice guidance with no visual LED feedback.

## CCS CONCEPTS

• **Human-centered computing** → **Collaborative interaction**; **Computer supported cooperative work**; *Empirical studies in collaborative and social computing*; Visualization systems and tools.

**KEYWORDS**

Collaboration, remote machine maintenance, virtual reality, light emitting diodes, LED, Industry 4.0

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**1 INTRODUCTION**

Many machines are complex and can only be repaired by specially trained experts. Although in the course of Industry 4.0 (*modern computer-assisted industry* or *smart factories*), with the help of sensors, (error) pattern recognition and artificial intelligence, the optimal maintenance time can be calculated, errors cannot be completely prevented. The failure of a machine can result in serious financial losses for a company and additional money and time must be spent for specially trained staff. While simple defects can often be fixed via email, telephone or video conference, more complex problems are usually difficult to solve remotely.

There has been a great interest in applying augmented reality (AR) and virtual reality (VR) to offline maintenance assistance and remote guidance tasks [6, 7, 10–13, 15, 19]. Many researchers confirm that AR and VR have various benefits. However, the technology does not yet seem to be mature enough to be used in daily routines in the same way we use smart phones, tablet computers or laptops today. It seems as it has not yet reached a satisfying trade-off between benefit, price and comfort. At this point, our idea comes into play. We condense down the concept of superimposing computer graphics over the real world to the simple illumination of low-cost LEDs on a physical object operated by an inexpensive micro controller. A remote expert sees the digital three-dimensional machine and can virtually select certain parts of it, which are then highlighted by corresponding blinking LEDs on the machine on the local worker's side. While the latter and the remote expert use verbal, bidirectional communication, the simple visual connection between them seems to facilitate and even significantly accelerate the work, as we describe in this paper.

We decided to keep the system simple to be able to focus on specific effects. Therefore, our system and study have limitations for a real life application. We did not use video transmission in the conducted experiment to focus on the exclusive effects of LED indication. Furthermore, we do not use body or hand tracking of the local worker. This implies that the remote expert can not intervene if the local worker is going to operate the machine in a wrong way. Only the changes of the machine are tracked and transmitted in real

time. In a real world scenario, this setup would be not advisable in regards to machine as well as worker safety reasons. Further safety extensions will be necessary.

To the knowledge of the authors, this is the first study on referencing from a VR application to reality through LEDs for machine maintenance. We discuss the advantages and limitations of this method and the conducted experiment, in which we collected quantitative and qualitative data on usability and performance regarding required time and errors. In this paper we provide the following contributions:

- the presentation of a new idea of interaction between remote collaborators,
- the discussion and evaluation of this idea based on an experiment.

**2 RELATED RESEARCH**

Initially, we want to clarify the distinction between AR and reality, since LED indication seems to lie between these two concepts. Our system does not superimpose computer generated images onto the real world, but rather makes use of fixed LEDs on a machine to create simple, computer-generated visual cues. Based on the definition of Milgram et al. [14] and Azuma [1], since no head-mounted display or tracking is used, the classification of indication through LEDs tends more towards reality than to AR. Therefore, our system can be classified as a VR-to-reality application. Nevertheless, because of the similarities between AR and our approach and also due to the lack of research in the field of VR-to-reality applications based on LED indication, we conducted our research also in the field of AR.

There has been an extensive line of research in the field of collaboration in AR and VR, but only a few researchers have focused on (remote) collaboration supported by LEDs.

In the following section, we list basic patterns of human behavior as well as research in the field of inter-personal communication. In the light of these findings, we mention related work and establish a connection to certain aspects of our system.

**Shared spaces and referencing**

Buxton coined the terms 'person space' and 'task space' [4] in the context of face-to-face communication and telepresence. The person space is where verbal and non-verbal cues such as speech and gestures are exchanged between the collaborators. The task space, on the other hand, describes the area in which they work together on a physical object such as an architectural model on a table or a machine in a room. Moreover, the task space is the area where an object is referenced. As Buxton described, remote collaboration often splits the task space into two disjunct spaces - resulting in a separated task space for each of the collaborators. Communicating via

video conference is a well-known example of that problem: working together and referencing to a physical object is difficult, since the shared 3D space of reference is missing. Even pointing with a finger can lead to misunderstandings caused by perspective errors.

Heiser et al. [9] conducted a study in which two collaborators had to generate an optimal rescue path for casualties on a campus map. The first test condition consisted of a natural, co-located and physical face-to-face communication. By contrast, the second condition included only a verbal communication channel in the same room in which both collaborators were separated by a curtain, so that they could effortlessly hear each other but did not have visual contact. A major result of the experiment was that pointing to a specific area had large effects on the nature and the outcome of the collaboration. Consequently, the face-to-face condition was significantly faster and yielded better results.

### General remote collaboration in VR and AR

VR and AR have been proven to alleviate the above mentioned problem of referencing to an object, because they allow the sharing of a common task space [2]. Various studies on remote collaboration have confirmed the positive effects of AR and VR with regard to time, errors and perceived mutual understanding, also called 'common ground' [17] (e.g.: [11, 12]). Also, some companies started to offer specialized AR and VR products for remote collaboration with a focus on industry use cases [6, 15, 19, 22].

Our approach takes up the idea of a shared task space. A reference between the virtual and the physical object can be visually transmitted by means of illuminating LEDs. Furthermore, information of the object (the machine) can be transmitted from physical space to virtual environment to render certain states of the digital twin such as the status of a valve, the temperature of specific items, the current wear of machine parts and similar collected data. This can also be used to give direct visual feedback regarding the local worker's current progress.

Lanir et al. [13] and Tait et al. [21] showed that offering an independent control of the scenario view to the remote expert supports remote collaborative work. This is mainly because collaborative systems for maintenance often utilize a camera being worn by the local expert. An often shaky image and the need for explicit and time-consuming verbal instructions for guiding the view of the camera can make collaborative tasks cumbersome. In our approach, offering the remote expert a 3D-rendered digital twin of the object, allows for free movement around it.

### Remote Machine Maintenance

A system related to ours is the *TeleAdvisor* by Gurevich et al. [7]. They developed a remote-controlled robot with wheels

that carries a camera and a projector on a movable arm. The remote expert sees the camera image, can remotely adjust the position of the robot and his arm by using a desktop PC and is able to project drawings and visual cues onto a surface by means of the projector. While we do not use a robot, the projection-based solution and a view that is controlled by the remote user have conceptual similarities with our approach. A major difference between this system and ours is that the former does not collect the internal data of the machine itself.

Sangregorio et al. [20] introduced an integrated system for supporting remote maintenance, which collects the data of a machine and transmits it to the remote expert. It used smart phones or laptops for visualization but did not utilize AR or VR.

Bottecchia et al. [3] created a maintenance system with self-made AR glasses and facilitated remote maintenance via the internet on a helicopter turboshaft engine. Furthermore, Oda et al. [16] used so called "virtual replicas" to communicate between VR and reality. Virtual replicas are tracked machine parts that exist physically and are rendered accordingly at the correct position in VR in relation to the machine. This allows direct visual feedback from the local worker to the remote expert and is similar to our work, since we render the corresponding position of rotary encoders and switches.

## 3 SYSTEM

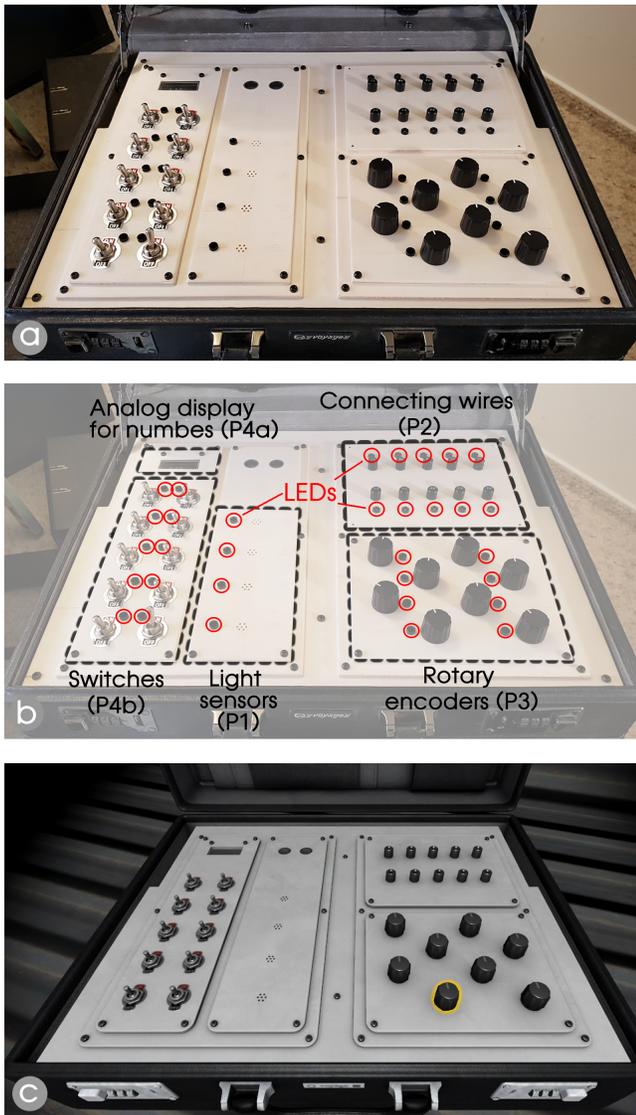
The system consist of a workplace in reality – the physical machine on the side of the local worker – and a VR workplace for the remote expert with a digital twin of the machine. The reason for using VR instead of a 2D desktop system is that way finding, navigation and three-dimensional understanding in VR is evidently easier and faster, as Pausch et al. [18] and Ware et al. [24] reported. Our current machine is rather small, however, the impact and benefit of VR will potentially increase on larger system.

The system for the experiment was developed having the creation of an escape game in mind, as *Gamification* has been already proven to be an effective motivation factor, as several studies have confirmed [8]. Since time is an important factor in our experiment, we assume that playing against time within an escape game leads to more constant results, because every participant tries to be as fast as possible. If another scenario were chosen, participants might engage in playful exploration of the environment instead of being focused on the actual task of the experiment.

The source code and building instructions for the system can be downloaded here: <http://git.preu.nrw:3000/hendrik/Bachelorarbeit/releases>

### Local worker side – the physical machine

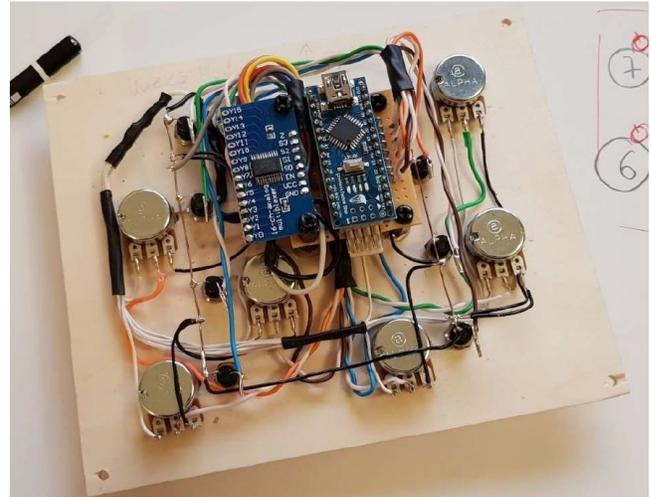
To represent a decent machine, a control panel with 32 interaction items, such as switches and encoders, was developed



**Figure 2:** a) 32 control items in a suitcase represent the machine b) 32 LEDs (one next to each item) are used for indication (red circles) c) The panel is shown to the remote expert in VR who selects a rotary encoder (yellow glow), which then activates the corresponding LED in the physical suitcase.

and placed into a suitcase, as Figure 2a shows. The dimensions of the control panel are 430 mm by 330 mm. The suitcase itself is part of the escape game story and was inspired by the game ‘Keep Talking and Nobody Explodes’ [23]. Each interaction item has one corresponding LED next to it, which is highlighted with red circles in Figure 2b. Additionally a display for numbers was built in the suitcase (top left corner) with LED backlight illumination. Each item is connected to one of six Arduino Nano micro controllers in the suitcase. These communicate through an I2C bus and transmit the

status data of each item and LED via Bluetooth to a Unity 3D application, which represents the VR workplace. Figure 3 shows the wiring of the rotary encoders and the Arduino Nano responsible for transmitting the state of the encoders as shown from the top side in Figure 2b on panel 3.



**Figure 3:** The back of Panel P3 (Figure 2). The states of the items and the LEDs of each panel are processed and controlled by Arduino Nano micro controllers.

### Remote expert side – the virtual machine

A Unity 3D application renders the digital twin of the suitcase, which can be seen in Figure 2c, for the remote expert. Furthermore, the states of each item in the suitcase, transmitted by the Arduino micro controllers, can also be rendered in real time to obtain direct visual feedback of the local worker’s progress. The physical LEDs can be turned on with a virtual pointing ray attached to the HTC Vive controller. The suitcase is scaled up by a factor of 3, whereby the actual size of the control panel in VR is 1320 mm by 990 mm. We observed that a larger virtual machine leads to more accurate referencing of the user.

## 4 EXPERIMENT

We conducted an experiment to evaluate our approach. Before the main experiment, we conducted a pilot study with three dyads to improve the procedure and ensure that every participant solely receives necessary information. Only the main experiment is reported below.

### Participants

18 dyads, 36 persons overall participated in the experiment (15 females and 21 males, ages 22 – 67 years, M = 35.9 years). The group of participants comprised students and members

of the local department of computer sciences (17 persons) as well as employees of two companies that are specialized on computer generated special effects and digital content creation (19 persons). Their experience level of VR and AR was rated on a 6-point Likert scale. 6-point was chosen to obtain at least a tendency. A summary of the collected data is visualized in Figure 5. The average time per dyad, including post questionnaires and debriefing, was 35 minutes.

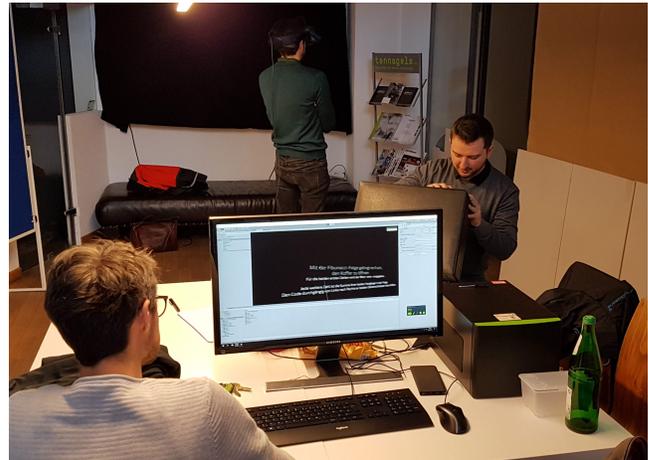
### Material

As illustrated in Figure 4, the participants who represented the remote expert, wore an head-mounted display (HTC Vive Pro) and use HTC Vive controllers for pointing. Those who represented the local worker, were instructed to sit in front of the suitcase, faced away from the remote expert. The dyads were co-located and sitting back to back in the same room. That way, they could not see – but easily hear – each other. We decided to emulate the remote connection (similar to Heiser et al.[9]) because it was an acceptable trade-off between possible problems and connection losses of the digital-verbal communication channel (which we did not want to track), the possibility to run the experiment with one test coordinator who observes the test criteria and the probably small impact of a real remote connection on this experiment, since there was no possibility to communicate in other ways than by means of the designated channels (Vive covers the face). The PC attached to the HTC Vive Pro included an Intel Core i7 4770K CPU, 16GB RAM and an Nvidia GTX 1070. The application had been created with Unity 3D version 2018.3.2f1 and ran throughout the experiment with 90fps. Times were recorded using the Unity application and, therefore, the sampling rate was 11.1 ms (90 frames per second).

### Method

The test conductor introduced the participants with a structured procedure ensure that every dyad received the same information in the same order. They were told about collaboration between VR and reality, why it could be useful and that the experiment focuses on recording the time and the errors that are made during the test. Errors were misunderstandings that resulted in a wrong operation of the instruments. It was randomly decided (within the Unity application via a random number generator) who was the remote expert and the local worker and which condition of the experiment was conducted – ‘with LED-indication’ or ‘without LED-indication’. The test was built as a between-groups design meaning that a dyad and also each person was only allowed to participated once to avoid biased results.

The HTC Vive Pro was adjusted (regarding interpupillary distance and to ensure a sharp image) and the test conductor made sure the controls for pointing and selecting were



**Figure 4: Experiment setup: The test conductor in front of the monitor observes the test. The local worker works with the suitcase while sitting. The remote expert wears an HTC Vive Pro and sees the digital twin of the suitcase.**

understood. At the beginning of the test, instructions were shown to the remote expert. They were placed as text on a large virtual info panel 1.5 m above the ground. Whenever a task was completed, the info panel of the remote expert was updated with new instructions.

The first task (Task A) was to open the 6-number combination lock of the suitcase by solving a simple numeric puzzle. During this task, no LEDs or indication were involved yet to provide a familiarization phase for the experimental setup.

The second task (Task B/Panel P1) was the first LED-indication task. It was composed of placing a flashlight onto the correct of four light sensors (panel P1 in Figure 2b).

The second referencing task consisted of informing the local worker about the correct colors and jacks of 3 colored cables (Task C/Panel P2). While the remote expert saw the correct wiring in his application, the cables on the local worker’s side were initially in a bag in the upper part of the suitcase and were easy to be spotted by the local worker. In sum six pointing indications were needed and wrong connections were counted as errors.

In the third referencing task, five rotary encoders needed to be rotated to certain angles (Task D / Panel P3). For this purpose, the remote expert had to highlight the corresponding encoder and communicate the rotation that was indicated in the VR application. The physical rotation of the encoders was then transmitted into the VR application to allow the remote expert to verbally communicate corrections such as ‘lower’, ‘90 degrees’ or ‘three o’ clock’. An error was recorded when a wrong encoder was rotated, since three of them had to remain in their position.

The fourth referencing task was to communicate four numbers that were displayed in a sequence on a physical display in the suitcase (Task E/Panel P4a). This sequence served as the solution for the flip switch panel (panel P4b). Only the remote expert was able to see the numbering of the switches which were not organized in any way but randomized. According to the number sequence communicated by the worker, the expert had to highlight the corresponding switches and the worker then needed to operate them. This resulted in a visual feedback given in the VR application showing which switch was used. An error was recorded whenever a wrong one was chosen.

Finally, the last task (Task F) did not include any referencing and consisted of searching an object in the suitcase. Performing Task F finished the experiment and the game was over.

All errors and times for every task were written into a text file the Unity application. During the experiment, the test conductor counted how often deictic and explanatory expressions were communicated. At the end, a post questionnaire was handed to the participants.

In sum, 17 LEDs were used for referencing. The test condition ‘without LED indication’ did not use any LEDs and only verbal communication was possible.

**Results**

In Table 1, the test results 1 for the conditions ‘with LED indication’ and ‘without LED indication’. The list includes time, number of errors, questions and deictic as well as explanatory expressions. One data set of ‘with LED-indication’ was rejected because one of the participants admitted he had previous knowledge concerning the solutions of certain tasks.

An independent-samples t-test was conducted to compare the completion times for all referencing tasks (B, C, D, E) (significance level  $p = .05$ ). Moreover, these data were tested for homogeneity in variance using a Levene’s test and did not show any salience. A Shapiro-Wilk test did not indicate that the assumption of normality had been violated. A noticeable fact is that there is a significant difference between the times for the two conditions ‘with LED indication’ ( $M = 344$  s,  $SD = 90.3$ ) and ‘without LED indication’ ( $M = 493$  s,  $SD = 149$ ) conditions;  $t(15) = 2.44$ ,  $p = 0.028$ . These results suggest that LED indication does influence completion time.

Furthermore, we conducted a Mann-Whitney-U test on the number of errors, questions and deictic as well as explanatory expressions. As a result, we found a significant difference between the groups of errors but neither for questions and the two types of expressions nor number of questions. Further details are shown in Table 2.

The results of the post questionnaires are visualized in Figure 5.

**Table 1: Summary of the data collected during the experiment.  $\emptyset$  stands for the average.  $M'$  stands for the median. Each row represents the results of one dyad.**

Time overall	Time for referencing tasks	Errors	Questions	Deictic expr.	Explic. expr.
With LED indication					
451 s	348 s	2	7	6	21
534 s	246 s	1	7	4	30
522 s	362 s	0	6	7	21
722 s	349 s	0	1	6	13
586 s	386 s	2	16	14	48
828 s	473 s	0	13	2	24
720 s	405 s	0	9	1	47
257 s	186 s	0	10	4	31
$M'$ 560 s	356 s	0	8	5	27
$\emptyset$ 578 s	344 s	0.6	8.6	5.5	29.4
Without LED indication					
919 s	657 s	4	16	5	37
604 s	315 s	6	7	2	36
980 s	691 s	15	9	6	47
601 s	371 s	6	5	3	30
575 s	336 s	4	23	6	27
1226 s	638 s	4	30	10	48
871 s	580 s	3	11	1	45
757 s	455 s	6	4	1	18
969 s	392 s	1	7	1	50
$M'$ 871 s	455 s	4	9	3	37
$\emptyset$ 834 s	493 s	5.4	12.4	3.9	39.0

**Table 2: Results of Mann-Whitney-U test with critical value of 15 (significance level of .05)**

	Errors	Questions	Deictic expr.	Explica. expr.
U-value	2.50	35.0	33.5	18.0
p-value	.002	.96	.85	.21
Mean "With"	4.81	8.89	8.72	7.31
Mean "Without"	12.7	9.12	9.31	10.5
Significant?	yes	no	no	no

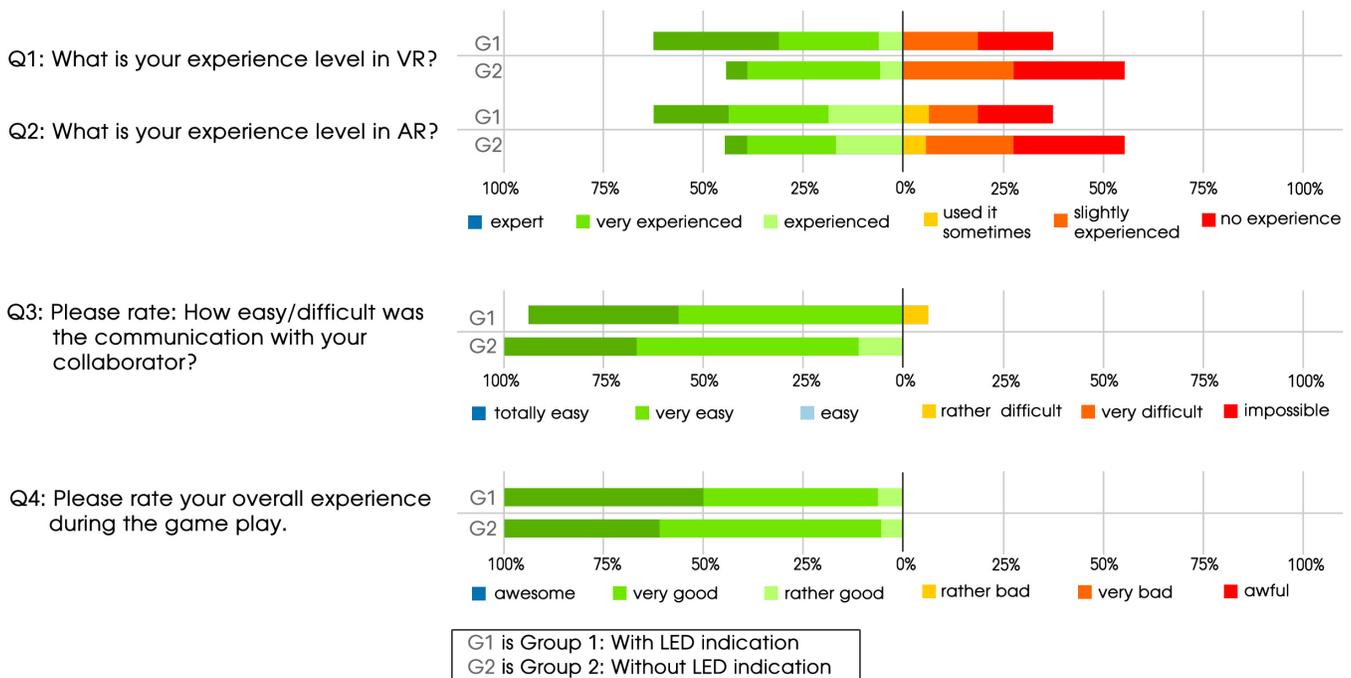


Figure 5: The results of the post questionnaire.

## 5 DISCUSSION

Group 1, ‘with LED indication’ seems to be more experienced with VR and AR technology which might have affected the results. Nevertheless, we found no significant difference between both groups.

The ratings for the question ‘How easy/difficult was the communication with your collaborator’ are surprisingly similar. We expected clearer differences between both groups and we assume that the simple structure of the control panel led to the similarities. If it were designed in a more complex way, the communication might be more difficult. Additionally, the ratings for ‘Please rate your overall experience during the game play’ only marginally differ from each other.

Although the number of questions, deictic and explanatory expressions was higher for the ‘without LED indication’ condition, we were not able to find a significant difference. However, we observed a different communication style between both groups, but we were not able to clearly classify it. The group ‘with LED indication’ was more determined, while the one ‘without LED indication’ was more exploratory.

## 6 CONCLUSION

In this paper we presented and evaluated the idea of creating a shared task space of a machine between two collaborators in VR and reality with the aid of indication by means of physical LEDs. As a first step towards exploring the possibilities

of the idea, an experiment was conducted and indicates a significant difference regarding completion time and number of errors between the two conditions ‘with LED indication’ and ‘without LED indication’, but we found no statistical difference for number of questions and deictic as well explanatory expressions. In the future, we want to further investigate the idea in the context of larger machines, since our test was conducted with a control panel of only 430 mm by 330 mm. Furthermore, extended concepts could manage the focus of the local worker through a chaser light effect with multiple LEDs in order to guide the worker to the intended position, that may be hidden behind other machine parts. Moreover, we want to investigate if a richer visual feedback for the remote expert can further accelerate the maintenance process. This could involve tracking the worker’s hand and visualizing it for the expert in VR to shorten the feedback loop and allow for intervening if the local worker is going to operate the machine in a wrong way.

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