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Improved interaction with collaborative robots – evaluation of event-specific haptic feedback in virtual reality

My Andersson[a], Anna Syberfeldt[a,*]

[a] *University of Skövde, Högskolevägen 3, Skövde, 541 45, Sweden*

Abstract

Industry 5.0 adopts a human-centric approach that views humans as a natural part of introducing new technology, such as collaborative robots. However, one of the main challenges in implementing collaborative robots is safety, including the sense of safety. Trust is also a primary challenge when establishing functional collaboration. Influencing factors includes experience and expertise, and research shows that Virtual Reality has the potential to perform such training. This research aims to investigate whether using virtual reality with appropriate feedback can be an effective platform for familiarization and training. In our experiment, we utilized haptic feedback from commercial Virtual Reality controllers to simulate physical interactions with collaborative robots. The experiment involved the participation of fifteen individuals. The results showed that participants regarded haptic feedback while moving as the most appropriate representation. This research aims to identify whether Virtual Reality with suitable feedback can serve as a familiarization and training platform.

Keywords: Collaborative robots; Human-Robot Collaboration; Virtual Reality; Haptic feedback; Industry 4.0; Industry 5.0

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1. Introduction

The next industrial transformation, Industry 5.0, is upcoming and with this paradigm shift comes a human-centric approach and an increased interest in adapting technology to human needs. Within Industry 5.0, humans are seen as a highly valuable and ever-evolving part of the process, that should be closely involved in designing and introducing new technologies, including robotic technology [1]. Collaborative robots are highly relevant to Industry 5.0 and the future [1]. Such robots have been used in manufacturing for many years [2]. When implementing collaborative robots there are many factors to consider from an industrial perspective [3]. Compared to traditional industrial robots, collaborative robots have been developed to work closely with humans and have smooth bodies without any intrusive edges [4]. This design feature is a response to one of the main challenges regarding the use of collaborative robots in industry,

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[*] Corresponding author. Tel.: +46 500-448577
E-mail address: anna.syberfeldt@his.se

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which is safety [5], [6], [7], [8]. A technical specification set out the required safety precautions to be considered when designing an application so that collaborative robots can work safely in close contact with humans [9].

Safety includes both physical safety (not being injured by the robot) [10], and the perceived subjective experience of *feeling* safe when interacting with the robot. It follows that for collaboration to be successful, humans must be willing to accept it. This willingness is affected by factors such as trust, previous experience with robots, and being included in the whole process from design to implementation [11]. Research has shown that trust is one of the key challenges to successfully implementing collaborative robots in industry [6], [12], [5]. References [11], [13] state that one key aspect influencing trust is previous experience, and in the same direction [14] mentions that uncertainty in an unfamiliar situation is a key component affecting trust in robots.

Familiarization with and training on collaborative robots does not necessarily require a physical robot [15]. Virtual Reality (VR) allows users to interact with virtual objects and experience the content presented, as well as other environments [16]. Research has demonstrated that VR offers a way to safely prepare and train future users for upcoming interactions with collaborative robots [6], [17], [18]. Reference [19] highlight that users are less affected by perceived risks in VR than in real situations. Reference [18] posits that VR is an affordable alternative to physical evaluation of future collaborative applications. It is, however, essential to provide realistic interactions and realistic object behavior in order to give a sense of realism [19]. To accomplish this, visual, audio, and vibration feedback have been used in virtual environments [20]. Standard VR controllers rely mainly on built-in vibration feedback, also known as haptic feedback [21], which can usually be adjusted for factors such as intensity, amplitude, and frequency.

As mentioned above, research has shown that trust is a prerequisite for successfully implementing collaborative robots in industry. Establishing trust and ensuring safety are two of the key challenges. Therefore, this research investigates whether VR with suitable feedback can serve as a familiarization and training platform to allow humans to gain broad-based knowledge and experience of collaborative robots rather than just being trained on a task-specific project in a virtual environment. It is hoped that this broader experience will increase trust in the long run. The particular experiment reported in this paper investigates whether haptic feedback from commercially available VR controllers is a potential candidate for representing two specific physical interactions with a collaborative robot. The VR controllers can provide varying haptic feedback with adjustable intensity, amplitude, and frequency.

1.1. Collaborative robots

Collaborative industrial robots have existed for many years. They work safely in close collaboration with humans, in what is referred to as human-robot collaboration [2]. Compared to traditional industrial robots, they are designed with smooth bodies without intrusive edges [4] and have adjustable attributes such as force and torque [22].

Research has concluded that collaborative robots can be used for manual assembly and material handling and processing [6], and that they can greatly improve ergonomics [23] as well as the quality of products and general efficiency [6]. Humans and robots are seen as complementing each other, with their respective strengths offsetting each other's weaknesses [24] [25] [26]. While humans contribute dexterity, intelligence, and adaptability, collaborative robots provide repeatability and accuracy. Combining the strengths of humans and collaborative robots improves efficiency, flexibility, and ergonomics [15], [23].

The four different levels of collaboration between a human and an unfenced rang from coexistence, where they share a working environment but no tasks, to collaboration, where they share workspace and tasks and interact simultaneously [2]. The ISO specifications further identify four collaborative working modes [9]:

- **Safety-rated monitored stop**: If a human or an object enters the robot's workspace, the robot should immediately halt.
- **Hand guiding**: A human controls the robot and its movements and can, by exerting some force, relocate the tool center point (TCP) of the robot to another desired position.
- **Speed and separation**: If a human or an object comes too close to the robot, reaching the minimum allowed distance between them, the robot should immediately halt. The robot can continue moving if the distance exceeds the minimum. The minimum distance depends on the speed of the robot and settings established by the operator in the safety features of the robot.
- **Power and force limiting**: If contact can arise between a human and the robot, the robot's allowed power and force is restricted according to the technical specifications.

1.2. Main challenges for collaborative robots

Safety is the most significant challenge when it comes to implementing collaborative robots in manufacturing [5, 6, 7, 8]. Both physical and mental aspects of safety are essential for successful implementation [10]. The closer the collaboration, the more attention must be paid to safety aspects during design and implementation [22].

Safety influences trust in new technology such as collaborative robots [10], [27], and trust is essential during the introduction and implementation of collaborative robots to achieve successful collaboration [12]. Definitions of trust, whether in the context of automation or collaborative robots, usually include aspects of safety [11], [28]. One key component contributing to a lack of trust in robots is uncertainty in an unfamiliar situation [14], which can be related to the main challenge, safety. It follows that a common influencing factor related to both models and frameworks of trust is previous experience [10], [11], [13], [29], [30]. However, such experience does not necessarily need to be physical when it comes to training and familiarization with collaborative robots [15].

1.3. Virtual Reality

VR is an environment in which all objects are virtual and the participant is devoted to the simulated environment [31]. References [17], [32] promote VR as a key to testing and evaluating a system beforehand to train future users in upcoming tasks, evaluate the system, and gather knowledge and opinions from more perspectives. Using VR simulations similar to those proposed by [17], [32] can also reduce errors in implementing the physical system, thus reducing the time from starting the installation until it is fully running, which can reduce costs in the long run. Previous studies, e.g. [33] have shown that virtual environments are suitable when it comes to training and familiarization with collaborative robots.

Reference [34] mentions that sensory feedback, that is, visual, auditory, or vibration feedback that our senses can perceive, is essential when using virtual environments for training purposes. Visual feedback in VR is feedback from the system received by the eyes and processed into information [35]. Vibration or haptic feedback in VR is defined by [21] as a type of feedback from the system to the user during events. Haptic feedback is said to have the potential to provide more realistic experience in a virtual environment [20], [21].

Reference [34] mentions that humans are biased toward visual feedback since humans collect most information by sight, even in a virtual environment. Two popular and common approaches to visual feedback in VR are object coloring and object halo [36]. Object coloring changes an object's color when a virtual hand approaches it, and object halo surrounds the object with a colored halo that increases in size when the virtual hand approaches it. Reference [36] recommends using them to grasp and release objects in VR.

2. Material and Method

The study investigates the effect of letting participants compare physical interactions with a collaborative robot to virtual interactions with a virtual collaborative robot using various forms of haptic feedback. The two actions investigated involved grasping and moving the robot around and then releasing the grip so that the robot suddenly stopped. Participants were exposed to different haptic feedback representations of their actions, in what are here referred to as blocks. First, they interacted with a physical collaborative robot, and then they interacted with a virtual representation of that robot in four different blocks. Questionnaires were presented inside the virtual environment, at the beginning, between each block, and at the end of the interaction. The experiment was conducted in 2022 during the 10th Swedish Production Symposium (SPS2022) arranged by the University of Skövde.

2.1. Experimental setup

Participants who met the inclusion criterion of being over 18 years old were given general information about the experiment, how it would proceed, and its aim. They were informed of their rights and asked to give oral consent to their participation.

After these preliminaries, the participants interacted with the physical robot. They used both hands to move it freely by holding the last joint, as in hand guiding. The robot was stopped from the teach pendant during the movements to simulate standstills so that the participants could experience the real inertia of the robot.

The virtual part of the experiment was initiated by putting on the VR headset, and controllers. The researcher instructed the participants to use the equipment inside the virtual environment at the beginning of the pre-questionnaire and in the training block, referred to as the No Vibration block. Thereafter the participants evaluated three blocks with different haptic feedback:

- **Movement** (M): Vibration only during movement. An even, low amplitude vibration was present as long as the participant gripped the robot with both hands. The vibration continued for one second after the participants released at least one of the grip buttons on the controllers.
- **Lost Control** (LC): Vibration only during standstill/breaks of the robot. An even, higher amplitude vibration occurred when grip was lost. The vibration continued for one second after the grip was lost and the participants released at least one of the grip buttons on the controllers.
- **Movement and Lost Control** (MLC): Vibration during movement and standstill/breaks of the robot. This block included both haptic variants. The low amplitude vibration during movement was directly exchanged for the higher amplitude during lost grip.

The first interaction in the virtual environment was a pre-questionnaire (Pre-Q). The purpose of the Pre-Q was to collect general background information about the participant such as gender, work role, previous experience, etc. Once this had been completed, the first block, No Vibration, was initiated. This block with no haptic feedback acted as a reference point and a training environment for the upcoming interactions. A questionnaire (Intro-Q) was filled out after the training session. It compared the physical interaction the participant had experienced to the virtual interaction without any added haptic. Thereafter the other three blocks with haptic feedback were presented in random order.

The experimental design as shown in Table 1 includes three out of six potential sequences of the three last blocks. Another questionnaire (Q), was given between every robot block containing haptic feedback. A post-questionnaire (Post-Q) took place at the end of the experiment. This was followed by a session of open dialog regarding their experience of the experiment in general.

Table 1. Experimental Design

Physical Interaction	Virtual Interaction									
Physical Robot interaction	Pre-Q	No Vibration	Intro-Q	LC	Q	MLC	Q	M	Q	Post-Q
Physical Robot interaction	Pre-Q	No Vibration	Intro-Q	M	Q	LC	Q	MLC	Q	Post-Q
Physical Robot interaction	Pre-Q	No Vibration	Intro-Q	MLC	Q	M	Q	LC	Q	Post-Q

2.2. Physical equipment

The experiment was set up in a conference environment. The hardware setup consisted of one collaborative robot, GoFa, CRB 15000 from ABB, positioned on a wagon close to the VR area (Figure 1), and one Oculus Quest 2 headset and controllers connected through Air Link to a laptop.

During the physical interaction, the researcher held the teach pendant to simulate robot standstills and control the emergency stop button. No tool was attached to the robot's end-effector to ensure safety during the physical interaction. The only buttons used on the controllers were the grip buttons designed and selected by the manufacturer to grip objects and one of the buttons on the right-hand controller labeled A to fill in the questionnaires.

The participants' view from the headset was observed by the researcher on a computer screen during interactions in the different blocks, both to understand how they interacted with the robot and to guide them if they had questions regarding the interaction.

2.3. Virtual world

The software used for the experiment was Unity 3D. Inside the environment, a representation of the GoFa robot was shown in a room on a cart (Figure 2). Both hands were required to grip the robot with the grab buttons on the

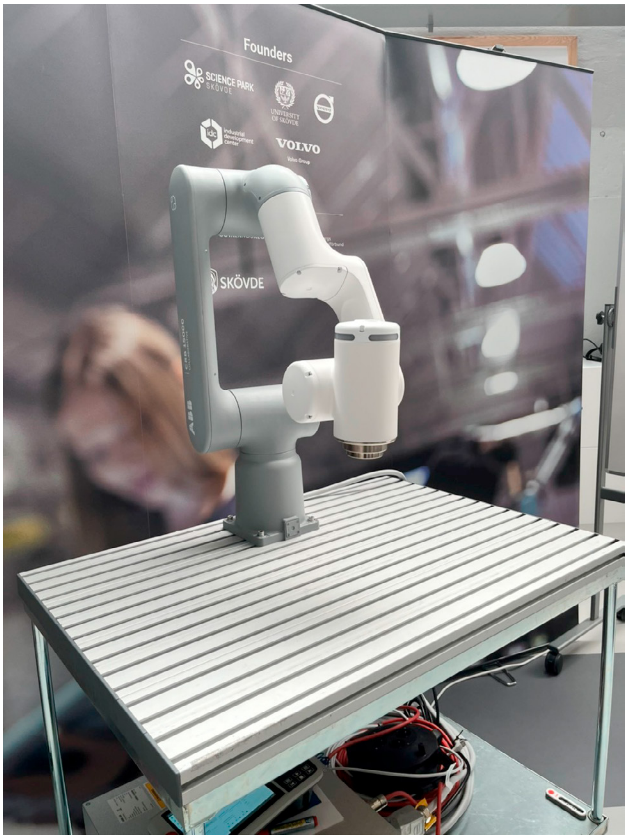

Fig. 1. The physical collaborative robot.

controllers. While the grab buttons were being held, the robot could be moved in the x, y, and z directions. Grip was lost if one or both controllers got too far from the TCP or from each other. The participants simulated this by separating the controllers and moving them faster than the robot could move during grip. Questionnaires for data collection were completed inside the virtual environment. They were all based on a toolkit established for Unity, as described in paper [37].

3. Results

There were fifteen participants, four female and eleven male. Three participants had previous experience working with collaborative robots and two of them had previous experience working with industrial robots. In total three participants had previous experience working with industrial robots. Seven had worked with or used VR before, two had experience in all three and eight had no previous experience in any of the three areas (Figure 3).

During the training session, the No Vibration block, the majority rated the robot and their interaction with it as feeling more real than unreal (Figure 4).

During the next three blocks, LC, M and MLC, the majority rated all three blocks as feeling more real than unreal, with the M block receiving the highest rating. In response to the second question regarded the enhanced feeling of working with the robots, the majority rated all the blocks as enhanced (Figure 5).

The vibration feedback in the M block was rated as the most suitable way to represent the real interaction. Figure 6 shows that No Vibration was rated as the least suitable way to represent the real interaction. LC and MLC were both also rejected as less suitable.

After the final block, participants had an opportunity to give feedback on the experiment. Some participants disliked the fact that the vibration continued for a second after they released the buttons when they lost the robot's grip. They

Fig. 2. View from Unity of the virtual environment.

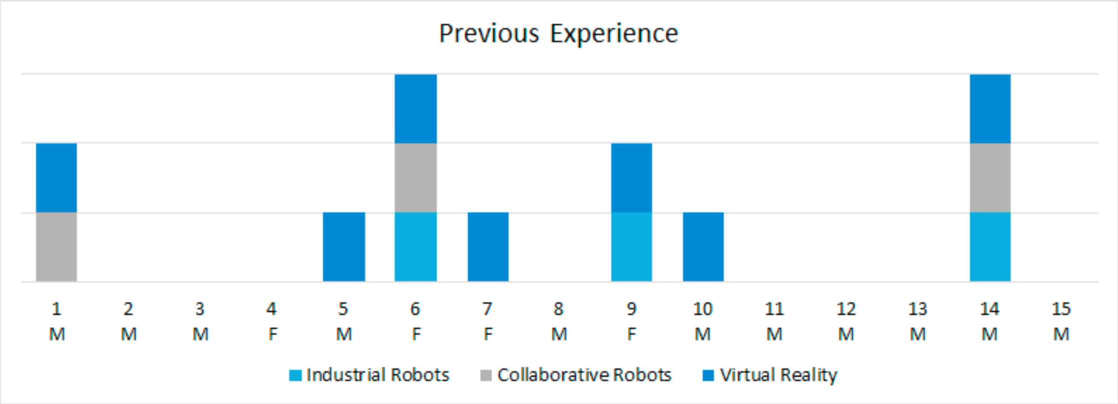

Fig. 3. Responses of the seven participants to the demographic questions who had previous experiences.

wanted the vibrations to stop immediately the buttons were released to make the interaction feel more natural. Some participants wanted to see improvements in the vibrations during Movement. The vibrations were constant, but these participants would have preferred some variation in the vibration pattern based on current speed or distance traveled. One comment that stood out was that there was really no need for vibration during Movement as the visual feedback was more than enough.

4. Discussion

Haptic feedback in VR and realistic interactions and behavior of objects in the virtual environment can establish a representative experience in VR where humans have the potential to influence development. There is no reason why companies, regardless of their size, cannot use commercially available VR equipment for familiarization and training purposes with collaborative robots. This approach offers a more affordable alternative to physical evaluation of workers, without any requirement for physical equipment and stagnant applications during training. It is thus important to create conditions to increase technical knowledge and trust in collaborative robots in the long run. The definition of trust used here is “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability” [11].

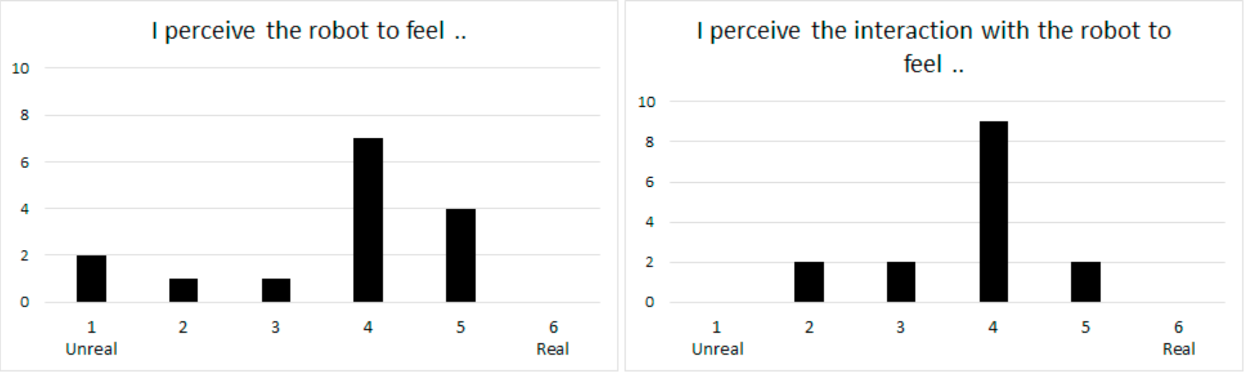

Fig. 4. Responses to the first two questions after training block Q1.

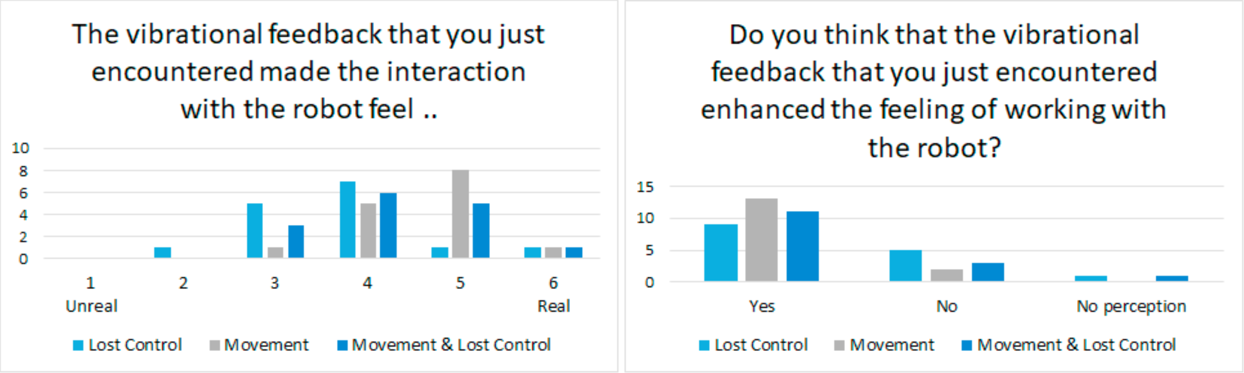

Fig. 5. Responses to the two questions following the blocks containing vibration feedback, Q2-Q4.

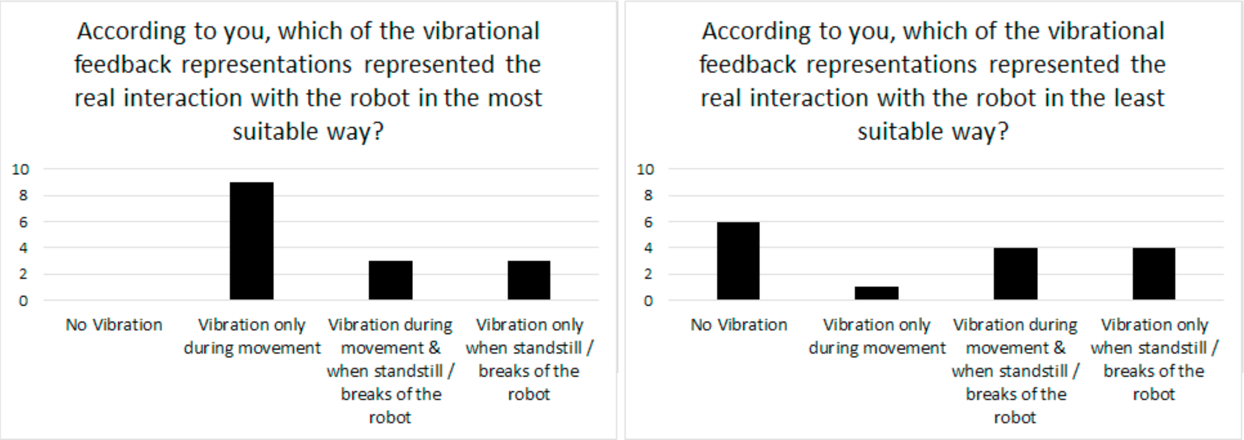

Fig. 6. Question and answers to the two last questions after all blocks, Post-Q.

Any experiment performed during a conference in an open environment has limitations. The participant's concentration will be affected by ambient sound and their awareness that others can see them interacting with the physical robot and wearing the headset and controllers and interacting in the virtual environment. Inclusion criteria for this study were limited to those over 18, and participating in the conference in some way. The limited number of participants and the convenient sampling make it impossible to generalize from the result.

It is also important to note that the majority of the participants rated all the interactions containing feedback in the virtual environment as more real than unreal, which might indicate a bias toward VR applications and an effect of the physical interaction and the No Vibration block they had previously encountered. The same pattern can be seen in the training block, No Vibration. However, some participants rated the robot as feeling unreal, far off the scale, compared to the other blocks where no one selected that option. The No Vibration block was deliberately chosen for the first encounter because it was assumed to be the least likely to be selected as the most suitable representation.

There were limitations in the virtual model. One that the participants mentioned was that the vibration did not stop immediately after the grip buttons were released. This aspect may have reduced the likelihood that a specific block would be selected as the most suitable representation of interaction. However, the effect appears to have been relatively small, as shown by the high number of participants who selected vibration during movement as the most suitable option. Another aspect to consider is the number of participants who selected two blocks, which included vibration during standstill, as the least representative.

The physical interaction with the robot was performed safely. The researcher focused on the ongoing interaction and held the teach pendant, ready to push the emergency button if something unexpected happened. There was never any need to use the emergency button. However, care was needed given the risk of collisions with physical objects if the work environment is limited and objects are nearby. During the experiment, no collisions with physical objects occurred during the virtual interaction. None of the participants stated that the virtual interaction made them nauseous (simulation sickness).

Two built-in functions of collaborative robots are the possibility of specifying the TCP speed and the degrees of joint rotation. The suggestion to map the vibration pattern to the robot's speed would serve the specific purpose of familiarizing and training future users of the robot's safety features. Knowledge and experience could be built up by allowing future users to familiarize themselves with the safety features in VR with haptic feedback to educate them about built-in safety features and train them on upcoming tasks with collaborative robots.

5. Conclusion

This was the first experiment in an investigation aimed at establishing a familiarization and training platform for future users of collaborative robots in VR. The goal is to provide broader experience of collaborative robots. It was found that participants favored the constant vibration feedback in the Movement block, but this finding cannot be generalized as the number of participants was small. To make the result more generalizable, the inclusion criteria should be more specific and there should be more participants. For this investigation, they should come from the Swedish manufacturing industry and be working with assembly, and thus potential future users of collaborative robots.

The literature identifies VR as a candidate to train future users on upcoming tasks with collaborative robots, for feedback variants in a virtual environment can enhance the feeling of attending to a situation in general. The literature also supports the use of visual feedback for impending events, such as a version of the object coloring used in this study. However, there is a need for more studies of interactions with collaborative robots using a broader scope of VR feedback to enhance the feeling of interacting with the robot. One potential reason for the lack of studies in this regard could be that all collaborative applications are more or less unique. The results of the current experiment should be viewed as guidance for future research. They point to the suitability of haptic feedback in VR for specific tasks shared by humans and robots.

Future research should identify whether familiarizing users with the built-in safety features of collaborative robots mapped to suitable feedback in VR can make users more open to learning by doing. Such openness could increase the efficiency with which joint tasks are carried out, and could draw on previous experience and expertise. In the long run, familiarization with the built-in safety features of collaborative robots with evaluated feedback can improve trust in these robots by increasing the factors influencing perceptions of safety, previous knowledge, and experience of VR. The next study will investigate the suitability of two vibration patterns during interaction with a virtual robot. One of the patterns will be mapped to the TCP speed, and the other will be a constant vibration during the robot's grasping. Future work also includes to investigate the combination of haptic and visual feedback in VR, to see if such combination can lead to even more efficient results.

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