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Virtual Fixtures in VR – Perceptual Overlays for Assisted Teleoperation, Teleprogramming and Learning

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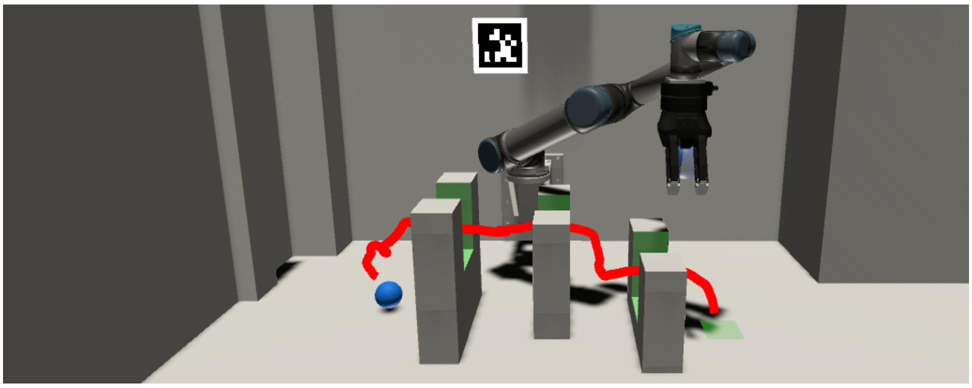

Figure 1: *The red line indicates a recorded trajectory of a single trial during the experiment, where the gripper is teleoperated to grasp the blue sphere on the left and to move it to the green goal zone on the right precisely and fast. In the experiment effects of visual and haptic assistance at difficult passages are examined.*

Abstract

Current advances in mixed reality (MR) technology achieves both, making the sensations more immersive and plausible, but also increase the utilization of these technologies in robotics. Their low-cost and the low effort to integrate such a system in complex facilities makes them interesting for industrial application. We present an efficient implementation of "virtual fixtures" [BR92] and the evaluation in a task of three different difficulties. Finally, it is discussed if the method is successfully implemented without real physical barriers and if human performance is effected in teleoperation or teleprogramming of industrial robots.

CCS Concepts

• ***Human-centered computing*** → ***Virtual reality;*** • ***Computer systems organization*** → ***External interfaces for robotics;***

1. Introduction

Building and using tools for enhancing and improving our capabilities is part of the human nature. In user interface (UI) design we specify interface metaphors in order to explain instantaneously how to interact with the UI. Several years of research during the coexistence of virtual reality (VR) and robotics demonstrated the benefits of combining them [Bur99, Tec15, Mac15, Mac]. Early human robot interaction (HRI) research of Louis B. Rosenberg introduced the ruler metaphor in combination with his major concept of virtual fixtures (VF) [BR92, BR93, Ros93]. To improve the operator's performance, he implemented a costly robot teleoperation system as a master-slave control system and presented images of the remote site to the operator meanwhile the movements of the operator were physically constraint in different ways. Current devices and systems within the *mixed reality continuum* [MK94] offer a nearly unlimited multitude of methods to control robots at different levels of autonomy [BFR14] The large increase in tracking and image quality of mixed reality devices effected the level of situation awareness (SA), presence and immersion positively and thus, makes it inevitable to think about new, even simpler ways to achieve better results or to change the application domain of already developed methods. Currently, low-cost VR devices and flexible, modular software systems like Unity3D and ROS are found in

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many publications of HRI UI design and settle down in industrial and private applications.

In this paper we examine the effects and utility of virtual fixtures without physical constraints in a low-cost setup involving the HTC Vive system for input and feedback. A user-study with within-subject design compares different aspects of user input during pick-and-place tasks of different levels of dimensionality. The results apply to user input for teleoperation, teleprogramming and learning methods. In the following *teleoperation* is referred to as realtime operation, *teleprogramming* as a method for predefining the execution of a following action and *learning* e.g. learning-by-demonstration for training behavioral models. In comparison to the former study of Rosenberg [BR92] we found the operators to be slower when fixtures are activated. Interestingly, operators seem to act more carefully than without these mechanisms when necessary.

2. Previous Work

Rosenberg started 1992 to publish on the topic of virtual fixtures with the desire to improve teleoperation methods [BR92, BR93, Ros93]. The fixtures were physical barriers, mounted on a fixture board, e.g. a table in front of the operator. The fixture board was not visible to the operator during operation. Instead, using a head-mounted vision system, the remote site with the actual robot was presented to the operator. The robotic task was to insert objects in holes of a task board. Rosenberg evaluated different design and patterns of fixtures at the task board and evaluated the performance. Rosenberg found fixtures to increase the task performance, especially the time to finish the task. Experiments also involved the combination with auditory signals. Rosenberg pointed out, that the way he implemented the fixtures is not necessarily the only way how virtual fixtures can be implemented and encouraged to try it in a different way. In 2008 Barros and Lindeman forecasted the utility of VR devices for robotics: "*The implementation of a mobile and easy deployable tracking system may trigger the use of trackers in the area of HRI. Once this is done, the robot community may benefit from the accumulated knowledge of the VR community on using this input device.*" [DBL09]. Recently, many publications combining Unity3D and ROS appeared [KSE*,MB15] HoloGrasp, a setup for co-located mixed reality human-robot interaction uses the Microsoft HoloLens to control a pick-and-place system in-situ [KSL*18]. Especially grasping tasks are of special interest in the field of mixed reality interaction with robots [KSC17]. Using an HTC Vive setup and a deep learning approach, virtual models of robots were taught by demonstration how to grasp a fish [DM17].

3. Implementation of Perceptual Overlays for Immersive Telerobotics

The system setup is implemented using Unity3D on a graphics workstation running Windows10. The robotic setup consists of a virtual model of a setup in one of our labs. For rendering in Unity we imported the planning model of the lab using an URDF parser from the Unity Asset Store. The inverse kinematics of the robot moving in realtime is based on published work of Starke et. al [SHMZ16] and causes the robot to produce plausible movements according to one tracked 6-DOF pose, represented by one Vive Controller as input device. The realistic virtual environment (VE) is presented to the user with an HTC Vive head-mounted display (HMD) using stereoscopic rendering.

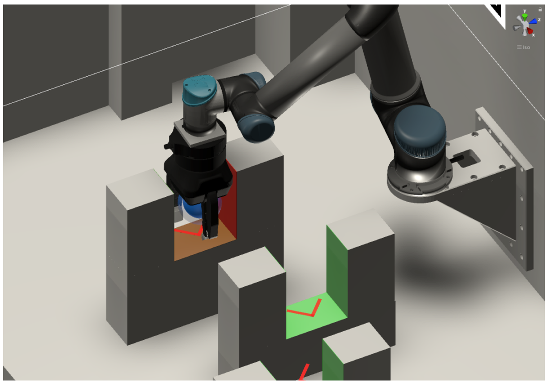

Figure 2: *Example of the visual implementation of a virtual fixture. The amount of red color indicates a close distance between the grasped object and the obstacle.*

According to Wickens' Multiple Resource Theory (MRT) Model [DP84] we implemented the virtual fixtures visually and haptic as multimodal feedback. The visual component causes a change of color of the delicate zones at the obstacles. According to our affordances of colors "green" marks a safe situation and "red" a possibly problematic situation. Using Unity's *lerp* function a transition between these two colors is generated and applied to the involved part of the obstacle (c.f. Figure 2). The reference points for calculating the distance between object and obstacle are calculated by a script attached to the obstacles. Raycasting technique is used to find the shortest distance between all surface points of the involved collider meshes. The haptic part of the feedback is directly triggered by collisions of either the meshes of the gripper or the mesh(es) of the grasped object. The intensity is adjusted using *TriggerHapticPulse* function of OpenVR with pulse durration of 3.5 ms per rendered frame. Thus, frequency is $\approx 90\,\text{Hz}$ and the ratio of active actuator is around 1/3.

In a pre-study continuous vibro-tactile feedback, as implemented for the color sweep, was found to distract the operators by letting them believe that a collision with an obstacle occurred. Following the results of the pre-study, the idea of comparing haptic vs. visual conditions was rejected. Thus, we decided to provide the operator with vibration feedback when the object or the gripper touches an obstacle, as expected by the participants of the study. The experiment setup, which is completely virtual, is transferable to robot control by adding a communication interface to ROS, an important robot middleware for academia and industry (c.f. [QCG*09, KSE*, KSL*18]). In this way the findings and implementation of this paper are applicable to real robot control. The experiment project is available at `https://github.com/denniskrupke/virtualFixturesExperiment`.

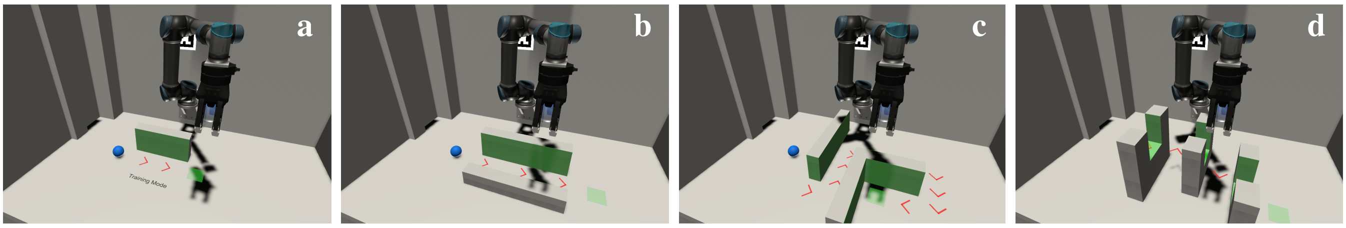

Figure 3: *Courses of different levels of difficulty. Difficulty is modeled by the number of Cartesian axes necessary to describe the resulting trajectories of the end effector. (a) Training course. (b) 1D course (C1). (c) 2D course (C2). (d) 3D course (C3).*

4. Evaluation of Multimodal Virtual Fixtures

4.1. Hypotheses

H1: Virtual fixtures increase the usability during teleoperation.
H2: Virtual fixtures effect the control precision of the operator.
H3: Virtual fixtures encourage operators to explore the workspace.

4.2. Questions

Q1: Are VFs applicable as an implementation without physical barriers.
Q2: Is there a difference between VF in realtime teleoperation and offline methods for teleprogramming or learning-by-demonstration?

4.3. Participants

We recruited 29 participants (7 female and 22 male, ages 20 to 32, $M = 24.25$). The participants were volunteering students of the local department of computer science. The ratio of female and male participants is representative for the members of our department and thus, represents the expected user group. If requested, the students obtained class credit for their participation. 16 of our participants had normal or corrected-to-normal vision and 11 of them wore glasses during the experiment. 1 participant wore lenses and 1 reported color blindness but had no issues with the given tasks. No other vision disorders have been reported. No disorder of equilibrium or motor disorders such as impaired hand-eye coordination was reported. 25 participants reported prior participation in experiments involving the HTC Vive. 4 participants attended the pre-study as well. Handedness was not relevant, due to the implementation, which allows either the left or the right hand for solving the task. The average time for the experiment including briefing and questionnaires was 40 minutes, the time spent with the HMD worn was about 20 minutes. The interpupillary distance (IPD) of each participant was measured and the HMD was adjusted accordingly in order to maximize the participants' precision of depth perception in VR.

4.4. Materials and Methods

The main device in the experiment was the HMD HTC Vive with its tracking system and one Vive controller. Participants were asked to stand in front of a virtual table and grasp a virtual model of the Robotiq 3-Finger Adaptive Gripper attached to a UR-5 robotic arm in order to control its posture by pressing the *grip button*. In this way the robotic manipulator follows directly the 4 degrees-of-freedom (DoF) (3 translational, 1 rotational around the vertical axis) pose of the Vive controller. The controller model is rendered with transparent shader. Additionally, pressing the trigger button closes the gripper and opens it on release. In this way the operator is capable of performing the virtual task of grasping the target object, moving it through the course and finally placing it on the goal zone. To ensure an immersive experience during the experiment, the virtual scene was stereoscopically rendered by the Unity3D engine (v. 2018.2.0f2) on a powerful gaming computer setup with Windows10, Intel Core i7-6900K, 2x Geforce 1080, 16 GB RAM running optimized code in order to achieve framerates above 90 Hz display refresh rate of the HMD.

In the experiment, we used a within-subject repeated measures 2 (noVF vs. VF) $\times$ 3 (courses) $\times$ 6 (repetitions) design. Before the experiment, all participants filled out an informed consent form and received written instructions how to perform the task. Participants had to perform training trials for each condition; one without virtual fixtures ("noVF") and one with fixtures enabled ("VF"). Furthermore, they filled out a demographic questionnaire before the experiment and after each condition the following questionnaires: NASA Task-Load Index (TLX) [HS88], Simple Usability Scale (SUS-PQ) [B*96], Slater-Usoh-Steed (SUS) [UCAS00], Situation Awareness Rating Technique (SART) [Tay90] and AttrakDiff2 [HBK03].

5. Results

In this section, we summarize the results and statistical analyses of our experiment. All statistical tests calculating p-values were done at the 5% significance level. Due to the growing importance of Bayes factor tests (c.f. [WLM*18]), we present Bayes factors in addition to the p-values.

5.1. Qualitative Analysis

In the following, the results from several standard questionnaires are presented. Figure 4 and Figure 5 summarize the qualitative scores.

AttrakDiff2 We tested the results for normality with a Shapiro-Wilk test ($p < .05$). In case of the pragmatic quality in the VF condition they were not normally distributed and we used a Wilcoxon Signed-Rank test. Other data showed no significant difference to

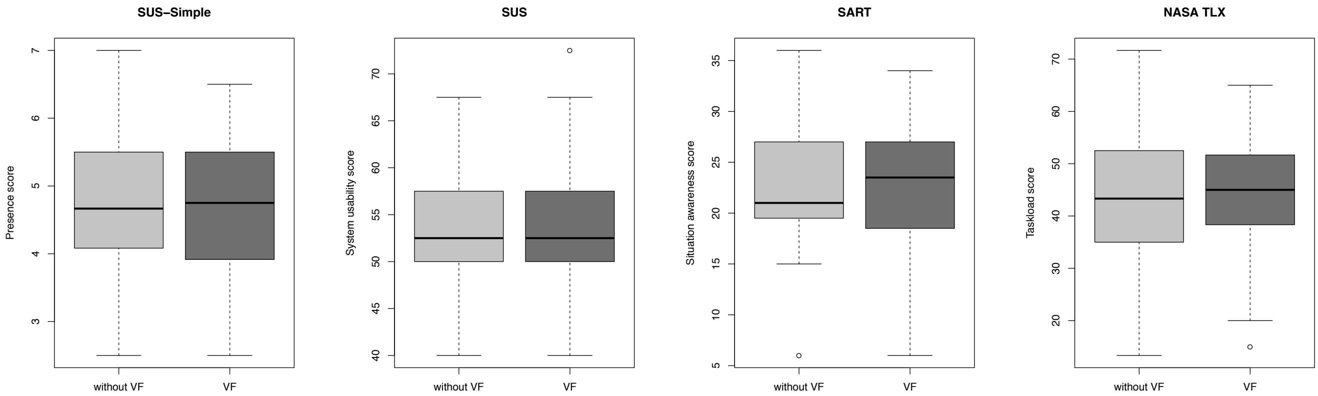

Figure 4: *Results of qualitative questionnaires.*

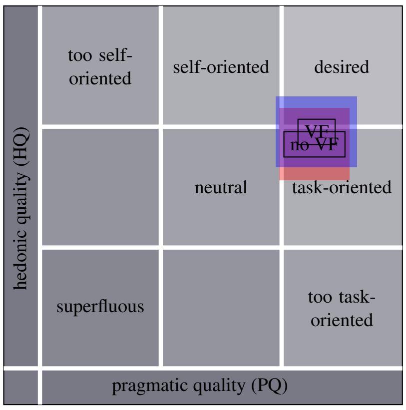

Figure 5: *Average values and confidence rectangles for the AttrakDiff questionnaire of both conditions: (red) "no VF" for the simple approach without virtual fixtures and (blue) "VF" for the implementation with visual virtual fixtures.*

normal distribution and thus, we applied paired samples T-Tests for the analysis. HQI ($p < .05$, T(27)=-2.2255) and HQS ($p < .05$. T(27)=-2.1152) showed significant differences. Calculating Bayes factors shows *moderate evidence* in both cases but additionally *moderate evidence* for the overall HQ. All other variables show *anecdotal evidence* for the null-hypothesis ($\mathcal{H}_0$). In Figure 5 the confidence rectangles for the two conditions are visualized.

SUS-Simple Shapiro-Wilk test of the scores was not able to show a significant difference to normality distribution. Evaluation of the Simple Usability Scale questionnaire revealed no significant difference between the two methods. *Moderate evidence* for $\mathcal{H}_0$ derives from Bayes factors.

SUS Slater-Usoh-Steed questionnaire showed no significant difference of the normally distributed scores and only *moderate evidence* for $\mathcal{H}_0$.

SART In the "VF" condition SART-D seems not to be normally distributed, which is the reason why we applied Wilcoxon Signed-Rank test instead of T-Test. Examining p-values showed no significant difference in overall scores or any part of the scoring procedure. Bayes factors indicate *moderate evidence* for $\mathcal{H}_0$.

NASA-TLX In the "VF" condition "effort" and in the "noVF" condition "frustration" the distribution is indicated as not normal and we applied Wilcoxon Signed-Rank tests. No significant differences arise from p-value analysis. Bayes factors show *anecdotal to moderate evidence* of $\mathcal{H}_0$ in all categories.

5.2. Quantitative Analysis

During the experiment we recorded several kinds of information about the single trials, such as the *time* from grasping the object to entering the target zone, the *distance* from the surface of the object to the surface of the closest obstacle, the number of *collisions* of the object and the gripper with the obstacles in the environment and the *exploration effort* of the participants, represented by the sum of their translational and the sum of their rotational head movements during the single trials.

Time Analysis of the needed time to finish the single course with a Shapiro-Wilk test confirmed a significant difference to normal distribution. Thus, Wilcoxon Signed-Rank tests were necessary to calculate p-values. All three courses show significant differences between the two conditions "noVF" and "VF" (C1: $p<.05$, V(29)=5571.5; C2: $p<.05$, V(29)=6038.5; C3: $p<.05$, V(29)=6227.5). Analysis of Bayes factors results in *anecdotal evidence* for $\mathcal{H}_0$ in case of course 1 (C1), *anecdotal evidence* for $\mathcal{H}_1$ in case of course 2 (C2) and *moderate evidence* for $\mathcal{H}_0$ in case of course 3 (C3). A summary is presented in Figure 6.

Precision During the trials, we calculated the shortest distance between the grasped object's surface and the surface of the closest obstacle. Only the means of distances in C3 with VF condition seem to be normally distributed and Wilcoxon tests were applied.

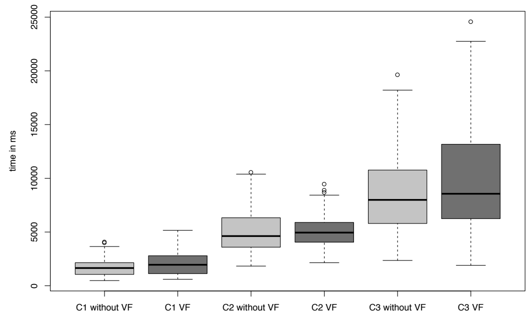

Figure 6: *Times to finish the courses.*

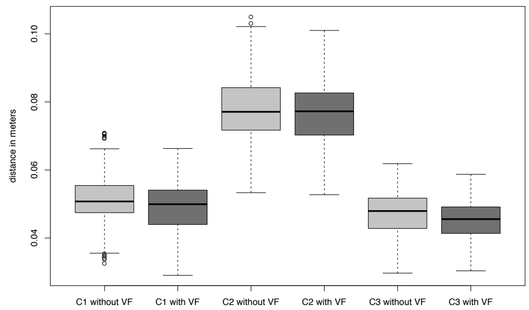

Figure 7: *Mean distances between grasped object's surface and the closest surface point of the obstacle.*

Means of distances for C1 ($p < 0.05$, V(29)=9188) and C2 ($p < 0.05$, V(29)=8458) show significant differences in the two conditions, as well as C3 ($p < 0.001$, V(29)=10036). Analysis of Bayes factors reveals *moderate evidence* for $\mathcal{H}_0$ in C1, *anecdotal evidence* for $\mathcal{H}_1$ in C2 and *extreme evidence* for $\mathcal{H}_1$ in C3. In Figure 7 a summary of boxplots is presented.

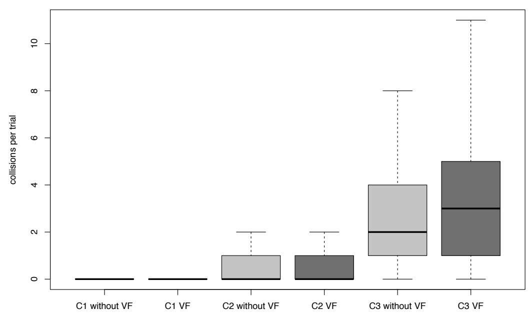

Figure 8: *Collisions of the gripper with the obstacles.*

Collisions Recordings of the gripper and the grasped object collisions show no normal distribution and no significant difference. Bayes tests claim *moderate evidence* for $\mathcal{H}_0$ in C1 and C2 regarding collisions of the gripper and *anecdotal evidence* for $\mathcal{H}_0$ in C3. In C1 no collisions of the grasped object occurred. C2 reveals *anecdotal evidence* for $\mathcal{H}_0$ and in C3 *moderate evidence* for $\mathcal{H}_0$ is calculated. As depicted by Table 1 the number of collisions of the gripper with the obstacles is lower without virtual fixtures, but in case of collisions of the grasped object with the obstacles it is lower when virtual fixtures are activated. Figure 8 summarizes the collisions of the gripper with the obstacles.

Table 1: *Total count of collisions.*

	C1	C2	C3	Total
Gripper noVF	13	128	461	602
Gripper VF	24	139	534	697
Object noVF	0	8	49	57
Object VF	0	3	41	44

Operator's Exploration Effort We tried to analyze the participants' exploration behavior during the trials to conclude if there is an effect caused by the additional feedback provided by the system. Thus, we recorded and summed up the translations (c.f. Figure 9) and the rotations (c.f. Figure 10) of the head separately during each trial. All recorded data shows significant differences to normal distribution. No significant difference between "VF" and "noVF" could be found. Regarding translation Bayes tests show *strong evidence* for $\mathcal{H}_0$. In rotational movements *strong evidence* for $\mathcal{H}_0$ was found in C2 and *moderate evidence* for $\mathcal{H}_0$ in C1 and C3.

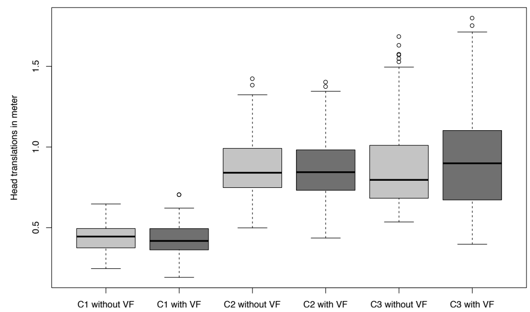

Figure 9: *Translational head movements of the operator.*

5.3. Discussion

From qualitative analysis using standard questionnaires we found a significantly higher hedonic quality with virtual fixtures enabled (c.f. Figure 5). Thus H1 is partially confirmed. No negative effect on the user experience and usability could be found by adding visual and haptic feedback to the system. Measuring situational awareness with an appropriate method is challenging. We expected

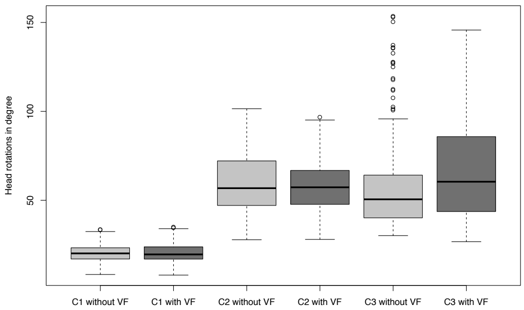

Figure 10: *Rotational head movements of the operator.*

an improvement with VF enabled, but no significant improvement could be shown. In Figure 4 a larger mean is clearly recognizable and some participants denoted in the final questionnaire the additional feedback to be helpful for their depth perception during the task. This could indicate a tendency to a larger SA but further investigation is necessary. Generally participants showed a quite high level of presence by not walking into the table or robot, despite, they were briefed to be free to walk around within the virtual environment.

Quantitative analysis revealed that participants took significantly longer in all three courses with "VF" enabled especially in C3 as Bayes factor analyses confirm. As reported by participants after the trials in an open question of the final questionnaire, the "VF" enabled condition encouraged them to try to be more precise. Our approach to record the exploration effort is limited by not including eye movements, which should be investigated in later work. Head movements (c.f. Figure 9 and Figure 10) showed a tendency to increased exploration behavior but the difference is not large enough to be significant. Thus, H3 needs further investigation to be confirmed. Analysis of the distance of the grasped object to the obstacles show that it is significantly smaller when VFs are enabled (c.f. Figure 7), which could explain the longer processing times of the single trials in that condition. Regarding collisions of the gripper and the grasped object with the obstacles in the environment no significant difference was confirmed. But having a closer look at the occurred collisions in Table 1 shows that with VFs enabled there where more collisions of the gripper but less collisions of the grasped object in total. The closer mean distance to the obstacles, which was triggered in the "VF" condition also increases the probability of collisions during directional changes of operator movements. The additional haptic feedback during a collision informs the operator to be too close to the obstacles. The combination of both could cause the lower amount of collisions of the grasped object during the trials. These effects should be investigated in a separate study. Thus, H2 is confirmed but the modalities are not clear. The haptic feedback is implemented to occur during collisions of either the grasped object, or the gripper. Since, the gripper is surrounding the object it "protects" the object. Increasing the size of the gripper's collider could increase the performance, meanwhile reducing the plausibility of the VE. Another reason why the performance was not increased by the visual fixtures could be their visibility, which depends on the users position and looking direction. Especially the 3D task is very difficult due to the tunnel-width of our implementation and needs both, good skills and the observation of all three independent inner surfaces of the u-shaped obstacles.

6. Utility of Virtual Fixtures in VR-based Interfaces

Q1 cannot be answered negatively. The original setup of Rosenberg [BR92] is very elaborate and costly. In our implementation the visual fixtures guide the user continuously during the operation of the robot. The haptic component increases the effect of the red color by informing the user about a collision, which is possibly the reason for less collisions of the grasped object with the obstacles in the environment. Future work should investigate methods, like using an enlarged collider for the gripper, to prevent the gripper itself of collisions.
Q2 questions the desired purpose of the mechanisms tested in this contribution. Realtime teleoperation needs additional safety mechanisms, likewise collision checks and collision-free planning. Resulting information should be integrated into the UI. Teleprogramming and learning-by-demonstration many scenarios can directly benefit from the presented findings. The experiment tasks described in this paper already offer some reduction of task complexity to reduce the mental workload. Collisions with a static object like the table surface are neglected since a path planning algorithm is capable of avoiding these issues easily. The tracked 6-DoF of a Vive Controller is reduced to 4-DoF, since, we limited the task to top grasp, which is quite common in pick-and-place tasks. These simplifications surely contribute to the good scores from qualitative analysis. Based on this work, support points sampled from trajectories of the user input is appropriate as input for motion planners generating movements of real robots.

To summarize, we implemented a low-effort version of the concept of virtual fixtures. The Unity3D project is available at GitHub. We evaluated our implementation in a user study and summarized the statistical analyses and findings. We are sure to contribute to future robotic user interface design with our results.

Acknowledgments

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