# Assistance Functions for Collaborative Haptic Interaction in Virtual Environments and their Effect on Performance and User Comfort

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***Abstract*— In shared virtual environments, multiple users can perform complex manipulations collaboratively, while receiving haptic feedback from the environment and other users. In single-user systems, dynamic assistance functions were shown to improve task performance; however, little is known about their effect on user perception. In this paper, state-of-the-art assistance functions presented for single-user systems are transferred to a multi-user system. Aiming to assess the effect of these assistance functions on objective and perceived task performance, as well as on user comfort, an experimental user study has been conducted with a typical collaborative haptic interaction task. The analysis of the results showed that some assistance functions significantly improved movement coordination compared to unassisted execution of the task. The results further indicate that the effects of an assistance function on subjective performance and comfort ratings depend on the level of movement control that the user is afforded. The results of this study provide useful information for the design of effective and comfortable assistance functions.**

***Index Terms*— VR, haptic feedback, multi-user, usability, task performance, experimental evaluation**

## I. INTRODUCTION

In shared virtual environments, complex manipulation tasks are jointly performed by multiple human operators, whereby each operator controls the movements of a virtual proxy via a human-system interface. In addition to visual feedback from the virtual scene, haptic feedback from the interaction with the virtual environment and the other operators may be provided, as haptic feedback was shown to have a positive effect on perceived realism [1] and user task performance in certain types of tasks [2]. The application areas for collaborative manipulation tasks in virtual environments range from haptic training of motor skills, e.g. for surgery [3] and rehabilitation [4], to virtual prototyping and computer games [5].

Control objectives for collaborative haptic interaction in shared virtual environments are robust stability, transparency as well as good task performance and a high level of coordination between the users. Regarding stability and transparency, the handling of latency issues, bandwidth limitations and packet loss in the communication channel are investigated for systems, where the operators are located at different places see e.g. [6], [7]. In order to improve task performance, numerous assistance functions have been proposed for single-user virtual and teleoperation systems. An overview of assistance functions applied to single-user teleoperation systems and physical human-robot interaction tasks is given in [8]. Most of these assistance functions are transferable to haptic interaction in virtual environments. However, to the authors' knowledge, assistance functions have not yet been introduced for *collaborative* haptic manipulation tasks.

Previous studies on haptic assistance functions tended to focus on technical properties of virtual environments, and, to some degree, on their effects on the user's motor task performance. However, rarely investigated is the question of how haptic assistance functions are perceived by the user(s). Compared with visual and auditory signals, haptic signals are generally more intrusive and may even directly interfere with the operator's intended movements. A number of studies in the areas of social, clinical, and engineering psychology suggest that the experience of a loss of autonomy or a restriction of motor control is perceived as uncomfortable and may even lead to frustration and distress, e.g. [9]–[11]. One can surmise that this effect would be even more pronounced in tasks which require collaboratively executed movements, as autonomy over movement control is further curtailed. Bias in perception may also affect the way in which work with a particular system is evaluated by its user(s), as studies on human-robot interaction suggest that the level of control that the user is given, changes the perception of performance with this system. For instance, [12] found that users tend to blame and credit the robot for faulty and successful behaviour, respectively, if this robot displays a high degree of autonomy. On the other hand, users seem to credit and blame themselves, if they believe that they were in control of the robot's behaviour. Furthermore, the social psychology literature offers sound empirical evidence for a particular attribution bias, whereby people tend to attribute behaviour of others to individual factors, whilst attributing their own behaviour to situational factors, [13]. This attribution bias may result in different perceptions of a system's behaviour, depending on whether this behaviour is attributed to oneself or an other. Thus, it seems likely that the perception of working comfort as well as task performance would be influenced by the level of movement control that an assistance function affords the user over the virtual

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environment. For the design of future assistance functions in general, and haptic assistance functions in particular, it is hence of particular interest to investigate both performance-, as well as perception-related aspects of assistance in virtual environments.

In this paper, we propose two selection criteria and an approach for transferring state-of-the-art single-user assistance functions to collaborative haptic interaction scenarios. As this article focuses on the effect of assistance functions, we assume negligible time delay between the operators. In order to evaluate the effect of the implemented assistance functions on task performance, as well as operator perception, an experimental user study was conducted. Hereby, the differences between three different assistance functions, adopted and slightly modified from literature, have been investigated. Using this approach, the following research questions have been addressed:

- Haptic assistance can measurably and noticeably improve task performance in collaboratively executed motor tasks.
- Depending on the amount of control that a particular assistance function affords the user, teamwork is perceived as more or less comfortable in performing a motor task collaboratively.

For the investigation of these questions, three assistance functions, presented for single-user haptic interaction, are transferred to collaborative haptic interaction, and a typical collaborative haptic interaction task has been chosen for the evaluation scenario.

The paper is structured as follows: the approach for transferring assistance functions from haptic interaction to collaborative haptic interaction, the investigated assistance functions as well as the control of the haptic devices and the haptic rendering of the virtual environment are presented in Sec. II. The experimental design and setup of the user study are reported in Sec. III, while the experimental results are shown in Sec. IV. The paper finishes with a discussion of the results in Sec. V and a conclusion in Sec. VI.

## II. ASSISTANCE CONCEPT

In this section, the transfer of assistance functions from haptic interaction to collaborative haptic interaction is discussed. Afterwards, a scenario for a collaborative manipulation task is described, together with three suitable assistance functions known from literature.

### A. *Assistance functions for collaborative haptic interaction*

Depending on the type of task, two approaches for applying assistance functions in collaborative haptic interaction systems can be distinguished: a *decentralized* and a *centralized* one. In the decentralized approach, the controller of each haptic interface is individually augmented with an assistance function, see upper image in Fig. 1. Thus, the decentralized approach is mainly suited for *sequential* manipulation tasks, such as building a shelf. For example, one operator may be picking up a board (subtask 1), while the other is fixing another board (subtask 2). For *parallel collaborative* manipulation tasks, the decentralized approach may lead to opposing assistance forces. For example, both users may be pulled towards different trajectories or may be under the influence of different potential fields. In contrast, the idea of the centralized approach is that the motions of the collaboratively manipulated object are guided rather than the motions of the single virtual proxies representing the different participants, see lower image in Fig. 1. The operators are therefore pushed/pulled towards a common trajectory/potential field.

Task-independent assistance functions, i.e., assistance functions where explicit task knowledge is not required, e.g. variable admittance/impedance controllers, see [8] for a summary, are applicable to any decentralized or centralized controller and, hence, also to any collaborative haptic interaction system.

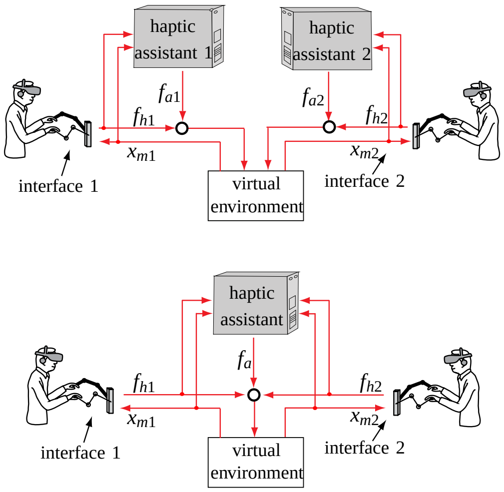


Fig. 1. Decentralized approach (upper image) and centralized approach (lower image) for applying assistance functions to collaborative haptic interaction systems

### B. *Scenario*

The present article focuses on parallel collaborative manipulation tasks, as this represents a novel way for applying assistance functions.

A maze is chosen for the scenario. A square box represents the object to be moved through the maze and two balls represent the virtual proxies to be controlled by the participant/s, see Fig. 2. The task was to move the box through the maze as quickly as possible without colliding with the walls. The operators did not have to grasp the object: the virtual proxies were connected to the box from the beginning of the experiment. There was no division of movement between the operators: each operator was able to move the box in all directions along the x/y plane.

### C. *Assistance Functions*

One task-independent and two task-dependent state-of-the art assistance functions were selected and slightly modified for the chosen scenario. As described in Sec. II-A,

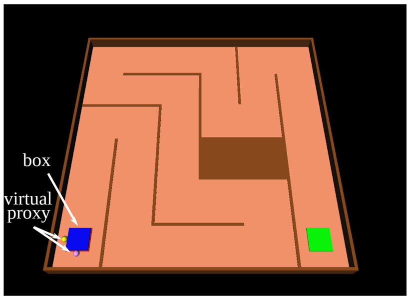


Fig. 2. Virtual scene

the assistance functions were applied to the collaboratively manipulated object.

**Variable damping (VD):** The variable damping approach of Duchaine & Gosselin [14] uses an intuitive relationship between haptic data and human intention to adjust the virtual damping of an admittance controller. Based on the time derivative of the input force to the admittance controller and the sign of the desired velocity of the admittance controller, desired accelerating and decelerating actions can be distinguished. While accelerating motions are facilitated with decreased damping, decelerating motions can be accomplished more easily with increased damping. This assistance function is task-independent and can therefore be transferred directly to the interaction point of the collaboratively manipulated object. For the given scenario, the input to the admittance controller is the sum of the human applied forces $f_{h1}$ and $f_{h2}$ and the forces from the virtual walls in the maze $f_{e1}$ and $f_{e2}$, denoted by $f_{adm}$, as well as the assisting force $f_a$. For the variable damping approach, the assisting force $f_a$ applied to the object with position $x_o$ and velocity $\dot{x}_o$ is

$$f_a = -\alpha \dot{f}_{adm} \operatorname{sgn}(\dot{x}_o)\dot{x}_o. \tag{1}$$

The parameter $\alpha$ is used to weight the amount of adaptation. In a small user study, Duchaine & Gosselin [14] demonstrated that the proposed adaptation leads to an improved task performance for a cooperative drawing task and a pick-and-place task. In this paper, the approach is adapted to the experimental setup introduced in Sec. II-B. The parameters are chosen as $d_0 = 40$ Ns/m in both directions and $\alpha_x = 0.2$ in x-direction and $\alpha_y = 0.8$ in y-direction. As the force measurements are noisy, a lowpass filter with 8 Hz cutoff frequency is applied to the force measurements.

**Virtual fixture based on computer-generated trajectory (VFC):** Virtual fixtures are used to enhance task performance in terms of execution time, precision and error rates for applications like teleoperated surgery or micromanipulation [15], [16]. Rosenberg, who was the first researcher in this area, describes virtual fixtures in [17] as perceptual overlays to improve performance. In this paper, virtual fixtures are applied to guide the operators' motions along a certain trajectory or path [18], as shown in Fig. 3. Task-relevant motions are hereby supported, while deviations from the desired path are constrained. Two types of virtual fixtures can be distinguished: active and passive ones. When using passive virtual fixtures, the applied user's force is scaled in order to drive the operator back to the desired path [19]. Thus, if the operator does not apply any force, the device does not move either. Active virtual fixtures, on the other hand, apply additional forces directed towards and along the desired path [20]. Thus, even if the operator does not apply any force, the assistance would accomplish the task.

In a collaborative haptic interaction scenario, the motion of the manipulated object is supported by the assistance function rather than the motions of each operator individually. For the chosen scenario, a mixture of active and passive virtual fixtures is used. Motions along the path are passively guided, while deviations from the path are assisted actively. This approach was chosen, as a passive virtual fixture did not show sufficient assistance in the curves to avoid collisions with the walls. With the passive virtual fixture along the path, the operator can still choose the desired speed. The centerline of the maze was used as a desired path for straight movements, while a circular movement was chosen for the curves.

For the given scenario and experimental setup, a scaling of 1.5/0.9 is applied to the tangential forces in the desired/undesired direction. The orthogonal forces are computed using a virtual spring with 8000 N/m stiffness.

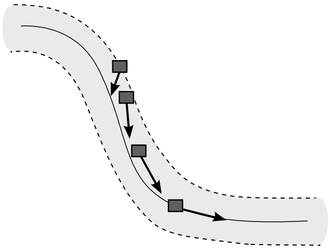


Fig. 3. Concept of guiding virtual fixtures applied to commonly manipulated object

**Virtual fixture based on human-generated trajectory (VFH):** Instead of a computer-generated path, a human-generated trajectory can also represent the desired path. When moving through the maze, humans develop strategies in how to move through the straight passages and how to go around corners. Thus, it can be hypothesized that virtual fixtures based on a human-generated path facilitate task execution, as the operators feel the way in which a human who is familiar with the scenario performs the task. Certainly, the human trajectory will not be centered between the walls as it is the case with the computer-based virtual fixture. Again, the guidance is applied to the manipulated object and therefore only indirectly to the operators. In order to avoid collisions with the walls, the VFH was therefore designed as a strong active virtual fixture. The virtual spring orthogonal to the path was set to 720.000 N/m and a constant force of 8 N pulled the operator in the desired direction tangential to the path. The computer-generated path and the path generated by one operator familiar with the scenario for the corresponding virtual fixtures are shown in Fig. 4.

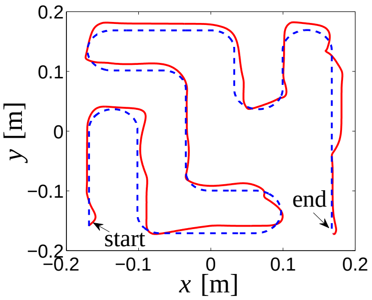


Fig. 4. Computer-generated path (dashed line) and human-generated path (solid line) for virtual fixture

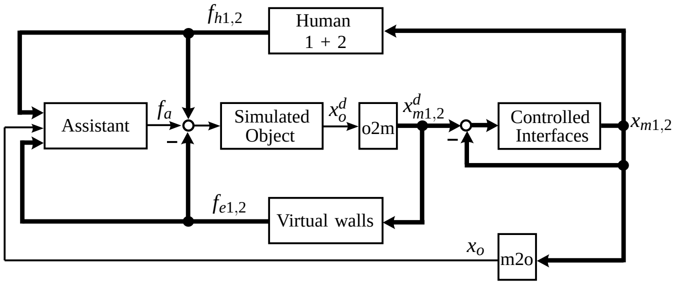


Fig. 5. Overall control structure for collaborative haptic interaction; o2m/m2o stands for the transformations from object/master to master/object coordinate system

### D. *Control & Haptic Rendering*

A common position-based admittance controller as proposed in [21] is used to stiffly couple the two master devices via a common object. Due to the stiff coupling, the relative positions between the positions of the haptic interfaces $x_{m1}, x_{m2}$ and the position of the virtual object $x_o$ is constant, i.e. $x_{m1} - x_o = const.$ and $x_{m2} - x_o = const.$. Mass-damper dynamics are chosen for the admittance in order to simulate the virtual proxies connected to the box pushed over the ground. Spring-damper models are used to haptically render the walls of the maze. In order to achieve a stiff haptic rendering, the desired position and velocity $x^d_{m1,2}, \dot{x}^d_{m1,2}$ of master device 1 and 2 is used instead of the measured position/velocity, as proposed in [22]. The resulting forces from the virtual environment are therefore calculated as:

$$f_{e1,2} = k_e(x^d_{m1,2} - x_w) + d_e \dot{x}^d_{m1,2} \tag{2}$$

where $x_w$ is the initial position of contact with the walls. The parameters are chosen as $k_e = 7000$ N/m and $d_e = 500$ Ns/m. The sum of human, environment and assistance forces are the input to the admittance, simulating the object coupled with the virtual proxies. The dynamic equation is given as

$$\underbrace{f_{h1} + f_{h2} - f_{e1} - f_{e2}}_{f_{adm}} + f_a = m_o \ddot{x}^d_o + d_o \dot{x}^d_o \tag{3}$$

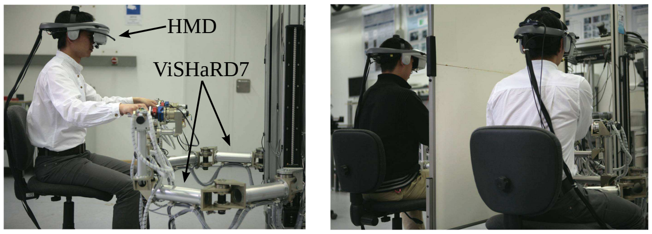
where $m_o, d_o$ are the mass of the object and the damping resulting from pushing the box over the ground. The desired positions for the haptic interfaces are tracked using high-gain PD-controllers in joint space. In order to simulate a heavy object in a damped environment, the virtual dynamics are selected as $m_o = 24$ kg and $d_o = 40$ Ns/m. The overall control structure is shown in Fig. 5.

## III. EVALUATION METHOD

### A. *Apparatus*

Two redundant 7 DOF ViSHaRD7 robotic arms were used as haptic interfaces. The arms have a relatively large, human-like workspace and a high force output capability, see [23] for a detailed performance analysis. The redundancy is used to decouple translational from rotational movements. Thus, movements were easily restricted to translational movements in the horizontal plane. JR3 6 DOF force/torque sensors are mounted at the end-effectors of the two devices and end-effector positions are obtained by applying the forward kinematics to the measured joint angles. The control runs at a sampling frequency of 1 kHz. Experimental data (end-effector positions, human/assistance forces, task completion time, collision time with walls) were recorded at the same frequency. Gravity forces are compensated in the force measurements. Aluminium bars mounted at the end-effectors are used as handle for the operator(s).

A single-user and a multi-user mode of operation were distinguished. In the single-user mode (SM), the participant grasped both handles, while in the multi-user mode (MM) each participant grasped one handle with his/her dominant hand, see Fig. 6. The virtual reality scenario was presented to the participants through a head-mounted display (HMD) with SXGA resolution and a frame rate of 30 Hz.



Single-user mode of operation    Multi-user mode of operation

Fig. 6. Experimental setup

### B. *Experimental design*

A 4 (assistance) x 2 (user mode) repeated-measures within-subjects experimental design investigated the effects of three assistance functions (VFC/VFH/VD) and a control condition with no assistance (NA) on task performance and work comfort in two different modes of cooperation (single-user/multi-user). Task completion time (sec.) and total collision time (msec.) constituted objective measures of task performance. Subjective task performance and working comfort were measured on respective single-item 5-point Likert-type scales. In addition, the perceived level of control over virtual proxy movements was assessed on a percentage scale.

### C. Procedure

Prior to the experimental trials, participants were given the opportunity to familiarise themselves with the experimental setup and the task requirements, which were to move the virtual box in the maze from a pre-defined starting point to a goal location using their input devices. Particular emphasis was placed on the requirement to avoid contact with the walls, whilst moving as quickly as possible through the maze. Prior to the experimental run, participants conducted a number of practice trials after each of which they were given feedback regarding their task performance. This instruction phase was designed specifically to ensure that all participants would approach the task in a somewhat consistent manner, so that effects could be attributed confidently to the experimental manipulations rather than individual style. Upon completion of the practice phase, each participant performed the practiced task a total of 24 times. In 12 trials, participants moved the box by themselves (single-user trials), whereas in the remaining 12 trials, participants worked in teams of two (multi-user trials). Half of all participants started with single-user trials, the other half started with multi-user trials. Each trial was conducted with a different assistance function or the control condition, whereby each type of assistance (including the control condition) would be implemented a total of three times. The order in which the different types of assistance were implemented was systematically varied. In multi-user trials, a portable wall and the HMD would prevent participants from communicating verbally or visually with each other. After each trial, participants completed a short questionnaire.

### D. Participants

An opportunity sample of 16 male and 16 female (N=32) participants took part in this study, all of whom were right-handed. Pre-trial screening questionnaires ensured that none of the participants suffered from impairments of their motor ability. Due to measurement irregularities, one person's data set had to be excluded from the statistical analysis of the results.

## IV. EVALUATION RESULTS

Data were inspected for outliers; scores with z-values of $\geq 3.29$ were removed. Furthermore, it was checked whether data met assumptions for parametric tests. Where these assumptions were violated, non-parametric tests were used or appropriate corrections were applied, as specified in the following sections. Since the focus of this article is on the effects of haptic assistance in collaborative tasks, only the results of multi-user trials will be presented in detail.

### A. Quantitative Teamwork Measures

In order to gauge the impact of the different assistance functions on objective task performance measures, parametric, repeated-measures ANOVA were conducted with assistance (VFC, VFH, VD, NA) as an independent variable and collision times (msec.) and task completion times (sec.) for three measurement intervals as dependent variables. Where Mauchley's test of sphericity was significant, degrees of freedom were adjusted with a Greenhouse-Geisser correction. Collision and task completion times for each assistance condition are depicted in Figures 7 and 8, respectively.

**Total collision time:** Since participants had been instructed to avoid contact with the walls of the virtual maze, the total amount of time (msec.) that the target object or the virtual proxies spent in contact with a wall was measured as an index of objective task performance. For multi-user data, practice had no significant effect on total collision time $(F(2,30) = 2.52, p = .10)$. There was, however, a significant assistance function main effect $(F(1.21,18.07) = 21.77, p < .001, \eta^2 = .59, \varepsilon = .40)$. Bonferroni-adjusted post-hoc comparisons (accepted $\alpha - level$ of $(p < .008)$) showed that VFC was the only assistance condition that significantly differed from the other three conditions, indicating that trials conducted with VFC resulted in significantly shorter collision times compared to trials with VHC or VD, as well as the control condition.

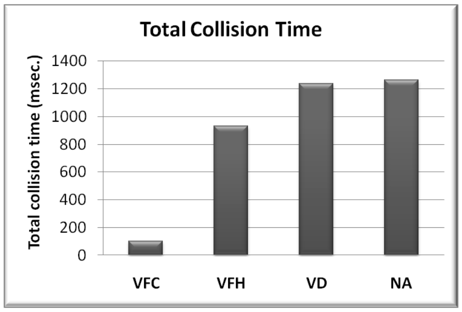


Fig. 7. Mean total collision times (msec.) for each assistance condition (N=31).

**Task completion time:** Another objective measure of task performance constituted the task completion time. For each trial, time was measured (sec.), starting with the appearance of a visual start signal, up to the point until the box was correctly positioned at the goal position. For multi-user trials, practice had a significant main effect on task completion times $(F(1.43,21.48) = 22.48, p < .001, \eta^2 = .60, \varepsilon = .72)$. Post-hoc comparisons found a significant reduction of completion times for each trial. Taking this practice effect into account, the analysis further found a significant assistance function main effect $(F(3,45) = 45.25, p < .001, \eta^2 = .75)$. Post-hoc comparisons showed that task completion times differed significantly in all conditions. The shortest time intervals were observed in trials with VFC, followed by VFH, with VD leading to the slowest completion times.

In summary, the data show that VFC resulted in the best task performance as indicated by speed and collision avoidance. VFH produced significantly faster trials than VD and the unassisted control condition (NA), although the latter two assistance functions performed similarly to VFH in terms of contact avoidance. VD resulted in similar collision times as were observed in the control condition (NA), but led to significantly slower trials.

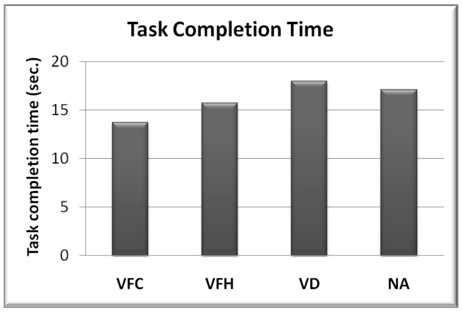


Fig. 8. Mean task completion times (sec.) for each assistance condition (N=31).

## B. Qualitative Teamwork Measures

After each trial, participants were asked to rate their own task performance as well as the general working comfort on a single-item, Likert-type scale ranging from 1 (very poor) to 5 (excellent). For a better overview, perceived performance and comfort ratings for each assistance condition are displayed in Figures 9 and 10, respectively.

**Subjective teamwork performance:** Ratings of the subjective task performance in multi-user trials showed that there were hardly any differences in ’very poor’, ’poor’ and ’average’ ratings between the VFC, VD and control condition (NA). Similar numbers of trials also received ’good’ or ’excellent’ ratings (VFC 68.82%, VD 70.97%, NA 65.60%). However, looking at these numbers more closely, it was found that task performance in trials with VFC was rated as ’excellent’ in more than two thirds of all trials with this assistance (45%), indicating a perception of superior performance in trials with VFC compared to trials with VD which was only rated ’excellent’ in 21.51% of trials, and the unassisted control condition with only 18.28% of ’excellent’ trials. In contrast, performance with VFH received ’good’ or ’excellent’ ratings in only 2.15% of trials, whereas ’poor’ and ’very poor’ ratings dominated (77.42%). Friedman’s ANOVA found a significant assistance main effect on multi-user performance ratings $(\chi^2(3) = 57.24, p < .001)$. Wilcoxon post-hoc comparisons with Bonferroni corrections for multiple comparisons confirmed performance ratings with VFH to be significantly lower than those of any other condition $(p < .008)$, whereas none of the other ratings differed significantly.

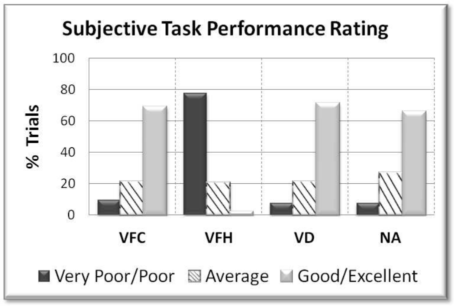


Fig. 9. Perceived performance ratings for each assistance condition (N=93).

**Teamworking comfort:** Comfort ratings reflected task performance ratings only partially. VD and the control condition led to ’good’ or ’excellent’ ratings in 77.42% and 72.04% of trials, respectively. Only 5-7% of VD and NA trials were rated as ’poor’ or ’very poor’. VFC seemed to divide opinions: only half of all trials with VFC were rated ’good’ or ’excellent’ in comfort, whereas 21.50% of trials were rated ’poor’ or ’very poor’. VFH received ’good’ or ’excellent’ ratings in only 8.61% of trials and ’poor’ or ’very poor’ ratings in 77.42% of trials. Again, Friedman’s ANOVA found a significant assistance main effect on collaborative performance ratings $(\chi^2(3) = 64.02, p < .001)$. Wilcoxon post-hoc comparisons with Bonferroni corrections for multiple comparisons found comfort ratings with VFH to be significantly lower $(p < .008)$ than those of any other condition, whereas none of the other ratings differed significantly.

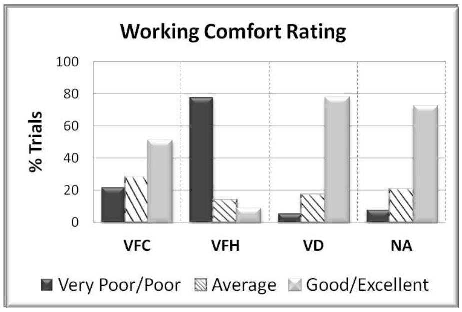


Fig. 10. Perceived comfort ratings for each assistance condition (N=93).

## C. Perceived Movement Control

Perceived level of control was measured after each trial with a single-item scale, on which participants indicated, how much control they felt they had over the movements of the virtual proxy ($0\% - 100\%$ in control).

In a first step, participants’s control ratings were correlated to those of their partners. Although one would suspect a negative correlation between partners’ control ratings (the more one person is in control, the less control is given to the partner), a Pearson correlation found a significant, medium-sized, positive correlation in control ratings between partners over all assistance conditions ($r = .46, p < .001$). Considering the significant positive correlation between partner ratings and a striking similarity in numbers to the single-user trials, it would seem that the system’s behaviour weighed more heavily on participants’ impressions than did the nature of the human-human cooperation. Since partners seemed mostly to agree with one another when rating the amount of control, further analyses were conducted with individual ratings, regardless of the team that they originated from.

**Users’ movement control afforded by assistance functions:** The means indicate that participants felt they had least control over virtual proxy movements with VFH. With an average control of 29%, they felt that the system was largely responsible for virtual proxy movements. On the other hand, VFC seemed to approximate an equal cooperation between the users and the system as participants felt they had about 44% control over movements with this assistance function. In comparison, participants indicated that they had more movement control with VD (62%) and the control condition (NA) (60%). An ANOVA confirmed a significant assistance function main effect $(F(2.34, 70.20) = 50.89, p < .001, \eta^2 = .63, \varepsilon = .72)$. Post-hoc comparisons with Bonferroni-adjustments for multiple comparisons indicated significant differences $(p < .008)$ in ratings between all assistance conditions except for ratings between VD and the control condition (NA).

**The effect of control on performance and comfort ratings:** It was investigated whether the level of control over virtual proxy movements, a dimension on which the assistance functions were clearly differentiated, influenced subjective performance and comfort ratings. The effect of control on the relationship between objective task performance, subjective performance and working comfort has been investigated by classifying all remaining trials into one of two categories: trials in which participants felt they were in control of movements (control $\geq$ 51%) and those in which they were not in control (control $\leq$ 50%). Mann-Whitney U and independent t-tests showed that in trials in which participants were in control of virtual proxy movements, significantly higher comfort $(U = 1859.50, z = -7.67, p < .001, r = -.6)$ and task performance ratings $(U = 1667.50, z = -7.67, p < .001, r = -.5)$ were given, even though significantly longer collision times $(t(146.97) = -2.87, p < .005, r = -.24)$ had been recorded for these trials than for trials in which participants did not feel in control. The trials, however, did not differ in terms of task completion times $(t(190) = -0.47, p = .64)$. Note that, since within-subject variance has not been taken into account in this analysis, these estimates are conservative and even larger effect sizes are theoretically plausible, if not suspected. Although a causal relationship cannot necessarily be inferred on the basis of statistical analysis, overall, the findings indicate that collisions influenced comfort and subjective performance ratings more when the system was in control of movement than when the user was primarily responsible for making mistakes.

## V. DISCUSSION

In summary, the purpose of this study was to investigate the influence of three different haptic assistance functions, virtual fixtures based on computer- (VFC) and human-generated (VFH) trajectories, and variable damping (VD), on objective and subjective task performance, as well as on perceived levels of comfort, in a collaborative task. Of particular interest was also the role of perceived movement control in judging task performance and working comfort. Compared to an unassisted control condition, VFC was found to significantly improve objective task performance, defined as speed and collision avoidance, in a transport task. Although ratings showed that participants noticed its superior performance, teamwork was rated as less comfortable with VFC compared to the unassisted condition. Virtually no distinctions in ratings were made between VD and the unassisted condition, despite the fact that VD significantly increased task completion times. Finally, teamwork with VFH was rated as least comfortable. It also made the impression on participants that task performance was significantly worse with VFH than without assistance, even though this was not confirmed by objective measurements.

Finally, the data indicate that when participants felt that they were not in control of the movements of their virtual proxy in a particular trial, they were more likely to consider negative task performance aspects in their judgment of comfort and subjective performance. An explanation for this finding can be derived from other empirical findings, e.g. [12], as well as the social psychological literature, e.g. [13]. These suggest that the entity which is perceived to be in control, is generally also held accountable for mistakes. By the same token, literature on attributional bias suggests that users tend to attribute their own performance to cross-situationally varying factors, whereas they attribute the system's mistakes to the system rather than coincidence or the difficulty of the task. Since intentional errors are more memorable than unintentional mistakes [13], collisions in trials in which the system was perceived to be in control decreased subjective performance and level of comfort ratings, even though the user collided less with the wall when the assistance function was dominating the movement of the manipulated object. Hence, the findings of the present study suggest a certain trade-off between control and subjective evaluations: if an assistance function cannot keep performance errors to a minimum, it is more likely to be judged unfavourable, the more intrusive it is. On the other hand, if assistance functions provide the user with more than 50% of movement control, the user is more likely to overlook performance errors made.

## VI. CONCLUSION

In conclusion, it is demonstrated that haptic assistance functions can be transferred to cooperative multi-user systems by applying the assistance to the commonly manipulated object. The experimental evaluation of these implementations show that some assistance functions significantly improve the degree of coordination and task performance compared to unassisted task execution. The present study further indicates that in collaborative virtual environments, the effects of assistance functions are qualitatively similar to single-user tasks. Albeit, teamwork with assistance is generally considered to be less comfortable than individual work in single-user trials, as more control is deferred. Although task performance was overall better with task dependent assistance than the task independent function, it was found that it is most likely not the aspect of task dependence, but the level of perceived movement control that primarily influences comfort ratings and subjective task performance. The more the operator feels in control of the movements, the more likely it is that he or she will overlook performance errors in judging task performance and working comfort. On the other hand, once the operator does not feel in control, evaluations are likely more influenced by mistakes, even if, in fact, less errors have been made. The findings of this study indicate that user perception is an important factor in the evaluation, and consequently applicability, of assistance functions in shared virtual environments and thus warrants closer investigation in the future.

## VII. ACKNOWLEDGMENTS

This work was supported in part by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on “High-Fidelity Telepresence and Teleaction”.

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