Barbara Deml
Universität der Bundeswehr
Human Factors Institute
D-85577 Neubiberg, Germany
barbara.deml@unibw.de

Human Factors Issues on the Design of Telepresence Systems

Abstract

The overall aim of this work is to provide some guidelines for the design of telepresence systems from a human factors point of view. Developers of such human-machine systems face at least two major problems: There are hardly any standard input devices, and guiding design principles are almost missing. Further, most often telepresence systems should enable both a high degree of performance and a high sensation of presence, and yet the relationship between these two variables is still a subject of research. To cope with some of the problems, two experimental studies are presented. Each focuses on a different aspect of interface design, which is of widespread interest in the field of telepresence systems. The first is related to the control of multiple degrees of freedom and the second refers to bimanual input control. Beyond this work, a meta-analytical study is presented to describe the relationship between presence and performance more precisely. Certainly there are more issues that have to be studied (e.g., perceptual aspects) to guide the design of telepresence systems. To provide a framework for these and further human factor aspects, a computer based design guide is suggested at the end. This tool addresses system developers and assists in realizing new interfaces more effectively.

1 Introduction

Current telepresence systems are not always intuitive and human operators sometimes have difficulty in using these systems. There are hardly any standard input devices, and guiding principles for interface design are almost nonexistent. Most often, telepresence systems afford spatial input commands and very often tasks have to be accomplished that would be done with two hands in real life. For this reason, it is important to know how well human operators are able to steer multiple degrees of freedom and to understand the particular problems they have with certain movement dimensions. Just the same, it is necessary to learn more on the principles of two-handed input and the particular roles, which both hands have in everyday tasks. Within this work two studies are presented (see Section 2): The first examines multiple degree of freedom control (see Section 3) and the second focuses on bimanual input control (see Section 4). The outcomes are discussed in terms of telepresence systems and more general design principles are derived.

Even beyond the problem of the nearly nonexistent human factors guidelines, there are further problems related to interface design. A major challenge of all these systems is to overcome the spatial barrier between the master-slave configuration and to evoke a sense of being at the remote side (Slater, 1999). This design goal is commonly summarized as sensation of presence. At the

Presence, Vol. 16, No. 5, October 2007, 471–487

same time it is also important to ensure a high degree of performance in teleworking environments. Although the relationship between presence and performance has been studied intensively, it still lacks empirical validation. To design telepresence systems effectively it is important to know whether both parameters are independent of each other, whether there is a causal relationship, or whether the interaction also depends on certain individual abilities or skills of the users. To answer these questions, a meta-analytical study is presented (see Section 5).

As it may be difficult to establish a relationship between more general experiments on the one hand and a certain application on the other hand, a computer based design guide is suggested at the end (see Section 6). Its application is rather straightforward: The interface designers are guided through a task analysis, which helps them to describe their application and their telepresence system. This information is matched with human factors knowledge (as gained by experiments and by literature review) to provide more specific design recommendations.

2 Experimental Framework

In most studies on telepresence systems the human operators are regarded as homogenous and interindividual differences between them are ignored. To allow a more detailed analysis, all participants were asked to run through a pretest at the beginning of each experiment. Thereby, their tendency of immersion as well as their sensorimotor skills were assessed.

While the term immersion refers to the quality of display technology, *tendency of immersion* is a cognitive parameter of perception that expresses the degree to which someone is able to identify himself with telepresence events. For measuring this trait variable Witmer and Singer (1998) proposed the Immersive Tendencies Questionnaire (ITQ). This instrument captures the individual engagement toward tedium events such as reading a book, watching television, or following sport events. It proved to be valid in various contexts: Blake, Casanueva, and Nuñez (2000), for instance, observed a positive correlational relationship between the ITQ-values and the reported sensation of presence. Thus, it may be assumed that a higher tendency of immersion eases presence and that some users get more easily involved in telepresence events than others do. Within this work an abbreviated German version of the ITQ was used, which was introduced by Scheuchenpflug (2001).

Further, there may be certain sensorimotor skills that are helpful for commanding telepresence systems. As, of course, it is not possible to capture such skills by paper-and-pencil tests, a diagnostic standard procedure was applied that is rather common in the field of job assessments (e.g., selection of pilots or crane drivers). Thereby, the following three tests have been chosen (Vienna Testsystem, 2007): The Sensorimotor Coordination Test (Prieler, 2002), the Two-Hand Coordination Test (Puhr, 2001), and the Time Movement Anticipation Test (Neuwirth, 2002). Each of the three tests takes about ten minutes; the first two measure a user's eye-hand and hand-hand coordination, the last one assesses an operator's ability to cope with delay. After having completed this testing, the main experiment was carried out (see Sections 3 and 4). Although there are various ways of measuring a user's performance, in all of these tasks *completion times* were a good indicator.

All participants answered a questionnaire, which was suggested by Scheuchenpflug (2001). It assesses three aspects of the presence construct, which are all relevant against a human factors background. The first factor measures the perceived quality of the interface. The items of the second factor ask about a user's current motivation and her involvement. The third factor measures the amount of spatial presence and expresses how well a human operator is able to focus her attention on a certain remote environment.

In the following two sections the main experiments are presented, whereas the results of the pretesting are discussed in Section 5.

3 Multi-Degree of Freedom Control

As most telepresence systems afford spatial inputs, three *translational* (horizontal x, vertical y, depth z) as well as three *rotational* (yaw θ_X, pitch θ_Y, roll θ_Z) degrees of freedom (DOF) are to be commanded. When reviewing the literature on multi-degree of freedom control, there are at least three issues that are relevant for the design of telepresence systems:

a). Zhai and Senders (1997a, b) studied various spatial input devices and found that about one fourth of all input commands are not on target and thus are uncoordinated.

b). Human operators tend to command subgroups, whereby either translational or rotational DOF are coordinated simultaneously (Masliah & Milgram, 2000; Todorov & Jordan, 2002). This was also observed by Imai and Garner (1965) when studying spatial perception. Within this experiment, humans tended to perceive translational and rotational DOF as separate units. In consequence, some teleoperations (e.g., space assemblies) might benefit from a bimanual input control, in which the rotations are steered by one hand and the translations are commanded by the other.

c). The DOF are not coordinated equally well. Motions with varying *depth* are commanded less efficiently than horizontal or vertical movements. When comparing different studies, the observed error ranges from 10% (Ware & Balakrishnan, 1994) up to 400% (Massimino, Sheridan, & Roseborough, 1989). These variations can be due to different experimental settings (e.g., task, input device, and availability of visual depth cues). Human operators seem to have much more difficulty in commanding rotational than translational DOF. Zhai and Milgram (1998) found an error increase of about 580%; Ware and Rose (1999) reported that it took about four times longer to rotate three-dimensional objects than to position them. To some extent this may be caused by joint constraints and by the time needed to reposition an input device. For this reason, it is not surprising that rotations are handled much faster with a Spaceball than with a data-glove. However, it is also reasonable that rotational movements increase the mental effort (see Shepard & Metzler, 1971). This cognitive load might be reduced by providing special input devices that have the same physical shape as the object at hand.

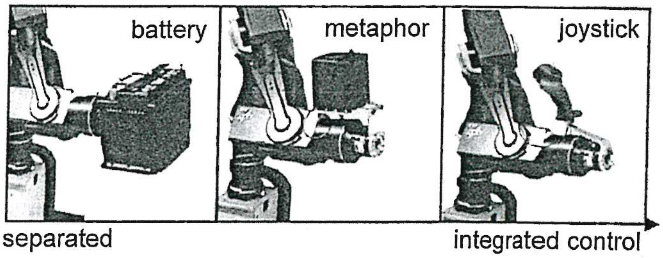


Figure 1. *Experimental setup for studying human motor control of multiple DOF. Three different input devices were provided, which are assumed to support either a more separated or a more integrated control of translational-rotational movements. To avoid any interference, all input devices were mounted on a manipulator.*

To gain a deeper insight into these issues, the following hypotheses were studied in an experiment:

H_1 Even with state of the art devices, a perfect, simultaneous coordination of spatial inputs is not to be expected.

H_2 Despite the users' tendency to command translational and rotational subgroups, an integrated or separated control of DOF also depends on the input device.

H_3 Though movements in the depth dimension are steered less efficiently than horizontal or vertical motions, this error is compensated for by the use of stereoscopic view.

H_4 Rotational movement coordination is demanding and can be improved by special purpose devices.

3.1 Experimental Setting

A peg insertion scenario, which is related to virtual product development, was realized as an experimental task and the participants ($N = 11$) were instructed to assemble a virtual battery into a car body. After a sufficient training period, the subjects repeated the task six times with three different input devices. In half of the trials they wore polarization glasses and in the other half they performed the task without stereo view (see Figure 1).

By adapting the plastic housing of a real car battery, an application specific input device was realized. Taking a closer look at the real world task, the battery is to be picked up, guided to the target position, and assembled by rotational movements. Though the task affords all DOF, translational and rotational motions are executed *sequentially* rather than simultaneously.

Furthermore, the participants were asked to assemble the virtual battery by use of a joystick. This input device is known for enabling a *simultaneous* control of translational-rotational movements (Buxton, 1986). A *medium position* between both devices was realized by a box, which constituted a metaphor for the battery.

To achieve a better comparability, all three input devices—the battery, the metaphor, and the joystick—were mounted on a manipulator, which was positioned in front of a projection screen and which was not required to be repositioned for rotational movements. Within each condition the participants' sensation of presence (Scheuchenpflug, 2001, see Section 2), their motion trajectories, and their completion times were recorded.

3.2 Results

In order to analyze a participant's motor control performance both a *temporal* and a *spatial* index of coordination are to be regarded:

3.2.1 Temporal Index of Coordination. Whenever two DOF are coordinated simultaneously, their movement errors will increase or decrease at a certain point in time *i* together. This is indicated by a correlational relationship greater than zero (see Zhai & Senders, 1997b). Thus, for instance, $r_{error}(X_i, Y_i) > 0$ denotes a coordinated behavior as the movement errors along the horizontal and the vertical dimension either increase or decrease together. In contrast to this, $r_{error}(\theta_{Xi}, Z_i) < 0$ indicates an uncoordinated behavior as an error reduction along the yaw angle corresponds to an error increase in the depth dimension, and vice versa.

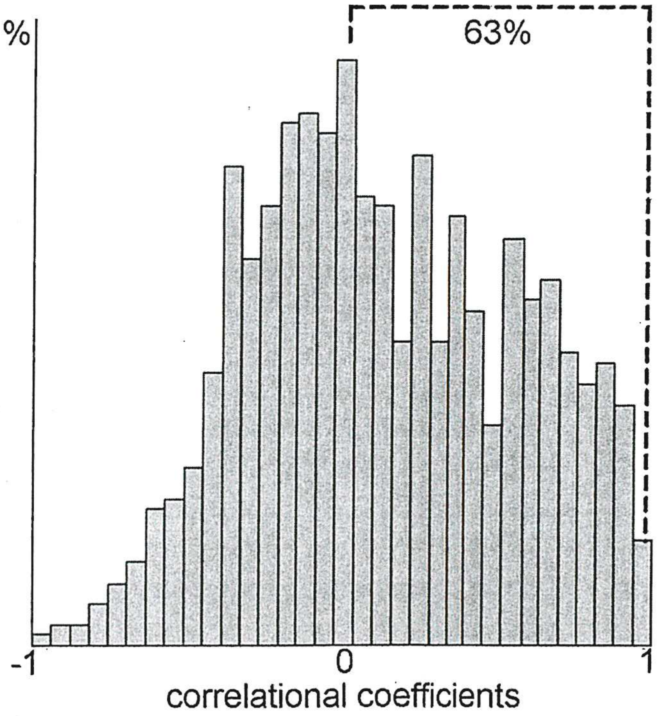


Figure 2. *Index of coordination. If two DOF are coordinated simultaneously, their movement errors will increase or decrease together. This is indicated by a positive correlational relationship between two DOF. An overall index of coordination is provided by the percentage (ordinate) of all correlational coefficients (abscissa) which are greater than zero. In this case, 63% of all movements are coordinated.*

For each experimental condition 15 pairs of correlational coefficients are to be considered: three translational $[r_{error}(X_i, Y_i), r_{error}(X_i, Z_i), r_{error}(Y_i, Z_i)]$, three rotational $r_{error}(\theta_{Xi}, [r\theta_{Yi}), r_{error}(\theta_{Xi}, \theta_{Zi}), r_{error}(\theta_{Yi}, \theta_{Zi})]$, and nine translational-rotational DOF $[r_{error}(X_i, \theta_{Xi}), r_{error}(X_i, \theta_{Yi}), r_{error}(X_i, \theta_{Zi}), r_{error}(Y_i, \theta_{Xi}), r_{error}(Y_i, \theta_{Yi}), r_{error}(Y_i, \theta_{Zi}), r_{error}(Z_i, \theta_{Xi}), r_{error}(Z_i, \theta_{Yi}), r_{error}(Z_i, \theta_{Zi})]$. In total there are 990 (15 × 6 trials × 11 subjects) correlational coefficients. By summarizing the percentages of positive and negative coefficients an overall index of coordination is provided (Figure 2). Within this experiment, 63% of all coefficients are greater than zero and thus, indicate a coordinated movement of two DOF. In consequence, 37% of all movements are uncoordinated (H_1).

To provide a more detailed interpretation, the amount of coordinated behavior is derived both for the movement dimensions (translational, rotational, and translational-rotational) and for the input devices (battery, metaphor, and joystick) separately. The percentages of positive correlational coefficients are summarized in Table 1.

Table 1. *Percentages of Simultaneously Coordinated Movements*

%	Battery	Metaphor	Joystick	Mean
translational	100	77	79	85
rotational	65	42	58	55
translational-rotational	40	54	53	49
mean	68	58	63	63

When comparing the movement dimensions, the participants are best in controlling translational DOF simultaneously. Just the same, it becomes apparent that the assembly task succeeds best with the battery as input device. A further interesting outcome is gained by a two factor analysis of variance. This procedure reveals a significant interaction effect, which can be described in more detail by Bonferroni post-hoc tests. The participants are able to coordinate translational DOF better when using the battery instead of the metaphor ($T = 4.30, p < .01$) or the joystick ($T = 6.20, p < .01$). In contrast to this, a simultaneous control of translational-rotational DOF succeeds better with the metaphor ($T = -4.21, p < .01$) or the joystick ($T = -4.43, p < .01$) than with the battery. Thus, both the joystick and the metaphor encourage a more integrated control of translational and rotational movements compared to the battery (H_2).

3.2.2 Spatial Index of Coordination.

Commanding multiple DOF simultaneously is only one criterion of coordination. Just the same, it is also essential that the assembly path is close to the optimal trajectory. Thus, for every point in time i the Euclidian distance T_i between the actual point t_i and the target point t_n is determined to derive the mean quadratic error (see Zhai, 1995).

$$T_{\mathrm{MQE}} = \sqrt{\frac{\sum_{i=0}^{N} (t_i - t_n)^2}{N}} \qquad (1)$$

The movement errors are analyzed for each of the six DOF separately (Table 2): In average, the mean rotational movement error is significantly larger (about four times) than the translational error ($T = -39.14, p < .01$).

Table 2. *Mean Quadratic Movement Errors (MQE) for All Six DOF*

Translations		Rotations	
X_{MQE}	0.0537	$R_{x\mathrm{MQE}}$	1.6681
Y_{MQE}	0.1949	$R_{y\mathrm{MQE}}$	0.1650
Z_{MQE}	0.1911	$R_{z\mathrm{MQE}}$	0.1376
mean	0.1466	mean	0.6569

An analysis of variance revealed no significant differences between the three translational movement errors (X_{MQE}, Y_{MQE}, Z_{MQE}). However, it seems to be a little bit more difficult to steer motion along the vertical and the depth dimension than along the horizontal axis. In contrast to this, there are significant differences between the three rotational errors ($R_{x\mathrm{MQE}}$, $R_{y\mathrm{MQE}}$, $R_{z\mathrm{MQE}}$). Though some rotations are commanded better than translations, pitching ($R_{x\mathrm{MQE}}$) was particularly error prone. It was 12 times less efficient than rolling ($R_{z\mathrm{MQE}}$); this difference is statistically significant ($T = -1.54, p < .01$).

The inefficient pitching motion may either be due to visual constraints or it may be caused by the input device (Figure 3 left). To provide a more detailed interpretation, a conjoint analysis was carried out (Backhaus, 2000). This statistical procedure is highly useful for designing new interfaces; it breaks down a system into its components and determines the utility of each attribute to the overall target criterion. Thus, it is possible to fig-

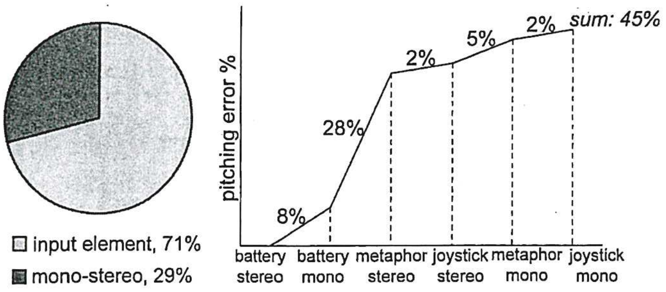


Figure 3. *Spatial coordination. A conjoint analysis revealed that spatial coordination is mainly determined by the input device and less by the availability of stereo view (left). To describe the difficulties for* R_{xMQE} *motions in more detail, the conjoint procedure is also used to derive the pitching errors for every experimental condition. The largest increase in error (28%) was found when replacing the battery with the metaphor (right).*

ure out an optimal combination and to derive the features a new system should have. The conjoint technique revealed that the spatial coordination of multiple DOF is mainly (71%) determined by the input device and depends less (29%) on the availability of stereo view (H_3).

The conjoint procedure is also helpful to explain the relatively large R_{xMQE} value in more detail. Therefore, the pitching error was derived for every experimental condition (Figure 3, right). It varied by about 45% over the whole experiment. The smallest error occurred when using the battery under stereo view; it increased by about 8% when stereo view was missing. Changing the input device and using the metaphor instead of the battery caused the largest (28%) increase in error. In consequence, it may be assumed that a special purpose device—such as the battery—reduces rotational movement errors effectively (H_4).

3.3 Discussion

Even with state of the art input devices, human operators seem to have difficulty in steering multiple DOF. Within this study about one third of all input commands was not on target. Probably due to a more difficult experimental setting this was even less than reported earlier by Zhai and Senders (1997a, b).

When taking a closer look at the motion dimensions, it is apparent that the coordination of translational DOF is given priority. As the rotational error (unlike the translational error) is limited to 360°, this strategy is reasonable. In order to optimize human motor control only the DOF needed for a certain task should be provided (H_1).

Despite the human tendency to perceive translations and rotations independent of each other, the outcome is also determined by the input device. To assemble the battery a separate control of translations and rotations is needed and thus a joystick, which supports a more integrated control, was inferior. In contrast to this, the joystick may be superior for tracking tasks, which afford fast, translational-rotational corrections (H_2).

Although the availability of stereoscopic information improved the motion efficiency, this must not be overestimated. Choosing the appropriate input device turned out to be more than twice as important (H_3).

It could not be confirmed that it is particularly difficult to control motion in the depth dimension or rotations in general (Zhai & Senders, 1997a, b). However, it is to be mentioned that the here chosen manipulator configuration should enhance rotational movements (e.g., no mental rotation needed by positioning the manipulator in front of the screen; no repositioning needed during rotations). Irrespective of the input device, only pitching along the x-axis turned out to be demanding within this setup. As this could be improved by using the battery, it can be concluded that rotational movements are mentally demanding and may be improved by a spatial input device, which reveals the same physical shape as the working object (H_4).

4 Bimanual Input Control

As most real world tasks involve both hands working together, it is not only important to focus on the control of multiple DOF, but also to consider bimanual inputs. While this may seem a somewhat obvious observation to make, it is surprising that there has been little formal evidence of precisely what advantages two hands can bring to teleoperative manipulation. For real world tasks this can easily be illustrated with the example of handwriting. Contrary to the common belief that handwriting is a unimanual action, Athènes (1984) found that the spontaneous writing speed was slowed down by about twenty percent when instructions prevent participants from touching the page with their nonpreferred hand. This is evidence that both hands do contribute to the overall performance in real world tasks, even in actions which seem to be unimanual.

For human–computer interaction the effect is less obvious. Some researchers find bimanual input control to be superior to unimanual, whereas others do not: Kabbash, Buxton, and Sellen (1994), for example, compared different input techniques for a drawing task. They found that a one-handed technique outperforms a two-handed pointer technique, even though a division of labor between hands was possible. Balakrishnan and Kurtenbach (1999) studied a docking task and found the bimanual technique to be significantly faster only for the last set of trials. In another experiment, Balakrishnan and Hinckley (2000) observed that, as the task difficulty increased, the participants stopped bimanual movements and adopted a sequential style, first moving one cursor and then the other. In contrast to this, Leganchuk, Zhai, and Buxton (1998) showed that participants gained benefit from a bimanual technique from the very beginning and that the effect became even larger the more difficult the task was. Due to the ambiguity of these empirical findings there are at least three hypotheses for further research:

a). Referring to the studies of Balakrishnan and others (Balakrishnan & Kurtenbach, 1999; Balakrishnan & Hinckley, 2000) it may be assumed that bimanual input increases the *sensorimotor load* on an inexperienced operator and requires training before paying off. For this reason it is likely that only users with higher sensorimotor abilities will benefit from a bimanual technique.

b). One risk of two handed input is to create a "tapping the head and rubbing the stomach" situation (Kabbash et al., 1994). That is, the users spend more time on coordinating the actions of their hands than on manipulating the task. In order to limit additional cognitive costs it seems to be reasonable to use *similar devices* for both hands.

c). These differences have to be analyzed carefully, otherwise adding a second device might even be worse than doing without it. From a technical point of view, bimanual interaction requires a pair of input streams and there is no reason for designing the input in the one hand different from that in the other. At the same time, it is obvious that the nonpreferred hand should be used for simpler or less accurate tasks (Raisamo, 1999). However, according to Todor and Doane (1978) there are situations in which the nonpreferred hand actually performs better than the dominant hand. When studying rapid aimed movements they found that the nondominant hand is superior for tasks with long distances and large objects. A similar conclusion can be drawn from a study in which right-handed subjects were instructed to produce random motion on a screen by controlling a pair of knobs (Guiard, 1987). Though the participants were asked to move as unpredictably as possible, their right hands tended to move faster and with smaller amplitudes than their left hands. In consequence, both hands seem to be specialized for working at different levels of scale. Whereas the *nonpreferred* hand shows a *macrometric specialization,* the *preferred hand* displays a *micrometric specialization.* Kabbash, MacKenzie, and Buxton (1993) studied pointing and dragging tasks. They, too, found an advantage of the dominant hand for small targets and small distances, while there was no significant difference for larger targets and larger distances. In contrast to the traditional view that one hand is superior to the other, the most important conclusion gained from these experiments is that both hands are complementary; each having its own strength and weakness. In order to develop bimanual interfaces more effectively the following hypotheses were addressed within an experimental study:

H_5 Devices that are designed to cover a larger workspace will perform better in the nondominant hand than in the dominant hand.

H_6 Two similar devices for both hands will yield better results.

H_7 A bimanual standard input increases the motor demand in an early learning period and only users with higher sensorimotor abilities will benefit from two-handed techniques.

4.1 Experimental Setting

There is a basic dilemma when comparing different interfaces. On the one hand, the interfaces differ in multiple dimensions and one common pitfall is to compare apples with oranges. On the other hand, an absolutely fair comparison across different input devices would be impractical. To face this dilemma, four rather different stylus and mouse devices were regarded.

Both a *PHANToM desktop* and a *PHANToM premium* (SensAble Technologies Inc.) were considered that differ mainly in their range of motion. Whereas the PHANToM desktop is controlled by hand movements pivoting at the wrist, the PHANToM premium enables arm movements pivoting at the elbow. As the particular strength of the nondominant hand lies in its large range of movement, it is reasonable to expect that the PHANToM premium will yield better performance when being controlled by the nondominant hand.

Furthermore, a *Spacemouse* (3D-Connexion, Logitech Company) and a *computer mouse* were also considered in the experiment. Since the conventional computer mouse is a two-dimensional device, a software adaptation was necessary to enable three-dimensional navigation. We applied a common technique, that is, pressing a mouse button down to switch vertical motion to motion in the depth dimension. Though this metaphor is less intuitive, the computer mouse was also considered as the users are highly accustomed to it. The Spacemouse is similar to the basic computer mouse, but instead of moving it on a table, it consists of a rate-controlled moveable ball. It does not need to be repositioned and thus is distinguished by an unlimited movement range. Since both the PHANToM premium and the Spacemouse are designed to cover a large workspace, both devices will yield better performance when being controlled by the nondominant hand (H_5). Besides optimizing the working conditions for each hand, an intuitive interaction syntax is required. Thus, for instance, two PHANToMs are likely to perform better than a PHANToM combined with a Spacemouse or a computer mouse (H_6).

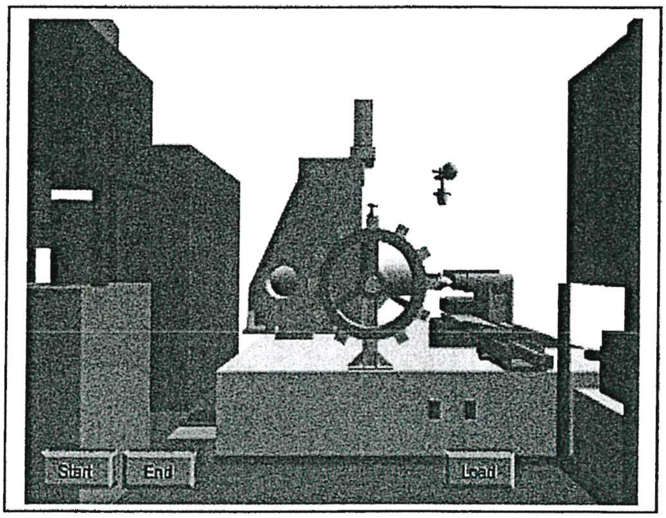


Figure 4. *Experimental task. After starting the scenario several tools had to be loaded in the environment in order to assemble them on a machine wheel.*

In most experiments the two variables "handedness" and "input device" are confounded. In order to determine the influence of both parameters all possible combinations of these four devices were considered. Thus, four one-handed and 16 two-handed configurations were distinguished. Since the participants might become fatigued when running through 20 experimental conditions, only six combinations were presented by a reduced Addelman design and the remaining values were derived by a conjoint analysis (see also Section 3.2).

The experimental study was carried out by 25 right-handed participants. After a sufficient practice session a virtual assembly task was presented, which requires point-and-click as well as pick-and-place elements. To avoid any bias toward an interface, the task afforded both translational as well as rotational movements (Figure 4).

When working with two devices, a division of labor between the hands is possible. While the one hand may do all the button-clicks, the other hand can concentrate on the assembly. The participants were reminded to take advantage of this, but they were not committed to

Table 3. *Bimanual Configuration**

	Nondominant	Dominant
Without input device	**1.7864**	—
PHANToM premium	1.2709	–0.5023
PHANToM desktop	–0.0687	**1.4894**
Spacemouse	–0.6937	–1.5847
Computer mouse	–2.7449	0.5977

*A conjoint analysis was carried out to derive the part worth utilities for each experimental condition. Thereby, high utility values indicate a high preference. The most preferred configuration is in bold.

it to ensure a natural input situation. As every participant ran through all experimental conditions the trials were systematically varied to avoid serial-position effects. Within every trial the completion times were recorded and after each assembly the participants had to answer a presence questionnaire (Scheuchenpflug, 2001; see Section 2). At the end all possible combinations (including those of the experimental setting) were described verbally and the participants were asked to do a preference ranking.

4.2 Results

The preference ranking corresponded very much to the reported sensation of presence and to the completion times. For this reason, the results presented below do mainly refer to the preference order. A conjoint procedure showed that the acceptance of an interface is determined to 59% by the parameter "handedness," whereas the variable "input device" accounted for 41%. Thus, the influence of both variables is almost similarly important. Since these percentages do not give any recommendation on how the interface is to be designed, the utilities of each configuration were figured out next (Table 3).

Most users do not want to have a second device for the left hand. In case they do, they would prefer a PHANToM premium. In contrast to this the PHANToM desktop and the Spacemouse are less accepted as nondominant input devices, but they are more preferred than the computer mouse. For the right hand, a PHANToM desktop is the device of choice. Despite its navigational problems, the computer mouse outperforms the PHANToM premium and the Spacemouse. To conclude, most participants prefer to work one-handedly with a PHANToM desktop.

When taking a closer look at the utilities of the nondominant input, two conditions, without input device and PHANToM premium, are ranked similarly. There are two possible interpretations. First, the participants do not care whether they have a PHANToM premium or no input device at all for the left hand. Second, the sample is heterogeneous; whereas some participants prefer to work with one hand, others favor a bimanual configuration. In order to explore the homogeneity of the sample, the dataset was run through a hierarchical cluster analysis (Euclidian distances as proximity measure, Ward algorithm for fusion; see Backhaus, 2000). This procedure revealed three different groups of users (Table 4). Group 1 prefers working two-handedly with a dominant PHANToM desktop and a nondominant PHANToM premium. In contrast to this, the members of the Groups 2 and 3 want to work with one device, a PHANToM desktop. Compared to Group 2, the Group 3 rejects an additional interface more strictly.

To explain the differences between the three groups, it is helpful to refer to the sensorimotor skills as assessed during the pretest session (Figure 5). It turned out that the members of Group 1 are not only better in judging the speed of moved objects (Time-Movement Anticipation Test), but are also better in steering bimanual movements (Two-Hand Coordination Test). For this reason, it can be concluded that this bimanual setting increased the motor load and only users with higher sensorimotor abilities preferred working two-handedly (H_6).

Finally, it is to be answered whether two similar interfaces are better than any other combination. Irrespective of whether a PHANToM-PHANToM or a Mouse-PHANToM configuration is used, dominant and nondominant inputs are often observed to be similar (Table 5, left). The conditions differ only

Table 4. *Bimanual Configurations for Distinct User Groups**

	Nondominant			Dominant		
group	1 ($N = 12$)	2 ($N = 5$)	3 ($N = 7$)	1 ($N = 12$)	2 ($N = 5$)	3 ($N = 7$)
Without input device	1.2969	**2.0791**	**2.5513**	—	—	—
PHANToM premium	**2.6098**	1.2618	0.2302	–0.6113	–0.4835	–0.2671
PHANToM desktop	0.2086	0.0150	–0.8514	**1.8221**	**1.6022**	**0.5329**
Spacemouse	–0.1414	–1.4708	–0.9314	–2.3495	–1.3495	–0.0786
Computer mouse	–3.9739	–1.8851	–0.9987	1.1387	0.2308	–0.1871

*For each experimental configuration and each of the three user groups, the part worth utilities are derived by conjoint procedures. For every group the most preferred configuration is in bold.

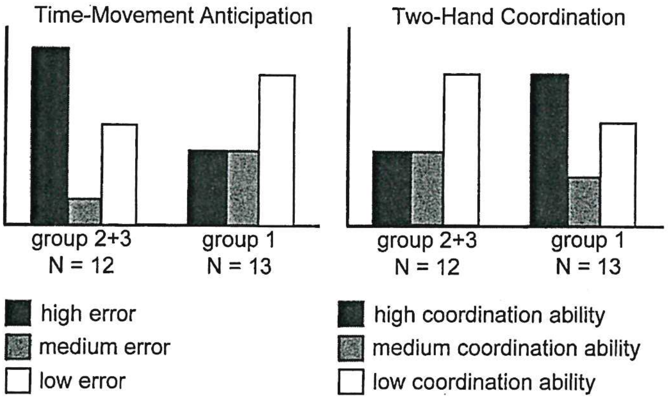


Figure 5. *Sensorimotor skills. Users who prefer two devices (Group 1) are better in the Time-Movement Anticipation Test (Neuwirth, 2002) and the Two-Hand Coordination Test (Puhr, 2001) compared to users who prefer one device (Group 2, 3). There were no differences concerning the more general Sensorimotor Coordination Test (Prieler, 2002; Section 2).*

when analyzing the spatio-temporal input behavior (Table 5 right). With a Mouse-PHANToM configuration both devices are mainly steered sequentially, much more simultaneous input commands occurred with two similar devices (H_7).

4.3 Discussion

As the two parameters, handedness and input device, are almost equally important, finding the appropriate input device is just as important as solving the question of handedness properly. Despite the argument that two devices are a natural metaphor to our hands, a bimanual input did not pay off for everyone. Here, a bimanual configuration increased the motor load on the operator and only participants with higher sensorimotor abilities yielded the benefit from an additional device (H_7). In order to be effective, bimanual interfaces must be designed carefully and at least two aspects have to be considered.

First, two similar devices should be available to avoid switching costs between the hands. For instance, more simultaneous bimanual inputs occurred when two PHANToMs were used instead of a Mouse-PHANToM configuration (H_6).

Second, the nondominant input device should cover a larger workspace than the dominant device. Here, the PHANToM premium, which requires less indexing, outperformed the PHANToM desktop for the nondominant hand. The rate controlled Spacemouse offers a large range of motion, too. Although this device is more accepted in the nondominant than in the dominant hand, it is not preferred by the participants. This might be due to the fact that rate control provides a less natural input mapping than position control (Zhai, 1995). It is likely that the Spacemouse will yield better performance for highly trained expert users (H_5).

Table 5. *Spatio-Temporal Input Behavior**

Percent of input commands	Dominant	Nondominant	Simultaneous	Sequential
PHANToM-PHANToM	53.42	46.58	75.00	25.00
Mouse-PHANToM	43.75	56.25	18.52	81.48

*Irrespective of whether a PHANToM-PHANToM or a Mouse-PHANToM configuration is available, both hands are used almost equally often (*left*). However, much more simultaneous movements were to be observed within the symmetric PHANToM-PHANToM configuration (*right*).

5 Presence and Performance

So far mainly human factors issues, which are related to the control of multiple degrees of freedom and bimanual input, have been discussed. As in each experiment, both presence and performance are measured; the relationship between these two variables shall be regarded in more detail now. Although this interaction has already been studied intensively in literature, it still lacks empirical validation: While in some studies a positive association could have been observed, others failed to achieve statistically significant results (Bystrom, Barfield, & Hendrix, 1999; Welch, 1999; Nash, Edwards, Thompson, & Barfield, 2000; Youngblut & Huie, 2003). This empirical ambiguity might be due to methodological reasons:

a). Most often the relationship between presence and performance is studied only within a single research context (e.g., a specific input-output configuration). For this reason, it is often not possible to draw more general conclusions.

b). A common statistical technique to study the relationship between two or more variables is through a correlational analysis. However, it is to be mentioned that no causal conclusions can be drawn by this approach. On the one hand, it may be argued that a higher degree of presence causes a more natural and thus more successful task accomplishment. On the other hand, it may also be reasoned that a user is motivated by a good performance and thus he reports a higher degree of presence. Within the context of teleworking environments this question of cause-and-effect is crucial. Increasing a user's sensation of presence is only reasonable when the first assumption holds true and presence actually does imply performance.

c). It is also possible that there is a more complex interaction that is moderated by further variables (IJsselsteijn, de Ridder, Freeman, & Avons, 2000; Mania & Chalmers, 2001; Sadowski & Stanney, 2002). For instance, such inter-individual differences between the human operators may play an important role, but are most often not considered.

To overcome these methodical drawbacks, a meta-analytical research approach was chosen. By this technique the results of several studies, addressing a set of related research hypotheses, are combined. Here, the outcomes of the two experiments mentioned above (see Sections 3 and 4) and that of a further study (Petzold et al., 2004) are summarized. In total, 96 subjects are regarded, all of whom participated in the pretesting session (see Section 2). Although the experiments focus on specific hypotheses, the same variables were assessed, namely *sensation of presence* and completion times as an indicator of *performance*. To draw comparisons between the different studies, the time values were categorized between 1— very fast and 5—very slow for each experiment. For sure, some information is lost by transforming a metric variable into a 5-level ordinal scale. But what is most important is that the performance ranking within each study remains the same. The following questions are addressed:

Table 6. *Coefficient of Determinations r^2 and Corresponding Significance Levels p*

	Sensation of presence	Performance
Immersive Tendencies Questionnaire	$r^2 = .21; p = .01^{**}$	$r^2 = .14; p = .07$
Sensorimotor Coordination Test *Scale: Mean rotational coordination*	$r^2 = .01; p = .12$	$r^2 = .16; p = .02^{*}$
Time-Movement Anticipation Test *Scale: Spatial anticipation*	$r^2 = .04; p = .10$	$r^2 = .21; p = .01^{**}$

*Results that are significant on a .05-level or on a .01-level are marked by one or two asterisks, respectively.

Q_1 Does a user's tendency of immersion also influence his task performance?

Q_2 Which (if any) sensorimotor skills are important for commanding telepresence systems?

Q_3 How is the relationship between presence and performance to be interpreted in terms of causation?

5.1 Results

A statistical indicator that expresses how certain one can be in making predictions from a moderator x_{Mod} to a criterion variable x_{Crit} is the *coefficient of determination* (CoD). This measure is the square of the Pearsonian correlation coefficient *r;* it represents the ratio of the variation shared by both parameters to the variation of criterion and moderator separately (see Equation 2). Although the CoD expresses the strength of the relationship, it does not indicate whether the observed correlation coefficient occurred by chance if the true correlation is zero. Therefore, it is necessary to do additionally significance testing.

$$r^2 = \frac{\mathrm{Cov}(x_{\mathrm{Mod}}, x_{\mathrm{Crit}})}{\mathrm{Var}(x_{\mathrm{Mod}})\,\mathrm{Var}(x_{\mathrm{Crit}})};\ 0 \le r^2 \le 1 \qquad (2)$$

The CoDs as well as the probabilities of the correlation coefficients are derived for all pretest variables concerning the two criteria, sensation of presence and performance. The most relevant results are summarized in Table 6.

In general, the CoDs are very low. For this reason differential-psychological variables, such as a user's tendency of immersion or her sensorimotor skills, seem to be only of little relevance for predicting the sensation of presence or performance. Anyway, for the presence parameter the highest value is to be observed for the ITQ scores. Here, 21% of the total presence variation can be explained by a user's tendency of immersion; the residual variance, 79%, remains unexplained. Nevertheless, the relationship can be described as very significant in terms of statistics. Though a user's tendency of immersion is also somewhat predictive for her performance, this result is not significant (Q_1).

The impact of sensorimotor skills on a user's task performance must not be overestimated. Only certain scales of the Time-Movement Anticipation test (Neuwirth, 2002) and the Sensorimotor Coordination Test (Prieler, 2002) turned out to be relevant; the results of the two hand coordination test (Puhr, 2001) seemed to be less important. In more detail, the ability to anticipate and to command rotational movements is to be pointed out as significant in terms of statistics. Thereby, it is to be mentioned that the ability of anticipation refers only to the spatial and not to the temporal domain (Q_2).

Both criterion variables—presence and performance—are correlated ($r^2 = .16$; $p = .04$, 5% significance level). As mentioned above, this does not imply a causal relationship per se. In order to determine whether a high sensation of presence actually causes a successful task accomplishment or whether the reverse relationship holds true, the following argumentation is helpful (Figure 6): The ITQ scores are correlated with the presence parameter and to a certain extent also with the performance indicator. In contrast to this, the sensorimotor skills (mean rotational coordination and spatial anticipation) have a significant impact on the completion times,

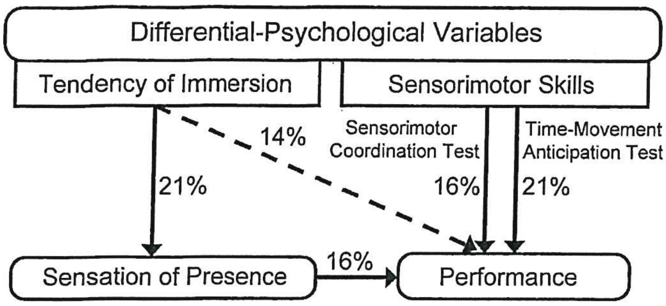


Figure 6. *Strengths as well as directional relationships of moderator and criterion variables as indicated by the Coefficient of Determinations.*

but are almost independent of an operator's sensation of presence. Thus, a task may have been accomplished successfully even without reporting a high degree of presence. In consequence, the relationship can only be interpreted meaningfully when arguing that a high sensation of presence has a positive impact on performance, and not vice versa (Q_3).

5.2 Discussion

Within these studies differential-psychological variables had only a small impact on the outcome of a telemanipulation task. Although highly immersive users take more benefit on applications for which a sense of being there would be helpful (e.g., virtual psychotherapy), they do not yield better performance in a teleworking setting (Q_1).

The telepresence systems that have been studied here represent the current state of the art technology and thus, these systems are not ideal (in terms of real anthropomorphic interfaces). However, given the available technology, the results show that certain sensorimotor skills (spatial anticipation of movements, control of rotations) are helpful when interacting with telepresence systems. If more sophisticated interfaces are available in the future, these skills will probably become less important. Nevertheless, it may be reasonable to consider an appropriate assessment procedure for certain jobs (e.g., robot assisted surgery). Just the same, this result is also important for improving current systems. Also, as users with lower sensorimotor skills should be able to achieve good results, the interfaces have to facilitate rotational movements, and the necessity of spatial anticipation should be reduced to a minimum. This finding is in line with other studies mentioned in Section 3 (Q_2).

A meta-analytical approach revealed a positive correlation between presence and performance. By taking into account further variables, a causal interpretation is possible and it is to be concluded that a higher degree of presence actually implies a faster task accomplishment. Within this work, performance was only operationalized by completion times and further, quality related performance criteria were not considered. Although it is difficult to compare the quality of various experiments, this limitation needs to be mentioned (Q_3).

6 Conclusion

Within the last few years a lot of effort has been put into the development of new telepresence technology. In contrast to this, far less research has been carried out to provide guiding design principles from a human factors point of view. Here, the results of two experimental studies are presented. The following more general, but relevant results for the design of telepresence systems are gained. (See also Deml, 2004.)

a). When realizing new interfaces, it is to be kept in mind that even with sophisticated technology about one third of all input commands will be uncoordinated. This problem may be minimized by enabling only those movement dimensions that are task-relevant, while freezing those that are not required. In practice, this is often solved through task-oriented automatic assistance by tuning low level control; in the field of virtual environments virtual guides and virtual fixtures are provided (Ouramdane, Davesne, Otmane, & Mallem, 2006).

b). Although human operators tend to perceive translations and rotations independent of each other, it is mainly the device that determines whether an integrated or separated control is to be observed. For this reason, it is essential to match the input device to the task requirements. Thus, for instance, a joystick will yield better results when an integrated control of translational-rotational motions is afforded. This is particularly important for tracking tasks, as here any deviation from the desired trajectory would decrease task performance immediately.

c). The movement dimensions are not homogeneous in terms of motion efficiency and more errors occur, for instance, when carrying out rotations along the z-axis. Thus, whenever a high degree of pitch is afforded, special purpose devices with the same physical shape as the working object are to be recommended. Keeping in mind that not only the anticipation of movements, but also the ability to control rotations are crucial for successful task accomplishment, this aspect should be considered thoroughly.

Besides realizing an intuitive control of multiple degrees of freedom, an appropriate design of ***bimanual interfaces*** is also often required.

d). In contrast to real world manipulations, the availability of two hands is not always better in telepresence settings. Here, only users with a higher degree of sensorimotor skills took benefit from a second input device. However, even for those users the second device has to be chosen carefully. As the motions of the nonpreferred hand are macrometric and imprecise, an isotonic device that offers a large range of motion should be used (e.g., the PHANToM premium).

Although elastic or isometric devices (e.g., Spacemouse) are designed to cover large workspaces, they are not always suited for nondominant input. As these devices are rate controlled, they are commonly less intuitive—at least for rather inexperienced users.

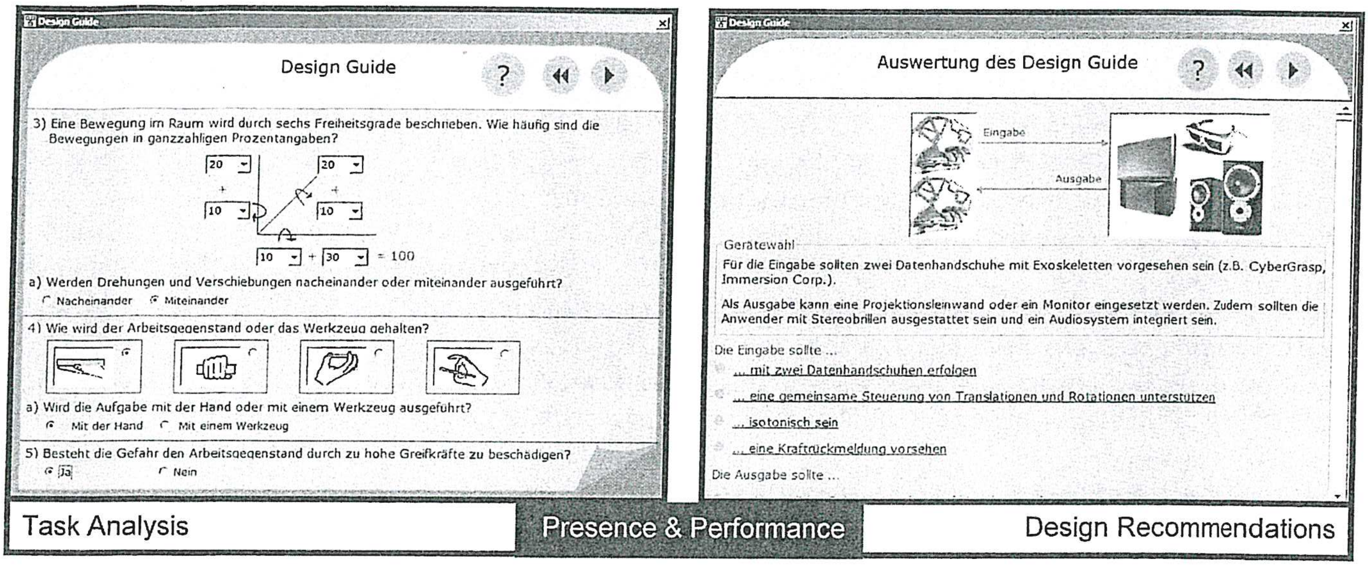
e). Although a second input device promises to have manual advantages, it is motor demanding. To provide a cognitive, bimanual frame of reference for all users, a fictive, virtual hand may be a good alternative to a second input device.

f). Finally, an issue that is rather obvious. For both hands two similar types of devices should be provided (e.g., two PHANToMs, or two mouse devices).

Within this work it was also shown that, in general, individual abilities have little influence on the task performance. For this reason, it is mainly the design of the interfaces that determines whether a certain telepresence system will be intuitive or not. As it is difficult to establish a relationship between more general experiments on the one hand and one's own application on the other hand, a kind of "automatic" evaluation would be desirable (e.g., Bowman, Johnson, & Hodges, 2001; Bowman, Gabbard, & Hix, 2002; Stanney, Mollaghasemi, Reeves, Breaux, & Graeber, 2003; Tromp, Steed, & Wilson, 2003). The results, which are gained by these and further experiments or by literature review, are integrated in a computer based tool, the "PRESENCE—*Design Guide*," to assist system developers (Figure 7).

This tool first guides users through a series of questions in order to describe a certain telepresence setting. Much attention was paid to the fact that this ***task analysis*** is relevant for a wide range of applications. For this reason rather complex scenarios were decomposed into more general subtasks (e.g., peg insertion, pick and place actions) and only these are assessed. To avoid the possibility of information being lost by such an abstract analysis, many further issues are addressed, too: the required degrees of freedom, the afforded grasping procedures, the task difficulty, the objectives (e.g., speed, precision), the working environment (e.g., range of motion), the working object (e.g., mass, stiffness, roughness), the human operator (e.g., degree of experience), and the impact of technological constraints (e.g., system delays). The applicability of the task analysis was revised by several developers of telepresence systems (e.g., minimally invasive surgery, microassembly, space assembly) within a workshop. All of them were asked to check whether the items are comprehensive, exhaustive, and in general suited to describe their system.

The information gained by the task analysis is used to predict both a user's sensation of presence and his degree of performance. The tool provides tailored ***design recommendations*** in the form of verbal descriptions. This shall be illustrated by a rather concise example. A task analysis might reveal that a lot of pitch movements are afforded, that the working space is fairly small, and that the target group is rather untrained or that no particular sensorimotor skills are to be expected. Of course, these and further items would be assessed more pre-



3) Eine Bewegung im Raum wird durch sechs Freiheitsgrade beschrieben. Wie häufig sind die Bewegungen in ganzzahligen Prozentangaben?

20 + 10; 20 + 10; 10 + 30 = 100

a) Werden Drehungen und Verschiebungen nacheinander oder miteinander ausgeführt?

○ Nacheinander ● Miteinander

4) Wie wird der Arbeitsgegenstand oder das Werkzeug gehalten?

● ○ ○ ○

a) Wird die Aufgabe mit der Hand oder mit einem Werkzeug ausgeführt?

● Mit der Hand ○ Mit einem Werkzeug

5) Besteht die Gefahr den Arbeitsgegenstand durch zu hohe Greifkräfte zu beschädigen?

● Ja ○ Nein

Gerätewahl

Für die Eingabe sollten zwei Datenhandschuhe mit Exoskeletten vorgesehen sein (z.B. CyberGrasp, Immersion Corp.).

Als Ausgabe kann eine Projektionsleinwand oder ein Monitor eingesetzt werden. Zudem sollten die Anwender mit Stereobrillen ausgestattet sein und ein Audiosystem integriert sein.

Die Eingabe sollte ...

- ... mit zwei Datenhandschuhen erfolgen
- ... eine gemeinsame Steuerung von Translationen und Rotationen unterstützen
- ... isotonisch sein
- ... eine Kraftrückmeldung vorsehen

Die Ausgabe sollte ...

Figure 7. *The "PRESENCE—Design Guide" assists in realizing new interfaces that enhance both the users' sensation of presence and their performance. System developers are guided through a task analysis and are provided with verbal design recommendations.*

cisely (e.g., percentage of pitching movements). But given this piece of information, the following may be recommended. It seems to be helpful to provide only one input device for the dominant hand, which should be position controlled and isotonic. It will be useful if the device reveals the same physical shape as the working object. To provide background information, all of these recommendations are linked to our own experiments or to further studies that are described in literature (e.g., Deml, Ortmaier, & Seibold, 2005; Petzold et al., 2004). The tool does not claim to be comprehensive, but was rather designed as a modular, expandible system to make the design of telepresence systems more effective.

Acknowledgments

This work was supported by the German Research Foundation (DFG) within the Collaborative Research Centre "SFB 453: High-Fidelity Telepresence and Teleaction System." The author would like to thank Carsten Preusche and Dr. Tobias Ortmaier (German Aerospace Center) as well as Bernd Petzold (iwb, Technische Universität München) for their very helpful cooperation.

References

Athènes, S. (1984). *Adaptabilite et developpement de la posture manuelle dans l'ecriture: Etude comparative du droitier et du gaucher.* University of Aix-Marseille II.

Backhaus, K. (2000). *Multivariate Analysemethoden: Eine anwendungsorientierte Einführung* (9. Aufl.). Berlin: Springer.

Balakrishnan, R., & Hinckley, K. (2000). Symmetric bimanual interaction. *Proceedings of the ACM Conference on Human Factors in Computing Systems,* 33–40.

Balakrishnan, R., & Kurtenbach, G. (1999). Exploring bimanual camera control and object manipulation in 3D graphics interfaces. *Proceedings of the ACM Conference on Human Factors in Computing Systems,* 53–63.

Blake, E., Casanueva, J., & Nuñez, D. (2000). Presence as a means for understanding user behaviour in virtual environments. *South African Computer Journal, 26,* 247–251.

Bowman, D. A., Gabbard, J., & Hix, D. (2002). A survey of usability evaluation in virtual environments: Classification and comparison of methods. *Presence: Teleoperators and Virtual Environments, 11*(4), 404–424.

Bowman, D. A., Johnson, D. B., & Hodges, L. F. (2001). Testbed evaluation of virtual environment interaction techniques. *Presence: Teleoperators and Virtual Environments, 10*(1), 75–95.

Buxton, W. (1986). There's more to interaction than meets the eye: Some issues in manual input. In D. A. Norman & S. W. Draper (Eds.), *User centered system design: New perspectives on human-computer interaction* (pp. 319–337). Hillsdale, NJ: Lawrence Erlbaum.

Bystrom, K.-E., Barfield, W., & Hendrix, C. (1999). A conceptual model of the sense of presence in virtual environments. *Presence: Teleoperators and Virtual Environments, 8*(2), 241–244.

Deml, B. (2004). *Telepräsenzsysteme: Gestaltung der Mensch-System Schnittstelle.* Doctoral dissertation, Universität der Bundeswehr, München, Germany. Available at http://137.193.200.177/ediss/deml-barbara/meta.html. Accessed 15 April 2007.

Deml, B., Ortmaier, T., & Seibold, U. (2005). The touch and feel in minimally invasive surgery. *HAVE 2005—IEEE International Workshop on Haptic Audio Visual Environments and their Applications.* Available at http://www.unibw.de/lrt11/team/mitarbeiter/deml/have. Accessed 15 April 2007.

Guiard, Y. (1987). Asymmetric division of labor in human skilled bi-manual action: The kinematic chain as a model. *Journal of Motor Behavior, 19*(4), 486–517.

Imai, S., & Garner, W. R. (1965). Discriminability and preference for attributes in free and constrained classification. *Journal of Experimental Psychology, 69*(6), 596–608.

IJsselsteijn, W. A., de Ridder, H., Freeman, J., & Avons, S. E. (2000). Presence: Concept, determinant and measurement. *Proceedings of SPIE: Human Vision and Electronic Imaging V,* 3959–3951.

Kabbash, P., Buxton, W., & Sellen, A. (1994). Two handed input in a compound task. *Proceedings of the ACM Conference on Human Factors in Computing Systems,* 417–423.

Kabbash, P., MacKenzie, S., & Buxton, W. (1993). Human performance using computer input devices in the preferred and non-preferred hands. *Proceedings of the ACM Conference on Human Factors in Computing Systems,* 474–481.

Leganchuk, A., Zhai, S., & Buxton, W. (1998). Manual and cognitive benefits of two-handed input: An experimental study. *ACM Transactions on Computer-Human Interaction, 5*(4), 326–359.

Mania, K., & Chalmers, A. (2001). The effects of level of immersion on presence and memory in virtual environments: A reality centered approach. *CyberPsychology & Behavior: The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society, 4*(2), 247–264.

Masliah, M. R., & Milgram, P. (2000). Measuring the allocation of control in a 6-degree-of-freedom docking experiment. *CHI'2000: Conference on Human Factors in Computing Systems,* 25–32.

Massimino, M. J., Sheridan, T. B., & Roseborough, J. B. (1989). One hand tracking in six degree of freedom. *IEEE International Conference on Systems, Man, and Cybernetics,* 498–503.

Nash, E. B., Edwards, G. W., Thompson, J. A., & Barfield, W. (2000). A review of presence and performance in virtual environments. *International Journal of Human-Computer Interaction, 12*(1), 1–41.

Neuwirth, W. (2002). *Zeit- und Bewegungsantizipation (Version. 24.00).* Mödling: Dr. G. Schuhfried GmbH.

Ouramdane, N., Davesne, F., Otmane, S., & Mallem, M. (2006). 3D interaction technique to enhance telemanipulation tasks using virtual environments. *International Conference on Intelligent Robots and Systems,* 5201–5207.

Petzold, B., Zaeh, M. F., Färber, B., Deml, B., Egermeier, H., Schilp, J., et al. (2004). A study on visual, auditory and haptic feedback for assembly tasks. *Presence: Teleoperators and Virtual Environments, 13*(1), 16–21.

Prieler, J. (2002). *Sensomotorische Koordination (Version 23.00).* Mödling: Dr. G. Schuhfried GmbH.

Puhr, U. (2001). *Zweihand Koordination (Version 23.00).* Mödling: Dr. G. Schuhfried GmbH.

Raisamo, R. (1999). *Multimodal human-computer interaction: A constructive and empirical study.* Doctoral dissertation, University of Tampere, Tampere, Finland.

Sadowski, W., & Stanney, K. M. (2002). Presence in virtual environments. In K. M. Stanney (Ed.), *Handbook of Virtual Environments: Design, Implementation, and Applications* (pp. 791–806). Hillsdale, NJ: Lawrence Erlbaum.

Scheuchenpflug, R. (2001). Measuring presence in virtual environments. *CHI'2001: Conference on Human Factors in Computing Systems,* 56–58.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171(972),* 701–703.

Slater, M. (1999). Measuring presence: A response to the Witmer and Singer Presence Questionnaire. *Presence: Teleoperators and Virtual Environments, 8(5),* 560–565.

Stanney, K. M., Mollaghasemi, M., Reeves, L., Breaux, R., & Graeber, D. A. (2003). Usability engineering of virtual environments (VEs): Identifying multiple criteria that drive effective VE system design. *International Journal of Human-Computer Studies, 58*(4), 447–481.

Todor, J. I., & Doane, T. (1978). Handedness and hemispheric asymmetry in the control of movements. *Journal of Motor Behavior, 10*(4), 295–300.

Todorov, E., & Jordan, M. (2002). Optimal feedback control as a theory of motor coordination. *Nature Neuroscience, 5*(11), 1226–2002.

Tromp, J. G., Steed, A., & Wilson, J. R. (2003). Systematic usability evaluation and design issues for collaborative environments. *Presence: Teleoperators and Virtual Environments, 12*(3), 241–267.

Vienna Testsystem. (2007). Dr. Gernot Schuhfried GmbH. Available at http://www.schuhfried.co.at. Accessed 15 April 2007.

Ware, C., & Balakrishnan, R. (1994). Reaching for objects in VR displays: Lag and frame rate. *Computer-Human Interaction, 1*(4), 331–356.

Ware, C., & Rose, J. (1999). Rotating virtual objects with real handles. *Computer-Human Interaction, 6*(2), 162–180.

Welch, R. B. (1999). How can we determine if the sense of presence affects task performance. *Presence: Teleoperators and Virtual Environments, 8*(5), 574–577.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments, 7*(3), 225–240.

Youngblut, C., & Huie, O. (2003). The relationship between presence and performance in virtual environments: Results of a VERTS study. *IEEE Virtual Reality*, 277–279.

Zhai, S. (1995). *Human performance in six degrees of freedom input control.* Doctoral dissertation. University of Toronto, Toronto, Canada.

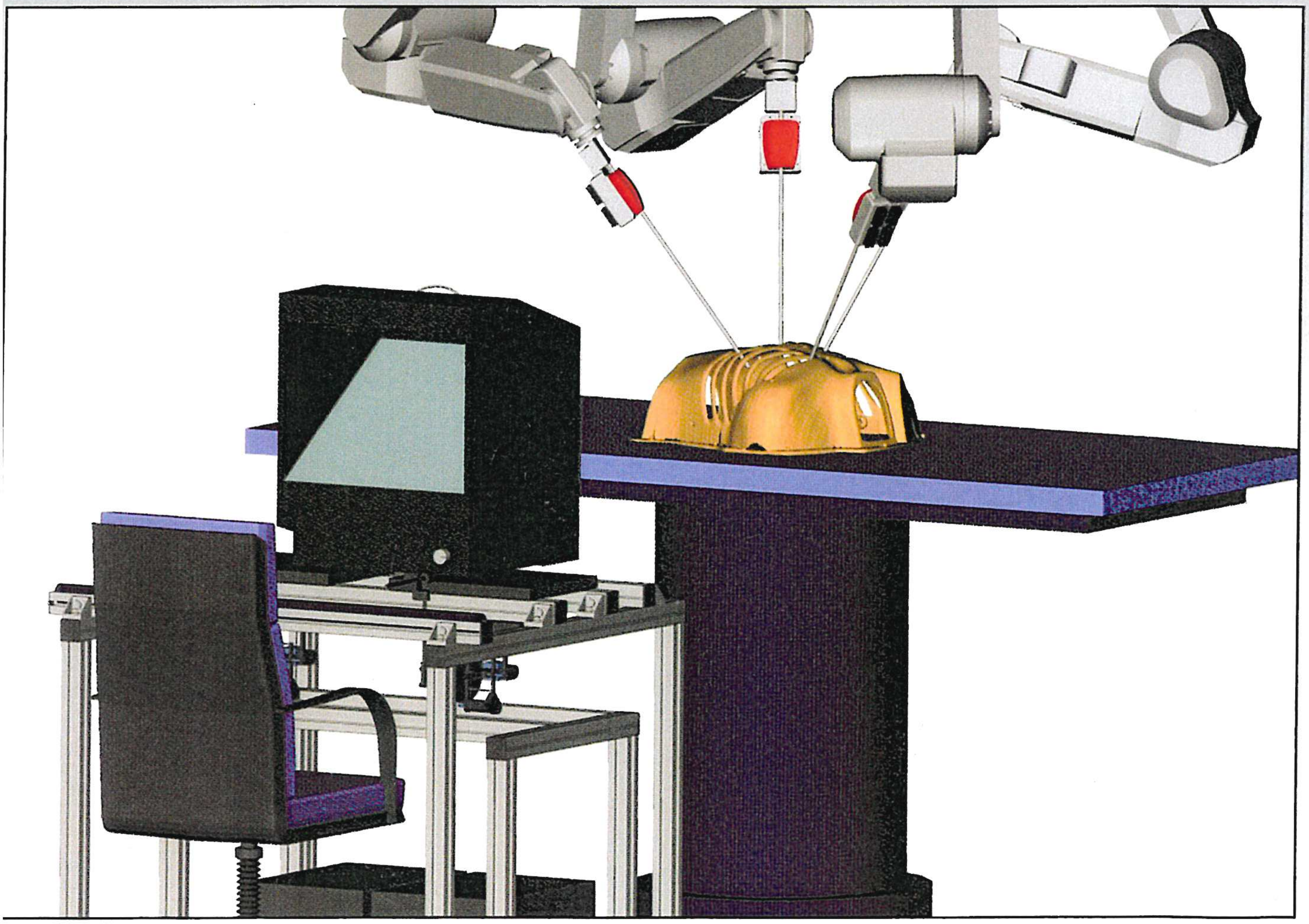
Zhai, S., & Milgram, P. (1998). Quantifying coordination in multiple DOF movement and its application to evaluating 6 DOF input devices. *CHI'1998: Conference on Human Factors in Computing Systems,* 320–327.

Zhai, S., & Senders, J. W. (1997a). Investigating coordination in multidegree of freedom control I: Time-on-target analysis of 6 DOF tracking. *Annual Meeting of the Human Factors and Ergonomic Society,* 1249–1254.

Zhai, S., & Senders, J. W. (1997b). Investigating coordination in multidegree of freedom control II: Correlation analysis in 6 DOF tracking. *Annual Meeting of the Human Factors and Ergonomic Society,* 1254–1258.

PRESENCE

TELEOPERATORS AND VIRTUAL ENVIRONMENTS



VOLUME 16 / NUMBER 5 / OCTOBER 2007

MIT PRESS