How VR-Based Reach-to-Grasp Experiments Can Help to Understand Movement Organization within the Human Brain

Abstract

This paper examines the potentials of VR technology for studying the neural organization of voluntary human movements. Here, motion studies are based on experimental set-ups in which subjects and/or patients interact with virtual instead of real objects. This VR-based approach is primarily motivated by the exact controllability of computer-generated experimental conditions. Stimuli such as appearance, characteristics, and behavior of objects can be varied and presented separately or in combination. Besides general benefits such as standardization, flexibility, and efficiency, VR provides a means to realize experimental scenarios that are very difficult or even impossible to build when using real, physical set-ups. This feature is demonstrated by the example of reach-to-grasp studies with perturbation, which play an important role for the study of human motor behavior. A first VR-based experiment is described that compares motor behavior when reaching and grasping a real and a virtual cube, respectively. The results of this experiment prove that VR technology can indeed lead to new insights about how the reach-to-grasp movement is organized within the human brain.

1 Introduction and Motivation

In the last few years, an increasing number of motion studies have been performed to determine how the human brain plans, organizes, and executes a voluntary movement. These investigations have been supported by the availability of advanced motion-tracking systems and the capability to register the kinematics of even complex movements in three dimensions at high sampling rates. Increasingly, neurologists attempt to identify the organization of human motor behavior by comparing the kinematic characteristics of movements performed by healthy subjects to those performed by patients suffering from focal brain lesions. (See, for example, Binkofski et al. (1995).)

Looking for new means to perform motion studies, researchers dealing with the neural organization of human motor behavior realize the potentials of virtual reality technology. In such studies, subjects and patients interact with virtual, computer graphic objects instead of real, physical objects. This paper will demonstrate that VR-based experiments—and especially VR-based reach-to-grasp experiments—promise new insights into human movement organization. Reach-to-grasp movements are of special interest because reaching and grasp-
ing are complex but highly automated movements, which also require the interaction with a target object. A successful reach-to-grasp operation requires that two tasks must be completed in parallel: first, the hand has to be transported towards the object (the transport component), and, second, the fingers must be adapted to the object’s size and shape (the grasp component).

Recently, several perturbation experiments have been performed to determine whether these two components are represented within the brain by two separate motor programs, and, if so, how these programs are coordinated (Jeannerod, 1981; Paulignan & Jeannerod, 1996). In perturbation experiments, one or more object characteristics—for instance, object position and/or size—are modified unexpectedly while a subject is grasping. Until recently, such experiments were insufficient to answer the above question. In these prior experiments, perturbations are usually implemented by a number of objects made of translucent material, which should be perceived by a subject as one single object (Paulignan et al., 1991a, 1991b). In perturbation experiments, one or more object characteristics—for instance, object position and/or size—are modified unexpectedly while a subject is grasping. Until recently, such experiments were insufficient to answer the above question. In these prior experiments, perturbations are usually implemented by a number of objects made of translucent material, which should be perceived by a subject as one single object (Paulignan et al., 1991a, 1991b). This effect is achieved by sequentially illuminating the objects, simulating a change of object position or size. It could be shown, however, that such complex mechanical set-ups are not only very inflexible, but can also lead to a wrong interpretation.

Typically, experimental set-ups intended for an isolated perturbation of the grasp component also slightly modify object location, thus requiring a non-desired adaptation of the transport component (Kuhlen et al., 1996b). Furthermore, by this method, a continuous movement from one position to another can be only inadequately realized.

These problems show that, so far, only insufficient and inflexible solutions exist for the creation of experimental scenarios in which subjects not only interact with static objects but with objects that change their characteristics and behavior. The next section will show that VR technology can provide a powerful and flexible means for motion studies in general and in the special case of reach-to-grasp experiments, because it enables the experimenter to easily and precisely adapt experimental scenarios to specific investigations.

2 Benefits of VR-Based Motion Studies

2.1 General Benefits

With the availability of VR technology comes the ability to study human motor behavior within virtual environments. First, such studies are of interest insofar as developers of VR devices and VR applications try to achieve an intuitive and natural interaction with virtual environments. Studies of motor behavior in real and virtual environments may give information about the quality of the developed interaction techniques. For instance, Burdea et al. (1992) and Richard et al. (1996) examined to what extent the performance of a manipulation task can be improved when providing an instrumented glove with integrated force feedback. We undertook the task of determining whether motion studies in virtual environments are not only useful to validate VR interaction techniques, but can also serve as a powerful tool for researchers dealing with the organization of human motor behavior.

This investigation into the use of VR techniques for examining human motor behavior is primarily motivated by the exact controllability of computer-generated experimental conditions. Stimuli such as the appearance, characteristics, and behavior of objects can be varied and presented separately or in combination. These possibilities provide the following potential benefits:

- **Standardization**—Because experimental conditions depend only on the programming of the virtual scenarios, standardization and reproducibility of experiments are guaranteed because the conditions are independent from a special location, date, or experimenter. Experiments can be performed in different locales under the same conditions by simply transferring the software.
- **Flexibility**—Computer-generated scenarios can be quickly and easily adapted not only to specific questions to be studied but also to individual motor skills of single subjects. This is especially important in clinical studies of patients suffering, for instance, from sensorimotor disturbances. By programming gradual variations of the degree of difficulty, a very smooth transition from simple, low-dimensional...
tasks up to complex motor tasks can be realized. Combining special input techniques and virtual scenarios, minimal motor output carried out by a handicapped patient can produce even complex movements within the virtual space. This allows us to study the conceptual aspect of the movement process independently from a well-functioning patient’s motor effectors.

- **Efficiency**—By using a suitable user interface as introduced by Kuhlen et al. (1998), an experimenter can interactively create even complex computer-generated scenarios without any programming knowledge. The process of building experimental set-ups can thus be accelerated significantly.

- **Realizability**—The greatest potential for VR-based motor studies can be found in the possibility to generate scenarios that are difficult or even impossible to create with conventional set-ups. By the example of reach-to-grasp experiments, this benefit will be demonstrated in the remainder of this paper.

### 2.2 Benefits of VR-based Reach-to-Grasp Studies

In the special case of reach-to-grasp experiments, real target objects can be replaced by virtual, computer graphic objects. In addition to the general benefits listed above, such an approach is motivated by the possibility to easily and quickly generate and vary perturbation experiments. The following examples stand for questions that VR technology allows us to examine for the first time:

- VR-based experimental set-ups differ principally from real scenarios in that a subject has no tactile nor force feedback when touching virtual objects, assuming that no special devices for the simulation of these stimuli such as the PHANToM (Massie, Salisbury, & Kenneth, 1994) are employed. It is therefore possible to examine the influence of haptic feedback on human motor behavior.

- Within the same virtual environment, a change of object position in a perturbation experiment can be implemented as an immediate translation or as a continuous movement of the object to its new position. The experimenter can arbitrarily select velocity and trajectory of the moving object.

- In contrast to perturbation experiments completed so far (Paulignan et al., 1991b), a change of object size can be realized in a way that subjects have to adapt only their finger shape, so that an isolated perturbation of the grasping component becomes possible.

- Using virtual scenarios, not only object position and size but also object shape can be changed allowing an experiment to localize cortical structures that are specialized in object recognition and identification.

### 3 Experiment

This VR-based experiment compares motor behavior when reaching and grasping a real and a virtual object, respectively. By such an experiment, the role of haptic feedback for the planning and execution of a reach-to-grasp movement can be investigated for the first time.

#### 3.1 Methods

**3.1.1 Subjects.** Eight right-handed normal subjects (age 24 to 54 years, mean of 36) participated in the experiment. All subjects were naive with respect to the goal of the experiment and were tested for the ability to view stereoscopically (Roth et al., 1997).

**3.1.2 Apparatus.** Figures 1 and 2 sketch the experimental set-up, which is not only adequate for this concrete experiment, but can be used for any VR-based reach-to-grasp study. Because the experimental environment is illustrated and validated in detail elsewhere (Kuhlen et al., 1998), a brief description shall be sufficient here.

When developing virtual scenarios suitable to replace real scenarios in neuropsychological experiments, special care must be taken to the visual presentation of the objects with which test persons have to interact. The presentation of a virtual object must not influence the subject’s motor behavior. This requirement can be
guaranteed only if the visual perception of real and virtual objects are identical. The visualization technology used here is based on a high-resolution graphics monitor and stereo shutter glasses. In addition, an electromagnetic tracker attached to the glasses measures the subject’s head position in real time. As a result, the projection can be dynamically adapted to the subject’s viewpoint so that virtual objects are perceived as stationary in 3-D space. By means of this technology, in CAVE-applications well known as “viewer-centered projection” or “virtual holography” (Kuhlen et al., 1996a), in principle all physiological and psychological cues for a natural visual perception can be realized except for a small mismatch between accommodation and convergence. In experiments described by Kuhlen et al. (1998), it can be shown that perception errors resulting from this mismatch are negligible if the negative parallax for the scenario is not too large.

To register a subject’s hand and finger movements, an optoelectronic motion-tracking system is preferred to an instrumented glove, because in reach-to-grasp experiments the fingertip positions are of high importance. Using optoelectronic tracking, these positions can be measured very accurately by simply placing markers directly at the fingertips. In this experiment, movements were recorded by a Selspot II system, equipped with two cameras and sampled at 100 Hz. Position markers were attached to the thumb, the index finger, and the wrist.

At the beginning of a trial, subjects had to put the hand on a pressure-sensitive plate, which here signals the beginning of a movement. In perturbation experiments, the plate can also serve as a signal for the start of a perturbation.

3.1.3 Procedure. The subjects were instructed to reach and grasp the real or the virtual cube accurately and at a convenient velocity, using the precision grip. The cube should not be lifted or moved. The study comprised three blocks of trials with a break of ten minutes between them.

Block A: Presentation of a Real Cube—A red, wooden cube with a side length of 4 cm was presented to the subject. The cube was fixed onto a robust track, centered in front of the monitor with its back face touching the screen. After two test trials, every subject grasped the cube ten times.

Block B: Presentation of a Virtual Cube—A red, virtual cube with a side length of 4 cm was presented to the subject. The cube was visualized in such a way that it was perceived by the subject to be at exactly the same position as the real cube in block A. Again, subjects grasped ten times, preceded by two test trials.
Block C: Randomized Presentation of a Real and a Virtual Cube—The virtual and the real cube were presented to the subject in a randomized order, ten times each. Between single trials, the subjects’ eyes were closed, so that the cubes could be exchanged without their knowledge. On command, the subjects opened their eyes and started grasping. They were informed that reaction time would not play any role for the experiment.

4 Data Analysis

In principle, data analysis follows the methods of the numerous studies documented in the literature. Trajectories (marker positions over time) are filtered employing a dual-pass Butterworth filter (cut-off frequency: 10 Hz). Whereas the transport component is characterized by the velocity profile of the wrist, the grasp component is represented by the aperture profile, being calculated as the Euclidean distance between the markers at thumb and index finger over time. The following kinematic parameters have been extracted (see, for example, Winter (1990)) and analyzed by statistical methods: maximum velocity, maximum acceleration and deceleration of the wrist marker, maximum aperture, and maximum/minimum aperture velocity.

The high-dimensionality of the motion data in combination with a high intra- and interindividual variability made it impossible to employ statistical tests directly. Instead, a cluster analysis based on Kohonen’s self-organizing maps (SO Ms) (Kohonen, 1995) has been performed on the transport and the grasp components and preceded the statistical tests. In principle, SO M is a special kind of artificial neural network. A high-dimensional input (here, human motions, represented by multiple marker trajectories) is projected onto a two-dimensional map of artificial neurons (the Kohonen map). A training phase takes care that this projection preserves topology of the input data, that is, motions that are similar to each other are projected onto neighbored neurons in the map, while input patterns that are very different appear at a large distance from each other. The result of a data analysis by SO Ms consists of a set of classes of motor behavior, thus making it much easier than statistical tests to discover inter- and intraindividual heterogeneity when very little is known about the structure of the input patterns. A detailed description of SO Ms as applied to the analysis of human motions can be found in Kuhlen (1998). Finally, after having established classes of similar motor behavior, hypotheses on single kinematic parameters have been made and proved or disproved by statistical significance tests.

5 Results

5.1 Blocks A and B: Transport Component

Table 1 compares the transport components of the reach-to-grasp movements towards the real object (‘‘real grasping,’’ block A) and the virtual object (‘‘virtual grasping,’’ block B).
As in real grasping, the transport component in virtual grasping is determined by an asymmetric velocity profile with a single maximum. Movement times are nearly identical. The deceleration phase takes approximately two-thirds of this time. However, small but significant differences (paired $t$-tests based on the eight mean values of all subjects) arise from smaller velocity ($p < 0.05$) and deceleration maxima ($p < 0.01$) in virtual grasping. Higher standard deviations of these two parameters in virtual grasping result from interindividual differences, whereas, within subjects, the variability is approximately identical for blocks A and B.

### 5.2 Blocks A and B: Grasp Component

A questioning showed that none of the subjects had the impression that motor behavior during virtual grasping is different from that during real grasping. However, a SOM cluster analysis of the motion data shows not only that the grasp component of virtual grasping is very different from that of real grasping, but that the grasp component of virtual grasping is further subdivided into two different classes, despite identical transport components for these two classes. Looking closer at the single kinematic parameters of these two classes (see Table 2 and Figure 3) for single subjects, the following characteristics can be found by statistical tests:

#### 5.2.1 Strategy 1

Five subjects show an aperture profile determined by a correction of the finger opening that starts at the beginning of the deceleration phase, approximately 15 cm away from the virtual object. This correction leads to a later maximum aperture velocity and to a larger absolute aperture maximum, which appears at the same time as in real grasping (at approximately 60% of movement time).

#### 5.2.2 Strategy 2

The grasp component of subjects following strategy 2 typically shows a very early and fast opening of the fingers. As a result, the kinematic parameters show an earlier time of maximum aperture and a larger maximum aperture velocity. Here, closing of the fingers takes 70% of movement time (only 40% in real grasping for all subjects and in virtual grasping for subjects with strategy 1). In contrast to strategy 1, subjects who follow strategy 2 do not show a uniform reaction with regard to the amount of maximum aperture.

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**Table 2.** Kinematic Parameters (Mean Values and Standard Deviations) of the Grasp Component for Real Versus Virtual Grasping. For Virtual Grasping, Two Different Strategies Could Be Identified

<table>
<thead>
<tr>
<th></th>
<th>Max. aperture [mm]</th>
<th>Rel. time of max. ap. [%]</th>
<th>M ax. ap. velocity [mm/ s]</th>
<th>Rel. time of max. ap. velocity [%]</th>
<th>Min. ap. velocity [mm/ s]</th>
<th>Rel. time of min. ap. velocity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>83.4</td>
<td>58.2</td>
<td>292.6</td>
<td>15.3</td>
<td>216.0</td>
<td>78.2</td>
</tr>
<tr>
<td></td>
<td>(8.3)</td>
<td>(14.2)</td>
<td>(108.9)</td>
<td>(7.2)</td>
<td>(69.8)</td>
<td>(7.8)</td>
</tr>
<tr>
<td>Virtual</td>
<td>91.3</td>
<td>48.6</td>
<td>350.9</td>
<td>25.5</td>
<td>195.2</td>
<td>67.0</td>
</tr>
<tr>
<td></td>
<td>(18.0)</td>
<td>(15.9)</td>
<td>(123.5)</td>
<td>(17.2)</td>
<td>(70.8)</td>
<td>(16.1)</td>
</tr>
<tr>
<td>Virt.—real</td>
<td>7.9</td>
<td>-9.6</td>
<td>58.3</td>
<td>10.2</td>
<td>-20.8</td>
<td>-11.2</td>
</tr>
<tr>
<td>Virtual strategy 1</td>
<td>97.7</td>
<td>59.9</td>
<td>341.2</td>
<td>39.8</td>
<td>-236.3</td>
<td>73.6</td>
</tr>
<tr>
<td></td>
<td>(19.7)</td>
<td>(6.3)</td>
<td>(157.6)</td>
<td>(9.9)</td>
<td>(67.7)</td>
<td>(11.2)</td>
</tr>
<tr>
<td>Virt. 1—real</td>
<td>11.8</td>
<td>1.2</td>
<td>39.7</td>
<td>20.6</td>
<td>4.5</td>
<td>-3.7</td>
</tr>
<tr>
<td>Virtual</td>
<td>84.7</td>
<td>30.7</td>
<td>381.9</td>
<td>8.1</td>
<td>-168.0</td>
<td>54.5</td>
</tr>
<tr>
<td>Strategy 2</td>
<td>(19.7)</td>
<td>(7.1)</td>
<td>(114.2)</td>
<td>(3.3)</td>
<td>(52.4)</td>
<td>(18.3)</td>
</tr>
<tr>
<td>Virt. 2—real</td>
<td>1.3</td>
<td>-27.5</td>
<td>89.3</td>
<td>-7.2</td>
<td>48.0</td>
<td>-23.7</td>
</tr>
</tbody>
</table>
During the ten repetitions in experiment 2, no subject showed a learning effect or a switch from one strategy to the other. Reducing the different strategies to the times of maximum aperture and aperture velocity allows for the visualization of the movements as clusters in a two-dimensional plane (Figure 4). While strategy 1 is characterized by a later maximum aperture velocity along with a nearly identical time of maximum aperture, this relation is reversed for strategy 2.

5.3 Block C

Surprisingly, for the randomized presentation of a real and a virtual cube, none of the kinematic parameters show significant differences for real and virtual grasping in either the transport or the grasp component. A comparison of results for blocks A and B clarifies that the grasping behavior is similar to that for the repeated presentation of the virtual cube (block B), no matter whether a real or a virtual cube is being grasped during the randomized presentation. This result is substantiated by a mapping of the motions of block C onto a SOM that has been trained with motion data of blocks A and B: reach-to-grasp movements of C, whether real or virtual, are mapped onto neurons in the map area of block B, whereas block A neurons are not hit. A data analysis related to single subjects demonstrates that all, except one, show the above reaction for the transport as well as the grasp component: that is, they adopt their grasping behavior from the behavior observed in block B. The remaining subject shows the opposite behavior with regard to the grasp component, the aperture profile being adopted from that in block A. Again, questioning revealed that none of the subjects was conscious of the different strategies.

Figure 3. Aperture profile of real versus virtual grasping for a subject following strategy 1 (left diagram) and a subject following strategy 2 (right diagram).

Figure 4. Mean time of maximum aperture versus mean time of maximum aperture velocity of real and virtual grasping for the eight tested subjects.
6 Discussion

The results found in this VR-based experiment support some existing hypotheses on the neural organization of the reach-to-grasp movement, like Jeannerod’s hypothesis of visuomotor channels, and they also lead to the new assumption of a biphasic programming of the grasp component.

6.1 Hypothesis of Separate Visuomotor Channels

The lack of force and tactile feedback has a unique influence on the transport component, but it can lead to two different strategies for the grasp component. This result proposes that the transport and grasp components are separately controlled by the human brain. In this regard, the results support Jeannerod’s well-known hypothesis of two different visuomotor channels for the transport and the grasp component (Jeannerod, 1981). However, the results are inconsistent with Jeannerod’s assumption of an invariant, temporal coupling between the components: for virtual grasping, the characteristic profile of the transport component remains nearly unchanged, while the time of maximum aperture occurs much earlier for strategy 2. Thus, for some subjects, grasping a virtual object leads to a motor behavior in which the times of maximum deceleration and maximum aperture no longer coincide. This shows that, in contrast to Jeannerod’s assumption, the transport and grasp components are not tightly coupled.

6.2 Functional Coupling of Transport and Grasp Component

R. Marteniuk et al. (1990) could show that the kinematic profiles of transport and grasping components change with varying precision and manipulation requirements. Increasing requirements lead, among others, to an earlier finger opening. Therefore, they propose a coupling that is rather functional, task specific than temporally invariant. These findings are supported here: grasping a virtual object is obviously more difficult than grasping a real one, resulting partially in an earlier maximum aperture (strategy 2), or being compensated for by means of a larger aperture in the deceleration phase (strategy 1), a reaction that can also be observed in fast reach-to-grasp movements (Wing, Turton, & Fraser, 1986).

6.3 Biphasic Programming of the Grasp Component

As reaction on the presentation of a virtual instead of a real object, the aperture profile either changes in the acceleration phase and remains unchanged in the deceleration phase, or vice versa; that is, it starts in a normal way and continues with a change in the deceleration phase. This finding supports the hypothesis that not only the reach-and-grasp component but also the grasp component itself can be subdivided into two separate programs, responsible for the acceleration phase and the deceleration phase, respectively. The lack of haptic feedback then leads, specific for single subjects, to a variation of one of the two programs.

6.4 Optimization of a Reach to Grasp Movement

In a random presentation of a real and a virtual cube, all subjects (except one) reach and grasp the real object as if it were a virtual one, as if the real object would give no haptic feedback. Thus, the occasional grasping of virtual objects seems to impede the optimization of the movement. Obviously, it is not possible for the human brain to instantly adapt the programming of a reach-to-grasp movement to the changing conditions and to optimize the movement profile. Therefore, it seems that the optimization of such a movement must be learned anew. The results of the presented study support the hypothesis that haptic feedback plays an important role for this learning procedure.

7 Summary and Future Work

By the example of reach-to-grasp studies, we have demonstrated that VR technology provides a powerful...
means to investigate human motor behavior. By VR, it becomes possible to realize experimental scenarios that are very difficult or even impossible to build when using real, physical set-ups. We have performed an experiment that compares reaching and grasping a real and a virtual cube, respectively. A detailed discussion of the experimental results not only supports previously postulated hypotheses about human movement organization (like the existence of two separate, functionally coupled channels in the brain for the transport and the grasp component), but also leads to new insights. The results of our experiment support the new hypothesis that the grasp component itself is further subdivided in exactly two separate channels, responsible for the acceleration phase and the deceleration phase, respectively. After the basic experiment presented in this paper, we are currently performing several experiments that profit from the unique potential of VR technologies. These experiments comprise perturbation studies to investigate differences in motor behavior when virtual objects change their position instantly or continuously. In another experiment, a mouse with six degrees of freedom is used to control a virtual arm in all dimensions. By this experimental setup, it should be possible to translate minimal motor inputs into complex movements within the virtual environment, allowing us to examine whether handicapped patients are conceptually able to perform complex tasks.

Recently, a PHANToM haptic device has been added to the VR equipment to investigate how such “artificial” force feedback influences motor behavior in reaching and grasping. Virtual scenarios are no longer visualized on a graphics monitor, but on a HoloDesk, a projection device introduced by Steffan and Kuhlen (1998) and consisting of two projection surfaces at table size that are arranged perpendicular to each other. This visual environment enlarges the interaction volume considerably and allows for a more intuitive and natural access to the virtual environment.

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References


