CHAPTER

Verifying advantages of two-handed interaction

In this chapter, the anticipated advantages of two-handed operation for 3D manipulation tasks are evaluated. Two experiments are described in which two-handed operation was compared to one-handed operation. In the two experiments, the interaction devices and the user interface techniques described in the previous chapter were used. Performance and workload of two-handed operation was compared to that of one-handed operation in an assembly task.
Two assembly tasks have been conceived and evaluated for use in the experiments. One of these was selected as experimental task in both experiments. The results of the first experiment suggested that the use of two hands led to faster assembly and to a division of workload between the two hands. However, confirmation of shorter completion times was made only in the second half of the experiment, indicating a learning effect. It could not be established that faster assembly with two hands was caused by the advantages of bimanual operation. Because of the experimental design, the subjects were divided in two groups that both performed one- and two-handed assembly but in a different order. Therefore, the effect found could have been influenced by the order in which the subjects performed one- or two-handed assembly.
That was the reason for conducting the second experiment: to verify the findings of the first experiment. In the second experiment, new subjects were invited and they were divided into two groups but now assigned either to the one- or two-handed assembly exclusively. The results of the second experiment confirmed and validated the findings of the first. Two-handed operation led to shorter completion times and to a division of workload between the two hands without increasing the total workload. These findings were again found in the second half of the experiment (after approximately 40 minutes of experience with the system). Therefore, shorter completion times with two-handed operation were not the result of the order of exposure to single-handed or bimanual operation.

After a description of the goals and hypotheses of the experiments, the chapter continues with a presentation of the two tasks that have been evaluated for their fitness to serve as experimental task. Then, the methods and materials common to both experiments are presented. Methods exclusive to each experiment are presented in the separate sections about each experiment and combined with the results and discussions.

4.1 Goal of the experiments

The goal of the experiments was to establish whether advantages of two-handed operation would materialize in 3D modeling tasks representative for conceptual design. In addition, it was the first time that novice users were confronted with the Frogs interaction devices and the interaction techniques presented in the previous chapter. Therefore, a secondary goal of the experiments was to observe how the subjects interacted with the system and to assess whether there were flaws in the design of the Frogs or the software. Next, it is argued why an assembly task was chosen. This is followed by the hypotheses.

4.1.1 The choice for an assembly task

The main reason for choosing an assembly task was that it was regarded a common task in the conceptual phase of the design process. In the conceptual phase, a designer often investigates different arrangements of functional elements in a design. This part of the design phase has been referred to as the synthesis phase (Verstijnen, 1997). During the synthesis phase, the elements of a design remain intact, only their spatial relationship is modified.
In the analysis phase, the structural representation of a design is analyzed and reinterpretation can lead to new structural representations. It was shown that the synthesis phase is easily accomplished before the mental eye but externalization by means of sketching can aid the designer in the analysis phase. The analysis phase has been shown more difficult to perform without externalization.
Extrapolating the mental processes to 3D modeling, an assembly task represents support for the synthesis phase of the design process. The advice for computer support of the synthesis phase is that it should be effortless and occur quickly, so as not to hinder the analysis phase. In the synthesis phase, the goal is to produce a model that is then explored and restructured in the analysis phase.

An assembly task represents a larger part of the functionality of a CAD system than matching and docking tasks that are commonly used in interaction device studies (Hinckley, Tullio, Pausch, Proffitt & Kassell, 1997; Zhai, Milgram & Buxton, 1996). An example of a matching task has been presented in Chapter 1, in the evaluation of the Turntable. An assembly of an object out of several parts is more involving than that. In most matching and docking tasks for instance, there is no need to select objects because the interaction device controls only one object during the task. In an assembly of multiple objects, selection needs to be included as soon as the number of parts outnumbers the number of interaction devices. The increased complexity of the assembly task implies that the conditions of an experiment with an assembly task are less controlled because subjects have more freedom to decide how to accomplish the task.

4.1.2 Hypotheses

In Chapter 2, potential advantages of two-handed operation were listed. In the experiments, performance and workload benefits were evaluated by comparing the results for one- and two-handed operation of the same assembly task. Performance was measured by establishing the time needed to complete an assembly task. Workload was measured by calculating distances and rotations of the hands involved in completing the task. The accuracy of the assembly was not studied explicitly. Instead, an assembly was considered correct when the objects were placed such that their positions and orientations matched within a fixed threshold value.

Regarding performance, it was expected that two-handed operation would lead to shorter completion times than one-handed operation. In Chapter 2, two reasons for higher performance of bimanual operation were given and both were expected to manifest themselves in the assembly task. The first reason was that a temporal overlap of the actions of both hands can occur in an assembly task. For example, with two hands, objects can be brought together instead of bringing one object to a stationary target object. The second reason was that both hands can remain in their individual "home position". This can also occur in an assembly task, for instance when one hand is used to hold an object on which several other objects are placed with the other hand. Among the other benefits of two-handed operation are the possibility to explore more task solution strategies and an increase of spatial awareness. These effects can also have a secondary contribution to decreased task completion times. Table 4-1 lists the hypothesis for mean completion times.

H_0	$M_{time,C2} = M_{time,C1}$		
		H_1	not H_0

Note: H_0 = null hypothesis, H_1 = alternative hypothesis, M = mean, time = completion time, C1 = one-handed operation, C2 = two-handed operation

Table 4-1
Hypothesis for mean completion time

H_0	$M_{dist,C2} = M_{dist,C1}$
H_1	not H_0

Note: dist = distance

Table 4-2
Hypothesis for distance

H_0	$M_{rot,C2} = M_{rot,C1}$
H_1	not H_0

Note: rot = rotation

Table 4-3
Hypothesis for rotation

Regarding workload, it was expected subjects would experience an equal amount of workload when working with two hands as when working single-handedly. Table 4-2 and Table 4-3 list the hypotheses for the cumulative variables distance and rotation respectively. The consequence of an equal workload is that when working with two hands, the workload of the dominant hand alone will reduce. This was expected on the ground that with two-hands, the workload can be divided between the hands. The workload for the dominant hand reduces if the total workload is not increased and the non-dominant hand is actively taking part in the assembly. The ratio of dominant and non-dominant hand activity will be determined.

4.2 Two-handed assembly task

In the previous chapter, two selection techniques, dependent and independent selection, were presented for assembling objects with two hands. One of those had to be chosen for the assembly task. Independent selection requires a subject to operate two cursors and subjects need to select objects with both hands separately. Preliminary testing suggested that this was more difficult than dependent selection where only the dominant hand needs to select objects. It was therefore decided to use dependent selection in the experiments. In Chapter 5, this issue is addressed in detail when an experiment is described in which dependent and independent selection are compared.

Besides the relation to a common design task, a criterion for the assembly task was that the task should be accomplishable, both with one hand as well as with two hands. The task should invite subjects to use both hands but should not be unnecessarily difficult to accomplish with one hand only to avoid a biased result.

Two assembly tasks were conceived and evaluated for use in the experiments. The first task was a stacking task that proved to have some difficulties. The second task was a puzzle task and it addressed the problems of the stacking task.

4.2.1 The stacking task

The stacking task was the first attempt in creating an assembly task for the experiment. What follows is a description of the task and the way in which it was completed with the interface techniques described in the previous chapter. This is followed by the description of a limited pilot test in which the task was evaluated.

Description of the stacking task

In the stacking task, subjects were asked to assemble an object by putting several pieces on top of each other. Five different objects were used with profiles as depicted in Figure 4-1. To aid the placement, every object was given a feature to help the subjects decide where the front side of the object was. In addition, the sides of the objects were of different colors and the objects were textured to help the alignment process. The texturing was also meant to help reveal how close the object was to the subject. With 2D displays, it is sometimes difficult to distinguish a small object close to the viewer from a larger object further away. The depth of the objects is more easily understood when the objects are textured (with the assumption that perspective projection is used).

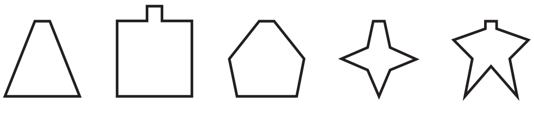
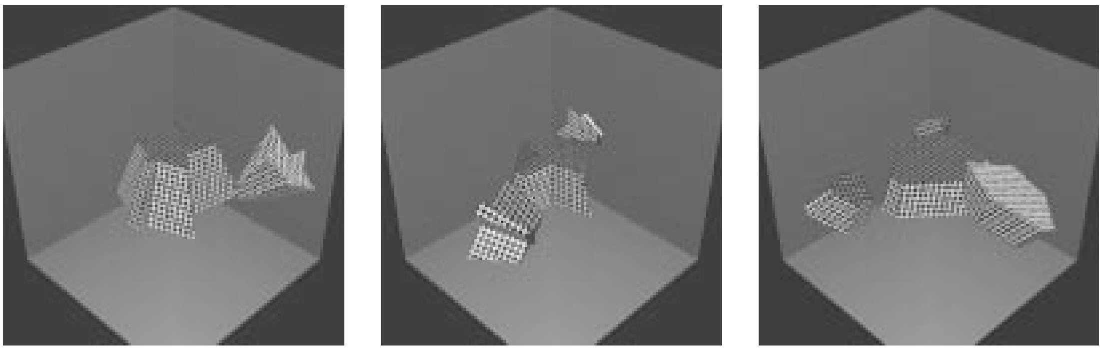


Figure 4-1. Profiles of the objects used in the stacking task.

Figure 4-2 shows three different configurations with three of the shapes of Figure 4-1. Configurations consisted of two, three or four objects with the same profile. The objects were tapered toward the top to create segments of decreasing size. The base object of the stack was always placed upright in the center of the scene.
In Figure 4-3 it is shown how the centers of the rest of the objects

Figure 4-2. Three assembly configurations with different shapes and numbers of objects.



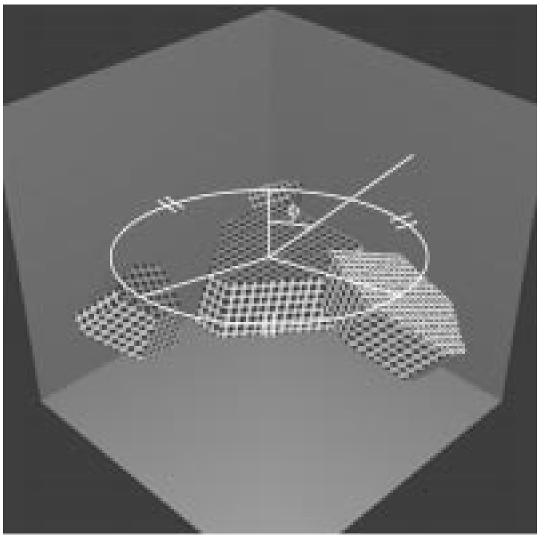


Figure 4-3. Distribution of objects in the stacking task.
The centers objects of the objects are located on a circle through the center of the base object, parallel to the ground plane.

were positioned on a circle, parallel to the ground plane centered at the center of the scene. The centers of the top objects on the circle were equally distributed over the circle and the circle was rotated over a random angle (the angle ϕ in Figure 4-3). Finally, the top objects on the circle were rotated around their center, each with a randomly chosen rotation axis and rotation angle.

One-handed operation

To complete the task with one hand, subjects were offered one Frog to operate the 3D star-shaped cursor. The cursor is shown in Figure 4-4. To prevent the cursor from disappearing, the position of the cursor was confined to the contents of the workspace, indicated by the three rectangles in the figure. With the cursor, objects could be identified and moved for placement on top of the other object(s). A fixed sequence was used for the assembly, starting with the placement of the second largest object on top of the base object. The rest of the objects were placed in order of decreasing size on the assembly in progress. The steps in the assembly of two objects are depicted in Figure 4-5 (CD-ROM, 4-1). The first step was to position the cursor such that an object could be selected using cursor-based ray casting, a selection technique presented in the previous chapter. The selection of an object was indicated with the presence of a wireframe box around the object. Selected objects could be moved as long as the selection button on the Frog was pressed. The assembly was finished as soon as the positions and orientations of both objects matched within a threshold value, during a fixed period. After a match, the two assembled objects snapped together, a “snap” sound was played and the objects behaved as one object from that point on.

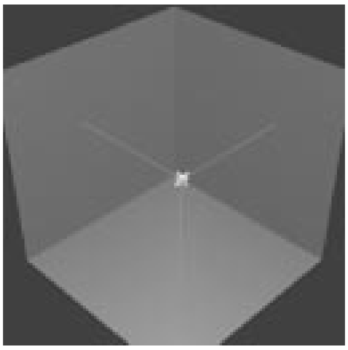


Figure 4-4. The workspace in which assembly takes place. The star-shaped cursor in the center is connected by assist lines to the boundaries of the workspace indicated by the three rectangles.

For configurations with three or four objects, this process was repeated for every object. Again, the sequence of placement was determined by the size of the objects: larger objects were placed

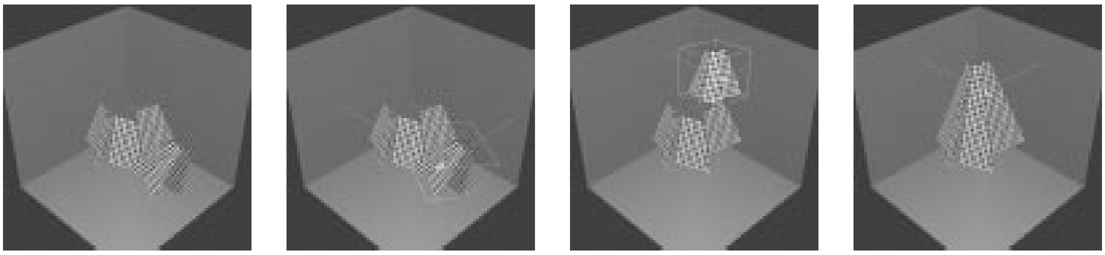
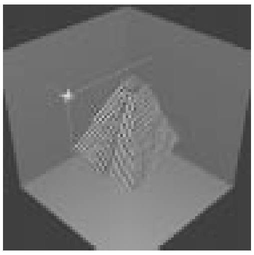
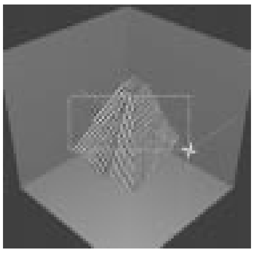


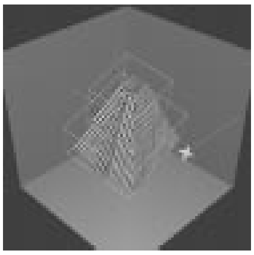
Figure 4-5. The steps involved in the assembly of two objects with one hand

before smaller objects. The steps described might suggest that a placement took place in a single continuous gesture. However, the subject was free to complete the assembly in a series of selection and drag actions as well. Moreover, in some cases a series of selection and drag actions was unavoidable, for instance when an object needed to be rotated over an angle larger than comfortable for a subject.



Subjects were also offered the opportunity to select and drag several objects together. This functionality allowed subjects to rotate the objects being assembled and judge the state of the assembly from a different view. Because of the 2D display, a change of view was sometimes necessary to complete the assembly. In some cases, two objects seemed to line up well enough for a snap in one view but when viewed from another side, they might be displaced (see Figure 4-6). With the possibility of dragging objects concurrently, the state of the assembly could be preserved because the relative displacement and rotation of both objects does change when they are dragged together. When the objects are dragged separately, the accomplishment of the previous drag can be invalidated easily. Figure 4-6 shows the procedure for a concurrent drag of two objects (CD-ROM, 4-2). First, the 3D cursor is moved to a position beside the objects to prevent a single object being selected. Then, the selection button on the Frog is pressed and the Frog is moved while the button is held down. A selection rectangle appears to indicate the rectangular selection area. Upon the release of the selection button, all the objects with projections inside or intersecting the selection area are selected which is indicated with a bounding box surrounding the selected objects.





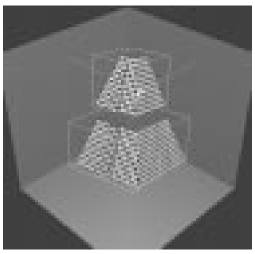


Figure 4-6. The steps involved in the concurrent dragging of two objects.

Finally, both objects can be moved by using the selection and drag procedure for a single object on either of the selected objects.

Two-handed operation

With two-handed operation, the Frog for the dominant hand was used the same way as it was used with one-handed operation. The Frog for the non-dominant hand was used to move objects with the dependent selection mechanism introduced in Chapter 3. In the stacking task, the non-dominant hand can aid the dominant hand in two actions. First, it could aid the selection of objects with the dominant hand. In addition, the non-dominant hand could aid the placement of an object dragged with the dominant hand by moving and orienting the target object to facilitate the placement.

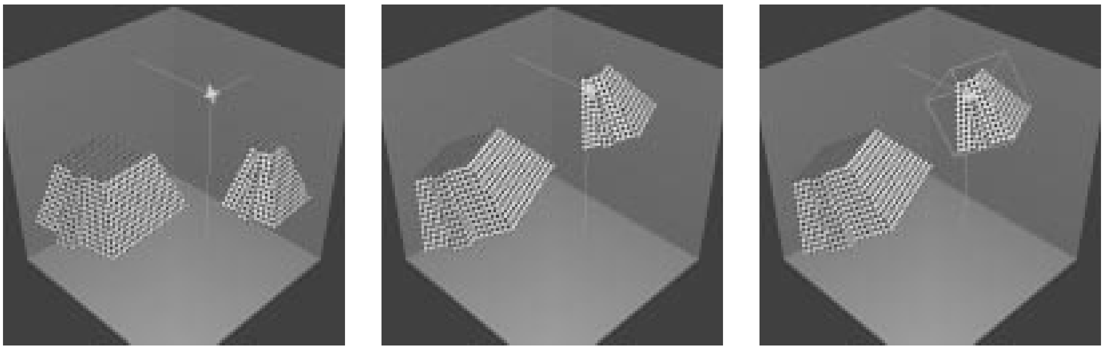


Figure 4-7. Selecting an object with two hands in the stacking task.

Aiding the selection of objects with the dominant hand is illustrated in Figure 4-7. (CD-ROM, 4-3). With the dependent selection technique, all objects are moved and rotated by non-dominant hand activity except those dragged with the dominant hand. Therefore, instead of moving the cursor to the object to be selected, the object can be moved to the cursor or both activities can occur simultaneously.

The concurrent placement of an object on the target object is illustrated in Figure 4-8. (CD-ROM, 4-4). The dominant hand selects the object to place on the target object. The dependent selection technique provides control over the target object with the non-dominant hand as soon as the dominant hand has selected the object. Subsequently, both objects can be brought together, instead of moving only one at a time as in single-handed operation.

Evaluation of the stacking task

A pilot test with eight subjects was conducted to see whether the stacking task met the requirements set for the assembly task in the

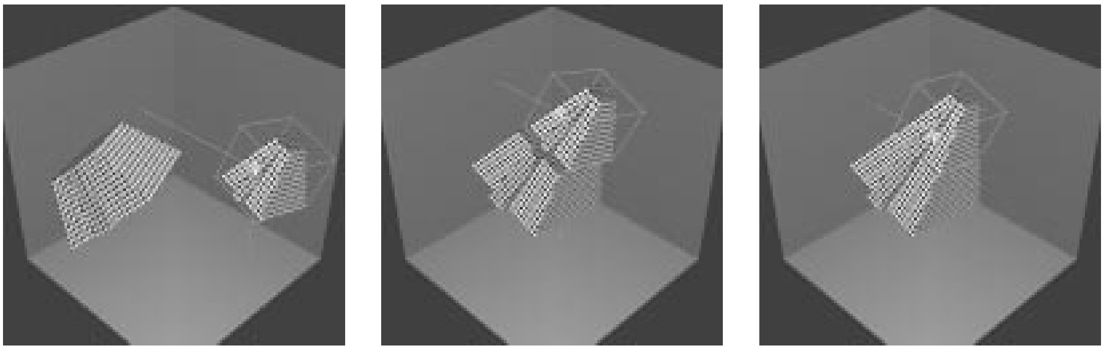


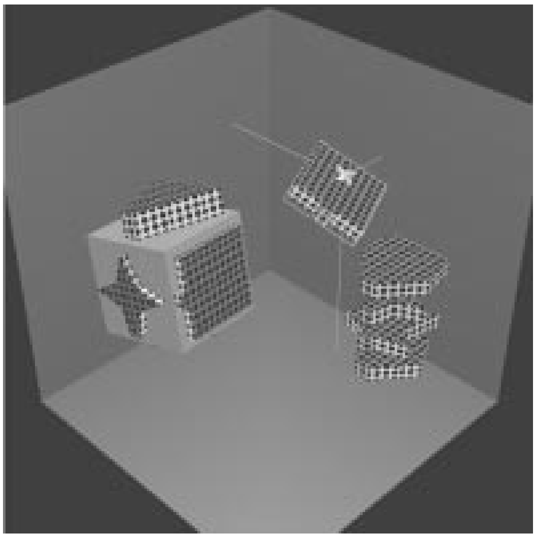
Figure 4-8. Assembling objects with two hands in the stacking task.

experiment. The main requirements for the assembly task were that it should not be biased either towards one- or towards two-handed operation and that it should allow the potential benefits of two-handed operation to come forward. It was found that in the two-handed condition of the pilot test, the non-dominant hand was not used much and the anticipated use of the non-dominant hand for changing the view on the objects was not realized as expected. The hypothesis was that this was caused by the fact that there was no need to change the view on the assembly in progress.
The stacking task provided the base of the stack centered at the scene and oriented upright. The other object(s) could be placed on the stack with ease and therefore the stack did not need to be rotated for a placement. This was supported by observations of the singled-handed assembly. When completing the stack with one hand, subjects did not rotate the stack frequently either.

In terms of completion times, it was found that mean values for completion times of one- and two-handed operation did not differ significantly. A thorough analysis could not be conducted because there were only eight subjects and conditions were not equal for all subjects. However, the indicated absence of a difference was surprising because the mere presence of concurrent activity of two hands was expected to reduce the completion times. In the two-handed condition, subjects could move two objects towards each other for assembly, as opposed to the one-handed condition where only one object can move to the base object for assembly.
The results of the pilot test suggested that the concurrent placement of both objects alone would not lead to performance benefits for two-handed operation.

Later it was realized that the stacking task resembled the assembly of a number of objects lying on a table. The fact is that, given the stacking task in real life, it can easily be done only with one hand. The pilot test showed that the stacking task could also be completed without the need for moving or rotating the stack with the other hand. In a sense, the stacking task is uniform because all the objects are placed on the base object in the same way. The assembly in progress remains in its original state most of the time. The result of the test was that the stacking task should be abandoned for the comparison of one- and two-handed operation. The issue of the absence of performance benefit in the stacking task was left open for future research.

Figure 4-9. Example of a configuration of the puzzle task. The triangular shape has been fetched from the pile and placed upon the cube. The rectangular shape is being dragged towards the cube for placement.



4.2.2 The puzzle task

The puzzle task was conceived to create a task less uniform than the stacking task. With the puzzle task, objects need to be placed on different sides of a base object. It was expected that with this task, subjects would have more profit of the support for the non-dominant hand because the task forces them to rotate the base object for placements of objects on all sides of the base object.

Description of the puzzle task

Figure 4-9 shows an example configuration of the puzzle task while being completed. The cube shape on the left is the target object. On the right are the pile objects to be placed on the corresponding shapes on the target object. Assembly of these objects takes place in a fixed order. In the figure, the triangular object has been fetched from the top of the pile and has been placed on its counterpart on the cube. The placement of the rest of the pile objects follows the same procedure. In the figure, the rectangular pile object is being dragged towards the cube. The use of colors and textures aids the assembly by providing cues about the orientation and depth of the objects. In contrast to the stacking task, the arrangement of objects is not symmetrical. Therefore, the configuration in Figure 4-9 is meant for right-handed subjects. In the experiment, left-handed subjects were presented with a mirrored version of the configuration with different initial positions and orientations of the cube and the pile objects.

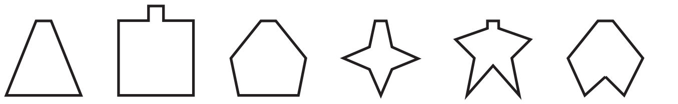


Figure 4-10, Profiles of the objects used in the puzzle task

The profiles of the six pile objects are shown in Figure 4-10. The profiles of the objects in the puzzle task are identical to those used in the stacking task except for the addition of one shape. Six shapes are used, one for each side of the cube.

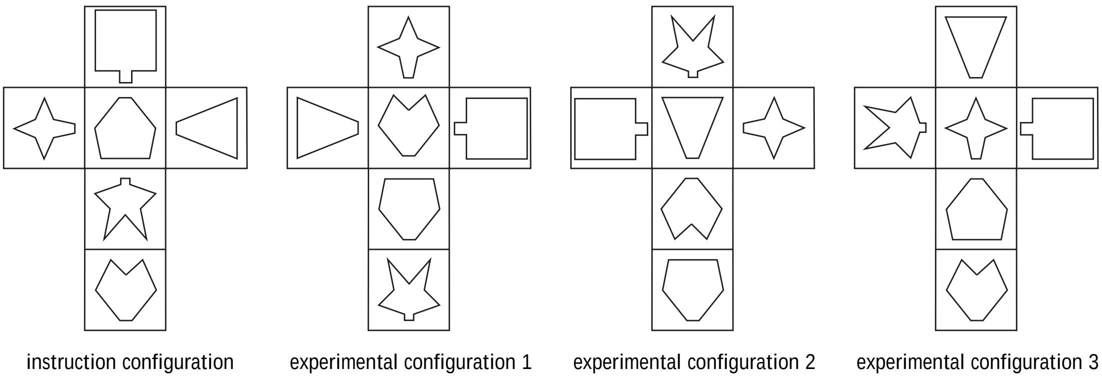


Figure 4-11. The four configurations of the cube in the puzzle task.

Figure 4-11 presents four different configurations of the cube. The introduction of different configurations was expected to help avoid subjects to become familiarized with the cube. One configuration was meant for instructing subjects while the other three were used in experimental trials.

The puzzle task was operated with the same Frog devices and software used in the stacking task. Thus, the operation of the puzzle task resembles that of the stacking task. The main difference compared to the stacking task operation is that only the cube and the pile object that is up for placement are moveable. For example, at the start of a trial, only the triangular pile object and the cube can be moved. The next, rectangular-shaped object can be dragged only after the placement of the triangular shape has been complet-ed. Like in the stacking task, a completed placement was indicated with a “snap” sound, a disappearing wireframe selection box and unification of both objects. This process repeated until all pile objects had been placed upon the cube.

Evaluation of the puzzle task

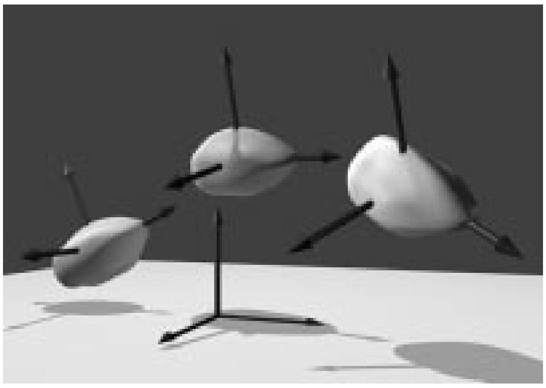
A pilot test with four subjects confirmed that the puzzle task was suitable for comparing one- and two-handed operation. The fact that objects needed to be placed on all sides of the cube forced subjects to search the sides of the cube for the next target shape. This had the effect that the task was more engaging and it did put more emphasis on the inspection phase when subjects planned the strategy for the next placement. With two-handed operation, the puzzle task made the subjects use their non-dominant hand more than the stacking task did. Like the stacking task, the puzzle task could be accomplished with one hand as well as with two hands (although it was more laborious to do so).

4.3 Materials and methods

The two experiments discussed below have a lot in common. The puzzle task used in both experiments has been described in the previous section. The experimental design, the associated procedure and the subjects differed between the experiment and these will be discussed in the sections about the experiments. What follows are the materials and methods common to both experiments. First, the calculation of the experimental variables performance and workload is shown. Then, the set-up of the system is presented.

4.3.1 Calculation of performance and workload

The performance was established by measuring the time that was needed to place the six pile objects on the cube. Workload was established by calculating the distances and rotation angles



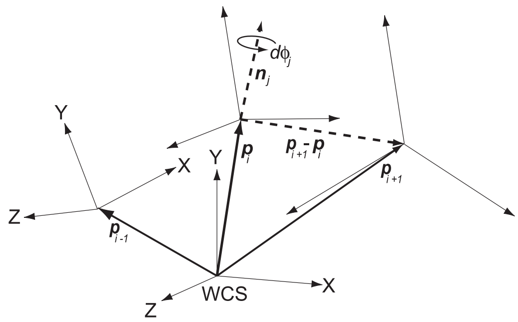


Figure 4-12. Translation and rotation of the Frog during three measurements

involved in completing the puzzle. The distance variable is the total displacement that the Frog underwent during the task. The rotation variable is the total rotation angle imposed on the Frog.

The position and orientation of the Frog were measured about 20 times per second. Figure 4-12 shows a sequence of three measurements. Both pictures show the reference frame of the Frog at three points in time. The point pi is the position of the Frog at measurement i with the total number of measurements equal to n and $i \in [1, n]$. The distance d_j between points is equal to $d_j = \| \boldsymbol{p}_j + 1 - \boldsymbol{p}_j \|$ with $j \in [1, n\text{-}1]$. The distance variable d is established by summing all the displacements of a Frog between the measurements, as shown in Equation 4-1.

$$d = \sum_{j=1}^{n-1} d_j \qquad (4\text{-}1)$$

The calculation of the total rotation $d\phi$ the Frog experienced during a trial follows the same procedure as the calculation of the distance. The rotation variable $d\phi$ was established from the individual rotation angles $d\phi_j$ a Frog experienced between measurements i and i+1 as shown in Equation 4-2.

$$d\phi = \sum_{j=1}^{n-1} d\phi_j \qquad (4\text{-}2)$$

What follows is an illustration of the derivation of the rotation angles $d\phi_j$ from the rotation matrices M_i that represent the orientation of the Frog at measurement i. The rotation a Frog experienced between measurements i and i +1 can be represented with the rotation matrix $\mathrm{R}_j = \mathrm{M}^{\mathrm{T}}_{j+1}\mathrm{M}_j$ with $j \in [1, n\text{-}1]$. From the diagonal elements of this rotation matrix, the rotation angle $d\phi_j$ can be extracted with the aid of Equation 4-3 (Goldman, 1991; Zeid, 1991).

$$\cos d\phi_j = \frac{(R_{j,11} + R_{j,22} + R_{j,33} - 1)}{2} \qquad (4\text{-}3)$$

One could argue that, conceptually, the way the rotation angle $d\phi_j$ represents the rotation of the Frog is equivalent to how the distance d_j represents the translation of the Frog. The distance ignores the direction of the translation and the rotation angle ignores the axis of rotation (see Table 4-4).

	position	orientation
measurement	vector $\boldsymbol{p}_i$	rotation matrix M_i
increment	vector $\boldsymbol{dp}_j = \boldsymbol{p}_{j+1} - \boldsymbol{p}_j$	rotation matrix $\mathrm{R}_j = \mathrm{M}^{\mathrm{T}}_{j+1}\mathrm{M}_j$
variable	Euclidian distance	Rotation angle
	$d_j = \|\| \boldsymbol{dp}_j \|\|$	$d\phi_j = \mathrm{acos}\ ((R_{j,11} + R_{j,22} + R_{j,33} - 1) / 2)$
ignored	direction of $\boldsymbol{dp}_j$	rotation axis of R_j

Table 4-4
Calculation of the distance and rotation variables

4.3.2 Experimental set-up

Most of the aspects of the system used for both experiments have been described. The Frog interaction devices were used to operate the test program that was built upon the ID8Model software. The interaction techniques employed in the test program have been documented in Chapter 3 and their use in the assembly task has been covered in the previous section.

Figure 4-13 presents the set-up used for both experiments.
The room in which the experiment took place was examined for the presence of electromagnetic fields that could influence the accuracy of the sensors inside the Frogs. The setup was surrounded by screens to reduce possible distraction of the subjects to the minimum. Subjects were seated on a chair adjustable in height and equipped with adjustable armrests. The wooden table in the picture was made especially for use with electromagnetic sensors. The 17-inch monitor was placed such that the center of the display area was at eye level. The electromagnetic transmitter of the Frogs was placed at the end of the table such that it did not hinder the movement of the subjects hands and care was taken to make sure that transmitter and monitor did not interfere. (CD-ROM, 4-5)

Figure 4-13. The experimental set-up.

The following hardware and software were used in the experiments.

Hardware:

- Apple PowerMac 8500 computer
- Two Apple 3D accelerators
- IIYAMA Vision Master Pro 17" monitor
- Two Ascension Flock of Birds tracking systems with two Frog interaction devices

Software:

- Operating system: Apple Mac OS 7.5
- Additional system software: Apple QuickDraw 3D 1.0.6
- Experimental software (CD-ROM, ID8AssembleOneTwo)

4.4 The first experiment

The presentation of the first experiment continues with the parts of the materials and methods specific to this experiment. Then, results are presented and discussed.

4.4.1 Experimental design

In the within-subjects design of the experiment, subjects experienced both of the experimental conditions, one- and two-handed operation. The subjects were divided in two groups that were exposed to single- and two-handed operation in different order. The first group started with one- and proceeded with two-handed operation. The other group experienced the reverse order of conditions.

4.4.2 Subjects

Twenty-four paid volunteers participated in the experiment, twelve males and twelve females. Half of the male and female subjects were assigned to the group that started with single-handed condition and the others to the group that started with the two-handed condition. They were all students from the departments of Industrial Design Engineering or Architecture of Delft University of Technology.
The age of the subjects ranged between a minimum of 18 and a maximum of 24, with a median age of 21. Their average use of 3D CAD programs varied to a large degree and ranged from a minimum of 0 hours to a maximum of 40 hours per week, the median value was 1 hour per week.

4.4.3 Procedure

Each subject experienced two sessions consisting of different conditions in succession. Completing both sessions took the subjects about one hour, including training. At the start of the experiment, subjects were asked whether they considered themselves left-handed in their use of the computer or for other tasks. The subjects that indicated that they performed some tasks left-handed were given the chance to try the system with either hand as dominant hand during the practice period. Before the start of the experiment, they were asked to make a choice for the left or the right hand. Two subjects chose to perform the experiment left-handed. The following procedure was used for the first condition.

First, the experimenter explained the system and gradually introduced the interface to the subject. Then, subjects trained the task with the interface corresponding to the experimental condition. Before moving to a position out of sight of the subject, the experimenter instructed the subjects to complete the trials as fast as possible and one practice trial was offered. These three steps took about twenty minutes to complete.

In the first session, the subject performed a run of six experimental trials with the experimental configurations of the cube shown in Figure 4-11. Before each trial, the subjects were reminded to put their hands into a comfortable start position and after each trial, the completion time was presented. Given the fact that there were three configurations of the cube and six experimental trials, each run of six experimental trials consisted of two blocks of three trials. Within each block, the three different configurations of the cube were presented in random order.

Before commencing with the second session, subjects received additional instruction and practice time if they belonged to the group that performed the second session with the two-handed condition. Both groups were allowed to train the condition of the second session. Then, the experimenter moved out of sight of the subjects and the procedure of the first session was repeated starting with the practice trial.

4.4.4 Results

In the following analysis, a statistical significance level of 95% was used for all statistical tests. For the comparison of the workload of one- and two-handed operation, the results for the distance and rotation variables are studied separately.

Completion times

Condition	M	SD	n
One-handed	151	33	24
Two-handed	139	43	24

Table 4-5
Mean completion times in seconds for the first experiment

The analysis starts with the results for completion times over the course of the whole experiment. The results in Table 4-5 show that the mean completion time for the two-handed condition was shorter than for the single-handed condition. However, the difference of 12 s between the mean completion times of the one-handed condition C1 and the two-handed condition C2 was not significant (t = 1.056, p = .9537).

As shown in Figure 4-14, mean trial completion times varied in the first session of the experiment, especially in the first three trials of the total of six trials in the first session. The mean completion time of trial seven was substantially larger than that of the sixth trial in the one-handed condition C1. The seventh trial was the first trial of the second session and the first one-handed trial for the group of subjects that started with the two-handed condition C2.

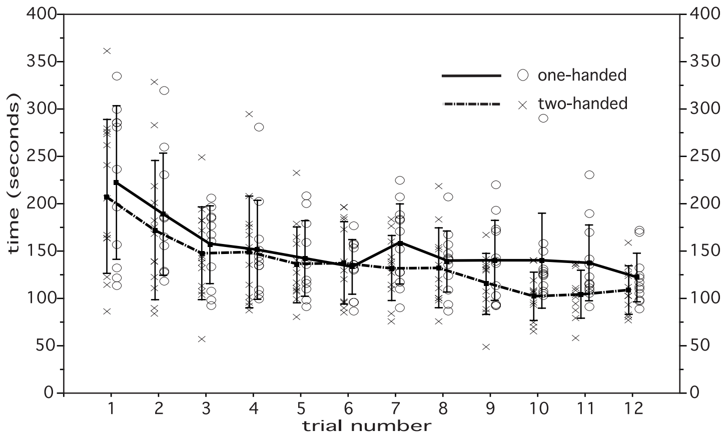


Figure 4-14. Effects of learning over the twelve trials of the first experiment for all the subjects. Error bars represent the standard deviation of the completion time per trial. The results of the individual subjects are indicated with the circles and the crosses.

The results for the completion times in each session separately are presented in Table 4-6 and Figure 4-15. Both the table and the figure show that the difference in completion times was small in the first session but considerably larger in the second session. These observations are confirmed by the statistical significance of the differences. In the first session of the experiment, the difference of 1 s between the mean completion times of conditions C1 and C2 was not significant according to the t ratio (t = 0.059, p = .9537). In the second session of the experiment however, the difference of 24 s between the mean completion times of conditions C1 and C2 was significant according to the t ratio (t = 2.439, p = .0233). The ratio of the mean completion times was M_{C2}/M_{C1} = 0.82. The standard deviation in this ratio was SD = 0.22.

Table 4-6
Mean completion times in seconds in the first and second session separately

	First session			Second session		
Condition	**M**	**SD**	**n**	**M**	**SD**	**n**
One-handed	162	35	12	139	27	12
Two-handed	163	47	12	115	21	12

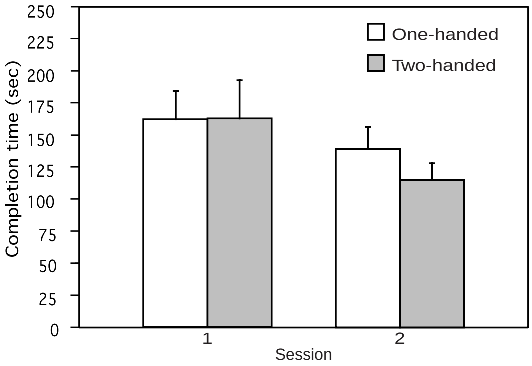


Figure 4-15. Mean completion times in seconds in the first and second session of the experiment, error bars represent 95% confidence interval.

An inherent characteristic of the within-subject design is the potential occurrence of asymmetrical skill transfer between the conditions of an experiment. The skill transfer could occur in this experiment too because there were two groups of subjects. Half of the subjects (group C1–C2) were exposed to the one-handed condition C1 first and the two-handed condition C2 later. The other half (group C2–C1) experienced the conditions in reverse order. An ANOVA of the Hands X Order interaction was conducted and a significant interaction was not found ($F_{(1,44)}$ = 1.677, p = .2021). In Table 4-7, the completion times of both groups are presented. The difference of 13 s between the completion times of the groups of subjects with different sequences was not significant according to the t ratio (t = 1.148, p = .2570).

Table 4-7
Completion times in seconds of the groups of subjects with different sequences of the conditions

Group	M	SD	n
C1-C2	139	37	12
C2-C1	151	40	12

Note. Group C1-C2 first performed single-handedly, then with two hands; group C2-C1 experienced the reverse sequence.

Table 4-8 shows the mean completion times for male and female subjects. Although the study was not conducted to investigate differences between males and females, it was found that female subjects achieved significantly longer completion times in the experiment (t = 3.865, p = .0003). An analysis of variance (ANOVA) was conducted to find the absence of a significant Hands X Sex interaction (F(1,44) = 0.011, p = .9169). In the second session of the experiment, the significance of the difference between completion times of males and females disappeared (t = 1.910, p = .0693).

Table 4-8
Mean completion times in seconds for male and female subjects

Gender	M	SD	n
Female	164	39	12
Male	126	28	12

Distance

Table 4-9 presents the results for the total distances in the second session of the experiment. Total distance in the single-handed condition C1 was the distance moved with the dominant hand only. For the calculation of the total distance in the two-handed

Table 4-9
Mean values of total distance in centimeters with both hands (second session)

Condition	M	SD	n
One-handed	997	259	12
Two-handed	1009	248	12

condition C2, the contributions of the distances of both Frogs were added. The difference of 12 cm between the means of the total distance of conditions C1 and C2 was not significant according to the t ratio ($t = 0.115$, $p = .9098$).

Table 4-10
Percentage of distance moved with the non-dominant hand in the two-handed condition (second session)

M	SD	n
38	8	12

Table 4-10 presents the percentage of distance moved with the non-dominant hand in the two-handed condition C2. The mean value shows that the non-dominant hand frog was used for moving a substantial amount of the total distance. This is shown in Figure 4-16 that presents the amount of distance moved with each hand in the second session of the experiment.

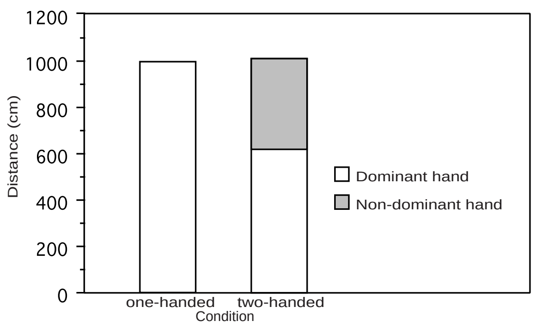


Figure 4-16. Mean values of distances moved with each hand (second session).

Figure 4-17 shows how the hands moved in one trial for each placement of a pile object separately.
The plots of the paths followed by the Frogs were generated from data of one of the subjects. The path of the left hand is shown left in the pictures. In the first three placements, the left hand was almost stationary. The subject placed the pile objects on the cube without rotating the cube. In the latter three placements, the left hand was used to rotate the cube to facilitate placement with the right hand.

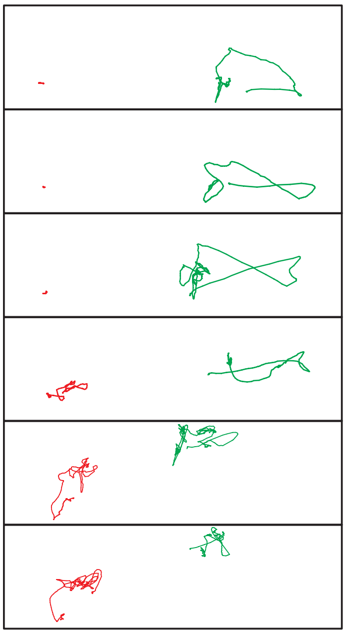


Figure 4-17. Perspective plots of the paths of the Frogs in the six placements of a trial. The left paths are plots of the Frog held with the left hand and the right paths those of the right hand held Frog.

Rotation

Table 4-11 presents the results for the total rotation of both hands observed in the second session of the experiment. The difference of 2 rad between the total rotation of conditions C1 and C2 was not significant according to the t ratio (t = 0.330, p = .7444).

Table 4-11
Mean values of total rotation in radians with both hands (second session)

Condition	M	SD	n
One-handed	67	19	12
Two-handed	69	14	12

M	SD	n
59	9	12

Table 4-12
Percentage of rotation executed with the non-dominant hand (second session)

Table 4-12 presents the percentage of rotation of the non-dominant hand Frog in the second session of the experiment. It shows that in the two-handed condition, the non-dominant hand was used for rotation more than the dominant hand. This can be seen in Figure 4-18 that presents the amount of rotation of each hand in the second session of the experiment.

4.4.5 Discussion

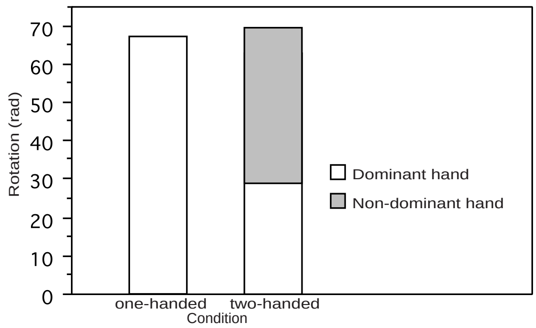


Figure 4-18. Mean values of rotations executed with each hand (second session).

It was found that two-handed operation did lead to significantly shorter completion times, but only in the second half of the experiment, as shown in Table 4-6. The completion times in the first session of the experiment and over the course of the whole experiment did not differ significantly. It was hypothesized that the occurrence of the difference later in the experiment was caused by two-handed operation being more difficult to learn. Performance benefits of two-handed operations appeared later in the experiment, as the subjects grew accustomed to the system. The analysis of this hypothesis however is complicated because of the within-subjects design of the experiment.
Two groups of subjects experienced the experimental conditions in a different order and that may have influenced the completion times in the latter half of the experiment.
The experimental design does not allow conclusions on how the sequence of the conditions might have influenced the completion times. It could be that starting with two-handed operation might have been beneficial because users might explore more task-solving strategies with two-handed operation. The subjects could have used

these later when they entered the single-handed condition. Evidence for the presence of this phenomenon in other two-handed systems has been reported by Hinckley, Pausch and Proffitt (1997). It could also be that starting with one-handed operation causes shorter completion times. In the experiment, subjects needed to acquire a lot of new skill in a short time. For example, they needed to learn how to operate the Frogs since none of the subjects had used a 3D interaction device before. Subjects that started with two-handed operation needed to learn to operate two Frogs from the start and that might have been a lot to learn at once. The length of exposure to each of the conditions might turn the balance towards either of the two possible influences but with the within-subjects setup used in the experiment this was difficult to analyze.

With regard to the workload in the second half of the experiment, it was found that the two-handed operation did not lead to significantly larger distances and rotation angles. Both the analyses of distances and rotations showed non-significant differences between one- and two-handed operation. The analyses also taught that in the two-handed condition, a substantial amount of workload was executed with the non-dominant hand. More than a third of the total distance was completed with the non-dominant hand.
For rotation, the non-dominant hand was used for more than half of the total rotation.

4.5 The second experiment

Except for the number of subjects and the experimental design, the second experiment was the same as the first one, including the hypotheses. To test them, the same system was used with the same test software.

4.5.1 Experimental design

In the first experiment, a within-subjects design was used. This experimental design hindered the interpretation of the results. Two-handed operation led to significantly shorter completion times only in the second session of the experiment. Because of the within-subjects design, it could not be verified whether this was the result of two-handed operation or of the asymmetric exposure to single- and two-handed operation. Therefore, in the second experiment described here, a between-subjects design was used to verify whether two-handed operation leads to shorter completion times. In the between-subjects design of the experiment, subjects experienced only one of the experimental conditions, either one- or two-handed operation.

4.5.2 Subjects

Twelve paid volunteers participated in the experiment, with male and female subjects equally distributed over the single- and two-handed conditions. The subjects were all students of the sub-faculty of Industrial Design and had not been involved in the first experiment. Their ages ranged between 18 and 27 with a median age of 22.5. Their average use of CAD programs per week ranged from no use at all to 20 hours per week, with a median value of 2.5 hours per week.

4.5.3 Procedure

The procedure of the experiment was identical to the procedure of the first experiment except that no additional training was necessary halfway the experiment. In the first experiment, subjects changed from one condition to the other. Therefore, additional training was given before they entered the second half of the experiment. In the second experiment, no additional training was given because subjects only experienced one condition throughout the whole experiment.

4.5.4 Results

In the following analysis, a statistical significance level of 95% was used for all statistical tests. The analysis starts with the completion times. Then, workload is analyzed by studying the distance and rotation variables separately.

Table 4-13
Mean completion times in seconds for the second experiment

Condition	M	SD	n
One-handed	157	37	6
Two-handed	121	26	6

Completion times

The analysis of the completion times of the second experiment starts with the presentation of the completion times realized in both sessions of the experiment. Table 4-13 presents the mean completion times of the one-handed condition C1 and the two-handed condition C2. Although a considerable difference was found between the means of the completion times for of the one- and two-handed conditions, the difference of 36 s between the means was not significant (t = 1.960, p = .0785), like in the first experiment.

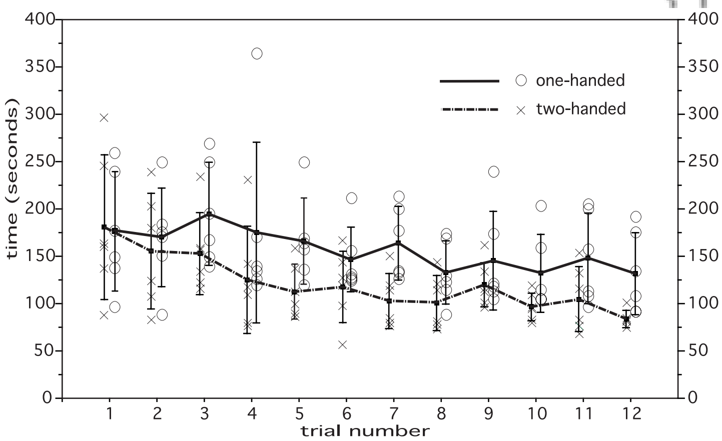


Figure 4-19. Effects of learning over the twelve trials of the second experiment. Error bars represent the standard deviation of the completion time per trial. The results of the individual subjects are indicated with the circles and the crosses.

Figure 4-19 presents the effects of learning per trial for the two conditions. The figure suggests that the subjects in the second experiment experienced a less steep learning curve than the subjects in the first experiment. In addition, it seems that subjects in the two-handed condition were still improving completion times in the later trials.

Table 4-14
Mean completion times in seconds in the first and second session separately.

	First session			Second session		
Condition	M	SD	n	M	SD	n
One-handed	172	39	6	143	38	6
Two-handed	141	37	6	101	18	6

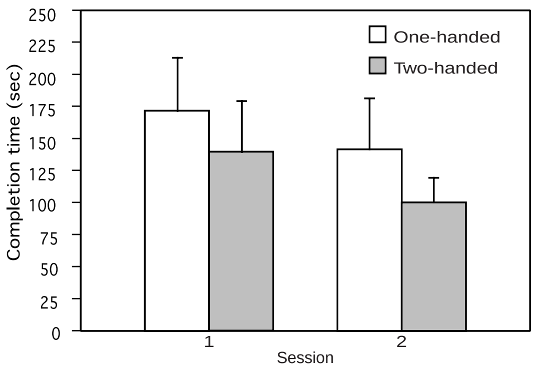


Figure 4-20. Completion times in the first and second session of the experiment, error bars represent 95% confidence interval.

The completion times for each session are presented separately in Table 4-14 and Figure 4-20. In the first session the difference of 31 s between the mean completion times of conditions C1 and C2 was not significant according to the t ratio (t = 1.416, p = .1870). This was also found in the analysis of the first experiment, just like the significant difference between the completion times of conditions C1 and C2 in the second session (t = 2.406, p = .0369). This time, the difference between the mean completion times was 42 s. The ratio of the mean completion times was M_{C2}/M_{C1} = 0.71.The standard deviation in this ratio was SD = 0.23.

Distance The distances for one- and two-handed operation in the second experiment are given in Table 4-15. The difference of 56 cm between the mean distances of conditions C1 and C2 was not significant according to the t ratio (t = 0.370, p = .7190).

Table 4-15
Mean values of total distance in centimeters with both hands (second session)

Condition	M	SD	n
One-handed	994	271	6
Two-handed	938	249	6

Table 4-16 presents the percentage of distance moved with the non-dominant hand in the two-handed condition. The mean value for the percentage suggests that the distance traveled with the non-dominant hand accounts for a substantial amount of the total distance.

Table 4-16
Percentage of distance moved with the non-dominant hand in the two-handed condition (second session)

M	SD	n
37	13	6

Rotation The values for the total rotation of both conditions are presented in Table 4-17. The difference of 1 rad between the mean values for total rotation of conditions C1 and C2 is not significant according to the t ratio (t = 0.093, p = .9275).

Table 4-17
Mean values of total rotation in radians with both hands (second session)

Condition	M	SD	n
One-handed	63	15	6
Two-handed	64	17	6

Table 4-18 presents the percentage of rotation executed with the non-dominant hand. The value for the mean percentage suggests that more than half of the rotation needed to accomplish the task, was executed with the non-dominant hand.

Table 4-18
Percentage of rotation executed with the non-dominant hand (second session)

M	SD	n
55	20	12

4.5.5 Discussion

The results of the second experiment were in line with the results of the first experiment. Again, two-handed operation was observed to lead to significant shorter completion times than one-handed operation (Table 4-14). The difference appeared in the second session of the experiment that started after subjects had been working with the system for a period of approximately 40 minutes. As in the first experiment, a significant difference in completion times was absent in the first session. This suggests that subjects were still learning the two-handed operation and gradually improved performance over the subjects in the one-handed condition. Support for this can be found in the large deviation values for the observed completion times in the first session (Table 4-14).

The mean values for the workload variables distance and rotation are close to those found in the first experiment. Again, in the second session, subjects in the two-handed condition used their non-dominant hand for more than a third of the total movement (Table 4-16). Furthermore, the non-dominant hand was used to accomplish more than half of the total rotation (Table 4-18). At the same time, the total movement and rotation between the one- and two-handed conditions did not significantly differ.

4.6 Observations

The qualitative evaluation of the experiment consists of observations obtained from watching subjects completing the experiment and discussions afterwards. The observations are categorized in task related and system related aspects. Task related observations describe solution strategies and the use of the hands in solving the puzzle. System related observations were made because this was the first opportunity to see whether the design of the interface and the Frogs exhibited flaws not revealed during pilot testing.

4.6.1 Task related observations

One assembly strategy was commonly used by the subjects. First, the cube was oriented such that the pile object could be placed on top of it. Then the pile object was actually placed on top of the cube. Only in a few occasions (fewer than 5% of all placements), subjects placed the pile objects on the sides of the cube. Even less common (fewer than 1% of all placements) was reverse placement when the cube was moved towards the pile object.

Subjects were very quick to adopt 3D interaction with a computer, although none of them had used a spatial interface before. They all commented that the system was easy to learn, with both one- and two-handed operation. A problem noted was that subjects sometimes confused the forward and upward directions when they wanted to move the cursor up. Instead of moving the Frog up, they moved the frog forward. The confusion generally occurred in complex and involving situations, such as the clutch action. A possible explanation is that the subjects were familiar with the mouse. In most mouse-operated interfaces, users have to move the mouse forward to bring the cursor up. The subjects could have fallen back on this when they arrived in difficult situations in the experiment.

Like 3D interaction, two-handed operation was accepted immediately. Almost all subjects used their non-dominant hand extensively and efficiently in the two-handed condition. Only one subject almost never used the non-dominant hand. Most subjects stated that they missed the Frog for the non-dominant hand in the one-handed condition of the experiment if they had started with two-handed operation in the first session. In the two-handed condition, the dominant hand was predominantly used for moving the smaller pile object while the non-dominant hand controlled the cube. This behavior is in accordance with behavior reported in studies of other two-handed interfaces and in studies of real world tasks (Hinckley, Pausch, Proffitt, Patten & Kassell, 1997).

The following observations are based on recordings of the movements of subjects and preliminary data processing. Until now, we analyzed the movement data globally, but not with numerical precision.

Typical behavior of subjects in the two-handed condition followed the observations described in the work of Guiard (1987). The non-dominant hand (the left hand for subjects that operated the cursor with the right hand) preceded the dominant hand in actions and did set the reference frame for the actions of the dominant hand. The cube was generally rotated first with the non-dominant hand to facilitate placement with the dominant hand as expected. Subsequently, the actual placement was done with the dominant hand. The anticipated use of the non-dominant hand for aiding the selection process occurred only later in the experiment. If the non-dominant hand was used, it rotated the object first, such that it would appear under the cursor for easy selection. Non-dominant actions were typically characterized by low temporal and spatial frequencies when compared to the actions of the dominant hand.
In the experiment, the non-dominant hand was mostly used to position and orient the cube coarsely, such that it facilitated the more precise placement of shapes on it with the dominant hand.
In the beginning of the two-handed sessions, subjects tended to

separate the left and right handed actions in time. Only later, as they became more experienced, left- and right-handed actions started to occur simultaneously.

Recordings showed no preferred position for the hands and arms. Sometimes subjects kept their elbows on the armrest, sometimes on the table, while others kept their hands on the table. These postures were not static, but instead subjects kept changing them over time.

4.6.2 System related observations

Almost all aspects of the system were according to expectations but some were unforeseen. Three unanticipated aspects are highlighted in this chapter.

The confinement of the cursor to the extents of the workspace (Figure 4-4) successfully prevented the cursor from getting lost but it had one less-desired side effect. Subjects were confused at times when they were unable to move the cursor to certain locations in the display space. This was caused by the fact that the workspace represents only part of the display space. In addition, the workspace was viewed from an angle and thus the cursor was limited to a non-rectangular area of the display space. To the subjects it appeared as if the cursor was confined to a rotated cube. Most of the confusion occurred when the cursor was situated in one of the corners of the box.

The clutch mechanism for the Frog held with the non-dominant hand was used as expected. It was mostly used for rotating the cube over large angles and less for changing the manipulation space. The clutch mechanism for the dominant hand however appeared to be a critical part of the interface because some of the subjects were confused even toward the end of the experiment. The clutch mechanism of the dominant hand was predominantly used for changing the manipulation space. A typical confusing situation was when the Frog was close to the surface of the table and the subject wanted to move the cursor down. The procedure taught to the subjects was to first press the clutch button (breaking the connection between the position of the Frog and the cursor) and then lift the Frog while holding the button (displacing the Frog

Figure 4-21. The Frog held with a precision grip.
Figure 4-22. The Frog held with a power grip.

without changing the position of the cursor). Some subjects found this confusing despite the training.

The general response to the shape of the Frogs was positive but there were some comments and suggestions from the subjects. The intended grip for the Frog was the precision grip, as pictured in Figure 4-21. This was appreciated by subjects but some of them commented that they sometimes liked to hold the Frog with their whole hand, especially the Frog of the non-dominant hand. This power grip (Figure 4-22) was avoided intentionally but the possibility of alternative grips might be included in a future redesign of the frog. Additionally, some of the subjects complained that two of their fingers remained unsupported by the shape of the Frog. Likewise, there were complaints about the presence of the wire attached to the Frogs. Subjects commented about the weight of the wire and it was observed that the wire did sometimes limit the amount of rotation that could be executed.

4.7 General discussion

The results of both experiments have shown that two-handed operation did lead to shorter task completion times. Trial completion times varied considerably. This is not very surprising, given the complexity of the task and the fact that subjects had never been exposed to a computer system with 3D interaction devices. Performance benefits of two-handed operation did not appear instantaneously. It took about 40 minutes before subjects working with two hands completed the puzzle faster than subjects in the one-handed condition did. Apparently, some learning was involved.

In addition, it was shown that two-handed operation did not lead to an increase of the total distance and rotation angles when compared to single-handed operation. Instead, it relieved the dominant hand of a substantial amount of moving and rotating.

The task used in both experiments was selected to represent a common task in conceptual modeling. It was meant to resemble the arrangement of functional elements of a design. In addition, the puzzle task has a lot in common with tasks where objects need to be manipulated from different sides. It is therefore believed that performance and workload benefits of working with two hands will also appear for other tasks than the puzzle task.

It was observed that some characteristics of the interaction design of the system might have been of influence to the deviations in completion times included. In both experiments, it was seen that subjects were confused by the clutch mechanism in some trials. On other occasions, the fact that the 3D cursor was confined to the extents of the workspace did lead to confusion. Both factors had a negative influence on completion times because they interrupted the workflow of the subjects.

The experiments not only tested the concept of two-handed operation but also tested to see whether the Frogs and the 3D interaction techniques developed were appropriate for the experimental task. It was expected that the subjects would need to acquire a lot of skill because none of the subjects used 3D interaction devices before. In addition, two-handed operation of a computer system was new to the subjects too. We can say that the combination of the Frogs and the interaction techniques was successful. Subjects quickly learned it, were enthusiastic about it and indicated that they thought it to be a welcome alternative to the familiar mouse operated CAD programs. Observations of subjects using the system and discussions afterwards pointed to possible improvements of the system. Among those are the shape of the Frogs, the clutch mechanism and the confinement of the cursor to the workspace.