CHAPTER

Establishing preferred interaction techniques for selection and clutch

Two-handed operation can lead to intuitive and efficient user interfaces for 3D modeling tasks. However, there is not yet a convention for two-handed operation in combination with 3D interaction devices. Only in a few experimental systems, two-handed operation has been combined with 3D interaction devices for the creation of highly responsive user interfaces. In this chapter, an experiment is described in which two aspects of two-handed, 3D interaction are tested for influence on performance, workload, concurrent two-handed activity and fatigue. The first aspect is the selection mechanism that determines how objects in the scene are selected. The second aspect is the clutch mechanism that determines how the manipulation space defined by the interaction devices is coupled to the display space. Performance times and workload were established with the same puzzle task used in the previous chapter.

The results presented in this chapter show that no significant differences were found between completion times achieved by subjects with the more generally applicable selection method (called independent selection) than with the more specialized selection method (dependent selection). This tells us that independent selection can be used in 3D user interfaces without sacrificing performance and increasing workload. This will help to design interfaces for other tasks than assembly alone.

In addition, it is presented that a displacement between the manipulation space and the display space as well as displacements between the manipulation spaces of each hand did not significantly influence performance times. A difference was found in the task strategy used by the subjects to complete the task and in the workload involved. It was observed that when the manipulation spaces of both hands could not be separated, the interaction devices would tend to collide when objects were brought together. This increased the task completion distance and reduced the amount of concurrent action of both hands.

5.1 Alternative interaction techniques for selection and clutch

In the previous chapter, it was established that two-handed operation has several benefits over single-handed operation in the context of a three-dimensional assembly task. This was in line with experience from other researchers that have applied two-handed 3D interaction in desktop systems such as JDCAD (Liang & Green, 1991), THRED (Shaw & Green, 1994) and Hinckley's neurological props interface (Hinckley, Pausch, Goble & Kassell, 1994b).
In immersive VR systems such as CHIMP (Mine), SmartScene (Multigen Inc) and Worlds in Miniature (Stoackley, Conway & Pausch, 1995), these results were achieved too. The two-handed interface that was used in the comparison was designed to be efficient and intuitive for the assembly task. Indeed, the interface proved to be more efficient than the one-handed interface. At the same time, the workload did not increase and instead, the workload was divided over both hands.
In this chapter, we take a closer look at alternatives for the two-handed interface of the previous chapter. While the interface proved to be efficient and easy to use, it was not established which factors might further increase the performance, degree of comfort and the general applicability of two-handed interfaces.

As for performance and degree of comfort, we specifically liked to know how the coupling between display and manipulation spaces could influence completion times, workload, concurrent two-handed activity, fatigue and user preference. As discussed in Chapter 3, the display and manipulation spaces can be unified or separated. With two-handed operation, the manipulation spaces of each hand could also be displaced. A separation of the display and the manipulation space is accomplished by activating the clutch mechanism introduced in Chapter 3. In the unified situation, the relation between the display and the manipulation space is fixed and users can employ their motor memory when acquiring virtual objects.

If the manipulation spaces can only be separated from the display space for both hands at the same time, there is no fixed relation between the interaction devices in the real world and the objects in the virtual world. However, as the manipulation spaces for both hands are identical, the relation between the devices in the real world is the same in the virtual world. Therefore, users can still

utilize their innate ability to know where their hands are relative to each other when they assemble objects.
When both manipulation spaces can be displaced from the display space separately, the frame of reference between the hands is affected too. In this situation, users are limited in employing motor memory or their ability to know where their hands are relative to each other. Every time the clutch mechanism is activated, the relationship changes and therefore, only a relative coupling exists. On the other hand, separating the manipulation spaces has the advantage that interaction devices do not have to get in each others way when two objects are brought together.
The interface used in Chapter 4 was of the last category because the manipulation spaces for both hands could be separated from the display space and from each other. Each of the two devices offered a clutch button to activate the clutch mechanism that controls the separation of display and manipulation space.

The two-handed interface used in Chapter 4 was targeted for the assembly task in the experiment. The dependent selection technique introduced in Chapter 3 made the selection of objects moved with the non-dominant hand dependent on the selection of the dominant hand. While suited for the assembly task, this selection method is not readily transferred to a general modeling environment with more tools than the assembly tool alone. Later, it was realized that for many tools it would be convenient that the non-dominant hand could select objects too. The independent selection technique in Chapter 3 offers the possibility to select objects with both hands. The choice for dependent selection was made under the assumption that the selection of objects with a cursor was difficult to do with the non-dominant hand and would thus lead to degraded performance. In this chapter, we will find whether independent selection does indeed lead to a decrease in performance.

5.2 Goal of the experiment

The goal of the experiment was twofold. First, it should establish how independent selection compares to dependent selection. Second, it should establish the influence of separated display and manipulation spaces. The variables chosen to study these effects are performance time, workload, concurrent two-handed activity, fatigue and user-preference.

It was decided to compare two conditions with two selection mechanisms in the experiment. The first condition offered dependent selection as the means to select the objects for control of either hand. In the second condition, independent selection was offered as selection mechanism.
With dependent selection, the selection of objects under control of the non-dominant hand is determined by the selection of the dominant hand. If the dominant hand is not dragging an object, the non-dominant hand controls the position and orientation of all the objects in the scene. When it is dragging an object, the non-dominant hand controls the position and orientation of the rest of the objects in the scene. Selection of objects with the dominant hand is accomplished with the cursor-based ray casting technique, as described in Figure 3-26 and Figure 3-27 in Chapter 3 (CD-ROM, 5-1).
With independent selection, the same cursor-based selection technique is offered for each hand separately. In this condition, objects to control are selected by each hand separately and a cursor is associated with each of the devices, as shown in Figure 3-28 (CD-ROM, 5-2).

The influence of the relation between display and manipulation spaces was studied by comparing the results of three conditions with different clutch mechanisms. The three conditions used independent selection with two cursors. The first condition offered no clutch mechanism and thus, the relationship between display and manipulation spaces for both hands are fixed. Furthermore, the display and manipulation spaces were unified, which means that the manipulation spaces were situated in front of the monitor, as described in Chapter 3 (CD-ROM, 5-3).
The second condition offered a combined clutch mechanism, which means that the manipulation spaces of both hands can be moved but only for both hands at the same time (CD-ROM, 5-4).
The third condition offered a separate clutch mechanism for each hand. Here, users can separate the manipulation spaces from each other (CD-ROM, 5-5).

Table 5-1 lists the combinations of the conditions used in the experiment. Notice that there is only one clutch condition for dependent selection. The reason is that dependent selection can not be realized without a clutch mechanism or with a combined clutch mechanism. A clutch mechanism is needed for the rotation of objects controlled with the non-dominant hand. Without this clutch mechanism, objects can not be rotated over large angles because of the physical limits of the hand. With independent selection, this problem is non-existent because clutching is only necessary to change the position of the manipulation space. The 3D cursor provides a means to rotate objects over large angles with a series of grab, rotate and release cycles.

Clutch mechanism	Dependent selection (one cursor)	Independent selection (two cursors)
No clutch	-	IndNo
Combined clutch	-	IndComb
Separate clutch	DepSep	IndSep

Table 5-1
Experimental conditions

It was decided to use the same puzzle task as described in Chapter 4. There, it was argued that the puzzle task represents a common task in 3D modeling environments. In addition, the results found for the puzzle task were hoped to be useful for designing the interaction of other modeling tasks. For instance, tasks where the non-dominant hand is used to hold an object while the dominant hand is modifying it.

5.3 Hypotheses

The four conditions in the experiment were compared on a number of dependent variables. Some variables were measured with the system (completion time, distance, rotation and combined two-handed operation time). Other variables were established with a survey (fatigue and ranking). The null hypothesis H_0 was the hypothesis that there were no differences between the values of the dependent variables between conditions. The alternative hypothesis H_1 was that the dependent variables would differ between conditions. If the null hypothesis H_0 is rejected, it is difficult to establish what the cause is because most dependent variables are influenced by a number of properties of the interfaces used in each condition. Next, some influences of the selection mechanism and the clutch mechanism on each of the dependent variables are presented.

The influence of the selection mechanism on the completion times was difficult to predict. It was assumed in Chapter 4 that independent selection would influence performance in a negative way

because it could be difficult to select objects with the non-dominant hand. In addition, dependent selection offers users the possibility to use their non-dominant hand as assistance for dominant hand selection and this could lead to a performance benefit. However, independent selection may offer more flexibility to users to decide on how to complete the task and may be easier to learn, thus leading to faster completion times.
The influence of the selection mechanism on the workload variables distance and rotation and on fatigue was difficult to predict too. There seemed to be no apparent reason to assume differences in workload and fatigue between independent and dependent selection.
With the survey, it was established how users experienced the difference between the dependent and independent selection mechanisms. Preliminary testing revealed that subjects were under the impression that operating two cursors would be more difficult than operating one. This suggested that they would prefer dependent selection. After using the system for a while, subjects stated that it was easier than they thought and that it offered them more freedom. That suggested that they would rank dependent selection higher.

A pilot test revealed that we could expect little direct influence of the clutch mechanism on performance times. Under normal circumstances, users barely used the clutch mechanism, only to readjust the manipulation space when objects were out of reach or to rotate objects controlled with the non-dominant hand over large angles in the dependent selection condition.
The secondary influences of displacing manipulation spaces however, were expected to have influence on fatigue and on the way the task was accomplished. Regarding task strategy, the no clutch and the combined clutch conditions have identical manipulation spaces for both hands and therefore the devices can get in each others way when objects are brought together. Therefore, subjects are forced to move one device out of the way to make room for the other. With displaced manipulation spaces in the separate clutch condition, this situation can be avoided and therefore the actual placement of one object on the other can be performed with two hands.
Regarding fatigue, in the no clutch condition subjects are forced to work in a fixed manipulation space and therefore forced to work

without support for their arms. Therefore, subjects were expected to experience more fatigue. Alternatively, subjects may change their strategy by bringing the objects to positions such that their arms have support. This could increase the amount of workload and therefore would lead to an increase of fatigue too.

The effects of the clutch mechanism on fatigue and task strategy could in turn influence on the completion times. The amount of actual influence of these second order effects on performance is difficult to predict.

5.4 Materials and methods

5.4.1 Experimental design

The results of the previous experiments, described in Chapter 4, suggested that subjects were still in the learning phase after completing the sessions. It was therefore decided to invite the subjects of this experiment for a period twice as long, to reduce the effect of learning. Due to the limited time available to carry out the experiment, a within-subject design was chosen because a small number of subjects could be invited and a large number of conditions were to be tested.

A pilot test and the previous experiments showed that a period of one hour of continuous use of the system was short enough to prevent subjects getting bored with the task. The same pilot tests suggested that three sessions could be completed within an hour, hence the decision to invite each subject for two periods of two hours, each period consisting of the same three conditions. Experiments were conducted at the same time of day to avoid diurnal variations.

Table 5-2 shows the experimental design that was used for one day. Subjects repeated the same sequence of conditions on the second day. It was not possible to test all the possible orders of conditions. To minimize potential asymmetric skill transfer, the number of sessions for each condition was the same and the order of conditions for the last four subjects was the reverse of that for the first four subjects. The design has the implication that in session 2, not all the conditions were present. Table 5-2 shows that conditions DepSep and IndSep were absent in session 2.

Subject	Session 1	Session 2	Session 3
1	DepSep	IndNo	IndComb
2	DepSep	IndComb	IndSep
3	DepSep	IndNo	IndComb
4	IndNo	IndComb	IndSep
5	IndComb	IndNo	DepSep
6	IndSep	IndComb	DepSep
7	IndComb	IndNo	DepSep
8	IndSep	IndComb	IndNo

Table 5-2
Experimental design for each of the two days of the experiment (for the names of the conditions, see Table 5-1)

5.4.2 Establishing dependent variables

The effect of the interfaces on the performance of subjects was compared using the completion times achieved. Workload was evaluated using the distances and rotation angles needed to complete the task as described in Chapter 4. The value of the distance variable d was established by summing all displacements of a Frog during a trial, as given in Equation 4-1. The value of the rotation variable $d\phi$ was established by summing all the rotations of a Frog during a trial, as given in Equation 4-2 and Equation 4-3. Concurrent two-handed activity was established by calculating the time spent in dragging two objects simultaneously.

In a survey after each condition, subjects were asked to indicate the amount of fatigue they experienced in their left and right arms, wrists, hands and fingers after each session. A five-point scale was used to gather the data using the labels given in Table 5-3.

Label	Value
not at all	0
hardly	1
considerable	2
much	3
very much	4

Table 5-3
Labels used to gather the fatigue users experienced and their values

At the end of the experiment, after the last session, subjects were asked for their opinion about the interfaces they had experienced. In the survey, they were asked whether each interface was “easy to learn”, “suited for the task” and “efficient”. A five-point scale was used to gather each of these impression variables, using the labels given in Table 5-4. In addition, subjects were asked to rank the interfaces they had been using and to base the ranking on their preference for using each interface in their daily practice. To establish the preferred interface, the best condition received three points, the middle two points and the worst one point.

Label	Value
disagree	1
disagree a little	2
neutral	3
agree a little	4
agree	5

Table 5-4
Labels used to gather impression variables and their values

5.4.3 Subjects

It was learned from the previous experiments that completion times can vary considerably. It was suspected that this variability was partly caused by subjects having different experience with CAD systems. In addition, differences in performance of male and female subjects were found, especially in the beginning of the experiments. To reduce variability in this experiment, it was decided to invite male subjects with considerable experience with CAD systems only.

Eight male, paid subjects with a background in Industrial Design Engineering were invited to the experiment. All subjects either recently graduated from our faculty or were in the final year of their study. The age of the subjects ranged between twenty-four and twenty-eight with a median value of twenty-six. They used 3D CAD programs in their work on a regular basis (about sixteen hours per week on average), while none of the subjects used 3D interaction devices for operating 3D CAD programs. Interaction devices used by the subjects include mouse, keyboard and drawing tablet. Some of them had some experience with other interaction devices (e.g. SpaceBall™, experimental interaction devices) but none of them had used them in combination with 3D CAD software.
The subjects entering the experiment chose to use their right hand as dominant hand, except one. Before the experiment, subjects were asked what their dominant hand was. They were offered the opportunity to try the first condition both ways if they indicated that they used their left hand as dominant hand for some tasks in daily life. Once the preference was established, their decision was final and the subject would finish the experiment with the dominant hand of choice. Two subjects indicated that they were left-handed for some tasks. One subject chose to use the left hand as dominant hand, while the other chose the right hand.

5.4.4 Procedure

Each subject experienced two identical sessions consisting of three conditions, each of the two successive days. Completing a session took the subjects about one hour, including training. The following procedure was used for each condition.

- The experimenter explained the system and gradually introduced the interface of the current experimental condition to the subject.
- The subject trained at the task with the interface of the current experimental condition.
- The experimenter instructed the subjects to complete each task as fast as possible and moved to a position out of sight of the subject. The subject then performed one practice trial.
- The subject performed a run of six experimental trials. As in the experiment described in Chapter 4, each run of six experimental trials consisted of two

blocks of three trials. Within each block, three different models were presented to the subject, in random order. Before each trial, the subjects were asked to put their hands into a comfortable start position and after each trial, the completion time was presented.

- Upon completion of the last trial of the condition, the experimenter asked the subject to complete a short survey about the amount of fatigue they experienced in their arms, wrist, hands and fingers.
- Upon completion of the experiment, the experimenter asked the subjects to complete a survey in which they were asked for their opinion about the following aspects of the system: ease of learning, suitability for the task and efficiency. Finally, subjects were asked to rank the conditions they had experienced.

5.4.5 Experimental set-up

The system used in the experiment was almost equal to the system used in the experiments described in Chapter 4. Apart from the changes needed to realize the interfaces tested in the new conditions with independent selection, there were some changes to the test software motivated by the observations of the previous experiments. These changes were common to all of the conditions in this experiment.

One of the observations in the previous experiment was that users sometimes struggled to move the cursor into (or out of) certain areas in the scene. This was caused by the shape of the workspace and the fact that the cursor was confined to the workspace.
The motivation for the confinement was to prevent the cursor from getting lost when subjects would accidentally move it out of the display space. The result was that not all of the display space was reachable and some of the subjects stated that they were confused about the confinement. Therefore, it was decided to confine the cursor to the display space. This also prevents the cursor from getting lost, while at the same time it does not hinder the subjects in reaching the entire scene.

A minor modification was that the shape of the cursor changed. In the previous experiment, the star shaped cursor of Figure 3-17 was used. In this experiment, the cursor with the dart shape of Figure 3-18 was used because it was believed to represent the state of the interaction devices better than the star shape. In addition, the dart shaped cursor facilitates the selection process. In contrast to the star cursor, the shape of the dart cursor presents the location of the hotspot more clearly and the user is free to orient the cursor such that the area of interest is visible.

Some of the conditions in the experiment required the presence of two cursors in the scene. Each cursor represents one interaction device in the scene and therefore confusion may arise as to which cursor is controlled by which device. As Shaw and Green (1994) found with the THRED system, confusion rarely arises when the display spaces of both hands coincide. Then, the user knows which cursor belongs to which device by relying on proprioception. However, in the IndSep condition, the display spaces can be separated and then, confusion may indeed arise. To reduce potential mistakes, the cursors were given different colors, one cyan, the other yellow and corresponding labels were attached to the Frogs.

Close inspection of the data captured in the previous experiments revealed that the samples were not equidistant. The data was sampled each time the screen was refreshed and the rendering time of the image varied. This was believed not to hinder the subjects much but for subsequent data processing, it was inconvenient. Therefore, a new display card was used that had the additional benefit that it rendered faster, thereby producing higher frame rates.

The following hardware and software were used in the experiment.

Hardware:

- Apple PowerMac 8500 computer
- NewerTech MAXPOWR G3 266MHz processor update
- ATI XClaim 3D accelerator
- IIYAMA Vision Master Pro 17” monitor
- Two Ascension Flock of Birds tracking systems with two Frog interaction devices

Software:

- Operating system: Apple Mac OS 8.5
- Additional system software: Apple QuickDraw 3D 1.5.4
- Experimental software (CD-ROM, ID8AssembleClutch)

5.5 Results

In the following analysis, a statistical significance level of 95% was used for all statistical tests. All results will be presented in graphical format (see Appendix for most of the data regarding performance and workload). The analysis of the completion times will show that completion times did not significantly change during the second day of the experiment but improved significantly on the first. It was therefore decided to perform the subsequent analysis with data of the second day only.

5.5.1 Performance

Completion times

The analysis of completion times starts with a study of the completion times realized in each session over the course of the experiment, combining the results of all conditions. This gives an impression about the learning curve that users experienced over the course of the experiment. Figure 5-1 presents the mean completion times for each session of both days. A one-way ANOVA (analysis of variance) indicated significant differences in performance times ($F(5,42) = 11.096$, $p < .0001$). Fisher's a posteriori LSD (Least Square Difference) test revealed that significant differences between successive sessions were found between successive sessions one and two and sessions three and four. The latter difference occurs between the last session of the first day and the first session of the second day. The second day exhibited no significant decrease in completion times and these sessions will be used in subsequent analysis.

Figure 5-2 presents the mean completion times per session again, but the results are split per condition. The numbers in the bars represent the number of subjects in each condition and show the consequence of the experimental design as discussed above. Not all conditions were tested with the same number of subjects in all sessions. For instance, some conditions (DepSep and IndSep) were not tested in sessions two and five.

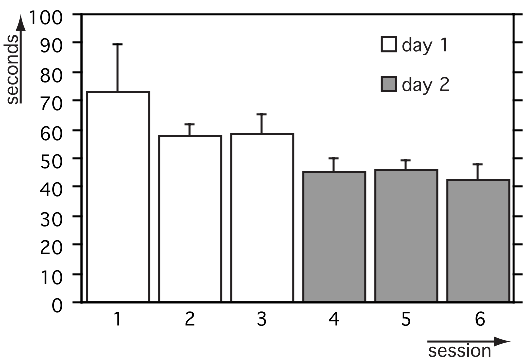


Figure 5-1. Completion times in seconds per session, error bars represent 95% confidence interval.

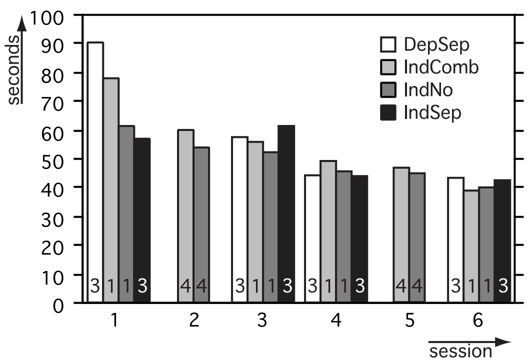


Figure 5-2. Mean completion times in seconds per session, per condition. The numbers in the bars represent the number of subjects in each condition.

Figure 5-3 presents the mean completion times for each condition in the sessions on the second day. It can be seen in the figure that the differences between the mean completion times realized with the interfaces were small. Indeed, it was found that the differences between the completion times are insignificant with a one-way ANOVA.

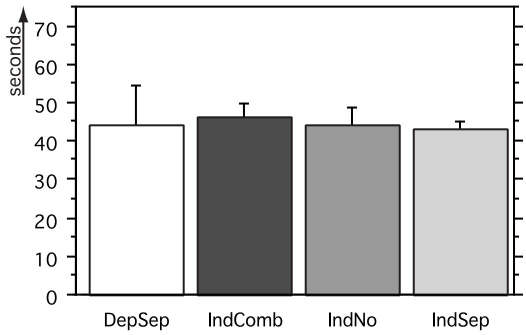


Figure 5-3. Completion times in seconds on the second day for each condition, error bars represent 95% confidence interval.

Clutch times

The combined clutch times were inspected to see what amount of influence the clutch activity might have had on the performance of each of the interfaces. The combined clutch time is the duration of the clutch action during a trial. The logical OR of both clutch buttons was used for the interfaces that offer a clutch mechanism for each hand separately (DepSep and IndSep). The values of combined clutch time for each condition are presented in Figure 5-4 as percentages of the trial completion time. Combined clutch time was obviously absent in the no-clutch condition (IndNo) and virtually non-existent in the other two conditions with independent selection (IndComb and IndSep). Only in the dependent selection condition (DepSep) a serious amount of combined clutch time was noted, almost all of which was executed with the non-dominant hand.

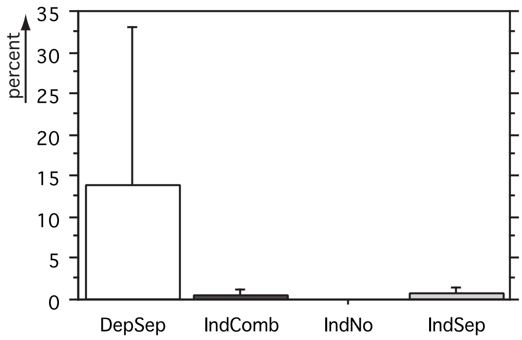
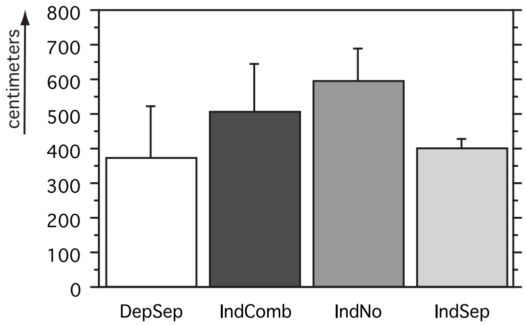


Figure 5-4. Mean combined clutch times as percentage of the completion time, error bars represent 95% confidence interval.

5.5.2 Workload

The analysis of the workload of each of the conditions was performed using the same variables distance and rotation used in the previous chapter. The distance variable d is the total distance the Frogs were moved to complete the trial. The rotation variable $d\phi$ is the total amount of rotation the Frogs were put through for task completion. For both variables, the values for each hand are presented first, then the combined value and the percentage of non-dominant contribution to this value. A combined value simply means that the contributions of both hands are summed.

Distance Figure 5-5 presents the mean values of distance for the non-dominant hand. A one-way ANOVA indicated a significant difference between the conditions ($F(3,20) = 5.489$, $p < .01$). Fisher's a posteriori LSD test revealed significant differences between conditions with separate clutching (DepSep and IndSep) and the condition without clutch (IndNo). In addition, the difference between DepSep and IndComb was significant.



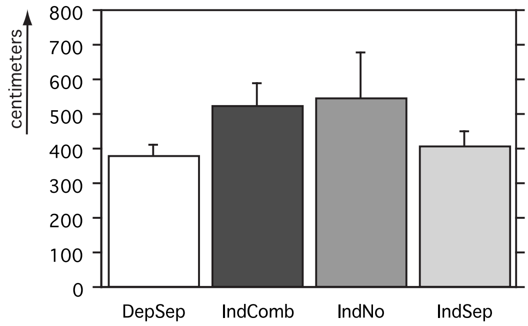


Figure 5-5. Distance of non-dominant hand Frog in centimeters for each condition, error bars represent 95% confidence interval.

Figure 5-6. Distance of dominant hand Frog in centimeters for each condition, error bars represent 95% confidence interval.

The results for the distance of the dominant hand Frog in each condition are presented in Figure 5-6. A one-way ANOVA indicated a significant difference between the conditions ($F(3,20) = 7.433$, $p < .01$). The Fisher's a posteriori LSD test revealed significant differences between the conditions with separate clutch (DepSep and IndSep) and the conditions without or with combined clutch (IndNo and IndComb).
Figure 5-7 shows the means of the combined distances of the non-dominant and the dominant hand. The results are comparable to those of the dominant hand only. A one-way ANOVA indicated a significant difference between the conditions ($F(3,20) = 8.016$, $p < .01$). Again, the Fisher's a posteriori LSD test revealed significant differences between the conditions with separate clutch (DepSep and IndSep) and the conditions without or with combined clutch (IndNo and IndComb).

An interesting phenomenon is present in Figure 5-8. The differences in distances between some conditions were significant. However, the mean values for the ratios of the non-dominant and dominant hand distance were almost equal for all conditions and their differences were not significant.

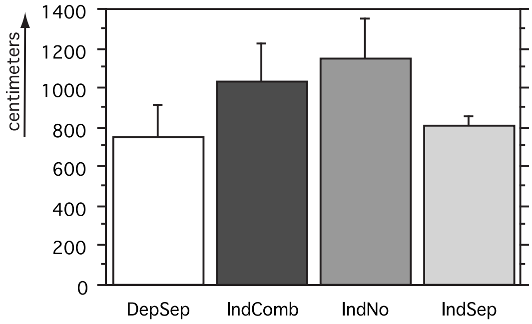


Figure 5-7. Combined distance in centimeters for each condition, error bars represent 95% confidence interval.

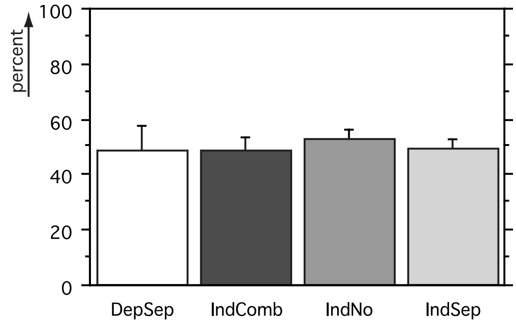
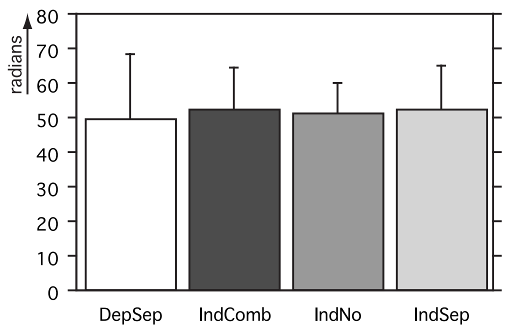


Figure 5-8. Percentage of non-dominant hand distance for each condition, error bars represent 95% confidence interval.

Rotation The values of rotation for the non-dominant hand Frog are given in Figure 5-9. The mean values for rotation were close for all conditions and significant differences were not present, as opposed to the mean values for non-dominant hand distance. The same is true for the values of the rotation variable for the dominant hand Frog, presented in Figure 5-10. Again, the mean values for rotation of each of the conditions were close and no significant differences were found.



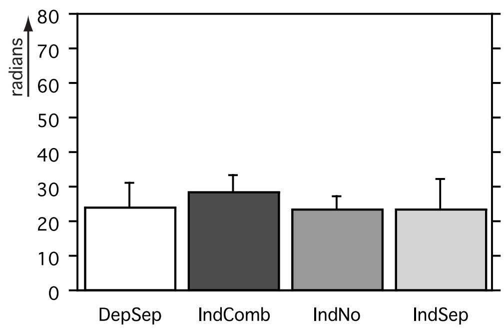


Figure 5-9. Rotation of non-dominant hand Frog in radians for each condition, error bars represent 95% confidence interval.

Figure 5-10. Rotation of dominant hand Frog in radians for each condition, error bars represent 95% confidence interval.

It is obvious that significant differences between the combined rotations were not to be expected from the values of the rotation variable presented in the previous figures. Indeed, Figure 5-11 shows that the mean values of the combined rotation were close for all conditions; significant differences were absent. Interesting to note in the previous figures is that the non-dominant hand carried out a larger amount of rotation than the dominant hand. This is illustrated in Figure 5-12 showing that in all conditions more than 65 % of the rotation was executed with the non-dominant hand.

The ratios of the non-dominant and dominant hand rotation did not significantly differ between the conditions, as was found for the ratio of the distances.

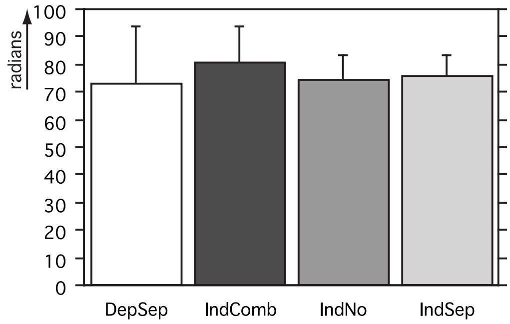


Figure 5-11. Combined rotation in radians for each condition, error bars represent 95% confidence interval.

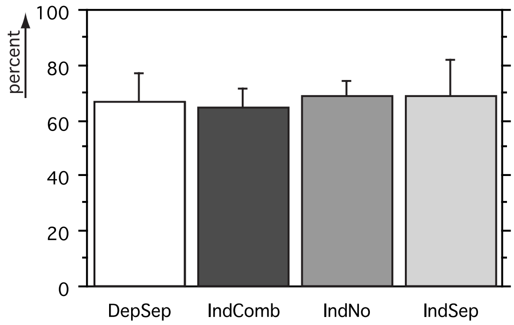


Figure 5-12. Percentage of non-dominant hand rotation for each condition, error bars represent 95% confidence interval.

5.5.3 Concurrent two-handed activity

Figure 5-13 shows the amount of simultaneous dragging of two objects as percentage of the completion time on the second day. The one-way ANOVA was used and indicated significant differences between the conditions ($F(3,20) = 20.206$, $p < .0001$). Fisher's a posteriori LSD test indicated that the differences between the DepSep condition and the other conditions were all significant. Furthermore, the differences between the IndSep condition and the two conditions with a fixed relation between the Frogs (IndComb and IndNo) were significant too.

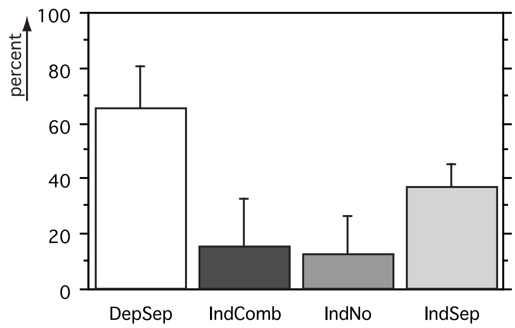


Figure 5-13. Time involved in simultaneous dragging of two objects as percentage of the completion time, error bars represent 95% confidence interval.

5.5.4 Fatigue

As can be observed in Figure 5-14, low values for fatigue were reported. The mean levels for fatigue all stayed under the level of "hardly" in all the conditions. The Kruskal-Wallis one-way analysis of variance by ranks was used to study the data because of the ordinal measurement of the dependent variables. No significant differences between the conditions were found.

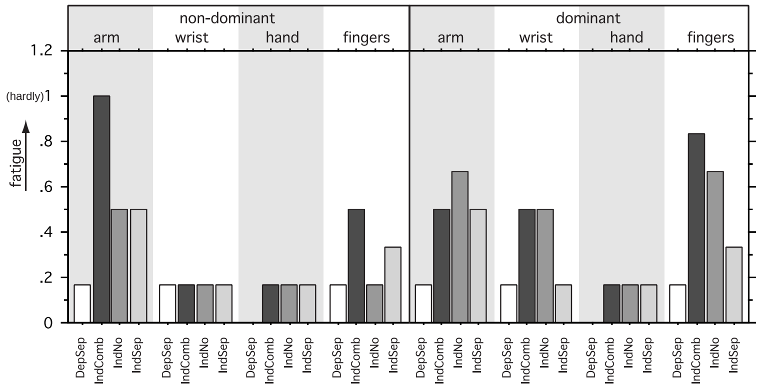


Figure 5-14. Mean fatigue experienced by subjects, per condition.

5.5.5 User preference

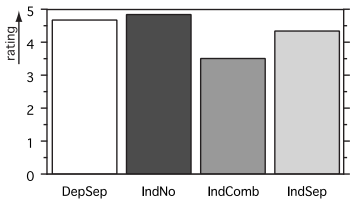


Figure 5-15. Mean values for easy to learn.

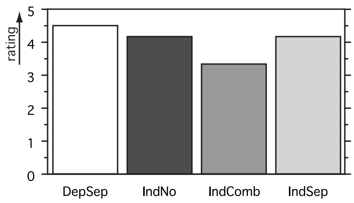


Figure 5-16. Mean values for suited for the task.

The results regarding user preference are shown in Figure 5-15, 5-16 and Figure 5-17. The overall mean values for all three dependent variables are above four (labeled “agree a little”). The mean values for the condition with combined clutching (IndComb) are lower than the other conditions for all three variables. However, significant differences were not found between the means of each dependent variable with the Kruskal-Wallis one-way analysis of variance.

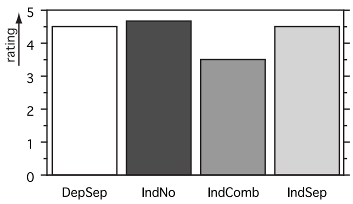


Figure 5-17. Mean values for efficient.

Figure 5-18 presents mean rank for each of the conditions. From the mean values of the ranking, one might conclude that the no-clutch condition was rated best and the combined clutch condition worst. Nevertheless, no significant differences were found between the results of the conditions with the Kruskal-Wallis test.

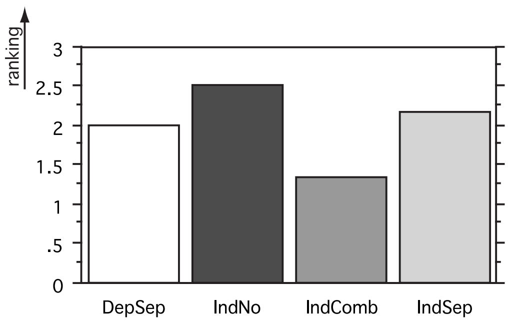


Figure 5-18. Mean values for ranking.

5.6 Observations

The experimenter was present to take notes during the experimental trials. Most of the observations resembled the observations of subjects in the two-handed condition of the previous experiment, as described in the previous chapter. Here, only observations regarding the clutch mechanism are listed.

An important observation, regarding the goals of the experiment, was that subjects took all efforts to prevent having to use the clutch mechanism. The subjects almost never used it after the initial setting of the work area, unless they were forced to, only in situations where objects were unreachable. In interviews afterwards, subjects commented that clutching seriously interrupted their workflow. Having to use the clutch mechanism distracted them from their task.
In all conditions, the subjects used their left hand for holding the cube shape and their right hand for holding the stack objects and placing them on the cube. In the dependent selection condition, this is of course almost unavoidable, but the same phenomenon occurred in the independent selection conditions.

Some of the subjects had trouble understanding the way the clutch mechanism worked, especially in the beginning. This was observed in the previous experiment too.
In the independent selection condition, some of the subjects did not use the clutch button on the Frog held with their non-dominant hand at all, although they used their non-dominant hand a lot. Instead of using the clutch button to rotate objects over large angles, they rotated the Frog in their hand. This is an effective method but the maximum achievable amount of rotation is limited by the wire attached to the Frog.

5.7 Discussion

Regarding completion times, the most important conclusion is that both the selection mechanism and the clutch mechanism did not lead to differences between the conditions. Surprising to find was that the selection mechanism had no influence on completion times. It was anticipated that task completion would be faster with the dependent selection mechanism because of its specialized nature. Apparently, subjects were not hindered by the fact that they had to select objects with their non-dominant hand in the conditions with independent selection. Therefore, the advice is to use the more generally applicable independent selection method. This selection method can also be used for other tasks than the assembly task.

The influence of the clutch mechanism and therefore the influence of displacing display and manipulation spaces proved to be insignificant on performance too. The clutch mechanism was believed to have influence on two levels. Direct influence because of the amount of time needed to perform the clutch operation and secondary influence because subjects would use different strategies to complete the task.
Clutch times as percentage of the total completion times were low in the conditions with independent selection, as was expected. A substantial amount of clutch time was found only in the condition with dependent selection. In this condition, the clutch is most used to rotate objects about large angles and not for changing the manipulation space. Hence, the direct influence of the clutch mechanism is believed to be low.

The clutch mechanism did have influence on the task strategy applied by subjects. It was hypothesized that differences would be found between the conditions in the strategy subjects used to complete the task. Device collisions were expected in the two conditions with a fixed relation between the Frogs (conditions IndNo and IndComb) when objects were brought in close proximity. Then, devices are close when the objects are near to each other, meaning that one of the objects has to be released to complete the placement task. The expectance was that this would lead to an increase of workload and decreasing concurrent bimanual activity. From the results of the conditions with independent selection, it can be concluded that the hypothesized differences did occur. In the condition with separate clutch, a significant lesser amount of distance was observed than in the conditions with combined clutch or without clutch (Figure 5-7). Observations of subjects supported the explanation that subjects had to move one hand out of the way to allow the other to place the object. In addition, the results for the time spend in simultaneous dragging showed that in the condition with separate clutch significant more time was spend in dragging two objects (Figure 5-13).

It seems that the clutch mechanism did not have to be used very often and users did not use it as long as it was not strictly necessary. They rather worked with their hands in the air for short periods or tried to avoid clutching in other ways (by moving objects to a comfortable position for instance). Nevertheless, the clutch mechanism still seems inevitable, especially when users are expected to work for long periods with the system and with tasks that are more complex. With the secondary influences of the clutch mechanism in mind, it therefore advised to provide a separate clutch for each hand. This offers users the most freedom in deciding the optimal manipulation space for each hand and it facilitates concurrent two-handed operation. Simultaneous two-handed operation could be most welcome for precise two-handed modeling tasks. An example of such a task is to hold an object with one hand while editing it with the other.

Regarding workload, the distance data showed that in some of the conditions, the Frogs had to be moved over significant larger distances. Nevertheless, the percentage of non-dominant hand distance did not differ between conditions. The amount of distance moved with the non-dominant hand approximately equals that of the dominant hand. For rotation, the non-dominant hand Frog was rotated more than the dominant hand in all the conditions.
Again, no significant differences were found between the conditions for the percentage of non-dominant hand rotation. The conclusion is that in all four conditions workload is balanced between both hands. This confirms the conclusions of the previous chapter in which one-handed operation was compared to two-handed operation.

All four conditions caused little fatigue to the subjects and differences between the conditions could not be established. Reported fatigue was very low even after one hour of use (Figure 5-14). It was expected that subjects would experience more fatigue in the condition without clutch than in the other conditions but that was not justified by the data. Even the no-clutch condition apparently offered the subjects enough opportunity to support their hands while completing the task. Alternatively, the rest period between trials could have helped to prevent fatigue. Both explanations imply that fatigue effects could have emerged after longer periods of continuous use.

The four conditions all scored high on the properties easy to learn, suited for the task and efficient, with the condition with combined clutching falling behind in mean values. Significant differences could not be established. The survey data showed that the condition without clutch received the highest mean value in the ranking and the condition with combined clutch the lowest. This ranking is probably influenced by the impression of the clutch mechanism. However, the differences between the conditions were not statistically significant. Hence, it seems safe to conclude that there was no apparent favorite interface for the puzzle task used in the experiment, although the IndComb condition received a substantial lower mean rating than the IndNo and IndSep conditions.