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Experimental Comparison of CAD Input Devices in Synthesis, Analysis, and Interrogation Tasks

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ABSTRACT

This paper presents an experimental investigation into input suitability for human-computer interaction during computer aided design operations. Specifically, three types of operations, synthesis, interrogation, and modification, are examined with respect to three different types of user interfaces, mouse, direct tablet, and indirect tablet. The study, using undergraduate student participants in an introductory engineering graphics course, demonstrates that the mouse performs the highest across the dimensions of completion time and number of errors. However, the direct tablet, using a stylus directly on the visualization screen, shows promise.

Keywords: CAD input device, human computer interface.
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1. INTRODUCTION

The advances in the computer hardware industry have allowed computer aided design (CAD) users to choose from an array of input devices, such as stylus and tablet, 3D mouse, virtual reality joystick, and direct monitor interface. Although these devices offer users different experiences, it is not clear which of them provides ***CAD users*** with the greatest benefit. Much of the work on CAD development has focused on how best to support designers working with 3D representations on the 2D surface of the computer screen [5, 32, 36]. On the other hand, the creation, manipulation, and interrogation of the CAD models from a user perspective is noticeably lacking in the research literature [2]. Pen-based user interfaces are becoming more widespread with the promise of power and versatility [6, 15, 30, 42]. These interfaces offer users an opportunity to use their familiar "pen-based" skills to interface with CAD [30]. While there have been studies on the usability of pen-based devices to digitize drawing information [23, 25, 40], little work has been done to consider the interactive nature of pen-based devices, especially in the domain of CAD input. The focus of the work presented here is to compare the performance of pen based systems with that of the mouse for CAD input and manipulation.

Input devices are the primary channel of interaction between the user and the computer where information in pictorially abstract form or structured textual form is ultimately transmitted to the user [21]. Physical properties, such as position, velocity, and pressure, are used by input devices to capture and transmit this information. Using an input device is a multifaceted experience that encompasses all of the following: (1) *The physical sensor* (roll ball on a mechanical mouse), (2) *Feedback to the user* (clicking sounds from a mouse), (3) *Ergonomic and industrial design* (form, color, and orientation of buttons), and (4) *Interaction techniques* (how users interact with hardware and software to accomplish tasks). A poor design in any of these areas can lead to usability problems [20].

The amount of information bandwidth that is communicated from the computer to the user is typically greater than the bandwidth of user input to the computer [21]. While users may be able to rapidly process information they perceive from the CAD system, their speed and accuracy with which they are able to communicate information to the system may be dampened by the use of the input device. This information bottleneck reduces the design efficiency and opens input device dependent opportunities.
Further, performance of many devices is set by the muscle groups with which the device is designed to connect [12]. Research suggests that perhaps muscle groups with large dedicated cortical areas are promising as input device transducers for high performance [12]. Experimental evidence suggests that stylus-type input devices exploiting the high bandwidth of the thumb and index finger working in unison are likely to yield high performance [4].
In summary, there is a bandwidth limitation at the user side because of the use of an input device and that the performance of the input devices depends on the muscle group to which they are attached. The hand and fingers have been found to have a larger cortical area devoted to them as compared to the wrist and forearm. With respect to CAD, designers are known to spend much time using paper and pencil generating models [13]. Also, humans are known to have well developed skills in manipulating pen-type devices [30]. Considering this and that the stylus and tablet have a look and feel similar to paper and pencil [2, 30], two questions are asked: "Is the stylus and tablet more efficient than conventional devices like the mouse in terms of input to a CAD system?" and "Can the stylus and tablet offer a more natural means of interacting with the CAD system?". Therefore, the objective of this research is to study and evaluate the efficiency of the stylus and tablet as a CAD input device and compare its performance against that of the mouse.

2. EXPERIMENTAL APPROACH

2.1 Subjects

Twenty seven participating students were chosen from a population of Clemson engineering undergraduate students who were between 19-25 years of age. All subjects were enrolled the Engineering Graphics 209 course, an introductory engineering modeling course using AutoCAD. The subjects were all right handed users and were all proficient in using the mouse. Right handed users were selected to ensure consistent setup and configuration of the three tested scenarios. None of the subjects had prior experience with the tablet and stylus, though they were allowed to experiment with the tablet and stylus input devices prior to the experiment until they felt comfortable. While the subjects were not given specific modeling sequence instructions, they had all been trained in efficient modeling techniques in the Engineering Graphics course. As the general activities of solid model manipulation are similar in most CAD systems, for experimental practicality and to refine the scope of the investigation, only AutoCAD was investigated here.

2.2 Devices

This research involved the comparison of three input devices: a mouse, a direct tablet interface, and an indirect tablet interface. Each device was used in conjunction with a standard QWERTY keyboard. The mouse, the keyboard, and the Wacom Intuous2 tablet (indirect tablet interface) were connected to a Sony VAIO Slimtop computer. The 15 inch LCD display of the Slimtop computer (1GHz Intel Pentium III processor) served as a direct tablet interface.

2.2.1 Direct Tablet Interface

The Slimtop tablet provided a pressure-sensitive work area which also was the output display. Users could orient the tablet surface as they desired while keeping the tablet on the work table (Fig. 1). This direct tablet interface is similar to the, now more common, Tablet PC's, except that it is a non-portable desktop configuration. A rocker switch on the VAIO stylus enabled the operations of double clicking and right clicking (Fig. 2). By default, the upper end of the rocker was set to the right click function, and the lower portion was set to the double click function. Double clicking could also be performed by tapping the tip of the pen rapidly on the surface of the tablet.
The use of the output display as an input interface provides a direct relationship between output and input, allowing natural pointing and drawing gestures to be used to input data [16]. The control-display ratio of this input device is 1:1 as the distance the cursor moves on the screen is equal to the distance the pen tip moves over the surface of the tablet. One of the disadvantages of using this kind

of an input device is that users constantly have to lift their arm towards the computer screen, which can cause fatigue. Also, the hand over the screen may obstruct certain parts of the display. Finally, users may also be prone to making pointing and selection errors due to parallax error [35].

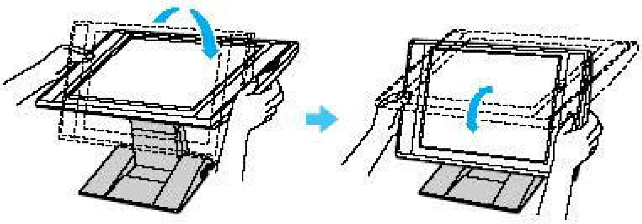

Fig. 1: Adjustability of the Direct Tablet Interface.

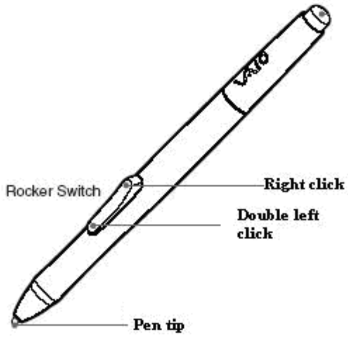

Fig. 2: VAIO pen.

2.2.2 Indirect Tablet Interface

A Wacom Intuous2 pen tablet was used as the indirect tablet interface in this study (Fig. 3). The indirect tablet interface was calibrated to have a control-display ratio of 1:1 to be consistent with the control-display ratio of the direct tablet. This allowed for a direct mapping between the movements of the pen on the surface of the tablet to the movement of the cursor on the screen. A pen similar to the one used with the direct tablet interface was used to control the movement of the cursor. This pen operated in the same manner as the pen used for direct tablet interface.

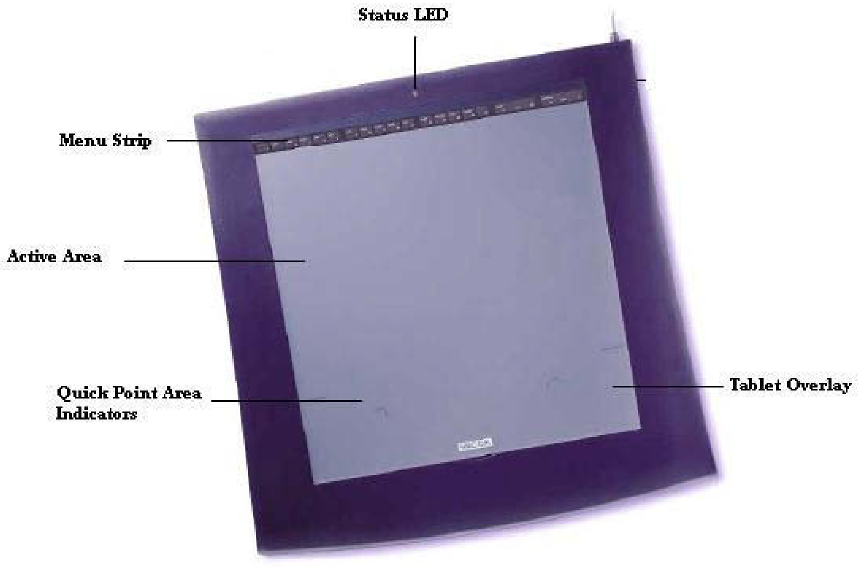

Fig. 3: Wacom tablet.

Graphic tablets provide users the freedom of orientation of the tablet surface. However, they occupy a considerable amount of space and do not allow direct eye-hand coordination, since they are removed from the display [16]. Some of the advantages of the graphic tablets are that the user's hand does not cover any part of the display, there are no parallax problems, and the user is not likely to experience fatigue associated with continually lifting a hand to or from the screen [41].

2.2.3 Mouse

The house has endured in an era in which technologies rapidly become obsolete as its properties continue to match the demands of desktop graphic interfaces [3]. Their features are best suited for pointing and selecting tasks, especially in menu-operated applications, and for dragging graphical objects around the screen. However, the mouse is not well suited for drawing as it can operate only in the relative mode [35]. Research comparing the mouse with other devices tends to show that pointing performance with a mouse is faster and more accurate than performance with other indirect pointing devices [11, 14, 28], but is inferior to direct pointing devices [22, 18, 34, 39]. Also, there is evidence that people can use a stylus as efficiently as they can a mouse for a range of office based tasks [26, 33]. The mouse has been found to be slightly faster and more accurate than a stylus; however this difference was reduced when the screen was tilted to enable easier interaction using the stylus [27]. The mouse used in this study had two buttons and an integrated roller wheel for scrolling.

2.3 Tasks

In this study the CAD tasks are classified into synthesis, modification, and interrogation. The synthesis task involves model development where subjects drew a 3D model according to the given specifications using AutoCAD. Modification consisted of making changes to an existing drawing, such as changing the dimension of a particular section and adding or deleting features. Interrogation consisted of determining certain properties of the model such as model dimensions, the number of surfaces, and the number of through holes in the model.

2.4 Models

Three distinct, but similar, 3D solid models (Fig. 4) were used in this study. The instructor for the AutoCAD course from which the subjects were drawn evaluated these three models to ensure that they were at the same level of complexity and difficulty, based on his experience in designing assignments and exams for the modeling course. Further, a similarity analysis was done to quantify how similar these three models are based on an examination of the primitives, the minimum number of Boolean operations, the number of constraining dimensions required, and the minimum number of synthesis and analysis operations. Based on this analysis, these three models were felt to be sufficiently similar to not impact the experimental design, though post-hoc analysis was done to verify this assumption. Detailed analyses of each task can be found in [6]. It is important that these models be roughly equivalent to control model choice as an experimental variable.

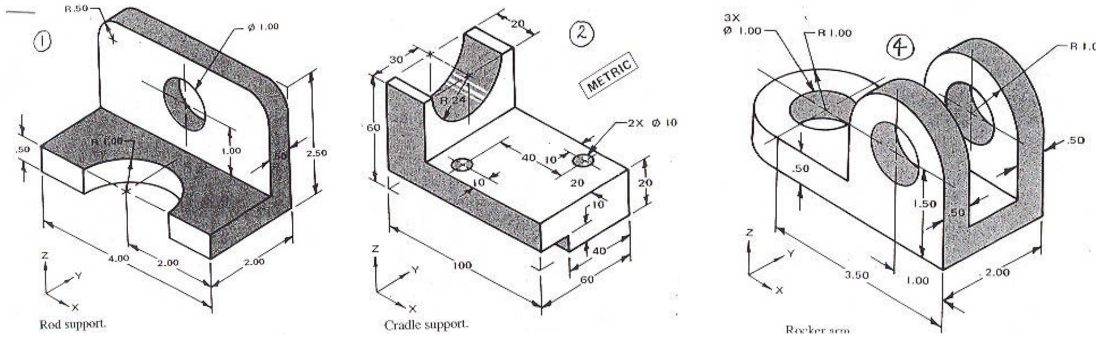

Fig. 4: Models 1, 2, and 3.

2.5 Experimental Design

A three factorial design was used for this experiment (Tab. 1). The two treatment factors were the type of input device and the type of task; while the design factor was the type of geometric model. The geometric model variable was considered as a design factor because the purpose of including this variable in this study was to facilitate performing of the tasks of synthesis, modification, and interrogation. Three geometric models were included so as to prevent the transfer effect between the individual tasks of synthesis, modification, and interrogation. Each factor had three levels: three input devices (mouse, direct tablet, indirect tablet); three tasks (synthesis, modification, interrogation); and three models. There were three replications for each device-task-model combination as shown in Tab. 1. The order of tasks was kept constant, varying only the order of models and interfaces. For example, Subject 1 performed synthesis of Model 1 using the mouse, modification of Model 2 using the direct tablet and interrogation of Model 3 using the indirect tablet. The response variables in this experiment were task completion time, number of clicks, number of keystrokes, and number of errors.

	Synthesis			Modification			Interrogation		
	Model1	Model2	Model3	Model1	Model2	Model3	Model1	Model2	Model3
Mouse	Subject 1 10 19	Subject 2 11 20	Subject 3 12 21	Subject 4 13 22	Subject 5 14 23	Subject 6 15 24	Subject 7 16 25	Subject 8 17 26	Subject 9 18 27
	Model1	Model2	Model3	Model1	Model2	Model3	Model1	Model2	Model3
Direct Tablet	Subject 9 18 27	Subject 7 16 25	Subject 8 17 26	Subject 3 12 21	Subject 1 10 19	Subject 2 11 20	Subject 6 15 24	Subject 4 13 22	Subject 5 14 23
	Model1	Model2	Model3	Model1	Model2	Model3	Model1	Model2	Model3
Indirect Tablet	Subject 5 14 23	Subject 6 15 24	Subject 4 13 22	Subject 8 17 26	Subject 9 18 27	Subject 7 16 25	Subject 2 11 20	Subject 3 12 21	Subject 1 10 19

Tab. 1: Experimental design.

2.6 Data Collection

The experiment was conducted at six weeks into the sixteen week semester. By this time subjects had a basic understanding of the engineering drawing concepts such as dimensioning, multi-view projections, and model representation and had been using AutoCAD for about four weeks. Before performing the experimental tasks, subjects were trained on the direct and indirect tablets. They performed simple tasks like 3D model development, pointing and selecting of menus, and model rotation. This familiarization period lasted approximately 15 minutes. Each subject was required to read and sign a consent form and then given a brief explanation of the experimental procedure and the tasks they were required to complete. An event recorder and a data logger were used to record the users' on-screen interaction with the AutoCAD environment. This facilitated the collection of task completion times, number of keystrokes, and number of clicks. While the subjects were performing the experimental tasks, data on the number of errors was collected by observing the subjects.

3. ANALYSES OF RESULTS

Quantitative measures of task completion time, number of clicks, and frequency of errors were recorded for each subject. A 3-way analysis of variance (ANOVA) was performed to examine main and interacting effects. For discussion on this type of statistical analysis, the reader is referred to [7, 19, 24]. In the case of a significant interaction effect, post hoc tests used to compare means.

3.1 Task Completion Time

Task completion time was recorded in seconds and measured the total time taken by a subject to perform each of the tasks of synthesis, modification, and interrogation using the input devices and geometric models assigned.

3.1.1 Analyses of the Task Time Completion

An ANOVA of the task completion time revealed a significant device×task interaction ($F(4, 54) = 2.91$; $p = 0.0298$), significant device effect ($F(2, 54) = 25.73$; $p<0.0001$), and a significant task effect ($F(2, 54) = 591.57$, $p<0.0001$). As seen in Fig. 5, an ordered interaction was observed. A post hoc Tukey's test was used to analyze the interaction between the device and task factors. Comparison of mean task completion time for each device across each of the tasks of synthesis, modification, and interrogation, revealed that there was a significant difference ($F(2, 54) = 22.57$, $p<0.0001$) among the three input devices for the synthesis task, a significant difference ($F(2, 54) = 7.09$; $p = 0.0018$) between input devices for the modification task and no significant difference between devices for the interrogation task as shown in **Error! Reference source not found.**.

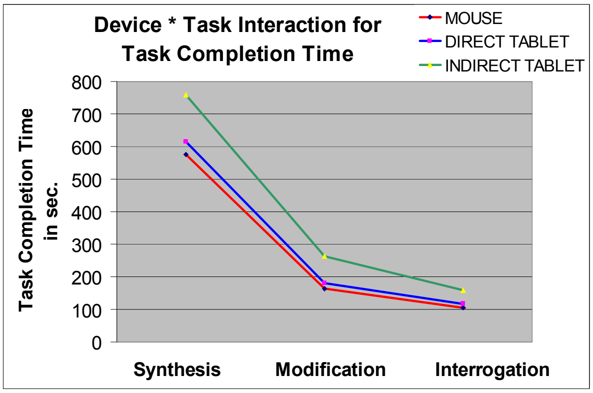

Fig. 5: Device × task interaction for task completion time.

Task	DF	Sum of Squares	Mean Square	F value	p value
Syn.	2	164596	82298	22.57	<0.0001
Mod.	2	51710	25855	7.09	0.0018
Int.	2	13789	6894.39	1.89	**0.1608**

Tab. 2: Device x task interaction sliced by task for task completion time.

Comparison of the devices for the synthesis task revealed no significant difference between the mouse and the direct tablet. Subjects using the mouse took an average of 40.1 seconds less than subjects who used the direct tablet for the synthesis task (Tab. 2: Multiple comparisons of devices across tasks for completion time.). There was a significant difference in task completion time between the mouse and the indirect tablet ($t = 6.39$; $p<0.0001$) and the direct tablet and the indirect tablet ($t = 4.98$; $p<0.0001$). For the synthesis task, on average, subjects using the mouse took 182 seconds less than subjects using indirect tablet, and subjects using the direct tablet took 141.9 seconds less than subjects using the indirect tablet as shown in Tab. 2: Multiple comparisons of devices across tasks for completion time.. Comparison between the devices for the task of modification revealed no significant difference between the mouse and the direct tablet, even though subjects using the mouse took an average of 18.1 seconds less than subjects who used the direct tablet for the modification task as shown in Tab. 2: Multiple comparisons of devices across tasks for completion time.. There was a significant difference in task completion time between the mouse and the indirect tablet ($t = 3.53$; $p = 0.0009$) and the direct tablet and the indirect tablet ($t = 2.90$; $p = 0.0054$).

3.1.2 Discussion of the Results of Task Completion Time

The fact that there was a significant device × task interaction implies that the average task completion time using different devices was different across the different tasks. For the task of synthesis, subjects using the mouse took the least time and subjects using the indirect tablet took the longest. There was no significant difference in task completion time between subjects who used the mouse and subjects who used the direct tablet. Also, subjects using the direct tablet took significantly less time than those

who used the indirect tablet. A similar result was found for the task of modification. However, there was no significant difference between the devices for the task of interrogation.
Task completion time includes time to form a goal, execute an action, and evaluate the outcome of the action. This is consistent with Norman's 'Seven Stages of Action': one action is for forming a goal, three for execution, and three for evaluation [31]. The seven stages are outlined as (1) forming the goal, (2) forming the intention, (3) specifying the action, (4) executing the action, (5) perceiving the state of the world (the CAD environment), (6) interpreting the state of the world (the CAD environment), and (7) evaluating the outcome.

Comparison	Task	Diff. Completion Time (sec)	t value	p value
Mouse vs. Direct Tablet	Syn.	40.1	1.41	0.1645
Mouse vs. Indirect Tablet	Syn.	182.0	6.39	<0.0001
Direct Tablet vs. Indirect Tablet	Syn.	141.9	4.98	<0.0001
Mouse vs. Direct Tablet	Mod.	18.1	0.64	0.5273
Mouse vs. Indirect Tablet	Mod.	100.6	3.53	0.0009
Direct Tablet vs. Indirect Tablet	Mod.	82.4	2.90	0.0054

Tab. 2: Multiple comparisons of devices across tasks for completion time.

Regardless of the type of task or model a subject was assigned, one would form a goal on how to approach the problem. The subject would then use the input device to perform the tasks of pointing and selecting and use the keyboard to enter alphanumeric data. If the subject made an error, he would correct it and move on to the next stage in the modeling process. Again, the times for all these processes are subject to variation, depending on the modeling strategy adopted by the subject.
Even though the mouse outperformed the indirect tablet, the task completion times of subjects using the direct tablet was comparable to those who used the mouse. One possible explanation for subjects performing poorly with the indirect tablet is their lack of experience with the device. This also holds true for the direct tablet, but the fact that it resulted in performance similar to the mouse is of significant importance. The time difference between the indirect tablet and the direct tablet may simply reflect the difference between using direct and indirect interaction devices. Alternatively, the differences could reflect the "distance" from the pen and paper metaphor, and suggest that as one moves away from a direct application of the metaphor, one begins to introduce additional requirements, such as monitoring cursor movements, which can impact upon performance times and overall performance in general [2].

3.2 Number of Clicks and Keystrokes

The total number of clicks and keystrokes were recorded for each of the tasks of synthesis, modification, and interrogation for each device-model combination to which a subject was assigned. These values included the clicks and keystrokes that resulted in an error and also the number of clicks and keystrokes that were used to recover from the error.

3.2.1 Analyses of the Number of Clicks

The number of clicks for each device-task-model combination was recorded, and an ANOVA revealed a significant task effect ($F\ (2,\ 54) = 125.76;\ p<0.0001$), as shown in Fig. 6. A post hoc Tukey's test to compare means clicks for each task revealed a significant difference between the tasks of synthesis and modification ($t = 11.48;\ p<0.0001$). The average number of clicks for synthesis was 108.5 and for that of modification were 40.2.

There was a significant difference between the tasks of synthesis and interrogation ($t = 15.22;\ p<0.0001$) and the tasks of modification and interrogation ($t = 3.74;\ p = 0.0004$) (
). The average number of clicks for the task of interrogation was 18.

3.2.2 Analyses of the Number of Keystrokes

The number of keystrokes for each device-task-model combination was recorded, and an ANOVA revealed a significant device × task interaction ($F\ (4,\ 54) = 7.3;\ p<0.0001$), a significant device effect *(F*

(2, 54) = 15.27), and a significant task effect *(F (2, 54) = 3345.2)*. As seen in **Error! Reference source not found.**, an ordered interaction was observed.

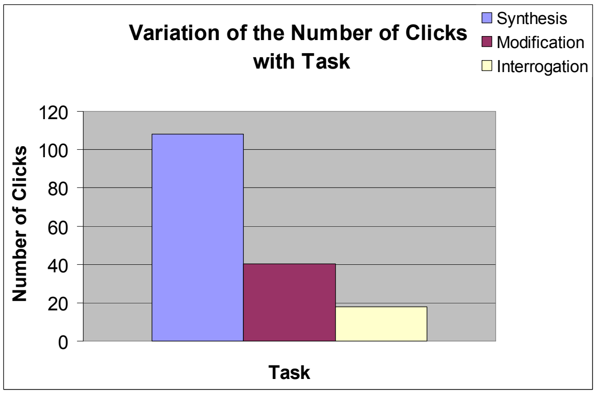

Fig. 6: Variation of number of clicks with task.

Comparison	Difference in the Number of Clicks	t value	p value
Syn. vs. Mod.	68.0	11.48	<0.0001
Syn. vs. Int.	90.2	15.22	<0.0001
Mod. Vs. Int.	22.2	3.74	0.0004

Tab. 4: Comparison of number of clicks across tasks.

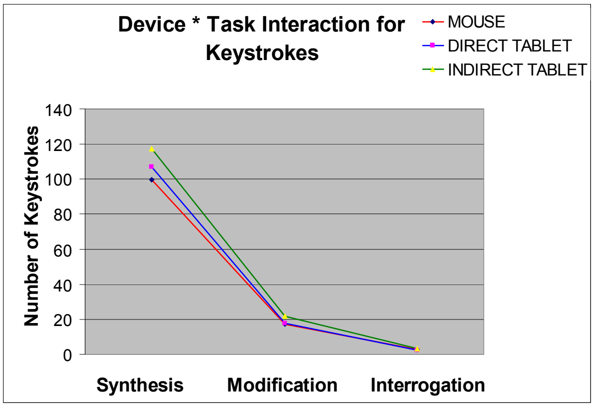

Fig. 7: Device × task interaction for keystrokes.

A post hoc Tukey's test on the interaction revealed a significant difference (*F (2, 54) = 27.7, p<0.0001)* among the three input devices for the synthesis task and no significant difference between devices for the modification and interrogation tasks, as shown in **Error! Not a valid bookmark self-reference.**

Task	DF	Sum of Squares	Mean Square	F value	p value
Syn.	2	1441.185	720.59	27.7	<0.0001
Mod.	2	111.185	55.59	2.14	**0.1279**
Int.	2	1.407	0.704	0.03	0.9733

Tab. 5: Device x task interaction sliced by task for keystrokes.

Comparisons of the devices for the synthesis task revealed that there existed a significant difference *($t = 2.96$; $p = 0.0046$)* between the mouse and the direct tablet. Subjects using the mouse took used an average of 7.1 less keystrokes than subjects who used the direct tablet for the task of synthesis, as shown in **Error! Reference source not found.**. There was a significant difference in the number of keystrokes between the mouse and the indirect tablet ($t = 7.39$; $p<0.0001$) and the direct tablet and the indirect tablet ($t = 4.44$; $p<0.0001$). For the synthesis task, on average, subjects using the mouse took 17.8 keystrokes less than subjects using indirect tablet, and subjects using the direct tablet took 10.7 keystrokes less than subjects using the indirect tablet.

Comparison	Diff. in the Number of Keystrokes	t value	p value
Mouse vs. Direct Tablet	7.1	2.96	0.0046
Mouse vs. Indirect Tablet	17.8	7.39	<0.0001
Direct Tablet vs. Indirect Tablet	10.7	4.44	<0.0001

Tab. 6: Multiple comparisons of devices across tasks for the number of keystrokes.

3.2.3 Discussion of the Results of the Number of Clicks and Keystrokes

Results showed that the number of clicks varied depending on the type of task, with the number of clicks for the task of synthesis being highest and that of interrogation being the lowest. The fact that the task of synthesis involved more operations than modification and interrogation is a probable reason why there was a higher incidence of clicks in this task. It is interesting to note the significant device-task interaction in the case of keyboard usage, which implies that there was a significant difference in the number of keystrokes for a particular task across the different devices. For the task of synthesis there was a significant difference across devices. This trend can be attributed to the higher incidence of keyboard usage to recover from errors, which were relatively large in the case of synthesis. In particular, subjects were observed to use the 'Esc' key repeatedly to recover from inadvertent activation errors.

3.3 Device Dependent Errors

Errors were classified into device dependent and device independent errors. From a cognitive psychology perspective [31], based on the cause of occurrence of these errors, they were further classified device dependent or device independent with description and lack of activation errors.

Device dependent errors can be considered 'Mode Errors' which occur when appropriate actions for one device have different meanings in different modes of operation [31]. The high occurrence of errors while using the indirect tablet can be attributed to the fact that some subjects believed that it functioned in a manner similar to a touch-pad on a laptop. As a result, when they wanted to move the cursor from one location to another, they would drag the pen very carefully over the surface of the tablet, constantly looking back and forth between the screen and the tablet to evaluate the consequence of their action. An easier and more efficient way to move the cursor is to pick up the pen and simply point to a position on the tablet which corresponded to the desired cursor position on the screen. The process of dragging the pen across the surface of the tablet led to inadvertent menu and object selection, which accounted for the high incidence of inadvertent activation errors. Another factor that inflated the occurrence of inadvertent errors while using the indirect tablet was sensitivity of the tablet surface. Constant muscle twitches in the user's hand made pointing and selection relatively difficult.

3.3.1 Analyses of the Number of Device Dependent Errors

Any inadvertent activation caused by the movement of the input device was considered as a device dependent error. An ANOVA of the device dependent errors revealed a significant device × task interaction ($F(4, 54) = 3.78$; $p = 0.0088$), a significant device effect ($F(2, 54) = 86.09$; $p<0.0001$) and a significant task effect ($F(2, 54) = 12.57$; $p<0.0001$). An ordered interaction was observed as shown in Fig. 8.

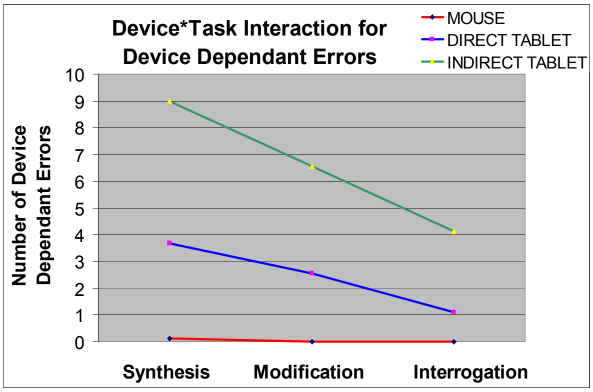

Fig. 8: Device × task interaction for the device dependent errors.

A post hoc Tukey's test on the interaction between the device and task factors revealed a significant difference (*F (2, 54) = 52.87; p<0.0001)* between the three input devices for the synthesis task, a significant difference (*F (2, 54) = 28.84; p<0.0001)* between devices for the modification task, and a significant difference (*F (2, 54) = 11.95; p<0.0001*) between devices for the interrogation task, as shown in **Error! Reference source not found.**.

Task	DF	Sum of Squares	Mean Square	F value	p value
Syn.	2	360.296	180.15	52.87	<0.0001
Mod.	2	196.518	98.26	28.84	<0.0001
Int.	2	81.407	40.70	11.95	<0.0001

Tab. 7: Device x task interaction sliced by task for device dependent errors.

Comparisons between the devices for the synthesis task revealed a significant difference (*t = 4.09; p = 0.0001*) between the mouse and the direct tablet. Subjects who used the mouse made an average of 3.6 fewer errors than subjects who used the direct tablet for the synthesis task, as shown in **Error! Reference source not found.**. There was a significant difference in the number of errors between the mouse and the indirect tablet (*t = 10.22; p<0.0001)* and the direct tablet and the indirect tablet (*t = 6.13; p<0.0001).* For the synthesis task, on average, subjects using the mouse made 8.9 fewer errors than subjects using indirect tablet and subjects using the direct tablet made 5.3 fewer errors than subjects using the indirect tablet, as shown in **Error! Reference source not found.**.

Comparison between the devices for the modification task revealed a significant difference (*t = 2.94; p = 0.0049*) between the mouse and the direct tablet. Subjects who used the mouse made an average of 2.6 fewer errors than subjects who used the direct tablet for the modification task, as shown in **Error! Reference source not found.**. There was a significant difference in the number of errors between the mouse and the indirect tablet (*t = 7.53; p<0.0001)* and the direct tablet and the indirect tablet (*t = 4.60; p<0.0001).* For the task of modification, on average, subjects using the mouse made 6.6 fewer errors than subjects using indirect tablet and subjects using the direct tablet made 4 fewer errors than subjects using the indirect tablet.

Comparison between the devices for the interrogation task revealed no significant difference between the mouse and the direct tablet. Subjects who used the mouse made an average of 1.1 fewer errors than subjects who used the direct tablet for the synthesis task, as shown in **Error! Reference source not found.**. There was a significant difference in the number of errors between the mouse and the indirect tablet (*t = 4.72; p<0.0001)* and the direct tablet and the indirect tablet (*t = 3.45; p = 0.0011).* For the task of interrogation, on average, subjects using the mouse made 4.1 fewer errors than subjects using indirect tablet and subjects using the direct tablet made 3 fewer errors than subjects using the indirect tablet.

Comparison	Task	Diff. in Number of Errors	t value	p value
Mouse vs. Direct Tablet	Syn.	3.6	4.09	0.0001
Mouse vs. Indirect Tablet	Syn.	8.9	10.22	<0.0001
Direct Tablet vs. Indirect Tablet	Syn.	5.3	6.13	<0.0001
Mouse vs. Direct Tablet	Mod.	2.6	2.94	0.0049
Mouse vs. Indirect Tablet	Mod.	6.6	7.53	<0.0001
Direct Tablet vs. Indirect Tablet	Mod.	4.0	4.60	<0.0001
Mouse vs. Direct Tablet	Int.	1.1	1.28	0.2071
Mouse vs. Indirect Tablet	Interrogation	4.1	4.72	<0.0001
Direct Tablet vs. Indirect Tablet	Int.	3	3.45	0.0011

Tab. 8: Multiple comparison devices across tasks for the device dependent errors.

3.3.2 Analyses of the Rate of Occurrence of Device Dependent Errors

The rate of device dependent error per task per minute is studied. An ANOVA of the rate of occurrence of device dependent errors revealed a significant device × task interaction (*F (4, 54) = 2.59; p = 0.0465*), a significant device effect (*F (2, 54) = 47.14; p<0.0001*) and a significant task effect (*F (2, 54) = 6.57; p<0.0028*). Fig. 9 illustrates the interaction pattern.

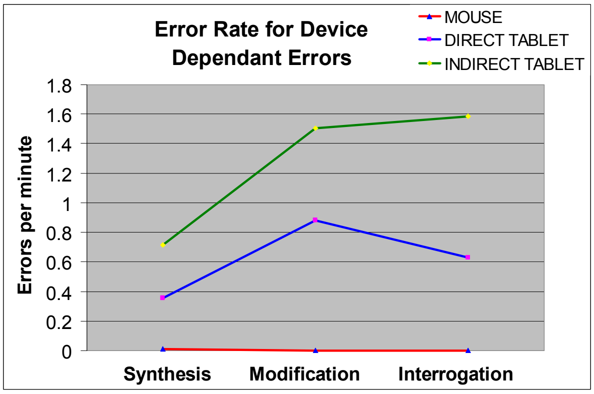

Fig. 9: Device × task interaction for the rate of occurrence of device dependent errors.

A post hoc Tukey's test on the interaction between the device and task factors revealed a significant difference (*F (2, 54) = 4.89; p=0.0112)* between the three input devices for the synthesis task, a significant difference (*F (2, 54) = 22.48; p<0.0001)* between devices for the modification task, and a significant difference (*F (2, 54) = 24.96; p<0.0001*) between devices for the interrogation task, as shown in **Error! Reference source not found.**.

Task	DF	Sum of Squares	Mean Square	F value	p value
Synthesis	2	11.428	5.714	24.96	<0.0001
Modification	2	10.292	5.146	22.48	<0.0001
Interrogation	2	2.239	1.119	4.89	0.0112

Tab. 9: Device x task interaction sliced by task for rate of occurrence of device dependent errors.

Comparisons between the devices for the synthesis task revealed a significant difference (*t = 3.13; p = 0.0028*) between the mouse and the indirect tablet. Subjects who used the mouse made an average of

0.7 fewer errors per minute than subjects who used the indirect tablet for the synthesis task, as shown in **Error! Reference source not found.**.

Comparison	Task	Diff. in errors/min.	t value	p value
Mouse vs. Direct Tablet	Syn.	0.3	1.53	**0.1329**
Mouse vs. Indirect Tablet	Syn.	0.7	3.13	0.0028
Direct Tablet vs. Indirect Tablet	Syn.	0.4	1.60	**0.1152**
Mouse vs. Direct Tablet	Mod.	0.9	3.91	0.0003
Mouse vs. Indirect Tablet	Mod.	1.5	6.67	<0.0001
Direct Tablet vs. Indirect Tablet	Mod.	0.6	2.76	0.0078
Mouse vs. Direct Tablet	Int.	0.6	2.8	0.0071
Mouse vs. Indirect Tablet	Int.	1.6	7.02	<0.0001
Direct Tablet vs. Indirect Tablet	Int.	0.9	4.22	<0.0011

Tab. 10: Multiple comparisons across tasks for the rate of occurrence of device dependent errors.

Comparison between the devices for the modification task revealed a significant difference ($t = 3.91; p = 0.0003$) between the mouse and the direct tablet. Subjects who used the mouse made an average of 0.9 fewer errors per minute than subjects who used the direct tablet for the modification task, as shown in **Error! Reference source not found.**. There was a significant difference in the number of errors between the mouse and the indirect tablet ($t = 6.67; p<0.0001$) and the direct tablet and the indirect tablet ($t = 2.76; p<0.0078$). For the task of modification, on average, subjects using the mouse made 1.5 fewer errors per minute than subjects using indirect tablet and subjects using the direct tablet made 0.6 fewer errors per minute than subjects using the indirect tablet.

Comparison between the devices for the interrogation task revealed a significant difference ($t = 2.80; p = 0.0071$) between the mouse and the direct tablet. Subjects who used the mouse made an average of 0.6 fewer errors per minute than subjects who used the direct tablet for the modification task, as shown in **Error! Reference source not found.**. There was a significant difference in the number of errors between the mouse and the indirect tablet ($t = 7.02; p<0.0001$) and the direct tablet and the indirect tablet ($t = 4.22; p<0.0011$). For the task of modification, on average, subjects using the mouse made 1.6 fewer errors per minute than subjects using indirect tablet and subjects using the direct tablet made 0.9 fewer errors per minute than subjects using the indirect tablet.

3.3.3 Discussion of the Results of Device Dependent Errors

Analyses of the results for the device dependent errors shows that there existed a significant device×task interaction, which implies that the number of errors committed using different devices was different for the different tasks. For each task, subjects using the mouse committed significantly fewer errors than those using either of the tablets. Subjects using the direct tablet committed significantly fewer errors than subjects who used the indirect tablet, except in the case of the interrogation task. It is interesting, however, to observe the device-task interaction in the case of the rate of occurrence of these types of errors. Even though the largest number of errors was observed in the case of synthesis calculation of the rate of occurrence of errors revealed that the frequency of occurrence of device dependent errors was the largest in the case of modification and interrogation. In particular, the highest frequency of errors was found in the case of subjects using the indirect tablet.

A possible explanation for the high incidence of mode errors using the tablets can be found in the 3-state model of input [9, 10]. This model categorizes the state of the system as out-of-range, tracking and dragging. In the case of a mouse, movement relative to a surface results in the cursor moving on the screen. This state can be categorized as tracking. When a user points at an icon, depresses the mouse button and moves the mouse while the button is depressed, the system enters into the dragging state. For the direct and indirect tablets, there is another state called the out-of-range state. In this state any movement of the pen or stylus is not registered by the system. The pen is activated as soon as it enters proximity, about 6 mm above the tablet's active area, bringing the system into the tracking state. Both tablets are pressure sensitive, and the tracking state can also be achieved by moving the pen while it was in contact with the active area of the tablet. At a certain pen-tip pressure threshold, the system will enter the dragging state. To select an icon, for example, a user would have to apply more pressure on the tablet surface (while the cursor was positioned over the icon). This state can also be achieved by moving the pen, in a range approximately 6 mm above surface of the tablet, and using the button controls on the pen.

In the case of the mouse, the actions of pointing and selecting are distinct. A user can distinguish the transition between these two states by the auditory feedback of the mouse button click. Also, the resistance of the mouse button, to a certain extent, prevents inadvertent transition between the tracking and dragging state. In the case of the pen and tablet however, there is very fine barrier between the states of tracking and dragging. Toggling between the two states is possible by the application of pressure. Furthermore, there is no feedback, either kinesthetic or auditory, to the user as to when this state transition has occurred. The lack of experience with using the tablet and the stylus is another factor that affected performance when using these devices. The physical appearance of an input device can affect a user's interpretation in terms of permissible actions. There will be some differences in people's knowledge of how to perform a specific task and how to use a specific device [2]. Studies illustrate the relationship between the performance on a video game and user's experience in using a particular interaction device [1]. The results of these studies suggest that it is necessary to know both the required control activity and the consequence of performing actions with a particular device. This finding lends support to the fact that the user's lack of experience with using a device can have an effect on performance.

3.4 Device Independent Errors

Device independent errors were further classified as 'Description Errors' and 'Lack of Activation Errors'. Description errors are those that occur with the correct action, but the wrong object. Lack of activation errors are those when the action is not completed [31]. A type of description error that was commonly observed was in the specification of object dimensions. As Fig. 10 and Fig. 11 illustrate, subjects made errors while specifying the dimensions of a cylinder, accidentally inputting the numeric value of the diameter as the radius.

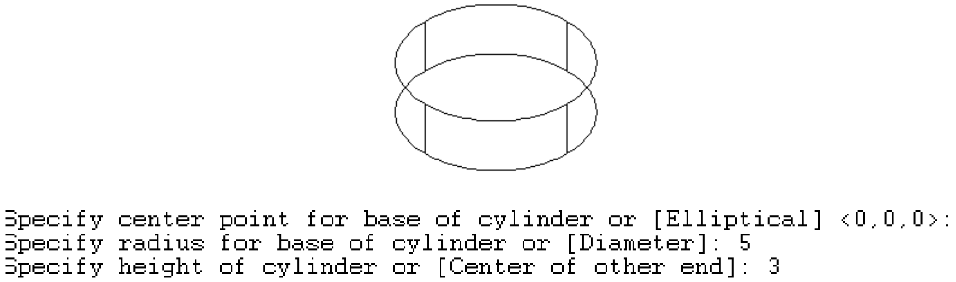

Fig. 10: Outcome resulting from description error.

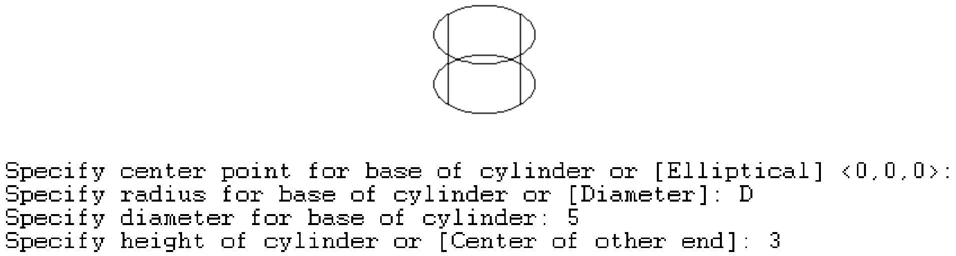

Fig. 11: Desired outcome.

Fig. 12 illustrates a common error that occurred while using the 'Fillet' operation. This was the consequence of performing the correct action on the wrong object.

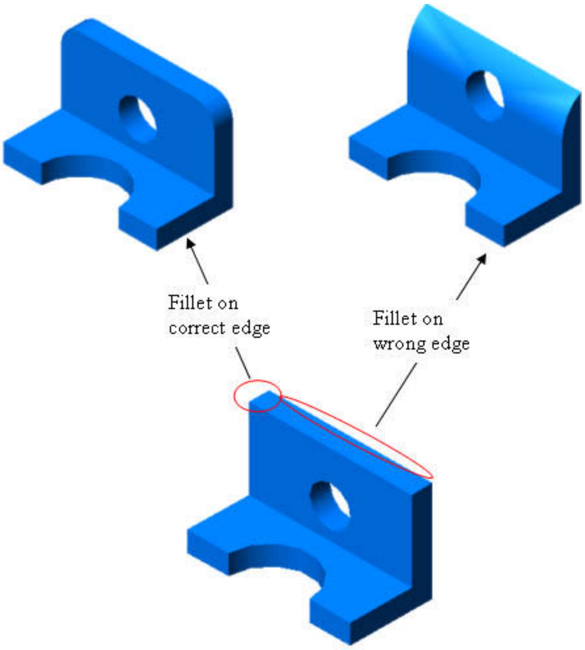

Fig. 12: Example of description error.

Lack of activation errors occur when an individual forgets to perform part of a sequence of actions [31]. In many instances, subjects forgot to perform the tasks of 'union' or 'subtract'. As a result the final outcome was different from the desired outcome. Fig. 13 illustrates the consequence of this type of error.

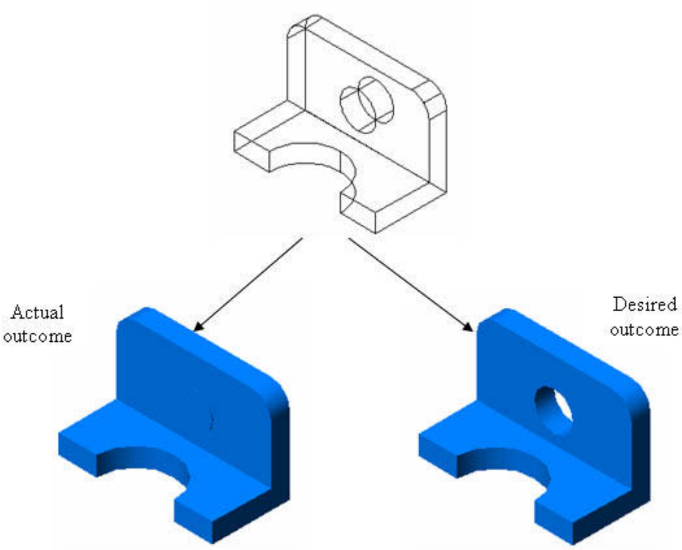

Fig. 13: Example of activation error.

3.4.1 Analyses of Results for Device Independent Errors
An ANOVA of the device independent errors revealed a significant task effect ($F\ (2,\ 54) = 46.35$; $p<0.0001$), as shown in Fig. 14.

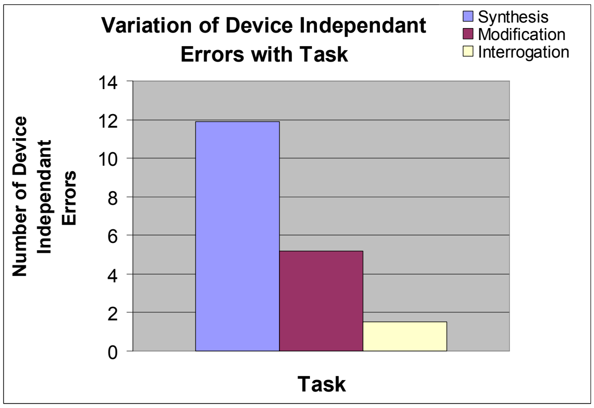

Fig. 14: Variation of device independent errors with task.

This result lends support to the assumption that the device independent errors were, in fact, not a function of the device and were dependent on the type of task. A post hoc Tukey's test on the task effect revealed that there was a significant difference ($t = 6.14$; $p<0.0001$) between the number of errors committed during synthesis and modification, as shown in **Error! Reference source not found.**. On average, there were 6.7 more occurrences of errors during the synthesis task than in the modification task. Also, there was a significant difference ($t = 9.49$; $p<0.0001$) between the number of errors committed during synthesis and interrogation. On average, there were 10.4 more occurrences of errors during the synthesis task than in the interrogation task. There was also a significant difference ($t = 3.36$; $p = 0.0015$) between the number of errors committed during modification and interrogation, with an occurrence of 3.7 more errors modification.

Comparison	Diff. in the Number of Errors	t value	p value
Syn. vs. Mod.	6.7	6.14	<0.0001
Syn. vs. Int.	10.4	9.49	<0.0001
Mod. vs. Int.	3.7	3.36	0.0015

Tab. 11: Comparison of device independent errors across tasks.

3.4.2 Analyses of the Rate of Occurrence of Device Independent Errors
An ANOVA of the device independent errors revealed a significant task effect ($F\ (2,\ 54) = 7.16$; $p<0.0017$), as shown in Fig. 15. A post hoc Tukey's test on the task effect revealed a significant difference ($t = 3.78$; $p<0.0004$) between the error rate during modification and interrogation, as shown in **Error! Reference source not found.**. On average, there was a difference of 0.8 errors per minute between modification and interrogation, with the higher frequency of errors occurring in modification. There was no significant difference between synthesis and interrogation or synthesis and modification.

3.4.3 Discussion of the Results of Device Independent Errors
In the case of device independent errors, a significant task effect was observed, implying that this type of error was task dependent. There were a significantly higher number of errors in the case of synthesis as compared to that of modification and interrogation. The least number of errors were found in the case of interrogation. The fact that the analyses of these errors did not reveal a significant device effect lends support to the assumption that this type of error does not depend on the type of input device and is more a function of a user's cognitive process. Even though the results

revealed that the highest incidence of errors was in the case of synthesis the highest frequency of errors was found in the case of modification.

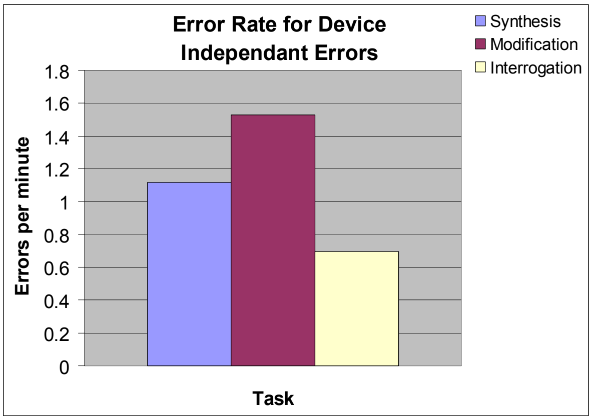

Fig. 15: Variation of the rate of device independent errors with task.

Comparison	Diff. in Errors/min	t value	p value
Syn. vs. Mod.	0.4	1.88	**0.0659**
Syn. vs. Int.	0.4	1.91	**0.0618**
Mod. vs. Int.	0.8	3.78	0.0004

Tab. 12: Comparison of the rate of occurrence of device independent errors across tasks.

4. CONCLUSIONS

This study was focused on comparing the mouse, the direct tablet and indirect tablet for CAD tasks. Though the mouse outperformed both the tablets, it is interesting to note the performance of the direct tablet. One possible explanation of the better performance of subjects using the mouse is the experience subjects had with using this device. Subjects on an average had 10 to 11 years of experience with using the mouse and none of them had ever used a tablet and stylus. Despite this, in many instances, the performance of the direct tablet was comparable to that of the mouse. This finding is of substantial significance because it alludes to the possibility that subjects may have performed just as well using the direct tablet if they had sufficient experience with the device. Also, one cannot disregard the indirect tablet because it ranked lowest in almost all quantitative and qualitative measures. Even though subjects had difficulty in using this device, many suggested that it was just a matter of time before they could adjust to it. Subjects also mentioned that the portability of the indirect tablet, which allowed them align the tablet according to their work posture, was a feature they considered useful. The feature is now realized in direct tablets through the portable Tablet PC configurations commercially available. Studies in human factors research often have limitations in their generality and this work is not exempt from these limits. Caution is exercised in considering the strength of the findings in the experiments for a number of reasons. First, the experience of subjects with using the input devices may have biased the results in favor of the mouse. Second, the differences in modeling strategies used by the subjects could have an effect on the measures of task completion time, number of errors, number of keystrokes and the number of clicks. Third, the tasks of synthesis, modification and interrogation, though conceptually different, require the basic operations of pointing, clicking and dragging. The interactive nature of the tablet and stylus was not utilized to the full potential as none of the operations involved familiar, “pen-like” actions, such as freehand sketching. Ultimately, the contribution of this research is in understanding mechanical engineering CAD specific modeling and interaction influences as related to the type of input mechanism. Other researchers have studied the role of input device on drawing and graphical interface interactions, but these have not focused on evaluating specifically CAD operations. It is our contention that CAD and engineering design operations should be studied distinctly as the role of the computer is increasingly becoming more than a document archival system and more of a collaborative sounding board, similar to the human-sketch dialog that has been proposed [29, 37, 38].

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