EVALUATING TEXTUAL ANNOTATIONS WITH INTERACTIVE 3D MODELS

By

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DEDICATION PAGE

The thesis is dedicated to my dear mother Anita Gupta, for her endless love and affection.

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ABSTRACT

Annotations play a key role in explaining and elaborating 3D illustrations. They support users in identifying and establishing a visual link between different components within a 3D model. However, one major issue with annotating 3D illustrations is that there are no standard guidelines that clearly define which annotation type or style to use or is preferred by users in supporting learning and identifying objects at different zooming levels. Often, the decision of which style to use is influenced by size of the components being annotated and the overall look and feel (i.e., reduced occlusion and visual clutter) of the annotated view in display. In our research, we try to understand how effectively the three types of textual annotation labels (internal, external, and annotation boxes) can support users in learning, identifying, and navigating through 3D objects. We report the results of a study that evaluates the efficiency and accuracy in searching for components inside a 3D model, measures the impact on learning (in recalling the names of various components and their locations), and analyzes for user preferences in interacting with a 3D model on a mobile form factor at different zooming levels.

Results of our study reflect that participants preferred external style annotations over internal and box style annotations, and that the participant's performance (for both efficiency and accuracy) in searching for components inside a 3D model was highest with external style annotations. We also found that participants recalled more components when annotated with external styles annotations. Our findings suggest that of the three textual annotation styles considered in this study, external style annotation is the best annotation style to use in an annotated 3D model.

LIST OF ABBREVIATIONS USED

GI	Graphics Interface
3D model	Three Dimensional models
3DA model	Annotated 3D model
AOI	Area of Interest
ROI	Regions of Interest
VNC	Virtual Network Computing
CAD	Computer Aided Design
CPU	Central Processing Unit
GPU	Graphics Processing Unit
SPSS	Statistical Product and Service Solutions
GD&T	Geometric Dimension and Tolerance
ISO	International Standards Organization

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Ankur Gupta

CHAPTER 1 INTRODUCTION

Annotations play a key role in explaining and elaborating 3D illustrations. They help users in identifying and establishing a visual link between different components within a 3D model. However, a key issue with annotating 3D illustrations is that there are no standard guidelines that clearly define which annotation style to use in a given situation or which style is preferred by users and supports them in learning and identifying objects at different zooming levels. Often, this decision is influenced by the size of the components being annotated and the overall layout (i.e., reduced occlusion and visual clutter) of the annotated view on display. In our research, we try to understand how effectively the three types of textual annotation labels (i.e. internal, external and annotation boxes) can support users as they learn, identify and navigate through 3D objects. We do so by analyzing their preferences, and evaluating their performance when searching for and later recalling components of 3D models. As this research is motivated by the increased use of devices in manufacturing setting (e.g., mechanics on a factory floor), we limit the size of the display to that of a mobile tablet screen and evaluated the above on three different zooming levels.

1.1 Research Challenges

Aircraft mechanics working on the factory floor often have to reference several data resources in order to do their job of correctly repairing, assembling, and installing thousands of parts, wires, brackets, etc, on the aircraft. Often they have to shift their focus from the task they are performing to these various data sources to access the correct knowledge and procedures for the situation at hand and then return to complete their task at hand. They have to work with several components that may be manufactured by different venders, may be upgraded and customized for different planes. Therefore the mechanics need to refer to various datasheet documents summarizing the product tolerances, performance, and other technical characteristics in sufficient details so that these maintenance and manufacturing engineers can integrate the components into the aircraft system. In addition, they also need to look at large 2D technical drawings (i.e., 2D CAD data conveying product manufacturing information such as geometric dimensions, tolerances, material strength and surface finish information). Furthermore, they increasingly are utilizing the 3D models of the components they are working with; which allows them to view the model from different angles to get a better understanding of the overall product design, its geometrical profile, and different interfaces. , the major issue is that aircraft mechanics can spend a lot of time in gathering relevant information and knowledge from different data sources and in switching back and forth between these information sources.

Motivated by this problem of the aircraft mechanics and engineers at Boeing, an information system that associates relevant information in form of textual annotations in the 3D models of the components that aircraft mechanics and engineers work has been proposed. This will create a single unified system that provides multiple layers of details and expert knowledge (by annotating the components directly in a 3D model) thus reducing the duplicity of 2D CAD drawings, and effort and time in accessing these technical product information from multiple sources. This approach allows the user to take the advantage of the rich 3D multimedia where users can adjust their views while interacting with the annotated 3D model to focus on the correct area of investigation, annotated with the relevant information they need to complete their tasks. It is anticipated that such a system hence will better support users at their tasks and increasing productivity. While such systems are emerging in industry, there are open questions as to how to design them.

Hence, in this thesis we examine what research has been done so far in annotating 3D models with textual annotations, what guidelines and best practices currently exists for annotating components of a 3D model. What annotations styles have been used or are preferred by users of such a system, and to what extent these annotation styles facilitate users at their tasks at hand. We next describe the common annotation styles used with 3D models. Internal style annotations (see Figure 1), external style annotations (see Figure 2) and box style annotations see (Figure 3), before providing an overview of the research that has been done in evaluating these textual annotations in a 3D model with respect to the impact they have on learning (providing users with a better learning environment), searching for components in a complex 3D model (enabling users to locate components and access relevant details quickly and conveniently), and user preferences (ease of usage, look and feel, visual clutter, etc) in interacting and exploring an annotated 3D model. Internal annotations are textual labels that are spatially bound (placed near) to annotating objects, on the other hand external annotations are textual labels that are placed away from the annotating object and use meta-graphical symbols such as connecting line to establish the link between the annotation and the referenced object. Annotation boxes are an extension of external annotations where the amount of textual content contained in the annotation is larger than for a typical external annotation (see Section 4.1.2 for more details)

1.1.1 User Preferences for Annotation Styles

Previous research has focused on developing effective and efficient algorithms for the layout of annotation styles [13], identifying how to place annotation labels to avoid occlusion [50], and on aligning annotation to follow the object structure being tagged with varying font sizes and shapes on personal computers [43,7]. These novel algorithms and approaches for annotating various 3D illustrations on personal computers have been effective; however, none of the research has focused on evaluating annotation labels from an end user perspective (i.e., gathering user preferences on different annotation styles to determine which of these are more appealing).

1.1.2 Impact of Varying Zooming Levels on a Mobile Form Factor

We found that there was no evaluation done to determine how effective these annotation styles are in supporting user tasks at different zooming levels. A single level of zoom limits the amount of information that can be presented to the user on a mobile (tablet) screen, making it difficult for the user to comprehend or interact with a complex 3D model. Hence comparing the different textual annotation styles also becomes difficult and meaningless, as at one zooming level users cannot experience the richness and true advantages that different textual annotations have to offer [41]. We are therefore interested in investigating whether a set style and layout of annotations would be effective on a mobile form factor (tablet screen size) with varying zooming levels. Moreover, we argue that on a mobile platform with limited computing power and a small screen size, running complex and computationally demanding annotation layout algorithms (yielding annotation labels with small font size) would not be feasible.

1.1.3 Impact on Learning

Another important factor to consider when annotating a 3D model is the optimal annotation setting for supporting users in the process of learning while they are interacting with the 3D model. For this reason we must take into account the effect of the cognitive workload (amount of information processed simultaneously by the finite amount of working memory) [14, 15] induced by annotations and its impact on their learning. We need to understand if a certain annotation style makes it easier for the end users to understand and retain the information provided in the annotated 3D model. To the best of our knowledge, no research has evaluated textual annotations in a 3D model with respect to the impact they have on learning and comprehension.

1.1.4 Impact on Search Performance

We also found that there are no studies that compare the different annotation styles in an annotated 3D model to determine which among these annotation styles help users to identify various components inside a complex 3D Model more efficiently (quickly) and accurately. However, we did find studies that make comparisons but for the annotation styles used in printed versus online text documents [31] and studies (e.g. [59]) where researchers have developed tools (search engine, using annotations and component names to build their search indexes) that help users to search for 3D models containing certain components. But none of these evaluate textual annotations designed to support users in searching for components inside an annotated 3D model.

1.1.5 Impact on Expertise

To evaluate textual annotations with interactive 3D models with respect to the above factors, we believe that it is also important to take into account the level of user expertise in interacting with 3D Models and software. All users are not alike and have different needs and individual differences across a variety of attributes such as product/domain knowledge, user experience and spatial skills that individuals acquire over a period of time [4,27], and that affects learning [8]. These subject variables, such as age, experience are difficult to control, being inherent to individuals, and have a direct impact on the user's ability to effectively learn to use CAD software [49]. For example novice users with less experience in controlling the flow of their interactions with the annotated 3D model will take more time to search for components inside a complex 3D model and will be more prone to making errors compared to an experienced user. Hence the difference in participant's performance (efficiency and accuracy) between a novice user and an experienced user (expert user) will vary significantly even though they both posses the same level of spatial skills (the ability to mentally manipulate 2D and 3D figures) and product/domain knowledge. For this purpose we must divide our participant base into user groups (such as expert users, intermediate users and novice users) based on their previous user experience in interacting with 3D models and 3D software and reflect upon the findings accordingly.

Hence, we believe that it is important to design and conduct a study which evaluates textual annotations at multiple zooming levels for performance (at user tasks of searching for 3D components), user preference (look and feel, user comfort), and impact on learning, (providing users with better learning environment), to determine which annotation type better supports users in their tasks and in interacting with a complex 3D model on a mobile (tablet) form factor.

In our study we have selected three textual annotations label types, similar to what has been used in the research [21]. In addition, we have introduced a transparency effect for annotation boxes to reduce occlusion, which is caused by displaying the annotation box labels over a 3D model, as displaying them in a free white background is not always guaranteed (see figure 3). For external annotation styles we have implemented fixed lengths connecting lines to account for visual clutter (see figure 2) based on the initial user feedback on annotation types and research methods we obtained from running a pilot study [22] (as described in section 3.10).

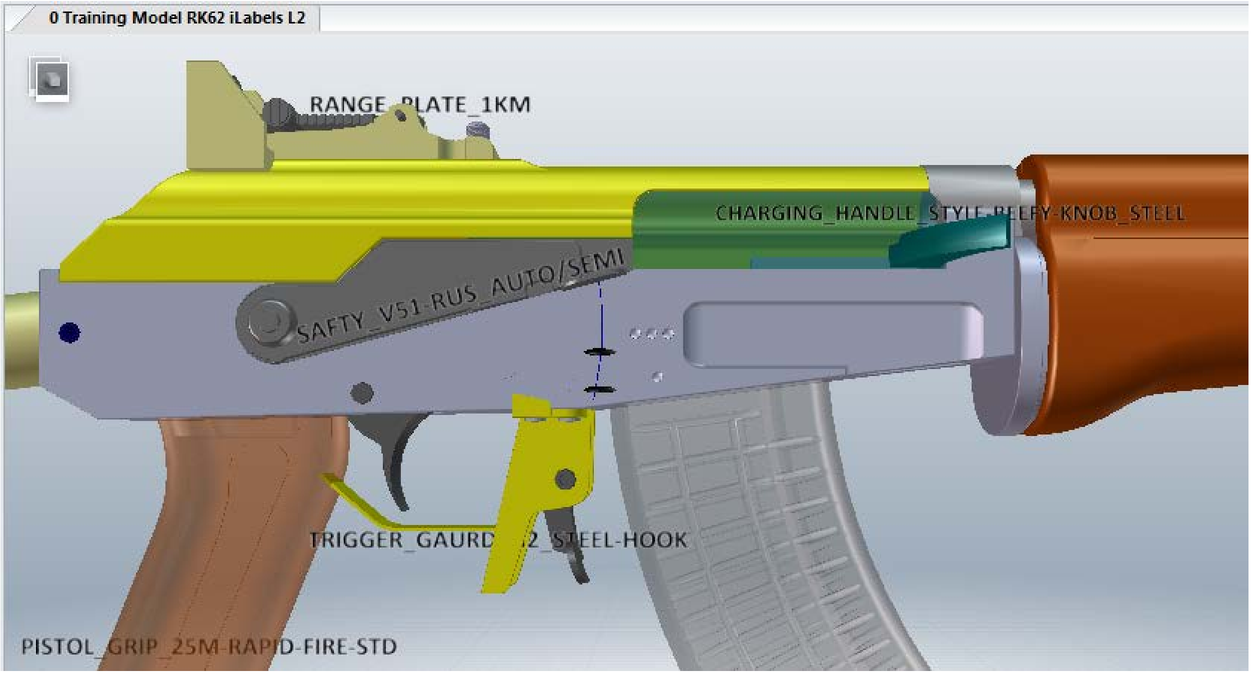


Figure 1: Training 3D model annotated with internal style textual annotations. The training model of RK-62 rifle was used to provide training on how to operate the 3D software used in the study and to make the participants familiar with the study setup and internal annotation style.

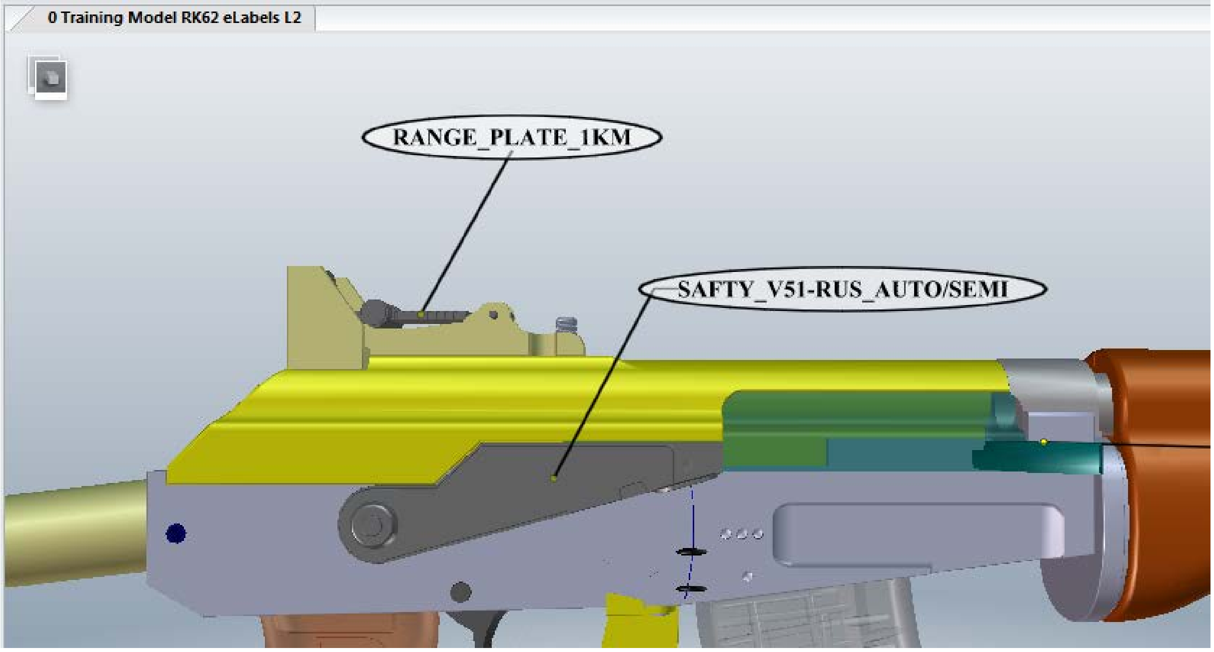
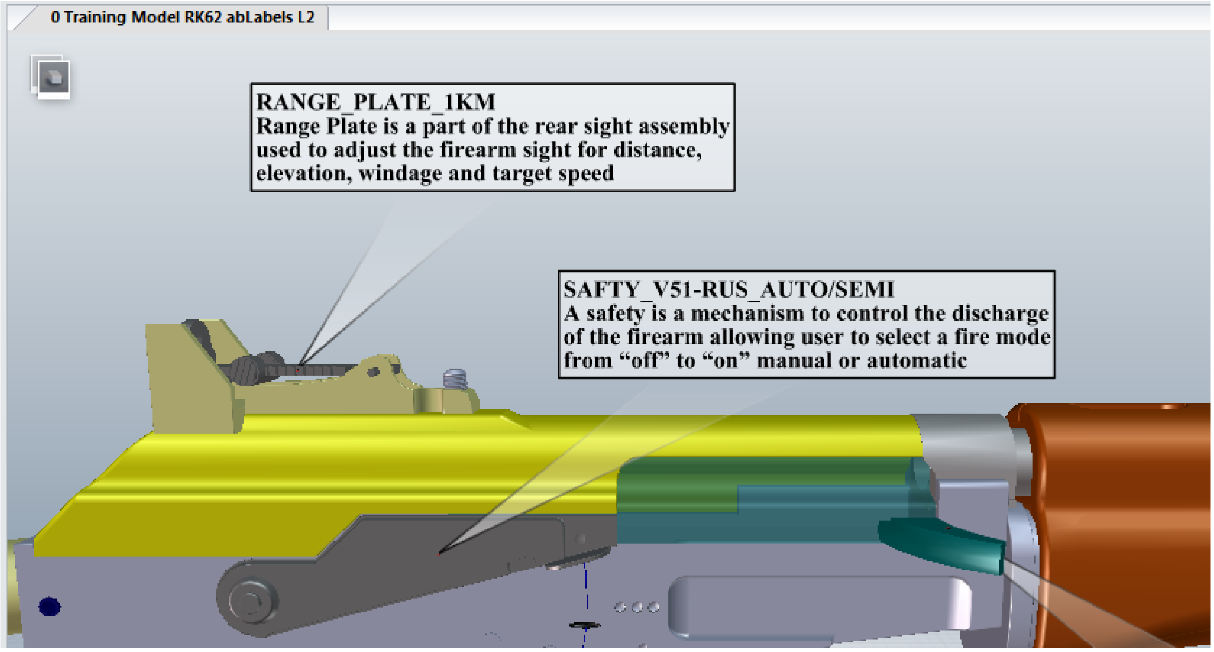


Figure 2: Training 3D model annotated with external style textual annotations. The training model of RK-62 rifle was used to provide training on how to operate the 3D software used in the study and to make the participants familiar with the study setup and external annotation style.



RANGE_PLATE_1KM
Range Plate is a part of the rear sight assembly used to adjust the firearm sight for distance, elevation, windage and target speed

SAFTY_V51-RUS_AUTO/SEMI
A safety is a mechanism to control the discharge of the firearm allowing user to select a fire mode from "off" to "on" manual or automatic

Figure 3: Training 3D model annotated with box style textual annotations. The training model of RK-62 rifle was used to provide training on how to operate the 3D software used in the study and to make the participants familiar with the study setup and box style annotation.

1.2 Contribution

Our research attempts to answer the following questions with respect to the three textual annotation styles (internal, external, and box style annotations) considered in this study:

a) Which annotation style is more appropriate for learner (beginners) versus expert users?

b) Which textual annotation style is more efficient (consumes less time) and is more accurate (has a low error count) when searching for components inside an annotated 3D model?

c) Which textual annotation style has the best look and feel, looks less complex or overwhelming, and is preferred by most users?

d) And how does all the above change with respect to a change in the zooming level at which the 3D model is being viewed?

An outcome of this research will be to establish guidelines that may be instrumental in developing effective product manuals for assembly lines workers and maintenance engineers in aeronautical, mechanical, and consumer electronics industries. We also hope that these guidelines will provide guidance to architects and design engineers in improving the overall look and feel of their 3D product models with appropriate textual annotations labels.

1.3 Overview of the Thesis

This thesis is divided into 5 chapters.

Chapter 1, Introduction, provides an overview of the rationale and purpose of this research. It is here that we explain why there is a need to undertake this research study, citing references to the recent research done in the given area and identifying the gaps, and explaining what new knowledge we are adding as an outcome of this research.

Chapter 2, Related Work and Background, briefly revisit the background discussed before explaining what has been accomplished in the research areas. This chapter is intended to raise awareness about research problems in this field and how our research study addresses them.

Chapter 3, Study Prototype, in this chapter, we present the design aspects of our implementation of the three textual annotations and the process of annotating a 3D model using 3D CAD software 3DVIA Composer.

Chapter 4, Methodology and Study Design, we provide specific research questions that our study will answer. The detailed view of the study design and measures incorporated to address these research questions. We next describe our independent and dependent variables and the different treatment conditions. We explain the number of participants needed for the study and the tasks performed by the participants with the study prototype. We then provide details about the study instruments used for collecting qualitative and quantitative data. Finally, we discuss the implemented controls for validity and reliability of the study results, the need for three 3D models (each with 27 unique components) in our research.and the plan for Data Analysis (statistical tests applied on the collected data in relation to the research hypotheses). The motive for this chapter is to provide the reader with a strong understanding of our complex study design details and the way we ran the entire study.

Chapter 5, Data Analysis and Results

Here we perform the quantitative and qualitative data analysis for our research questions and hypotheses. We first define our expectations (expected outcome) for the research questions, and later perform the analysis in SPSS. We report the significant findings first followed by the post hoc analysis. For non-significant results, we report the trend which may or may not be in line with our expectations for the observed data.

Chapter 6 Discussion

We summarize our significant results and frame meaningful guidelines based on the results of the study. We also discuss the limitations of our study.

Chapter 7 Conclusion and Future Work

We summarize our contributions and discuss future work

CHAPTER 2 RELATED WORK AND BACKGROUND

2.1 Moving from 2D Illustrations to 3D Models

In comparison to 2D images, 3D models offer more realistic reference views and functionalities to manipulate these views, reflecting greater details that make it easier to comprehend 3D objects. Their ability in supporting users in performing tasks such as navigating, identifying, and perceiving information about 3D objects via panning, zooming, rotating, fly-through and various other referential views is far more effective and facilitates better user interaction with and understanding of the 3D models.

Wu and Chiang [56] conducted a study with one hundred and twenty students to find better ways that could help students learn about orthographic views in a graphical course. In this study, they used two static depictions (2D illustrations) and two 3D visualizations for five surface styles of orthographic views. The result of the study revealed that students scored better on the ability test when learning with the two 3D visualizations compared to 2D illustrations and preferred 3D visualizations more as it provided them with better visual comprehension and understanding of the complicated features of the objects constructed by oblique and double-curved surfaces.

In a another study, Rakkolainen and Vainio [42] developed a 3D model of a city for mobile users, and explored the advantages offered by this three-dimensional representation of the city by conducting field trials and usability studies. They claimed that interactive three-dimensional environments (3D model) offered a more intuitive and user-friendly way to view location-based information than 2D maps. In this study, their participants were asked to search for a destination site from a pool of sample sites. View the route from the current location to the destination site and then walk their way up to the destination site completing the study task. During the walk participants could look at their current location in the 2D map and 3D view of their route at predefined check points. The results revealed that search and visualization of location-based information of a city became more intuitive and user friendly with 3D views compared to 2D maps. The users recognized landmarks, perceived distances, landforms, and found their way in the city more quickly and easily with the city's 3D model than with a symbolic 2D map.

In another study, Heautot et al [26] compared 2D and 3D illustrations in the medical field. They evaluated the concept of three-dimensional (3D) angiography and compared it to the existing 2D angiography for morphological characteristics of cerebrovascular diseases. The results of the study revealed that 3D angiography illustrations were superior to 2D angiography illustrations for both accuracy (sensitivity) and the quality of morphological analysis. The 3D approach provided medical experts (neurosurgeons) with a better view for more accurate analysis of the neck and to detect aneurysms which otherwise were difficult to detect with a plain 2D angiography image.

In Heautot et al's [26] research, they utilized the system "3D Morphometer" that constructed a 3D model from the set of two-dimensional (2D) angiography projections, obtained from X-ray angiography unit taken at different angles. Seventy eight patients with suspected cerebrovascular disease were studied via both the 3D and 2D angiography techniques. The 3D and 2D angiography images were reviewed by three medical experts (two neuroradiologists and a neurosurgeon) and after reviewing the images answered two questions. The first question was related to the detection of aneurysms, where they had to count the number of visible aneurysms and provide the vessel details on which these were found, and the second question was related to the qualitative morphological analysis. The order of the angiography images presented to the three medical experts was randomized for both the 3D and 2D angiography images. Their results revealed that with 3D angiography images the medical experts were able to detect two aneurysms that they missed with 2D angiography images and that the data collected during surgery for the 47 detected aneurysms further substantiated the quality of morphological analysis of the neck being more accurate compared to the 2D angiographic findings that were less conclusive.

2.2 Moving from 3D to Annotated 3D Models

The above studies have reflected on some of the benefits and advantages that 3D models and illustrations offer in comparison to 2D drawings and illustrations, such as facilitating learning, supporting users in developing a better understanding of the underlying concept, and identifying elements in 3D illustrations becomes faster and accurate. However an important component that often accompanies 3D illustrations is the annotations. Benefits of introducing annotations in a complex 3D model are many such as interactions becoming more meaningful, tagging components within an annotated 3D model highlights the location of objects, learning becomes easier, identifying components becomes faster, and interactions become more convenient when compared to an un-annotated 3d model.

Hamzalup et al [24] developed and tested the effectiveness of a web based virtual laboratory on the topic of torsion of engineered and biological materials. The virtual lab provided software mockup of the real lab experiment to provide students with a better understanding of the underlying abstract and difficult concepts of strength of materials. The virtual lab contained extensive data sets on different materials that could be tested for tensile strength and allowed students to explore the 3D model of the machine/apparatus by executing virtual walk through and zooming in addition to observing the elongation and breaking process. The 3D model of the machine was annotated with text, labeling important parts of the machine and provided a dedicated text box for presenting the material strength properties of the selected material. At the end of the experiment their participants (students) could download the load-strain graph and use this material property data to perform further analyses with other technical computing software, such as MATLAB™. Results of the evaluation revealed that the interactive virtual lab helped students with their understanding of torsion concepts and learned the concepts easily as compared to students who did not receive this treatment in study.

In addition to support learning, annotations also serve as landmarks, making it easier for the users to navigate with-in 3D model and adds to the overall look and feel of the 3D model. “Annotation in this context is the adding of expert knowledge to a 3D image”, (Simpson, J., 2004 p. 10) [46]. This knowledge could take the form of text labels describing certain parts of the 3D model, directional arrows depicting the flow of operations, or highlighted regions drawing user's attention to a specific portion of the 3D model.

In the Simpson's [46] research, she developed an annotation authoring tool called "Annot3D" that enabled anatomy instructors to add customized annotations to 3D visualizations for anatomy students in form of buttons, lines, text, clipping planes, spheres, and boxes. Annot3D provided instructors with a GUI interface for loading 3D models into a visualization system and allowed them to annotate specific parts of the 3D model with anatomy specific keywords and terms. Annot3D gave anatomy instructors the ability to control the order and presentations of annotations to teach effectively and emphasize on the parts of the 3D model that need to be discussed. Once a 3D model was annotated it was then saved as a package and distributed to students for review and self-guided study.

In another study, Sonnet, Carpendale, and Strothotte [48] experimented with different ways of associating text with 3D objects such as spheres, cones, donuts, cylinders, etc. They compared different methods of associating text such as attaching the text directly to the object with the help of a translucent polygon intersecting with the scene object, placing the text in the object's shadow (shadow annotations), and placing text in a separate window outside of the 3D scene window (dedicated textbox).

In the first part of Sonnet, Carpendale, and Strothotte [48] study, they evaluated whether a graphical method (shape of the object) can clarify the correlation between a part of the 3D model and its associated text. In the second part of their study they experimented with the same setup but with added hints where the annotated object's shadow was highlighted using a gray value that differs from the general shadow color and in another condition using the diffused color of the corresponding annotated object. In the final part of their study they evaluated whether a text label remains comprehensible during a scene exploration or not.

An interesting finding from that study [48] was that none of the evaluated visual techniques were perfect (graphical method with and without hints) and that each variation had its advantages and disadvantages for efficiency, accuracy (false object selection) in identifying objects. They concluded that the integration of these techniques with 3D models will strongly depend on the usage of the end application. For example, they recommended the use short textual labels instead of longer labels when annotating 3D objects as the use of long textual labels/descriptions may create occlusion and hide some of important components of the scene.

In another study, Jung, Gross, and Luen [30] explored sketching annotations in a collaborative 3D Web environment using a space pen. In this study they developed a space pen applet using (a) Java3D (to handle the 3D interactivity), (b) Java2D (to represent floor plans), and (c) space pen's 2D sketch recognition capabilities in 3D environment to support gestural commands to modify the 3D model. Their participants (designers) used the space pen for creating a temporary translucent drawing surface on the 3D model and then used this surface to collaborate by sketching annotations on the 3D model. They claimed that in the architectural domain where architects often have to collaborate with clients and other vendors to discuss design-related issues, a space pen system provides a convenient way of creating location specific annotations on 3D surfaces of the 3D models in form of textual comments, extended drawings, and markings such as spheres, arrows, call-out dots with identifiers to support asynchronous design collaboration.

In another research, Song, Guimbretière, Hu, and Lipson [47], extended the concept of sketching annotations on a physical prototype in a collaborative environment and merging it with 3D CAD tools. They explored on the possibility of the integrating design feedback and changes captured in form of annotations on a real physical prototype (miniatures 3D model) with the digital version of the model in 3D CAD tools. They argued that since interacting with models, both physical prototypes and digital 3D models, is an intrinsic part of the design process, where architects and design engineers go through several iterations and incremental modifications in the prototype design before arriving at the final design. They need a system that does not require heavy infrastructure or calibration on a per-model basis, is inexpensive and can be deployed easily in the field where physical prototype/models are frequently demonstrated or tested.

In Guimbretière, Hu, and Lipson's [47] esearch, they developed a plug-in for Solid Works [16] that used off-the-shelf Logitech io2™ digital pen [33] for capturing annotations and edits on the surface of the physical prototype and integrated the annotations and design changes with the software version of the physical 3D Model. The results of the study revealed that their participants, comprising of architects with varying experience, appreciated the overall system, the plug-in features and the ability to transfer design changes to a CAD tool to support rapid prototyping. They pointed out that this tool has a great utility in the design process called "massing" for architects.

In the another study, Boujut and Dugdale [7] have described the design of a potential 3D annotation tool that provides support for collaborative design work and evaluating activities in engineering design. They achieved this by analyzing the video data obtained from previous studies in line with other works in cognitive ergonomics to identify the different categories of annotations used by designers and other collaborative actors. The results of the study revealed that there were five broad categories of annotations used in a collaborative design scenario. These different types of annotation used in a design project were clarification annotations that highlighted a particular problem for attention and discussion, solution proposition annotations that reflected a tentative solution to fix the problem, solution evaluation annotations, that displayed the strengths and weakness of the proposed solution, solution validation annotations that stated the final acceptance or rejection of a proposed solution and technical constraints annotations that related to the specific technical constraints of the revised product design.

As a proof of concept in Boujut and Dugdale's [7] research, they developed a 3D annotation tool that was implemented in Java3D and was integrated with Solid Works [16] using different symbols for representing the five types of annotations. The user could use the plug-in to then attach a symbol in the 3D model/design and provide a suitable textual annotation, for example the red star-shaped annotation signals a technical constraint and the associated text specifies the specific technical constraint/problem. The 3D annotation tool was designed so that it is possible to view all of the annotations together at one time. A major advantage of using this approach was that the number and location of the annotation (design problems and fixes) were highlighted immediately, thus from a simple glance it became easy to spot the potential problem areas in the overall 3D design. However, they reported that displaying all annotations at once made the screen cluttered with textual annotations. Later, they refined this annotation viewing feature by allowing users/designer to view annotations based on their types or based on the authors who created them.

2.3 Annotations in Industrial Domain (Engineers and Manufacturing)

In the industrial domain, especially in engineering and manufacturing, engineering design is complex process/activity and has a huge impact on the final product being manufactured. The design activity starts from the initial design draft and goes through several design refinement cycles. The design refinement is an ongoing activity where design specs are tweaked to improve the overall quality, safety, performance and usability of the end product being manufactured and/or integrated with other products. Hence, it is important for an engineering design tool to offer designers the ability to capture feedback and design changes and maintain a history of design changes that were done at various stages in the design refinement cycle, thereby making a distinction between the initial and innovative design phases.

In addition, the design tool should also provide a structured support for displaying and presenting relevant information of the detailed engineering design. For example annotations could be utilized for presenting this information on a 3D CAD model. They could be used to convey the important technical details of the product design, instructions related to integration/installation of the product assembly, and information related to manufacturing processes such as geometric dimensioning and tolerance (GD&T) information [20], surface finish and material specifications.

ASME has developed standards such as ASME Y14.41.2012 [2] that provides a structured support in communicating product design and manufacturing information within an enterprise from design and engineering departments to the manufacturing floors. Here the PMI (product and manufacturing) information is presented in form of external annotations and can contain GD&T data and measures, welding symbols, surface finish and material specifications that depict the characteristics of the manufactured end product.

However, till date there is no guidance available on the different ways in which step by step technical instructions and process information can be presented in a 3D model. This information will help factory mechanics (working with multiple parts of the artifact) in selecting the correct machining process and tools as required in manufacturing the product. And will support them in their jobs of assembling or repairing parts and components of the complete end product. In our research we focus on how we can fill this gap by exploring and experimenting with the different types of textual annotations that can be used to provide this relevant information by annotating the different parts of a 3D model aircraft mechanics work with.

2.4 Improving Annotation Layouts and Usability

In the previous research and studies discussed so far, researchers have explored on the different ways to annotate 3D design/models. They have experimented with text (direct labels, external labels, text boxes), 2D and 3D icons (such as welding, GD&T and PMI symbols), meta-graphical objects (such as lines, arrows, primitive shapes, shadows, and colors) and numbers (such as surface dimensions and cutaway diagrams). We now turn our attention to the some of the recent research that have focused on improving the overall user interaction experience with annotated 3D models by developing computationally efficient, real time annotation-rendering algorithms.

These annotation rendering algorithms have improved the overall annotation layout by reducing occlusion and following the structure of the 3D objects with varying font sizes and shapes. For example, Cipriano and Gleicher [13], proposed a new technique for applying textual labels directly on 3D surfaces (known as internal annotations). They argue that an effective internal annotation technique must take into account the shape of the surface being annotated. They emphasize that for an annotation technique to be effective it must follow the structure of the annotated 3D surface and at the same time ensure that the textual details of the annotation labels are readable and legible from different viewing angles.

In Cipriano and Gleicher's [13] research, they claimed that the shape of the 3D surface is conveyed effectively and easily if the annotation labels are placed on the 3D surface as part of the surface texture, providing shape cues, meaningful landmarks and minimal occlusion as the label becomes part of the annotating object. The new text-Scaffolds algorithm generated fixed positions for the textual labels that are legible and at the same time provided shape cues for curved 3D surface. Their results revealed that the new scaffold-generation algorithm (in its un-optimized implementation) took less than 5 seconds where the original 3D model was inserted into 40x40x40 voxel field. They found that a field of this size results in generation of good placement of internal labels for a wide range of model sizes, where the system automatically constructs a path to place an internal label on an annotated input region. This text scaffolding technique was implemented in a visualization test bed that ran Windows on a HP dv2500t laptop, with an Intel T7100 CPU and Nvidia 8400M graphics processor.

In another similar study, Stein and Décoret [50] have developed a novel approach for dynamically rendering of box annotations (containing text and 2D images) in a 3D scene. To solve the NP-hard optimization problem in real-time they have used algorithmic and mathematical tools such as Apollonius diagrams to select labels in an appropriate order and compensate for the drawbacks of the greedy approach. The biggest advantage of their approach was that since most of the computations were performed in GPU with only log n passes. And a very limited amount of computations were transferred to the CPU, their algorithm achieved real time performance. The implementation was done using non-optimized C++ and OpenGL code on a GeForce 7800 GPU (graphics card) using an off-screen resolution of 512 by 512.

In another study, Ropinski et al [43] have proposed a new algorithm, motivated by internal labeling techniques found in anatomical atlases, where internal annotations were tweaked to follow the depth structure of the annotated object thus improving the shape cues further. They claimed that with their approach, the 3D layout for internal annotations is far more effective as the curvature of the annotated surface comes out more clearly and the expected perception of the overall structure of the annotated object is much clearer with 3D internal annotation when compared with the 2D layout of internal annotations. However they acknowledged that this expected gain in spatial comprehension is achieved at the expense of readability of the textual details where the distortion of the annotation text is influenced directly by the shape and depth of the annotated 3D object.

These novel algorithms and approaches for improving the overall annotation layout with 3D illustrations on personal computers have been effective and computationally efficient in rendering real time annotations. However, we found that none of these researches have focused on evaluating the annotation styles/layouts from an end user perspective. That is gathering user preferences on different textual annotation styles to determine which of these are the most preferred by users. Or in evaluating the characteristics/properties of annotation styles that influences user’s preference for a certain annotation style over other annotation styles. Or evaluating the extent to which different annotation styles support users in their interacting (exploring and navigating) and searching for components/parts inside 3D models.

ISO 9241-11 [29] defines usability as "The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use"[29]. The word "usability" also refers to methods for improving ease-of-use during the design process [29]. In this study, we measured the usability of annotation styles via post task questionnaire (see appendix [G] Post Task Questionnaire) where we collected ratings (on a Likert scale of 1 to 5) from our participants based on their interactions with different the textual annotation styles on a mobile (tablet) form factor. These rating were collected for usability factors such as readability of the annotations, overall look and feel (the occlusion and visual clutter caused by annotations, the display of annotation: visually appealing and pleasant or overwhelming, and distance from annotated object), perceived ease of usage (easy to use, easy to understand, supported users at tasks of searching, learning, navigating and exploring 3D models), and overall satisfaction (would users recommend the annotation style for searching, learning, and interacting with 3D models).

Evaluating annotation styles from an end user perspective is very important given the non-linear media nature of the annotated 3D models, where the current view of an annotated 3D model is the result of the series of interactions (pan, rotation, zoom in/out motions) the user has performed on the 3D model. And where the flow of these interactions is governed by the ability of a textual annotation style to support and facilitate users at their tasks. This is very different from other media such as sound, video, or automated animations that are linear in nature and where the interactions can be mapped on to a current time/position in the media and not user input.

2.5 Interacting at Varying Levels of Zoom

In addition, there has also been no evaluation of how effective the different annotation styles are in supporting users in their tasks at varying levels of zoom. When interacting with a 3D model users don't stay at one level of zoom, they often zoom in to see the finer and minutes details and often zoom out to get the overview of the 3D model.

For example, Fitzmaurice et al [19] developed Safe 3D Navigation tool for 3D models that augments the modal tools such as pan, zoom, orbit, look, etc, to facilitate freeform navigation in 3D scenes. The purpose for developing this tool was to help novice and new users with minimal or no 3D interaction experience to learn 3D navigation, and to provide better navigations tools to experienced professional 3D users. In their study, they start by first describing the major properties needed for safe navigation, then explain the features they implemented to realize these major properties and finally tested the effectiveness of their navigation system with usability tests.

In Fitzmaurice et al's [19] research, they built this safe 3D navigation tool in form of a 3D navigation widget (a semitransparent wheel menu of graphical buttons) that traveled with the user cursor. The zooming feature/button in this safe 3D navigation wheel menu provided a customized zooming range for novice and new users restricting the zoomed view of the 3D object such that the viewed object is always visible on screen even when zoomed to its maximum. Point zoom was disabled for the novice and new users. The results of their initial user studies revealed that in spite of controlling the zooming by defining a maximum and minimum object size for the zoomed view new users got into navigation trouble often and quickly (within 30 seconds) with the 3D navigation tool. However, their intermediate users on the other hand (with some experience in interacting with 3D models) learned to navigate the 3D models quickly and the number of errors (losing control) reduced significantly with time. Their expert users appreciated the safe 3D navigation widget and provided many suggestions to improve the tool further with more navigation features for expert users.

Another interesting finding from study [19] was that, in spite of providing a controlled zoom, their new and novice participants had difficulty in controlling their user interactions with the 3D model, for example they would pan and rotate more than the required amount and would eventually get lost in the 3D space. We discuss this impact of expertise in interacting with the 3D models and related research in the later part of this section.

In another study, Baudisch, Nathaniel and Stewart [3] explored the different ways in which large detailed documents can be presented on a relatively small screen with limited display resources. They compared three visualization techniques focus plus context screens, overview plus detail and zooming/panning combination techniques for performance, efficiency and accuracy, in extract information from large documents. They argued that for multi-scale documents used by professionals in fields such as architecture, 3D CAD design, and geographic information systems (GIS). These documents often exceeded the user-display's capacity of presenting the complete document with sufficient details while preserving the document's complexity. Users are forced to either access the information in parts by manually navigating (zooming and panning) from one section of the document to another or use appropriate visualization techniques (such as fly through, fisheye, etc).

In Baudisch, Nathaniel and Stewart's [3] research, in order to construct realistic study tasks, they interviewed 14 experts (visual surveillance and design professionals from various fields) to get a better understanding navigation requirements and routine operations/tasks they perform with such large complex documents. They covered all the five classes of activity in Plaisant et al.'s taxonomy of zooming behavior [39] such as image generation (frequently done in web designing, graphic design, and architecture), open-ended exploration (performed in submarine remote operated vehicle operation), diagnosis activities (done mostly in mechanical engineering and 3D CAD designing), navigation activities with GIS Maps, games, and monitoring activities performed in video surveillance and air traffic control.

An interesting finding from that study [3] was that zooming and panning documents was important part of the navigation process and was done frequently to view static and dynamic content of the multi-scale documents. The zoom in capabilities allowed users to view different levels of details, align components, and simplify selection, where as the zoom out capability provided users with the overall context. Panning was done to primarily to shift the area of focus or to explore neighbouring regions. Based on the results of the field interviews they constructed two study tasks, the first task required participants to identify the shortest path between two marked locations on a 2D map of downtown London and the second task required them to verify connections on a 2D circuit board. The multi-scale documents were presented via Adobe Photoshop. Results of the study revealed that participants were 21% and 36% faster with focus and context display screens. They argued that this gain in efficiency is on account of display characteristics of the focus and context approach where two levels of details are presented at the same time helping participants to save time on zooming interactions.

Focus plus context screens are one of the latest work in the field of navigation techniques for 2D multi-scale documents however this approach requires a heavy setup, involving a projector and a screen to provide the low resolution wall sized context screen, a LCD monitor sitting at the centre on the low resolution screen serving as the high-resolution focus display and a customized software used to synched the image content across both regions while preserving the high-low resolution for the context and focus screens, which is not always guaranteed on factory floors. However the important take away from this research is that two levels of zoom served better and that restricting users to a single level of zoom limits the amount of information that can be presented to them, and especially on a mobile (tablet) screen with a small display area makes it even more difficult for the user to comprehend or interact with the complex 2D/3D designs. Moreover to compare the different textual annotations styles without factoring zooming would result in an evaluation that fails to understand, if the effectiveness of a certain annotation style is on account of the level of zoom at which the user is interacting with the annotated 3D model or if it is the annotation style in general that is superior to other annotation styles.

At a single zooming level, the user cannot experience the richness and benefits that different textual annotations have to offer and also it is not possible to evaluate if different annotation styles will perform better or worse at varying zooming levels. We therefore are interested in investigating whether a set style/layout of textual annotations would be effective on a mobile form factor (tablet screen size) with varying zooming levels. In addition, we believe that on a mobile platform with limited computing power and small screen size, running complex and computationally demanding annotation layout algorithms such as in [4, 50, and 43] would not be feasible.

2.6 Cognitive Aspects of Learning (Limits of Working Memory)

Another important factor to consider when annotating a 3D design/model is the ability of annotations to support user learning. To evaluate if a certain annotation style supports user learning, we must take into account the effect of cognitive workload induced by the annotations on the users of such a system. Users will prefer those annotations that facilitate learning, where the application of a certain annotation style makes it easy for them to understand and retain the textual information provided to them in the annotated 3D model. The fact that we are dealing with the storage-specific aspect of working memory (i.e., where the number of objects an average human can hold in working memory upper limit of (7 ± 2) [35] has been revised to 4 [15]) makes it even more important that we do not overload the working memory of the user.

In some of the previous research related to the limits of working memory, Miller [35] discussed the similarity between the limits of one-dimensional absolute judgment and the limits of short-term memory. He hypothesized that in experiments on absolute judgment a participant can be considered as a communication channel presented with information (a number of stimuli) that varies in one dimension. In his study, the experiment was set up to measure the amount of transmitted information with respect to an increase in the amount of input information to the communication channel, where the output or amount of transmitted information will depend upon the channel capacity of the communication channel. Thus if his participant's absolute judgments were accurate, all of the input information will be transmitted and there will be no loss of information.

On the other hand, if his participants had reached their maximum performance on one-dimensional absolute judgment (the channel capacity) then the output or transmitted information will remain the same and there will be more errors or loss of information with respect to an increase in the input information provided to his participant. This threshold or asymptotic value after which participant performance starts degrading represents the greatest amount of information that the participant can process/yield about the stimulus in the absolute judgment experiment.

In Millers [35] study, he provided his participants with 10 different tones varying only in pitch (a stimulus that varied in one dimension) and their performance was measured based on the ability to correctly identify the tones. Results of his study revealed that participants performance was nearly perfect up to 6 different stimuli but declined as the number of different stimuli were increased. Overall his participants were able to correctly distinguish between 4 and 8 stimuli alternatives corresponding to a channel capacity (capacity of working memory of participants) to be approximately 2.5 bits of information.

In a similar study, Hake and Garner [23] evaluated the channel capacity for judgments of visual position, which they claimed to be significantly larger than 2.5 bits. In their study, their participants had to interpolate visually the distance between two scale markers that were presented at 5, 10, 20, or 50 different positions. There were two treatment conditions, the first one where their participants could use any number between zero and 100 to describe the position and the second treatment condition where the response of their participants to describe the position were limited to the options (possible stimulus values) provided in the experiment. In both of these cases, the results revealed the channel capacity for judgments of visual position was 3.25 bits of information (8 to 9 stimuli alternatives).

In the second part of Miller's [35] study, he discussed about the absolute judgments for multidimensional stimuli, where the researchers speculated that the addition of a second dimension to the stimuli will augment the channel capacity but at a decreasing rate. He argued that with the addition of dimensions to a stimuli the increase in the total channel capacity is achieved but at the expense of accuracy for any particular dimension.

In the third part of Miller's [35] study, he discussed about the span of immediate memory or recall (longest list of items that a person can repeat correctly immediately after the list of items was presented). He argued that absolute judgment is limited by the information capacity and immediate memory is limited by the number of items, where the information capacity is measured in bits and the memory capacity in chunks of information that a person can hold. He then hypothesized that the span of immediate memory is independent of the number of bits per chunk and since the memory span is limited by a fixed number of chunks, an increase in the number of bits of information per chunk (packing more information in each chunk, a process known as recoding) can increase this channel capacity.

In Miller's [35] research, he argued that recoding is an extremely powerful tool for increasing the amount of information that a person can hold and varies from person to person depending upon their knowledge and as a result what is counted as a chunk for that individual. He justified the existence of recoding with an example from our daily lives, where in order to remember the details of an interesting story or a special event of our lives; we rephrase (recode) the event making our own verbal description to remember the important details of the event thus retain more information by utilizing the recoding process. He claimed that memory span is approximately 7 ± 2 chunks for the same stimuli; however, the amount of information recalled varies significantly with the recoding scheme used in the experiment.

In another similar study, Cowan [15] argued that the memory limit, as in how much chunks of information can be retained at once in the working memory of average human mind is limited to 3 to 5 meaningful items for young adults. He claimed that to understand the nature of the working memory capacity limits we need to design study tasks that remove the processing-related aspect of the working memory such as processing strategies (encoding) and attention that augment the actual storage specific capacity limit of the working memory. For example, to remember to buy bread, milk, and pepper, one can form an image of bread floating in peppery milk. Similarly, to remember the concepts being taught in class one pays attention to what is being discussed in class rather than filling the working memory with distractions such as to do after the class ends.

In Cowan's [15] research, he used a version of the array memory procedure where there were multiple objects (comprising of circle and square objects) that were presented with different colors to minimize encoding. His participants had to retain items of one shape only (diverting attention) and the study task was to indicate if the test shape was in the correct position where the working memory was being tested under several attention conditions by varying the shape, color and position of the test object/probe. Results revealed that for young adults the number of items stored in working memory varied from 3 to 5.

To the best of our knowledge, we found that no research up till now has evaluated textual annotations in a 3D model with respect to the impact they have on user learning We believe that the ability to support user learning in an important aspect when comparing different textual annotation styles. An annotation style that supports user learning will be preferred by users as it allows them to remember more details and is more effective in conveying the technical information compared to other annotation styles. Thus supporting users in completing their tasks of installation/repair/assembly with this recently acquired new knowledge. In addition this annotation style will reduce the number of interactions with the annotated 3D model as the users will become familiar with the 3D model in a shorter period of time and searching for components will be much faster in the 3D model as users now, will be able to recall component positions and names more readily.

2.7 User Comprehension

Engineering and manufacturing installations are complex concepts often difficult to understand and apply in real world situations, especially in aircraft industry [11]. Practical training or experience with such installations is an essential part of the learning and comprehension process [10]. We can develop virtual environments and simulations such as interactive annotated 3D models and their animations to facilitate user learning and support users at installation/manufacturing tasks. And later use these systems to measure the extent of support for learning via component recall and retention of other technical details presented to users via different annotations styles and interfaces.

However, the level of comprehension (understanding) can only be tested either in field (on factory floors) or in a laboratory setting that simulates possible working scenarios of an assembly line. This would require us, to design realistic technical study tasks that will engage participants in performing a real installation or part of the installation process related to some work flow in a factory floor environment. Moreover we will need participants who are educated or familiar with the different aspects of the presented technical and manufacturing information, which they need to comprehend in order to complete the installation/repair study task.

Chervak and Drury [11] evaluated the use of a restricted technical language for maintenance job instructions, to determine whether or not it can reduce error rate in aircraft maintenance tasks caused on account of miss understanding or lack of comprehension of textual information presented to aircraft maintenance technicians. The results of the study revealed that the maintenance task errors reduced significantly with the use of a restricted technical language compared to original (English) and hybrid (combination of original English and restricted technical language). In their study, they recruited both experienced and inexperienced participants who performed two maintenance tasks (an easy maintenance task and a difficult maintenance task) on a small internal combustion engine.

In a similar study, Chervak, Drury and Ouellette [10] evaluated four actual examples of existing maintenance work cards (two easy tasks and two difficult tasks) for two aircraft types for comprehension tests. These work cards were provided by Boeing Inc and represented actual, realistic writing practices used in industry for writing maintenance manual procedures. This was done to compare the original English language written in these manual with the restricted technical language. Several experts such as technical communications researchers were involved to analyze both versions of each work cards in terms of total words, mean words per sentence, percentage passive voice, and Flesch-Kinkaid reading score. Task difficulty ratings were evaluated for each work card by experienced aircraft maintenance engineer. And One hundred seventy five licensed aircraft maintenance technicians from eight major air carrier maintenance sites were recruited to participate in the study. The comprehension test was timed and its performance was measured by whether each question was answered correctly and whether the technical content used to answer the question could be located correctly within the procedure.

An interesting finding of that study [10] was that for the two difficult work cards, a restricted technical language gave significant and superior accuracy results. In addition the non-native English speakers took significantly longer than native English speakers to complete the comprehension test; however the use of restricted technical language allowed non-native English speakers to achieve about the same level of performance as that of native English speakers. Despite potentially-reduced ambiguity, there are still feelings among some technical writers that restricted technical language prevents them from expressing instructions in the most obvious manner. And that the accuracy of the restricted technical language varies from one technical task to the other.

An example of a sample technical study task for our study could involve the installation of cooling pipes at the nose section of aircraft. This will require our participants to comprehend (understand) the technical annotations, and filter out material properties such as melting point and thickness of cooling pipes in order to select the correct welding procedure such as gas welding with an appropriate fuel mixture (oxygen with Acetylene/propane/Gasoline) to perform the installation correctly. As comprehension is closely tied to the correct understanding of the perceived knowledge and then applying this knowledge to complete the technical task, evaluating comprehension was out of scope in this study.

2.8 User Expertise in Interacting with 3D Models

Another important factor to consider when evaluating textual annotations with interactive 3D models is the level of user expertise in interacting with 3D models and software. It fairly difficult to establish that a certain annotation style is best for learning or searching for all users, as all users are not alike and have different needs. They vary on various scales of product/domain knowledge, experience with 3D models, spatial and computer skills that individuals acquire over a period of time, and that has known to affect learning [45,19,28]). For example, Sebrechts et al [45] explored the utility of three visualization techniques for displaying textual search results via 1D, 2D and 3D interfaces. They evaluated their participant's performance on 16 unique information seeking tasks on a set of documents where participants had to locate, compare, and cluster documents based on a certain criteria such as document title, key concepts, and document content.

An interesting finding of that study [45] was that the overall response time for participants varied with the task type for the three visualization conditions. For example, participants performance was much higher for search tasks where they had to locate document clusters (annotated with colors and represented as colored boxes and cubes in 2D and 3D visualizations) based on certain keywords compared to search tasks where participants first extracted key concepts from a content descriptor (i.e., comprehension) and then located relevant document clusters.

Another interesting finding of that study [45] was that there were significant interactions between visualization technique, information retrieval tasks, and user expertise. For example they found that their participant's computer skills were had a significant impact on the 3D visualization treatment condition compared to the textual and 2D visualizations treatments. For participants with greater expertise in interacting with 3D interfaces (such as experienced computer graphics professionals and gamers with high graphical user interfaces experience) were much faster and more accurate (less errors) compared to novice users for 3D visualization condition than for 2D visualization condition. They claimed that these results suggested that 3D visualizations cannot be evaluated adequately using only novice users.

In another similar study, Fitzmaurice et al [19] developed a Safe 3D Navigation tool that augments the modal tools such as pan, zoom, orbit, look, etc, to facilitate freeform navigation in 3D scenes. The purpose for developing this tool was to help novice and new users with minimal or no 3D interaction experience to learn 3D navigation, and to provide better navigations tools to experienced, professional 3D users. In their study they recruited participants with varying user expertise in interacting with 3D objects/models in a 3D environment ranging from new/novice users (computer users with experience in office automation software such as Microsoft outlook, excel, power point) to intermediate users (with some experience in interacting with 3D software and 3D games) to well experienced 3D users (such as design engineers, CAD professionals from mechanical engineering domain, and architects).

In Fitzmaurice et al's [19] research, they claimed that user expertise in interacting with 3D models had a significant impact on participant's performance in the exploring and navigating study tasks. They found that in spite of providing a controlled zoom where the range for maximum and minimum zoom was restricted such that the viewed 3D object was always visible on screen. New and novice users got into navigation trouble very frequently and quickly, within 30 seconds of the start of the task, as they had difficulty in controlling their user interactions with the 3D model. They reported that novice users for example, would pan and rotate more than the required amount deviating themselves from the defined navigation track and eventually got lost in the 3D space. They found that with intermediate users (with some experience in interacting with 3D objects/models) the number of navigation errors reduced drastically with time. They found that after three minutes the performance of intermediate users were comparable to that of expert users, suggesting that the safe 3D navigation tool supported intermediate users more than novice users, transitioning them from an intermediate level to expert user level for navigation and exploration study tasks.

In another study, Huk [28] investigated the educational value of 3D visualizations in cell biology education domain (plant and animal cell structures), where he argued that till data the impact of spatial ability on learning and comprehension in a three-dimensional (3D) visualization environment is not clear. He strengthened his claim by emphasizing the findings from previous research (existence of two contradicting theories the ability-as-enhancer and the ability-as-compensator theory). The ability-as-enhancer approach/hypothesis where learners with greater spatial ability benefit more from interacting with 3D models as they have enough cognitive capacity left for developing a better understanding of the underlying concepts. And the ability-as-compensator hypothesis where low spatial ability learners benefit more from the explicit graphical 3D representations as it overcomes their difficulty in mentally visualizing 3D objects and speculating their spatial orientation, freeing enough cognitive capacity to learn and comprehend the new details. He hypothesized that in the cases of cell biology education, interactive 3D illustrations depicting a cell structure will support learning and comprehension among high school biology students as it gives a student sophisticated information regarding the 3D structure of a cell.

An interesting finding of that study [28] was that neither the presence of 3D illustrations nor spatial ability (high or low) of students had any significant impact on perceived cognitive load from the presence of 3D models. In addition he reported that the overall recall scores of the students with high spatial ability were significantly higher compared to students with low spatial ability for the two treatment conditions (visual recall condition where the information was presented in a 3D illustration form and the auditory recall condition where the information was presented in a textual passage form). The reported findings are interesting as on one had hand they support the researcher's hypothesis that students with high spatial ability will score significantly higher than students with low spatial ability on visual recall (in presence of a 3D illustration/model). However, on the other hand it raises questions on how students with high spatial ability were able to score higher than the students with low spatial ability on the auditory (textual) recall that did not involve any graphical component and where the spatial ability had no role to play.

In another study, Chester [12] explored the different ways to support new and novice users such as students, to progress from a relatively simple to an efficient and expert user level in using 3D-CAD software. In his study he explored the range of Meta cognitive processes (strategies) and best practices used by 3D-CAD domain experts during the design process while interacting with the 3D-CAD models and software. He argued that domain experts unlike new or novices users possess high levels of product/domain knowledge with well developed cognitive structures in the form of schemas. This enables them to recognize different domain specific patterns, and develop a deeper and more structured level of understanding of the presented information compared to other users.

In Chester's [12] research, he emphasized that identifying product/domain expertise in 3D-CAD domain is a difficult task. As there are no gold-standards or standardized tests that can qualify or quantify the level of product/domain expertise possessed by users working with 3D CAD models and software. This situation is further aggravated by the presence of a variety of different 3D CAD software and applications currently used in the industry and lack of peer nomination as domain experts through professional recommendations and associations. Making it even more difficult, to identify domain experts (users with high product/domain knowledge).

In Chester's [12] research, in order to recruit participants (product/domain experts - users with high levels of product/domain knowledge in 3D-CAD domain) for his research, he built a criteria based on the work of previous research such as [34] and [9], done in the area of identifying domain expertise. In these studies, Meig [34] and Charness and Schultetus [9] have defined few criteria for selecting domain experts such as, users with high performance on tests that measures product or domain specific knowledge, high peer ratings and recommendations, user's education level related to the specific domain, industry/software certification, and years of experience in the field. These studies [34] and [9] defined product/domain expertise as "consistently superior performance on a specified set of representative tasks for the domain that can be administered to any subject" (Mieg, 2001, p.76) [12].

To recruit participants for his research study Chester [12] established the following criteria for identifying potential research subjects: (a) They have a certain number of years of experience in the domain, (b) currently use 3D-CAD software on a regular basis, (c) peers regard them as possessing domain expertise and (d) have experience in teaching/training others in their domain. Once he was able to identify a domain expert in 3D-CAD domain, he then used this domain expert to evaluate the domain expertise of his other potential research participants for his research.

Being inherent to individuals, these variables (such as product/domain knowledge, experience with 3D models, spatial and computer skills) are difficult to control and have a direct impact on the performance of users in interacting with CAD and 3D software. For this purpose, in designing our research study, we have taken into account, the level of user expertise in interacting with 3D models and software, and reflect upon the findings accordingly.

In our research study, we do not evaluate the domain expertise of our participants with respect to the 3D models used in the research study. As these 3D models may belong to multiple domains (such as mechanical, medical, and aeronautical domains) and would require us to design knowledge test in these different domains with help of identified domain experts. Moreover evaluating domain expertise with respect to the 3D models used in the research study is out of scope, as the research deals with user expertise in interacting with 3D models and software, and not the domains of the 3D models used in the study.

We do however evaluate our participants for previous (product) knowledge about the 3D models used in our research study and exclude those participants who possess prior knowledge about the 3D models and/or their components used in our study (please see section 3.3 Independent Variables). This exclusion of participants from the user study with prior knowledge about the 3D models is done to protect the study data from getting corrupted (data from search and recall tasks). Participants with previous product knowledge about 3D models will know exactly where to find a certain component inside a 3D model thus bypassing the use of textual annotations and similarly for recall tasks participants with previous or prior knowledge about 3D models and/or it components will use their previous knowledge in recalling the components names on the recall sheets (please see section 3.7 Study Tasks).

In our study we do not evaluate our participants for spatial skills. Sspatial skills or spatial ability refers to the mental ability of an individual to visualize the 3D structure of objects from their 2D representations, and/or to speculate the spatial orientation of the 3D object from different viewing angles [28]. Our study does not measure how well our participants can visualize or speculate the shape, structure, or orientation of the 3D annotated components mentally, as participants are provided with textual annotated 3D models (and not 2D or 3D illustrations) and are free to interact with them at all times during the study task.

Nor does the performance of our participants in the designed study tasks have any dependency of user's spatial visualization ability. In fact it is their control over the user interaction operations such as panning and rotating a 3D object by the correct amount that has an influence over their performance in the study tasks. For example in the search task, we measure the time taken and the errors made by a participant in the process of correctly identifying a 3D object annotated by the component's name, and in the recall task, we measure if the participant can recall the name and position of the annotated components in a un-annotated 3D model correctly. In both these study tasks participants are always provided with an interactive 3D visualization of the components and do not have to speculate (mentally visualize) the possible orientation outcome of a user interaction.

In this study, we have divided our participant base into three user groups (such as expert users, intermediate users and novice users) based on their previous experience in interacting with various 3D models and 3D software and reflect upon the findings accordingly.

2.9 Types of Textual Annotation Styles

There are several types of textual annotation styles that have been developed and experimented with. For example, Hamzalup et al [24] used annotation techniques such as simple text (names) to label important components in a 3D visualization (please see figure 4.a). In addition they have also made use of static (fixed position) text boxes for presenting textual and graphical aspects of information, such as material strength properties (please see figure 4.b). For implementing the 3D scenes they used X3D [58]. This software enabled the researchers to design and modify some basic properties of the 3D scene (such as placing labels) and customize the user interface as seen by participants. The annotated 3D graphical visualization was then presented to their participants using a web browser that had a special X3D plug-in called Bit Management X3D player [5] to render the annotated 3D model.

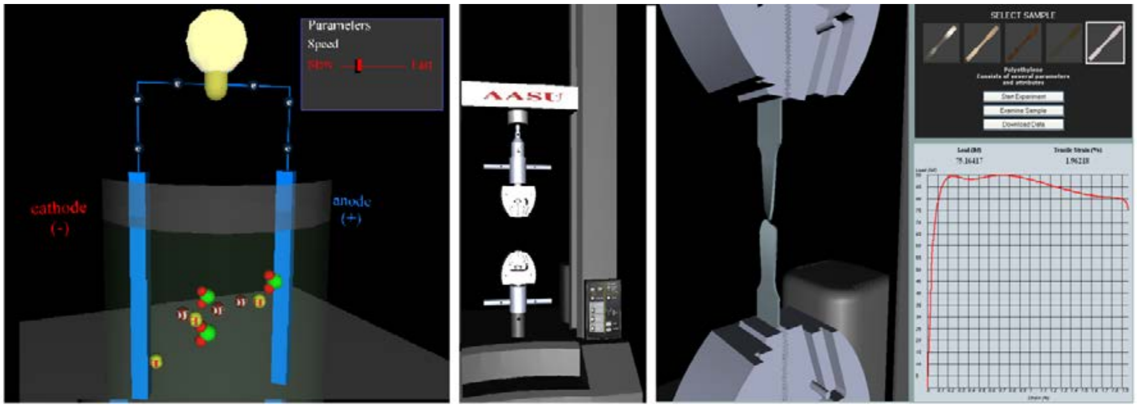


Figure 4: (a) Interactive 3D visualization of electrolysis of water, (b) Annotated 3D model of Instron^{TM} 5566 (TTM) Tensile Testing Machine with load-strain graph [24].

Oulasvirta, Estlander and Nurminen [37] compared the embodied interaction of users with a 3D versus 2D mobile maps in a field experiment. In their study, they made use of m-LOMA [36], a mobile 3D city map of Helsinki city that was custom tailored for Nokia N93, Nokia's first few phones with 3D accelerated hardware. They annotated the 3D mobile model map of Helsinki city with road signs, landmark symbols (red marker arrows) and street names. The name of the current street was placed in a dedicated text box located on the upper part of the 3D display (see figure 5.f) and the other street choices, street names, were placed inside the 3D map (see figure 5.e) as internal labels.

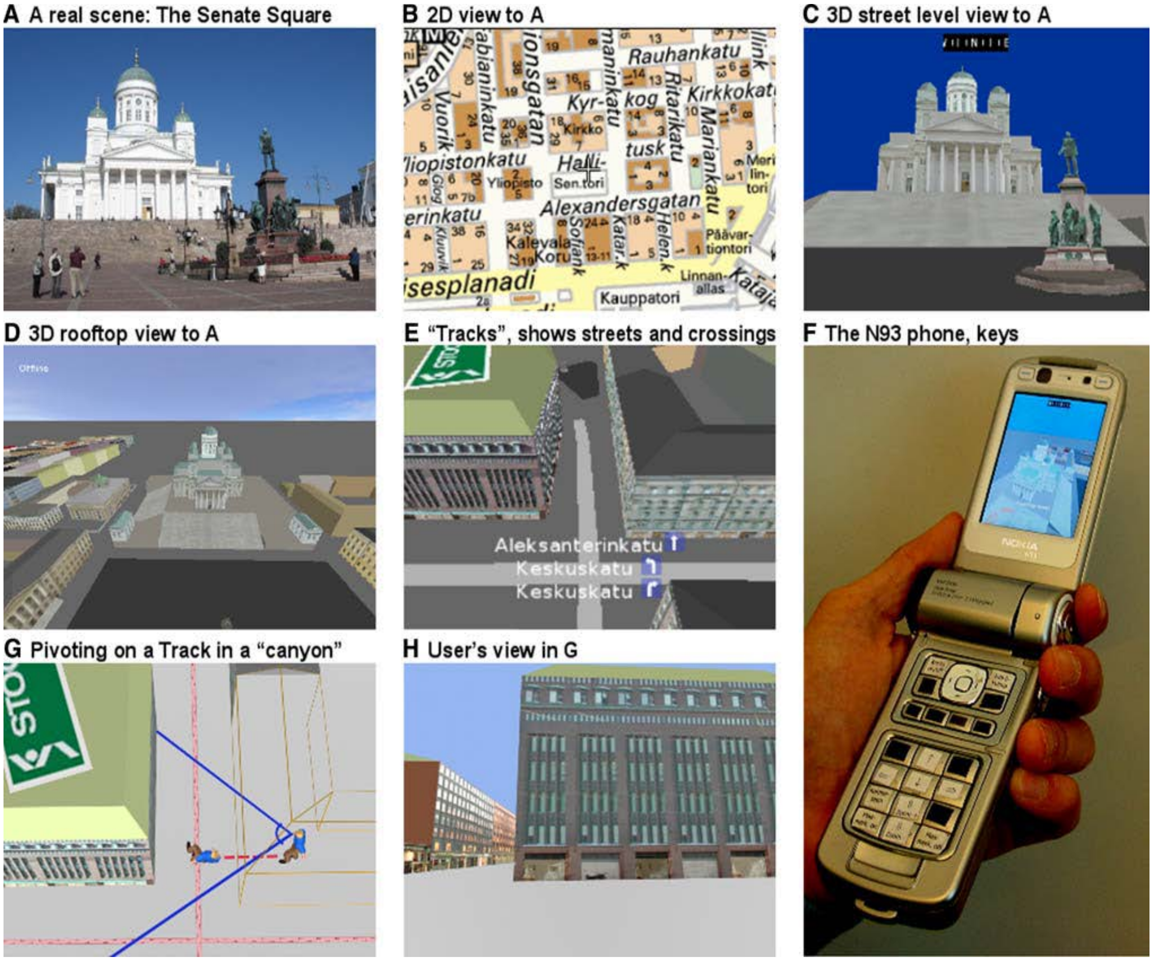
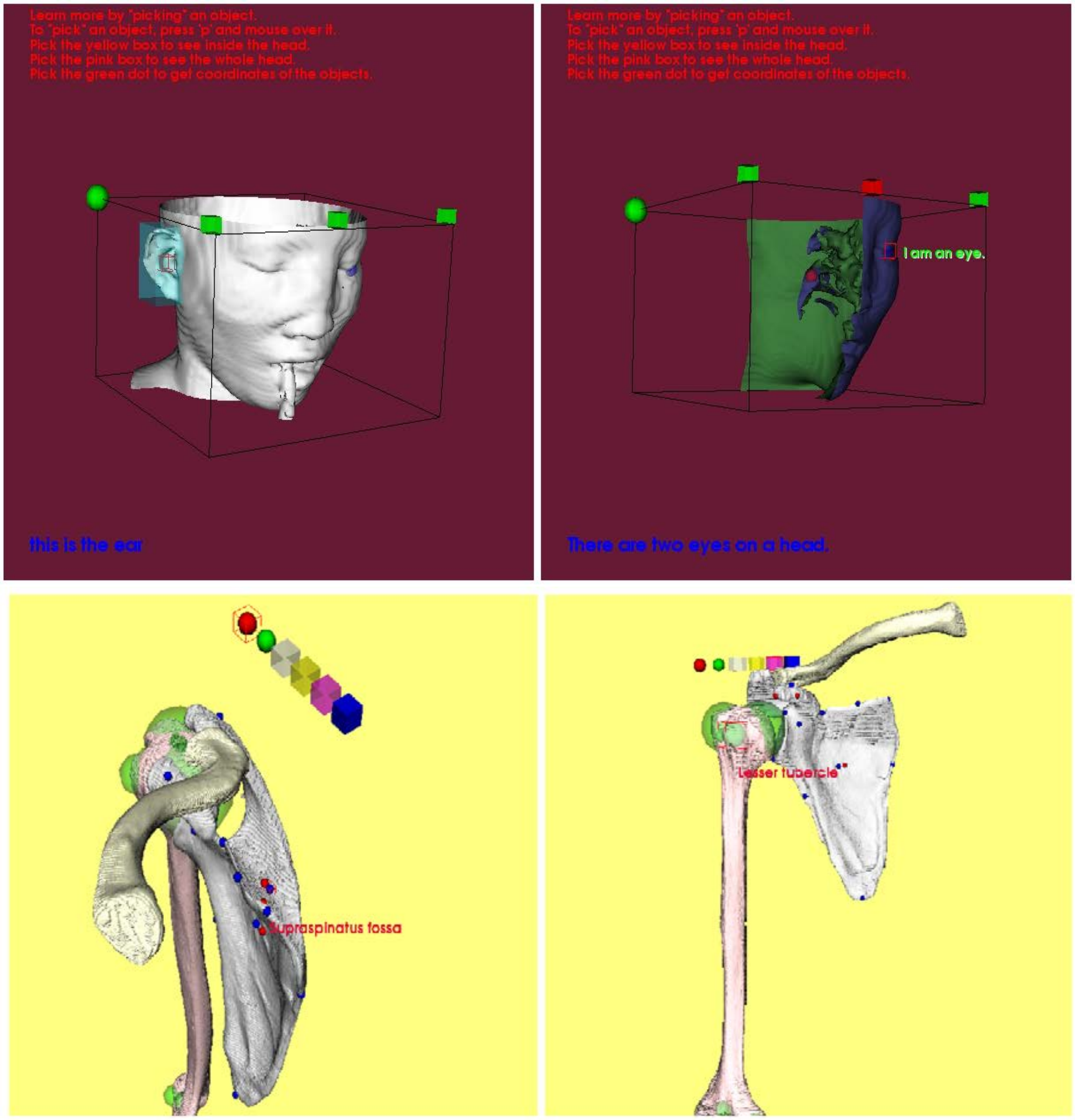


Figure 5: The user interface of m-LOMA. (a) Real scene Senate Square, (b) 2D map view of Senate Square, (c) 3D view of Senate Square, (d) roof-top-view of Senate Square, (e) 3D street view of Senate Square, (f) Nokia N93 phone, (g) track view, pivoting on a track in "cannon", (h) 3D track view [37].

Simpson [46] developed an annotation authoring tool called "Annot3D (see figure 6). This tool enabled its end users (Anatomy instructors) to create anatomy specific annotations (textual labels) to describe certain body parts of insects and animal in a 3D model. The end users could also control the order and presentations of annotations to teach effectively and emphasize more on specific parts that were complex and needed an elaborate explanation.



Learn more by "picking" an object.
To "pick" an object, press 'p' and mouse over it.
Pick the yellow box to see inside the head.
Pick the pink box to see the whole head.
Pick the green dot to get coordinates of the objects.

this is the ear

Learn more by "picking" an object.
To "pick" an object, press 'p' and mouse over it.
Pick the yellow box to see inside the head.
Pick the pink box to see the whole head.
Pick the green dot to get coordinates of the objects.

I am an eye.

There are two eyes on a head.

Figure 6: Annot3D (a) 3D model of head, annotation (ear) display at the lower left corner of the 3D view/screen (b) annotations diplayed for the selected object (eye), over the object itself, (c) 3D model annotated with symbols (red and blue spheres), selecting a red or blue sphere displays the associated textual annotation, (d) annotations diplayed for the selected object (bone joint) in addition to annotation symbols [46].

Sonnet, Carpendale and Strothotte [48] experimented with different methods of associating textual annotation with 3D objects/models. They experimented with ways such as placing the text in the object's shadow (shadow annotations), attaching text directly to the object by enclosing this annotation in a translucent polygon that intersected with its relevant 3D object and placing text in a separate window outside the 3D model, in a dedicated textbox area. In addition, the researchers experimented with transparency of annotation labels. They placed the annotations inside semi-transparent white boxes and at times inside grey shadows of the components (see figure 7.a and figure 7.d). They played with the color of the shadow of components (see figure 7.b and figure 7.d) and the association of an annotation with its component with or without connection lines (see figure 7.a and figure 7.b). Lastly, they also looked at the possibility of displaying the textual details in a separate dedicated window outside the 3D model (see figure 7.c). They recommended the use short textual labels compared to longer labels when annotation objects, as the use of long textual labels/descriptions may create occlusion and hide some of important components of the 3Dscene.

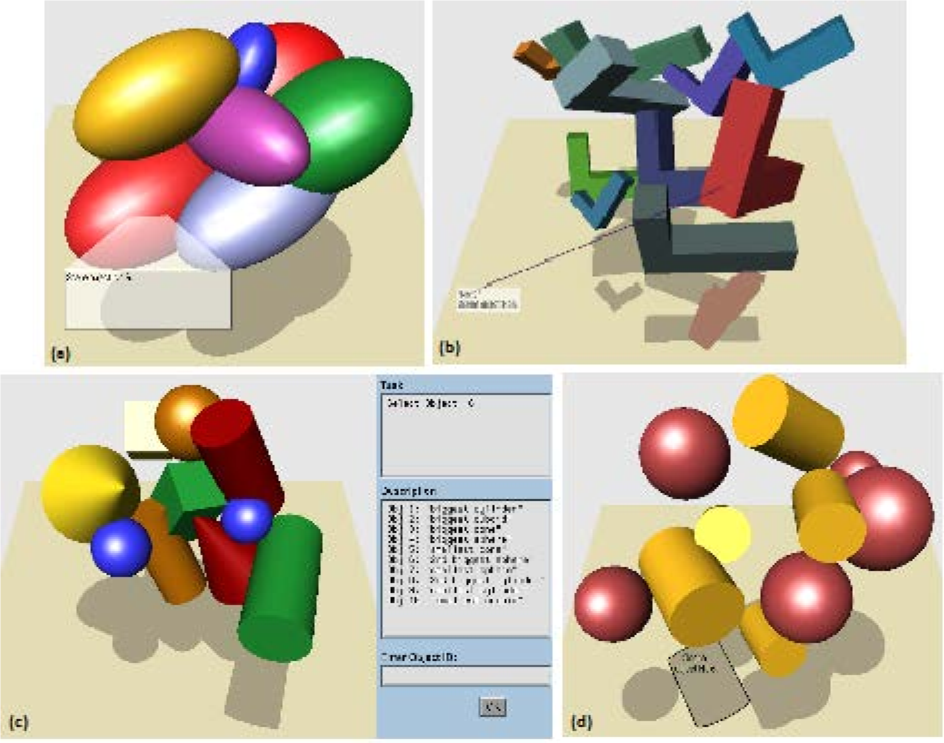


Figure 7: Association of Text with 3D models (a) annotations are directly attached to scene objects using translucent polygonal shapes, (b) simple line and text label annotation technique with additional hints diffused colored shadow, (c) 3D model and separate dedicated text area, (d) annotations are located within the objects' shadows in the scene [48].

Jung, Gross and Luen [30] experimented with creating their own annotation surface inside a 3D model, and then used this surface to sketch their custom annotations. As the drawing surface became part of the 3D model, this method provided a convenient way of creating location specific annotations on 3D surfaces of 3D models. These custom annotation styles included textual comments, numeric measurements, and custom markings and extended drawings, used primarily for design collaboration between architects. Here the location and proximity of the annotation drawing surface with a specific 3D component established the visual association of textual and/or non textual annotations with the parts of the 3D model (see figure 8).

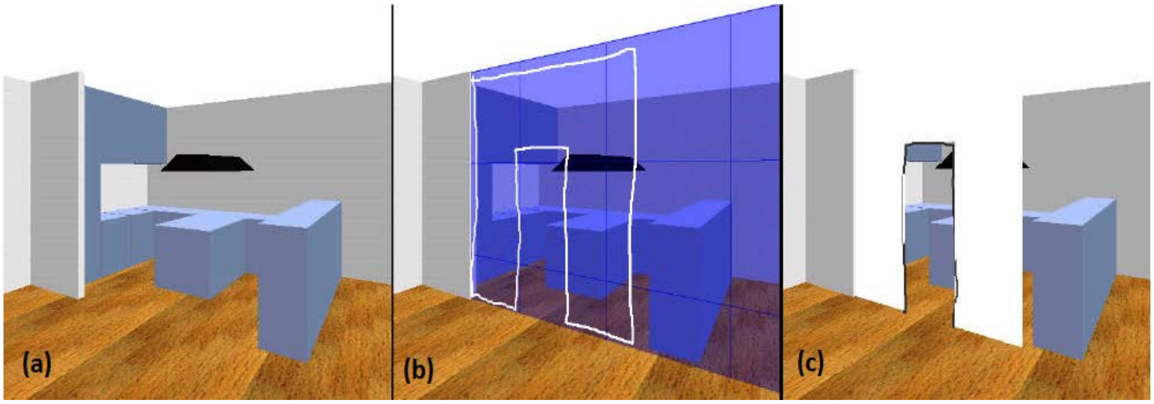


Figure 8: Proposing a design change to the model. (a) Initial state, (b) sketching a new wall on a temporary drawing plane, (c) suggested model changes (right) posted to the server for comment [30].

In a similar study, Song, Guimbretière, Hu and Lipson [47] developed a plug-in for Solid Works [16] that used off-the-shelf Logitech io2™ digital pen [33] for capturing surface annotations and edits made on the physical prototype and mapped them on to the surface of the 3D components (see figure 9)

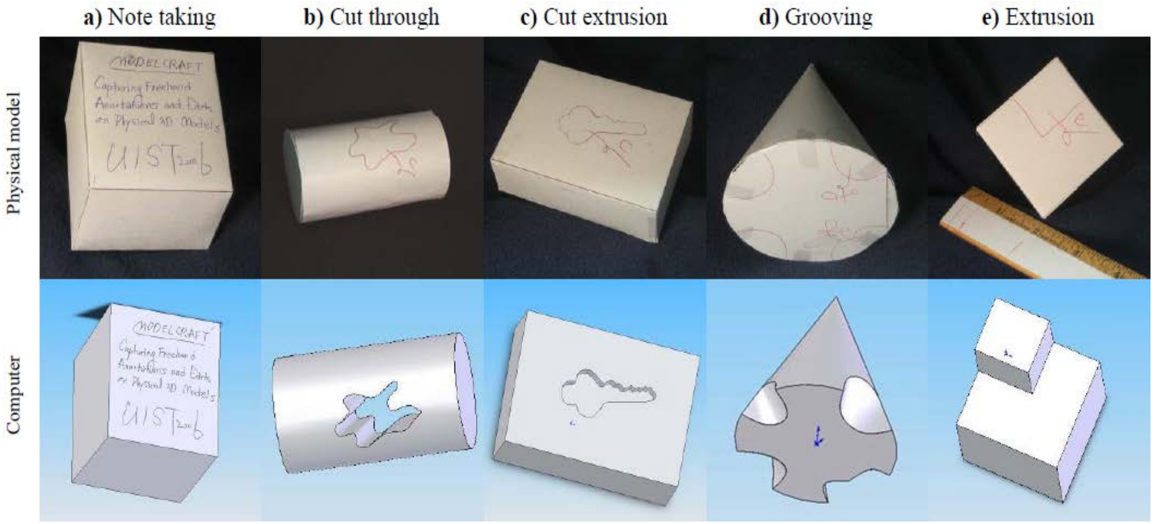


Figure 9: Current command set. Annotations are done with a black pen; edits are done with a red pen [47].

Boujut and Dugdale [7] developed a new type 3D annotation tool for CAD design engineers and integrated it with Solid Works [16]. To annotate a 3D object, the end user first chooses an appropriate annotation symbol then attached this annotation symbol to some 3D component in the 3D model/design, and finally, provided a textual description for the annotation. For example, the red star-shaped annotation symbol implied a critical technical constraint annotation and the associated text specified the exact issue or technical constraint/problem (see figure 10).

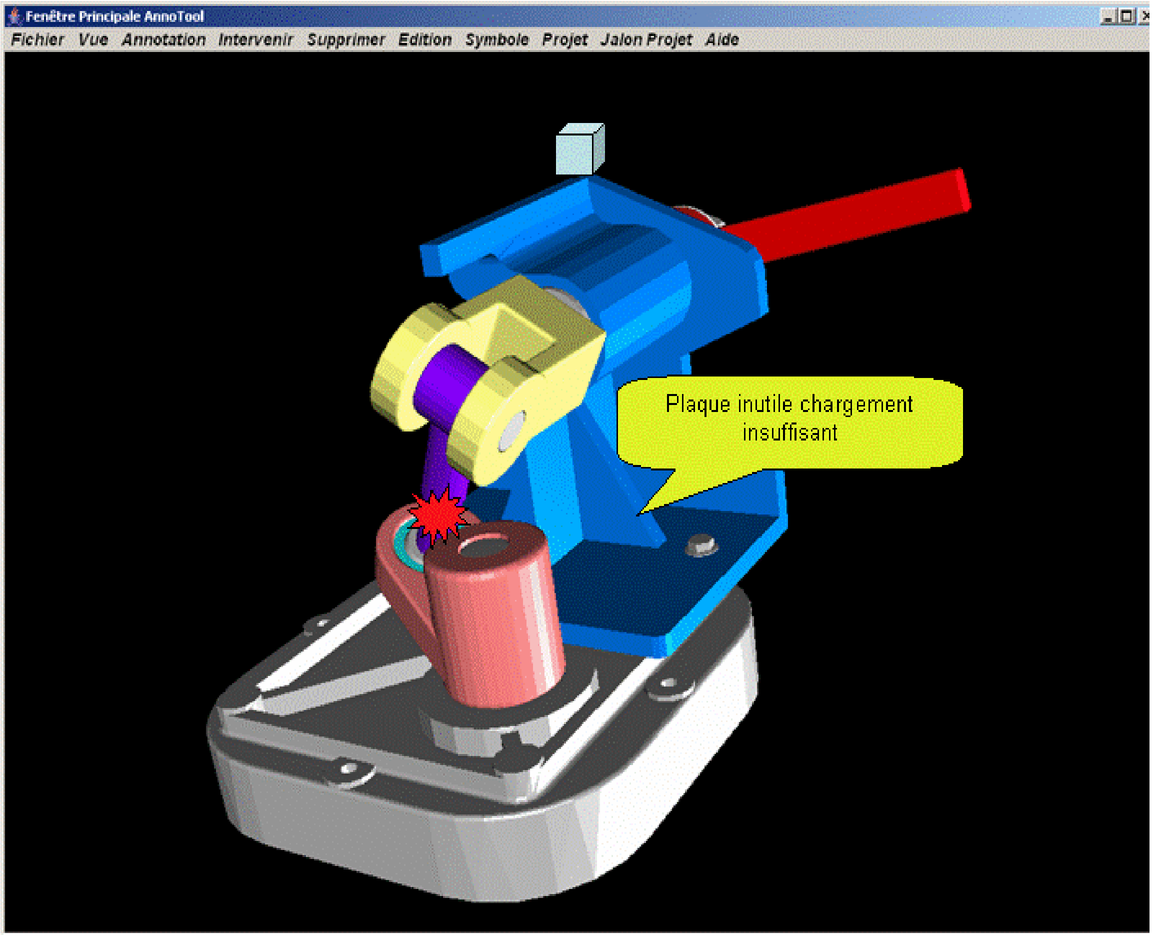


Figure 10: Red star-shaped annotation signals a technical constraint, the associated text specifies the exact problem [7].

In industrial domain, ASME (American Society of Mechanical Engineers) has developed standards such as Y14.41.2012 [2] that uses external annotations to communicate product and manufacturing information (PMI). These external annotations comprises of technical codes, welding symbols [57], geometric dimensional measures, tolerance data and other manufacturing specs that are written inside/on a rectangular box (annotation box) and attached to the specific 3D part/component with connecting lines (see figure 11).

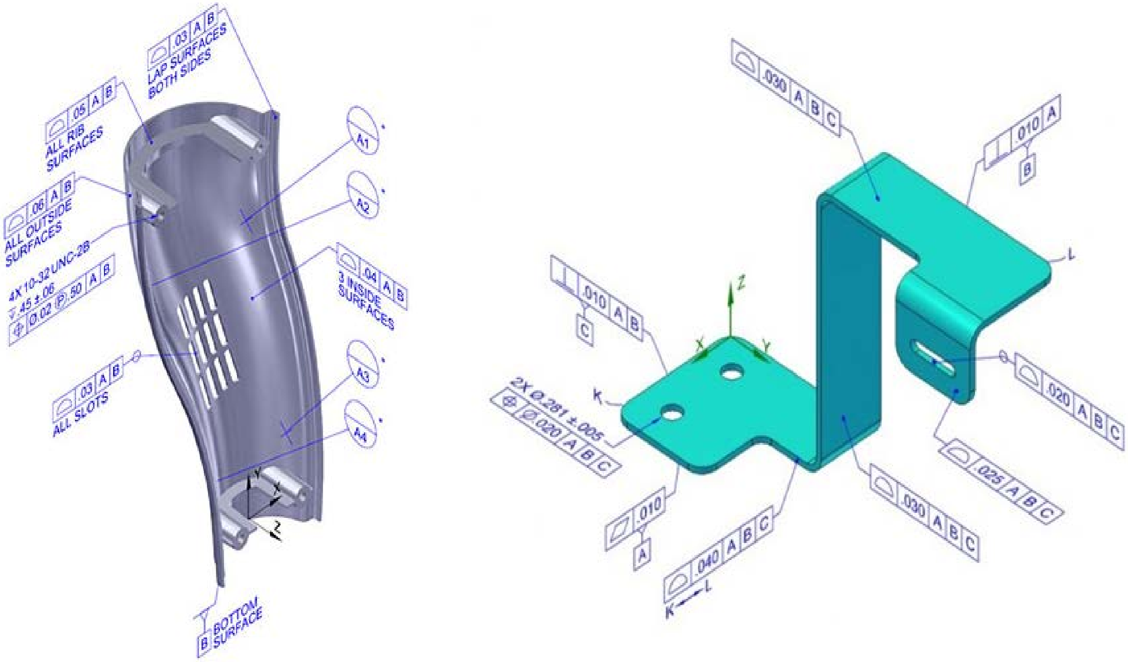


Figure 11: Example of PMI [40] information as described in ASME standard Y14.41.2012 [2].

Ropinski et al [43] and Cipriano and Gleicher [13] developed a new annotation rendering algorithm for internal annotation style/techniques that takes into account the shape of the surface being annotated. The textual annotations were tweaked to follow the surface trajectory [13] and 3D depth structure [43] of the object being annotated. These new algorithms and labeling techniques have improved the perception of the overall structure of the annotated object by providing better shape cues. However, the researchers have acknowledged that this gain in spatial comprehension was achieved at the cost of readability of the textual details (see figure 12 and figure 13). In their implementation of internal style annotations the extent of distortion of the text is influenced by the shape and depth of the annotated 3D object where the text may or may not be legible from a wide range of viewing angles. In another similar study, Stein and Décoret [50] developed a novel approach for dynamically rendering annotations, in a 3D scene. In their study, they have rendered box style annotation containing both text and 2D images (see figure 14).

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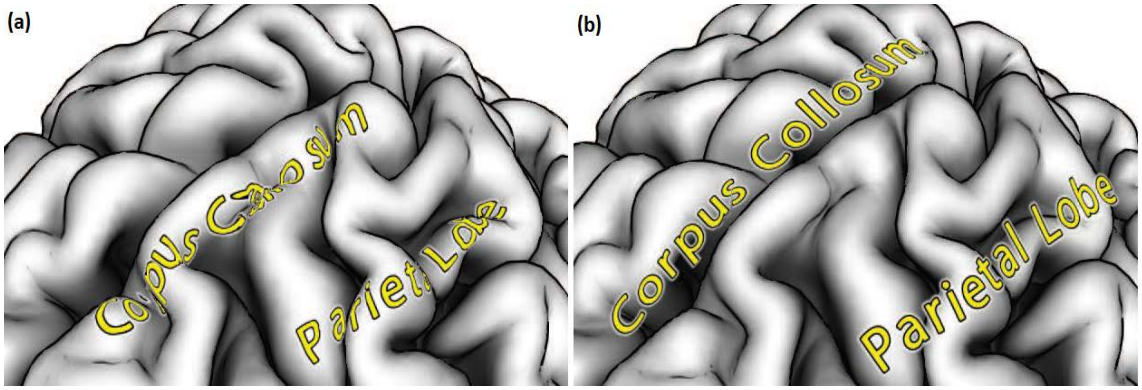


Figure 12: Labeling the brain surface: (a) labels placed directly on the surface details cause the text to be distorted and partially occluded. (b) Text scaffolds [13].

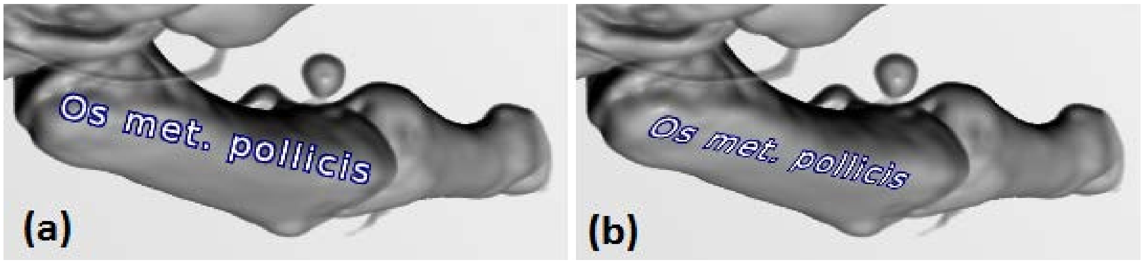


Figure 13: (a) Internal 2D labels, (b) Internal 3D labels follow the 3D depth structure of the component being annotated [43].

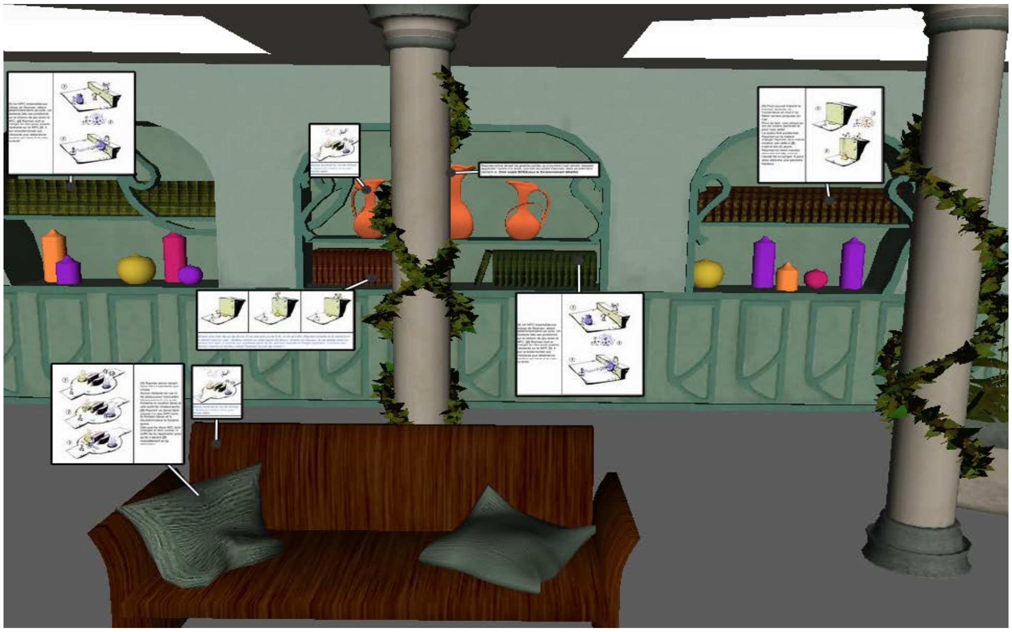
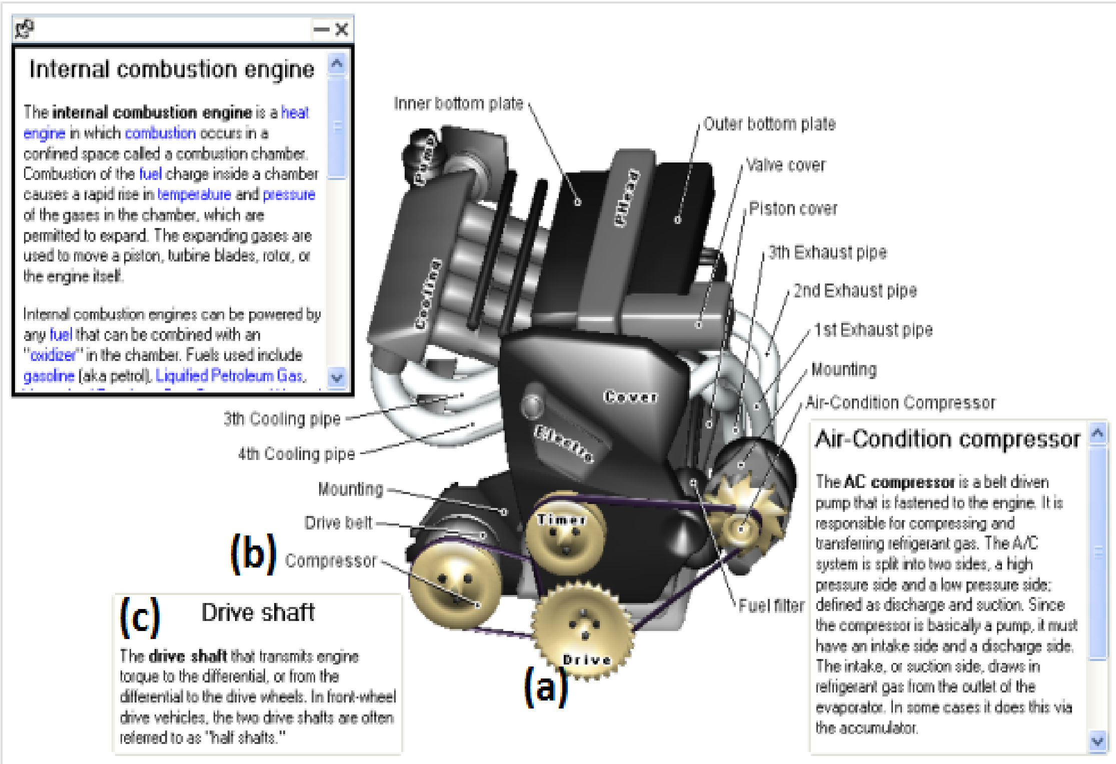


Figure 14: An example of dynamic labeling for a complex scene [50].

Götzelmann et al [21] developed a novel algorithm that determined which annotation style (internal, external or box style annotation) works best to annotate different components in an interactive 3D visualization, in real time. They further elaborated that their algorithm leveraged multiple metrics and local strategies in order to achieve an effective and aesthetic label layout with user adjustable weights while annotating 3D components. For example, the algorithm first determined the free white background on the user screen to place box style annotations that contain comprehensive textual details (see figure 15.c). Later the algorithm determined the placement of internal style annotations based on the dimensions of the 3D components being annotated. The algorithm annotated a 3D component with internal style annotation only if it could fit the annotation label inside the 3D component while maintaining the readability of labels (see figure 15.a). Otherwise, it changed the annotation style to external annotation style (see figure 15.b). With a change in the level of zoom, the novel real-time algorithm switched the style of the textual annotations from internal to external annotation style and vice-versa.



Internal combustion engine

The **internal combustion engine** is a heat engine in which combustion occurs in a confined space called a combustion chamber. Combustion of the fuel charge inside a chamber causes a rapid rise in temperature and pressure of the gases in the chamber, which are permitted to expand. The expanding gases are used to move a piston, turbine blades, rotor, or the engine itself.

Internal combustion engines can be powered by any fuel that can be combined with an "oxidizer" in the chamber. Fuels used include gasoline (aka petrol), Liquified Petroleum Gas,

Air-Condition compressor

The **AC compressor** is a belt driven pump that is fastened to the engine. It is responsible for compressing and transferring refrigerant gas. The A/C system is split into two sides, a high pressure side and a low pressure side; defined as discharge and suction. Since the compressor is basically a pump, it must have an intake side and a discharge side. The intake, or suction side, draws in refrigerant gas from the outlet of the evaporator. In some cases it does this via the accumulator.

Drive shaft

The **drive shaft** that transmits engine torque to the differential, or from the differential to the drive wheels. In front-wheel drive vehicles, the two drive shafts are often referred to as "half shafts."

Figure 15: Annotating a 3D visualization with three different annotation styles.(a) Internal style annotation, for example "Drive", (b) external style annotation, for example "compressor", (c) box style annotation, for example "Drive shaft" [21].

In our research, we have selected three most commonly used textual annotations these are internal, external and box style annotations. These annotation styles (are similar to what has been implemented in the study [21]. In addition, we have tweaked these annotation styles in our implementations, based on peer review and feedback received from the pilot study. We have developed our study prototype using 3DVIA Composer, the latest commercial off the shelf 3D CAD tool available in the market from Dassault Systems. The changes to our implementation of annotation labels include the transparency effect for annotation boxes to reduce occlusion caused by displaying the annotation box labels over a 3D model; as displaying them in free white background is not always guaranteed (see figure 3). In addition, we have implemented fixed length external annotation (callouts) labels to account for visual clutter (see figure 2). We discuss the design details of our implementation of the three annotation styles later in Chapter 3 Study Prototype and the detailed study design in chapter 4 Methodology.

In this research, we evaluate textual annotations with interactive 3D models with respect to the above discussed factors. We believe, it is important to design a study that compares different textual annotations at multiple levels of zoom, for performance (efficiency and accuracy at the task of searching for 3D components), user preference (comparative rankings and ratings on four usability factors such as readability, overall look and feel, perceived ease if usage and satisfaction), and impact on learning (providing users with annotations that support learning) to determine which textual annotation style best supports users with varying level of user expertise in interacting with 3D models and software, at the task of searching for components, recalling component names and in interacting with an annotated 3D model on a mobile (tablet) form factor.

CHAPTER 3 STUDY PROTOTYPE

In this chapter, we present the design aspects of our implementation of the three textual annotations and the process of annotating a 3D model using 3D CAD software 3DVIA Composer.

3.1 Study Prototype

We used 3DVIA composer software by Dassault Systèmes to build our prototype. The prototype comprised of three 3D models annotated with three textual annotations styles (internal annotation style, external annotation style and box style annotations). Before annotating these models, we ensured that the 3D models have enough components and details such that users can distinguish and select at least 27 unique components just on the outer shell of the 3D model (please see section 4.11.3 need for 27 unique components per 3D model). 3D models in general contain a lot of details; however, these details are packed in layers and do not reside on the skin but more on the inside of the model, and only are visible when the outer shell is peeled off by using a special interaction mechanism such as x-ray, peeler, onion skin, digger, etc. To ensure that we have 27 unique visible components on the outer surface of the 3D model, we had to explode and merge several complex and detailed parts, removing all the internal parts and layers of details that were not visible to the user, in order to create new parts that were visible and could be selected on screen with a mouse click. In addition, we added the functionality of highlighting this new clickable 3D component every time user hover their mouse on it. We also added colors to the 3D model to separate the different components from each other and to reflect on the actual practices and usage of the 3D model in a real industrial setting where few components of interest are highlighted from the rest of the 3D model with a set of colors. Our first 3D model was a dental milling machine (see figure 16, 17, and 18 depicting the front, side and top view of model#1), the second model in our study was a 2-stroke miniature aircraft engine (see figure 19, 20, and 21 depicting the front, side and top view of model#2) and the third model used in the study was a three stage turbo-jet propulsion engine of a commercial aircraft (see figure 22, 23, and 24 depicting the front, side and top view of model#3).

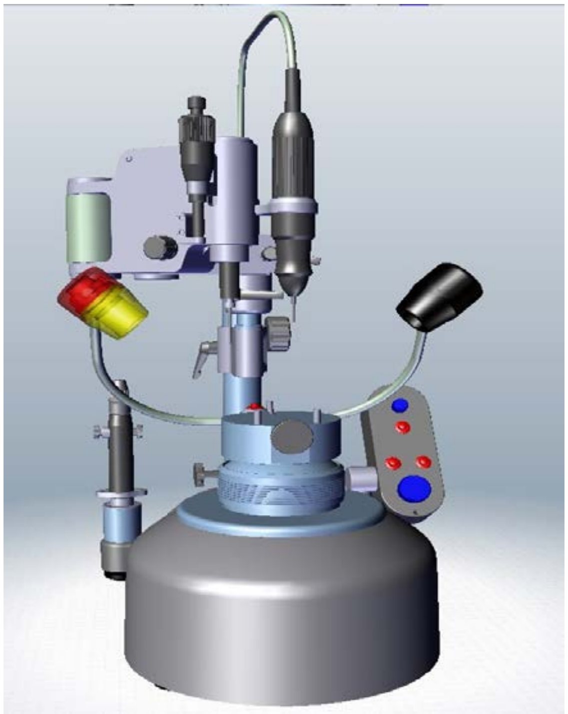


Figure 16: Front View of Model #1 [1].

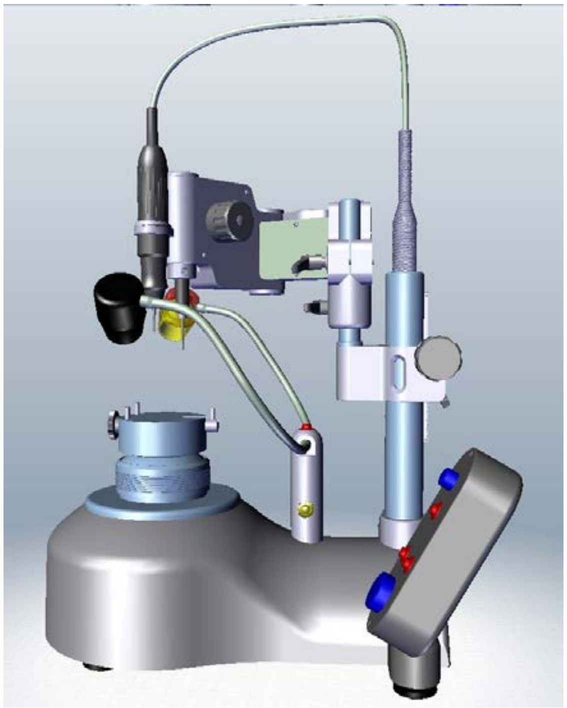


Figure 17: Side View of Model #1 [1].

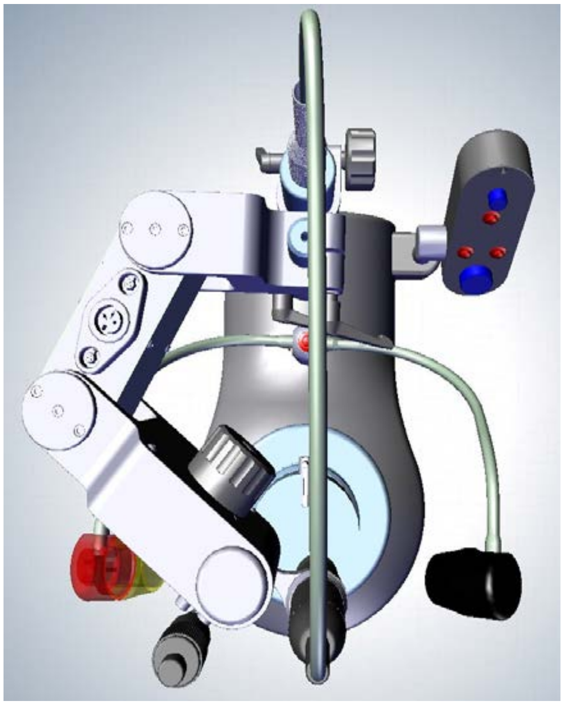


Figure 18: Top View of Model #1 [1].

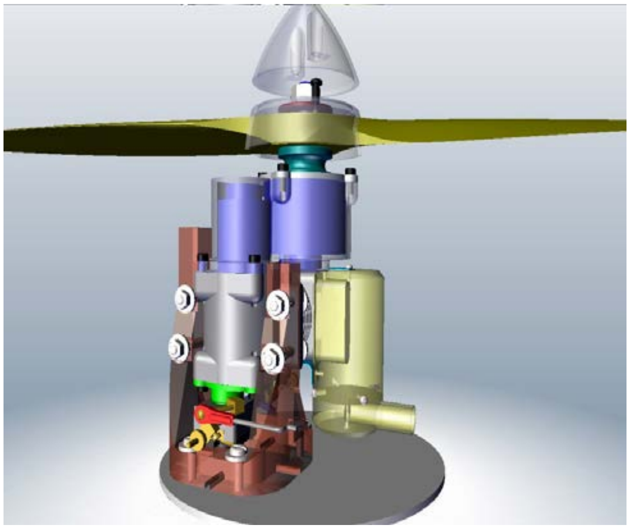


Figure 19: Front View of Model #2 [53].

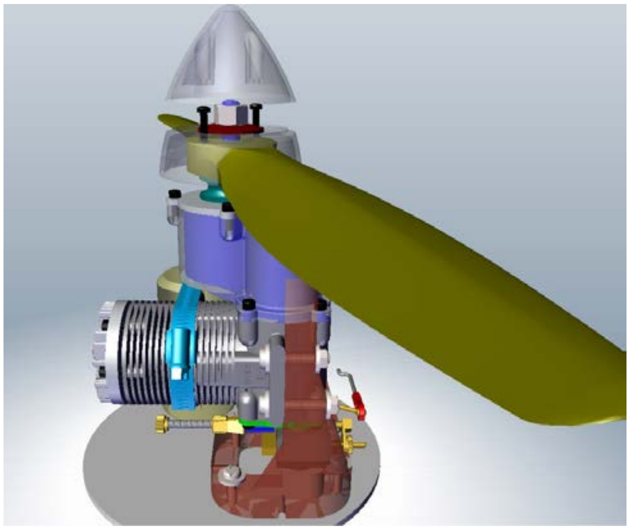


Figure 20: Side View of Model #2 [53]

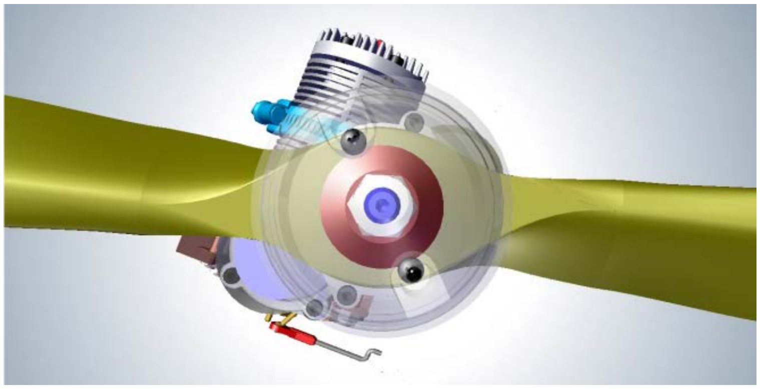


Figure 21: Top View of Model #2 [53]

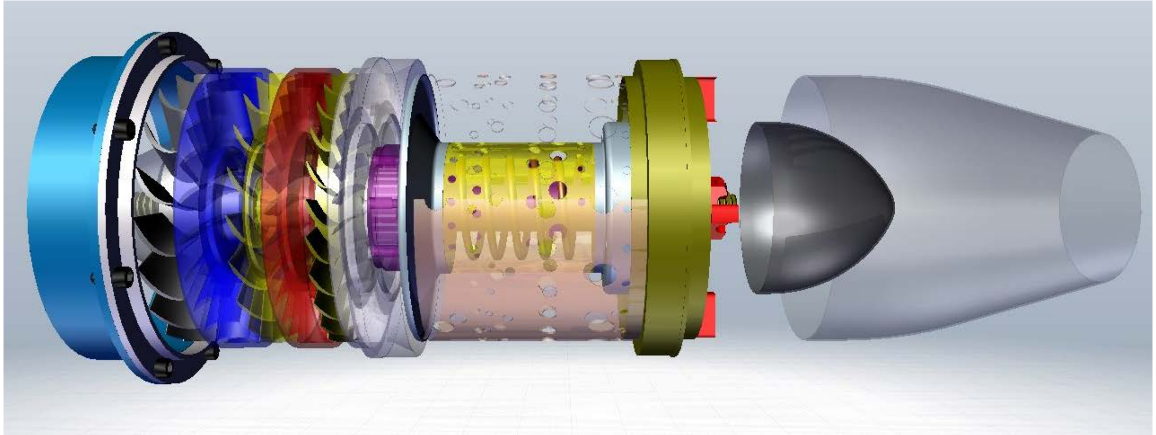


Figure 22: Front View of Model #3 [17].

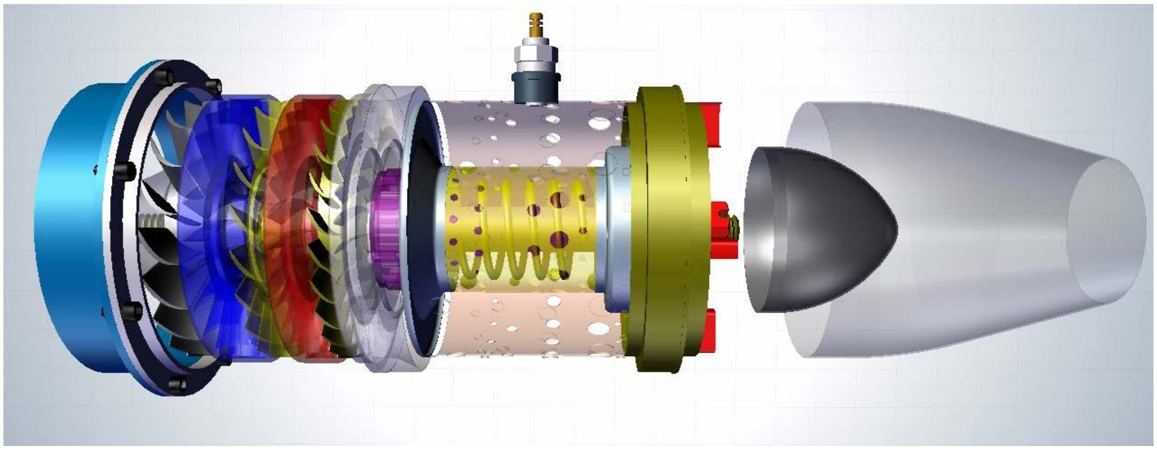


Figure 23: Top View of Model #3 [17]

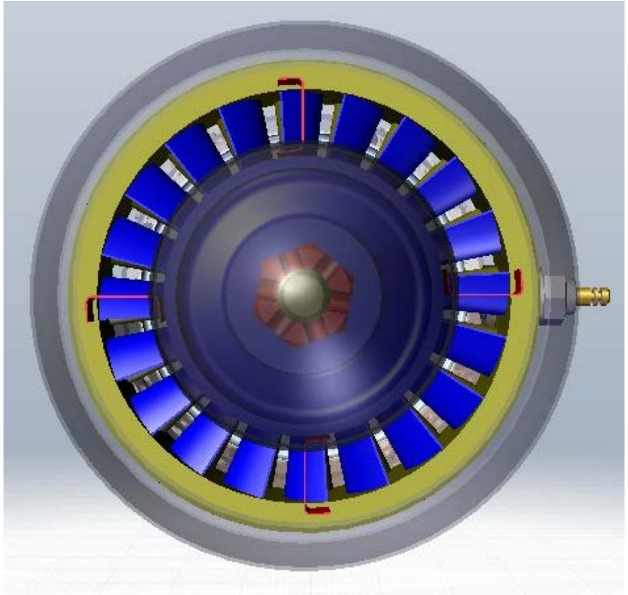


Figure 24: Side View of Model #3 [17]

3.1.1 Complexity of the 3D Models

We ensured that the three 3D models used in this study were similar in complexity and size, and had dissimilar annotated components. Having dissimilar (orthogonal) components was an important criterion in selecting these models as we wanted to control for learning effects, where knowledge attained in interacting with first 3D model improves the performance of participants on subsequent study tasks. There are many ways of measuring complexity of a 3D model (please see Rossignac [44] for more details) these include Morphological complexity (which measures smoothness and feature size), Algebraic complexity (that measures the degree of the polynomials needed to represent the shape in its implicit or parametric form), Topological complexity (that measures the number of handles and visible components), Combinatorial complexity (which measures the complexity of a 3D model based on the number of vertices in a polygonal mesh).. Our 3D design software (3DVIA Composer), measured the complexity of a 3D model by measuring the number of triangles required to build the structure of the 3D model and the number of visible and occluded parts in a 3D model. We adjusted these parameters to ensure that the three 3D models were similar in complexity. The number of triangles varied from 105000 to 115000 for our three 3D models for the visible geometry with the number of occluded part reduced to zero and number of selected parts varied from 30 to 50.

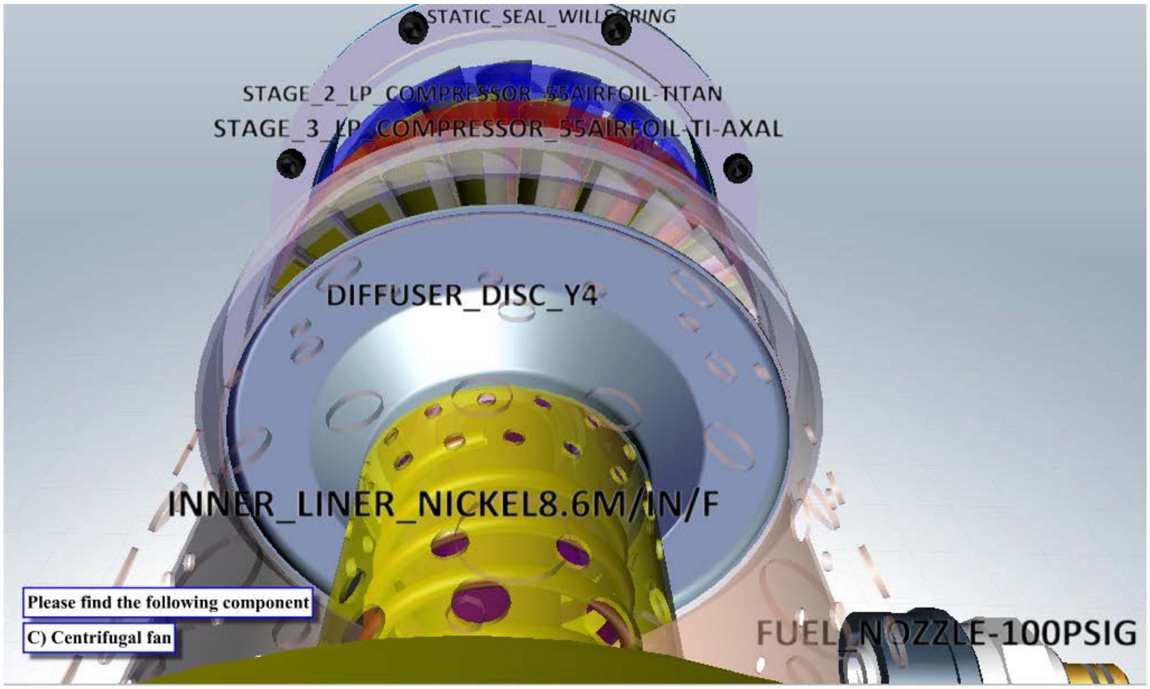
3.1.2 Types of Textual Annotation Styles

For this study, we have selected three textual annotations styles similar to what has been used by Götzelmann et al [21]. These are internal annotation style, external annotation style and box style annotations.

3.1.2.1 Internal Annotation Style

Internal annotations are textual labels that are spatially bound to the object of interest. They have the inherent advantage of easy visual association on account of the close proximity of the annotation with the 3D object/component they are annotating. As these textual labels are normally placed on top of objects they require no additional meta-graphical components such as connection lines or anchor points to associate themselves with their respective 3D objects. In previous research (e.g., Ropinski et al [43]) internal labels have been found to occlude parts of the annotating 3D objects because the annotated part falls under the foot print of the textual annotation. If the layout of the internal annotations is flat (horizontal or inclined) and 2D in nature (i.e., not following the structure or shape of the annotating 3D object) on the user screen, they are termed as 2D internal labels placed in a 3D space relative to the 3D model, Hartmann et al [25]. If theses labels follow the 3D structure/geometry of the annotating 3D object they are termed as 3D internal labels, Hartmann et al [25].

Currently many researchers are investigating how to develop effective and efficient algorithms to generate an automatic layout scheme for placing internal 3D labels that follow the depth and shape of the 3D objects in real time and that are sensitive to the dynamic user interaction [4, 7, and 43] (that is computing label placement with respect to a change in view triggered by user interactions, such as a pan motion or a rotate motion). While distorting the text (arrangement of letters) of an internal label to follow the 3D shape of the annotating object is done with the hope that it will provide a better spatial comprehension. This gain is achieved at the expense of readability of the annotations. Moreover these algorithms are complex and require a robust dedicated hardware setup (strong CPU/processing capabilities and fast caching/memory), which is not always guaranteed on a tablet/mobile platform with limited resources. Hence on a mobile platform, it is not feasible to evaluate 3D internal labels. In our research we evaluate 2D internal labels which have a flat (horizontal or vertical) layout on user screen (see figure 25).



Please find the following component

C) Centrifugal fan

Figure 25: 3D Model #1 with internal annotations (3D component not visible).

However when annotating 3D objects with internal labels there were many design issues that we had to face, we describe these and their implemented workarounds. The first issue with internal annotations was the size of label (font size of the textual details) when annotating smaller objects. In order to annotate components that were smaller in size such as screws and nuts, we had to reduce the size of the internal label to place the textual details inside the 3D component (see figure 26). This meant that for smaller components the internal annotation label would be even smaller making the text inside the annotation label un-readable. This got even worse when annotations were presented at lower zooming levels on a tablet screen such as zooming level 1, where the overall 3D model occupied 85% of the total screen (see figure 27).

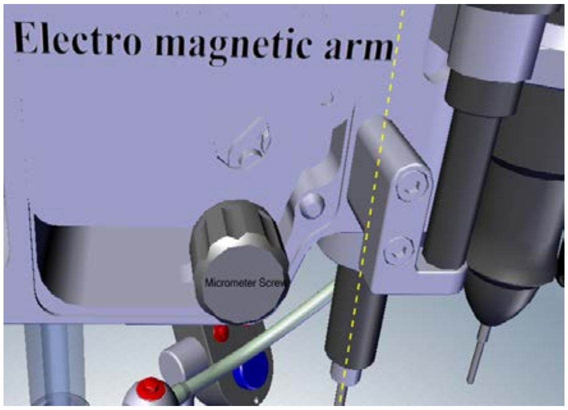


Figure 26: Internal annotation “micrometer screw” somewhat readable at zooming level 3, for small sized annotated 3D component Micrometer screw of Model #1 [1].

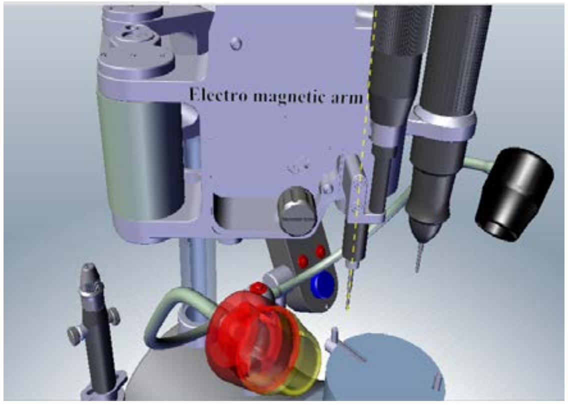


Figure 27: Internal annotation “micrometer screw” not readable at zooming level 1, for small sized annotated 3D component Micrometer screw of Model #1 [1].

To solve this problem Götzelmann, Hartmann, and Strothotte [21] have fixed the font size of their internal annotation (to ensure its readability) and then calculated if the size of the 3D object on screen is large enough to place the label within the visible dimensions of 3D object (as in 100 % internal to the object). If so, the annotation was implemented as internal otherwise other the annotation was implemented as an external annotation with connecting lines. In our research, we are comparing the three different styles of textual annotations (internal, external and box style annotations). Implementing internal annotations only for 3D components that are big enough to hold them well and not annotating smaller 3D components with internal style annotations as in the above study will produce inaccurate or biased results when comparing the three annotation styles. To make a fair comparison between the three annotation styles we must annotate all selected components (of varying dimensions) with each annotation style in sequence/tandem and then compare the results of the study. Hence in our research we have selected 27 components of varying dimensions, annotated these with each of the three annotation styles and then compared the collected data to evaluate the three annotation styles on certain factors/variables (our study design as described later in section 4.2 resulted in the need for 3 models with 27 unique components per model; details of how we controlled the order these models/parts can be found in section 4.11). However, this raised an important design issue that is how we will annotate 3D objects with smaller dimensions than the annotation label itself. To solve this problem we tried several approaches, for example, we first attempted to place the internal label either on the flat surfaces of the large 3D object and for small sized 3D components we placed the internal label in close proximity to the annotated component as 2D labels similar to the approach in Ropinski et al [43]. However a key problem with this approach is that when we pasted our internal labels on either the surface of the 3D objects as stickers (leveraging the smooth surface) or in close proximity to the annotated component (see figure 28). The internal annotation labels became cramped and unreadable as a user rotated the 3D model when piloting with this implementation (see figure 29).

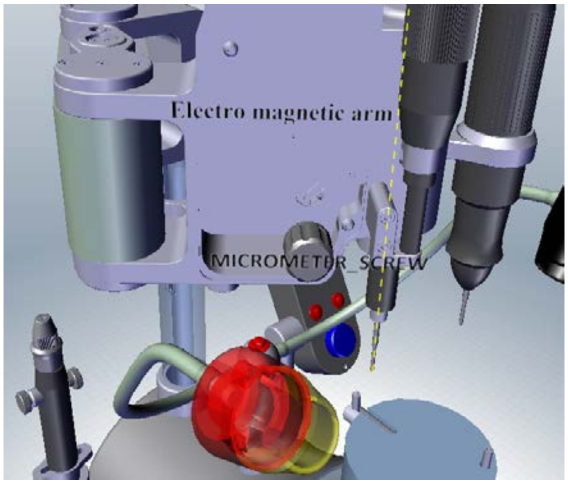


Figure 28: Internal annotations "micrometer screw" before rotation, Model #1 [1].

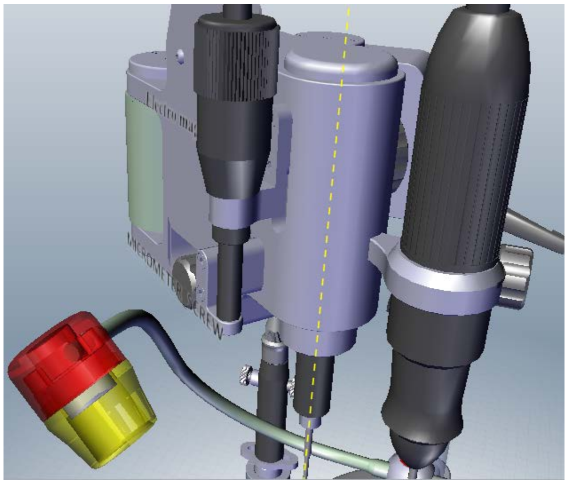


Figure 29: Internal annotation "micrometer screw" cramped after user rotation, Model #1 [1].

To fix this problem, we adopted a different design implementation for internal annotations where we attached the internal label as a 3D text object in close vicinity, instead of a static 2D text plate on the surface of the 3D object. This implementation of internal annotations as a 3D text object improved the readability of our labels which could now be read from all viewing angles (see figure 30 to figure 35). By implementing the internal annotation using this approach (annotation labels behaving as 3D text object with 2D flat layout), the user can read the annotations even when the 3D model is tilted/rotated, from a wide viewing range.

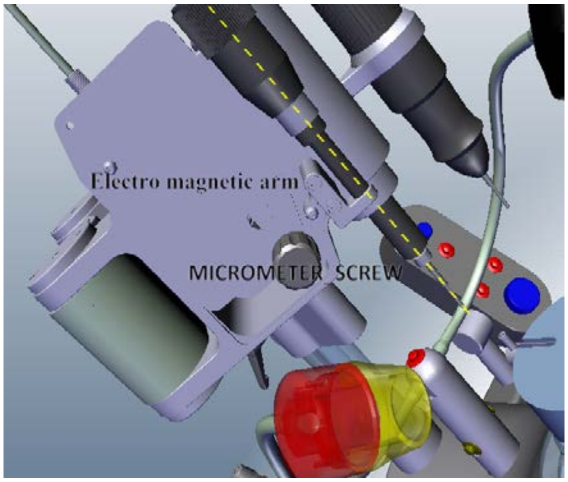


Figure 30: 3D Internal annotations, rotated counter clockwise along z-axis, Model #1 [1]

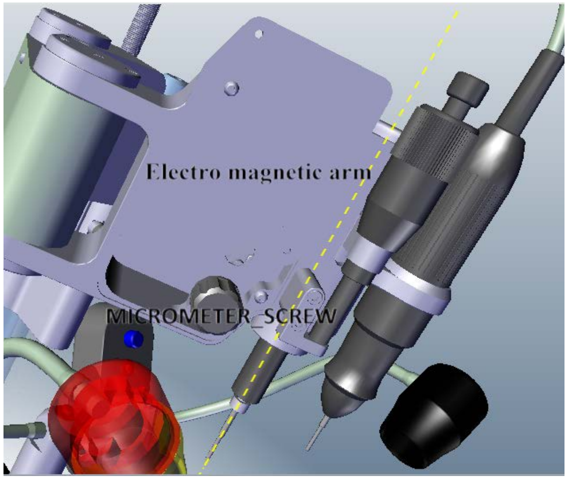


Figure 31: 3D Internal annotations, rotated clockwise along z-axis, Model #1 [1]

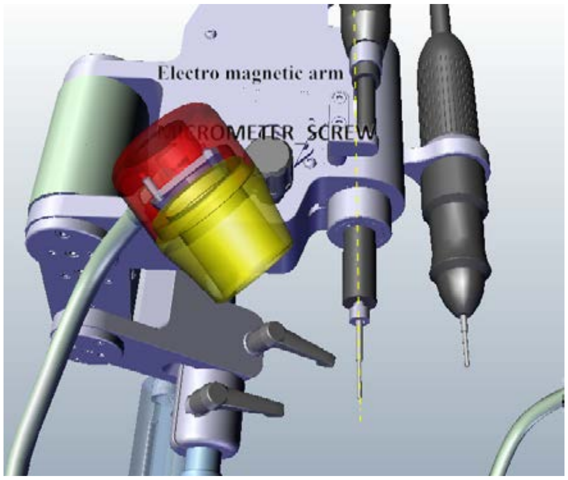


Figure 32: 3D Internal annotations, rotated clockwise along x-axis, Model #1 [1].

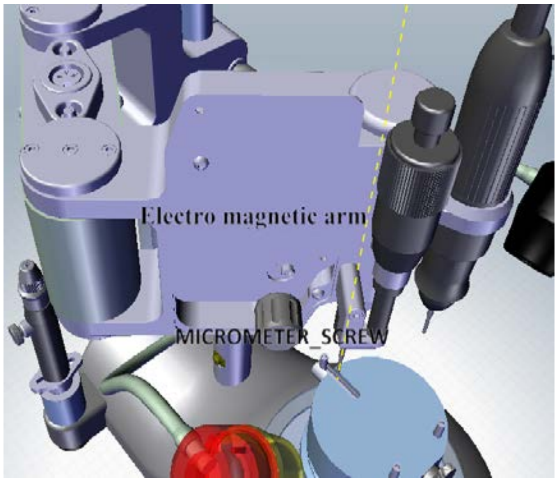


Figure 33: 3D Internal annotations, rotated counter clockwise along x-axis, Model #1 [1].

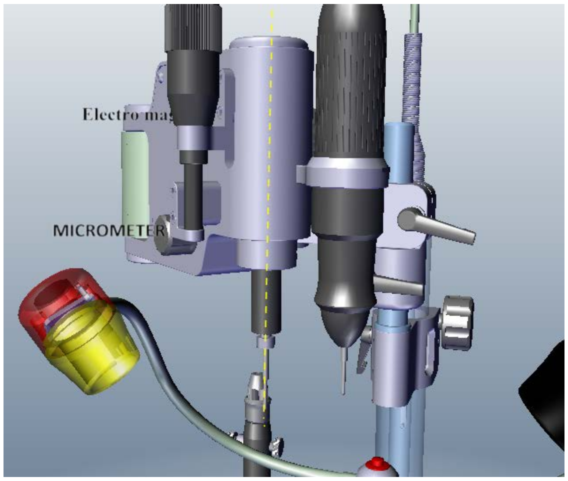


Figure 34: 3D Internal annotations, rotated clockwise along y-axis, Model #1 [1].

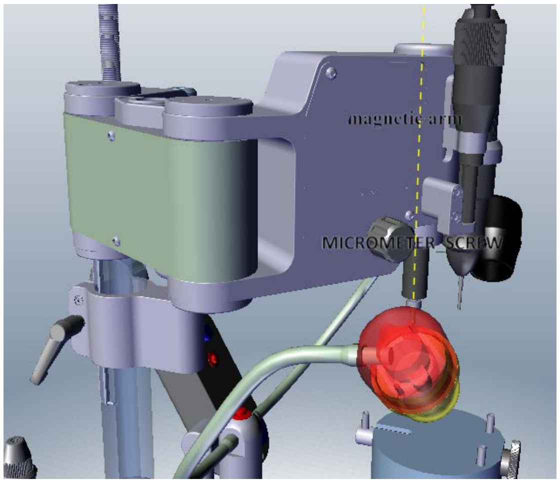


Figure 35: 3D Internal annotations, rotated counter clockwise along y-axis, Model #1 [1].

However, an issue with this approach was that the annotation's text (being long) often merged and lay hidden inside the annotated 3D object when the 3D model was rotated along certain axis for example the y-axis of rotation (see figure 34 and figure 35).

To overcome this side effect, we carefully placed the internal annotations on top or bottom of the 3D object and aligned the centre of the internal annotation label with the centre of the 3D component (see internal annotation "spindle switch" in figure 36.d).

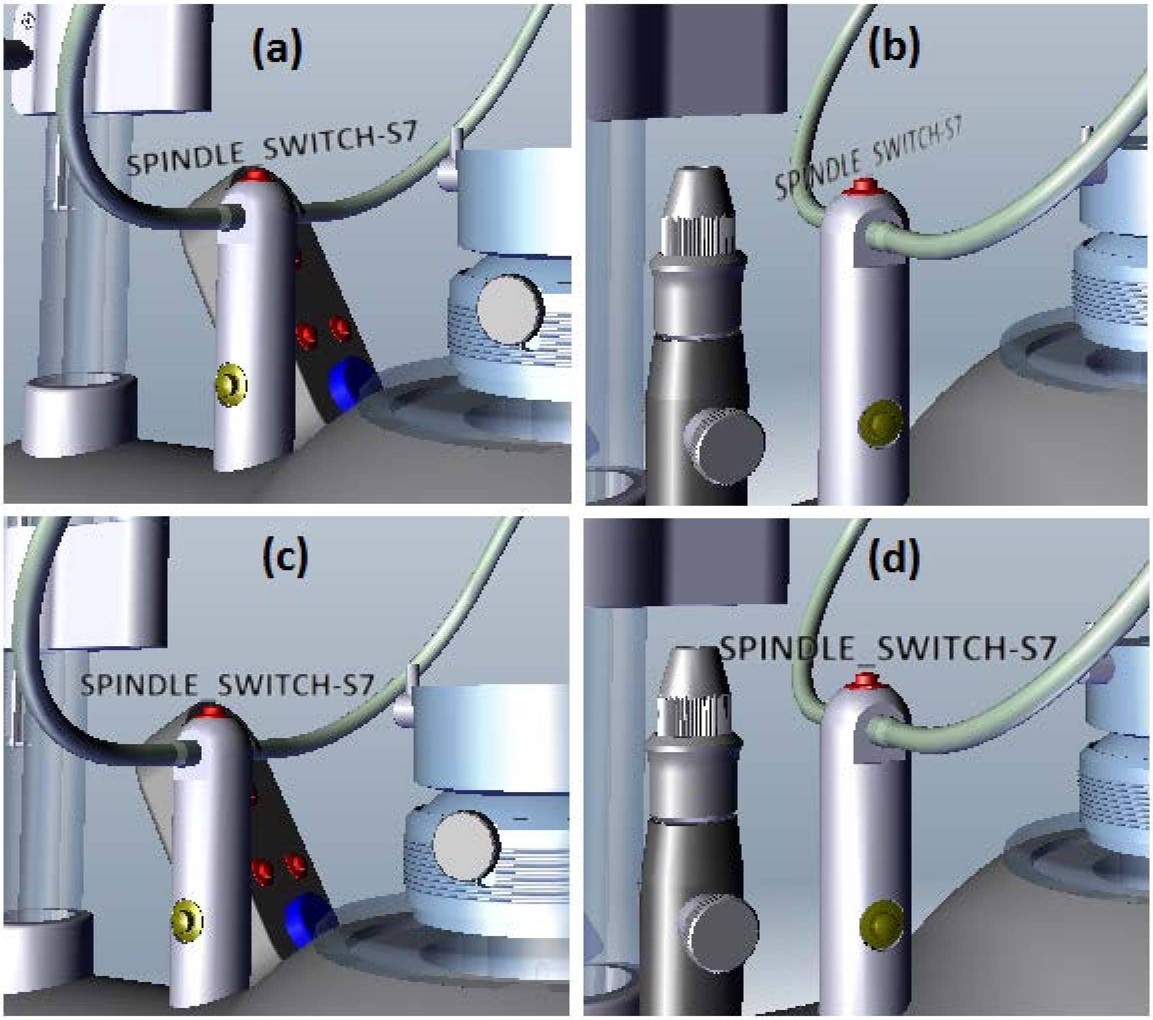


Figure 36: Internal annotation label "spindle_switch-s7" (a) annotation label implemented as 2D internal style annotation (b) text of a 2D internal annotation label gets cramped on rotation (c) annotation label implemented as 3D internal style annotation (d) with centre of the 3D internal annotation label aligned with the centre of the 3D component, Model #1 [1].

However this fix worked only in those cases where the component being annotated was small in dimension and there was free space around this component, such that the internal annotation would not overlap or get hidden inside neighboring components.

When annotating bigger components such as long symmetrical cylinders choosing one static point for placing the internal annotation label would restrict the visibility of the internal label as the 3d object the label annotates (long cylinder) was itself visible from a wide range of viewing angles. Similarly for smaller 3D components that were packed close to other smaller components, it became difficult to place the 3D internal labels as these would overlap or hide inside the neighboring components. To resolve these problems, we reduced the opaqueness of the big annotated 3D object or that of the surrounding 3D objects, to ensure that the 3D internal labels were visible and positioned at the center of the annotated 3D object (see figure 37). In addition we made these annotated components clickable, such that when a user hover the mouse these annotated components got highlighted. We developed this solution with the help of our peers (graduate students) who had previously worked with 3D objects and animation in academia, and made use of merge parts functionality and opacity property of the components in 3DVIA Composer.

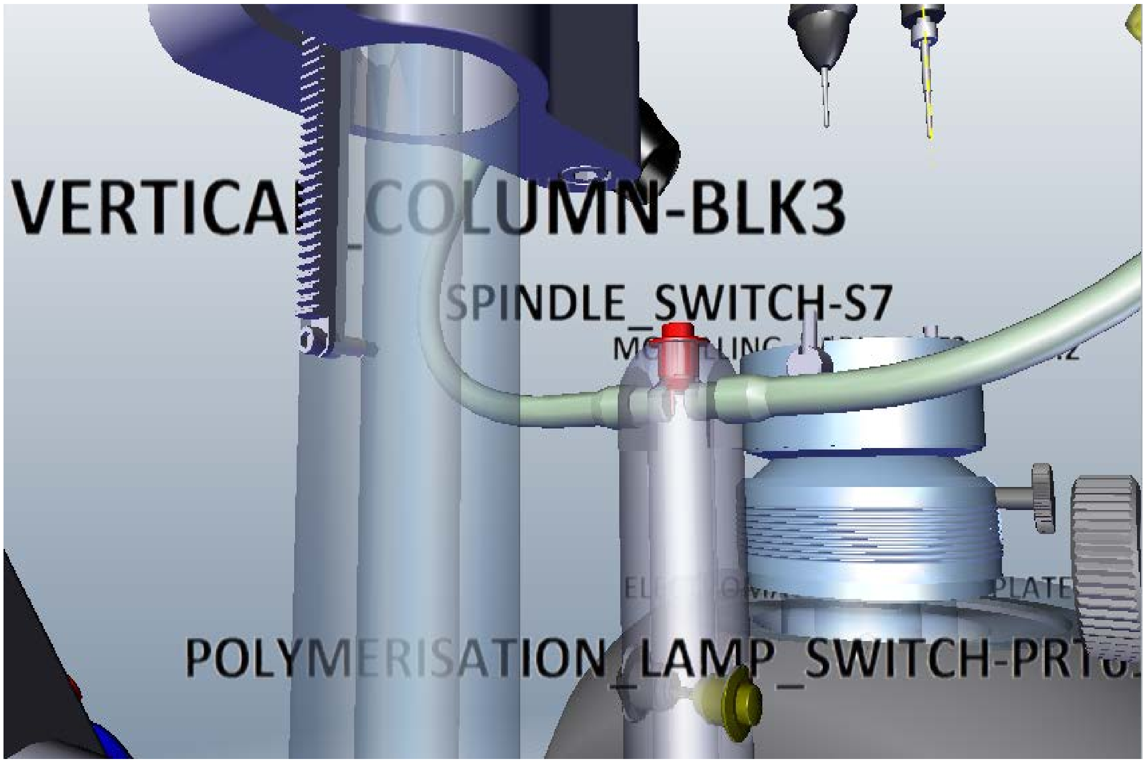
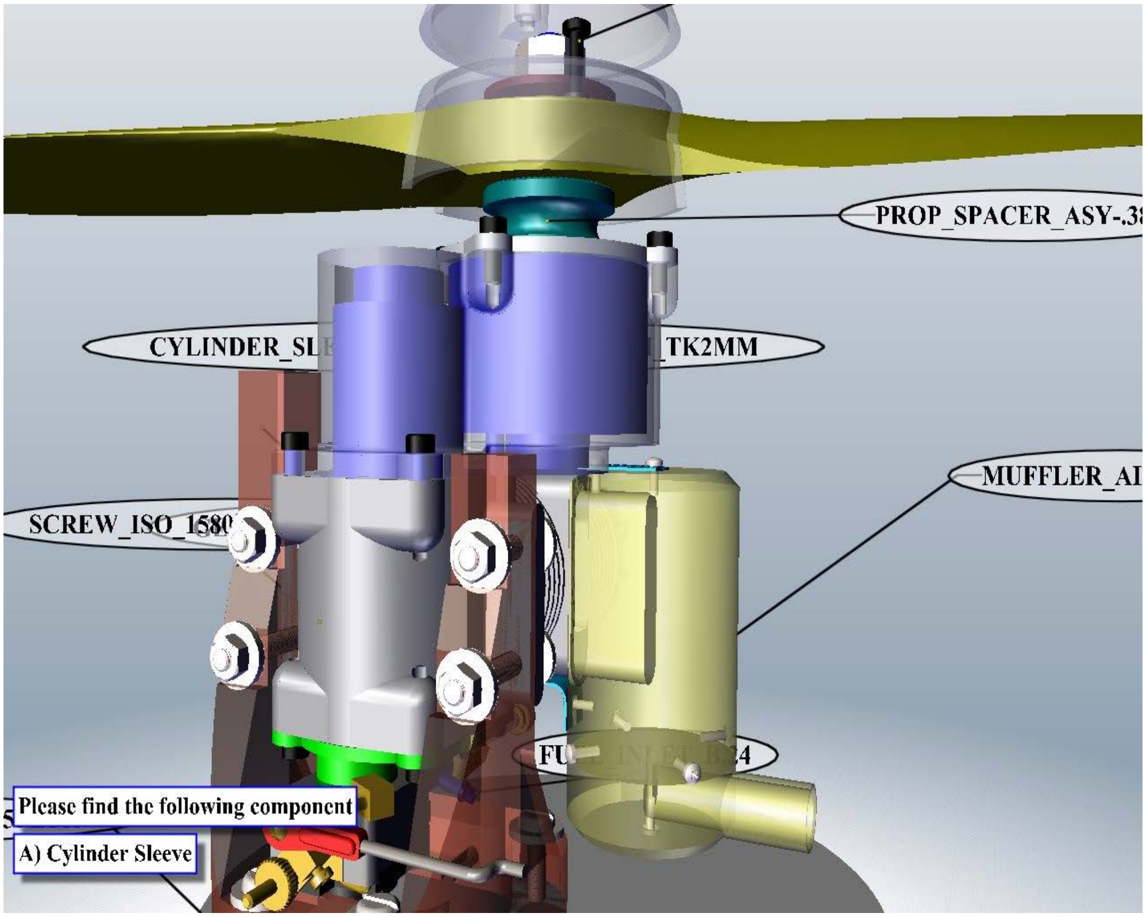


Figure 37: Internal annotation labels with semi-transparency objects.

Another important design aspect of our implementation of the internal style annotation is the varying font size. As the internal labels are actually 3D text objects, the 3D text objects closer to the user screen have a larger font compared with the labels (3D text objects) far from the user screen. In spite of the fact that the height of all 3D text objects (labels) was kept at the same.

3.1.2.2 External Annotation Style:

External annotation style is extensively used to annotate dense sets of objects or points in an illustration [18]. The presence of connecting lines linking the textual annotations with their relevant parts on a 3D model facilitates annotating areas in 3D models where there is a lot of detail, or where multiple components are packed in a small volume. In the external annotation style, the textual annotation does not reside on the surface of the 3D model; rather, textual annotations are placed away from surface of the 3D model. These textual annotations are floating over the 3D model like a balloon and attached to the various components of a 3D model with connecting lines emanating from the textual annotations and the ending at anchor points placed on the 3D model (see figure 38).



Please find the following component

A) Cylinder Sleeve

Figure 38: 3D Model #2 with external annotations (3D component partially visible).

As external annotations are displayed in the vicinity of the referenced component, they do not occlude the annotated object in a 3D model; however, they do occlude the components or parts of the 3d model that fall under the annotation's foot print. For example, in cases where the user is zoomed in and there is no free white space to display the textual annotation, the label occludes some portion of the 3D model falling under its foot print. If the placement of the textual annotation labels is fixed on the screen with adaptive connecting lines extending (and/or contracting) from the textual annotation to the anchor points on components of the 3D model they are termed as 2D external annotations [25]. When the textual annotations are placed in a 3D space relative to the 3D component and the textual annotation moves with the 3D object as the user view is rotated, they are termed 3D external annotations [25]. In our research we evaluated the 3D external annotation style. When annotating the 3D model with 3D external labels, we ensured that the labels were at a constant distance throughout the three 3D models. However, as the three 3D models used in this research were of different dimensions, we made sure that the ratio of the length of the 3D external annotations to the cube root of the volume of the 3D model was same throughout the three 3D models. This design aspect of our implementation of 3D external labels is unique to our research and is influenced from design of the pilot study prototype and results of running the pilot study, Gupta et al [22]. To annotate components in a 3D model with equal length 3D external annotations, we followed the following approach. We first found the most appropriate view for viewing a 3D component that is from where the object is visible most clearly (this was accomplished with the help of a peer review during the design stage). We then sketched a sphere with a fixed radius (for example 100 pixels for the model#1) from the center of the 3D object being annotated and used this curved surface area as the candidate locus of points to place the textual details of the external label (see figure 39 and figure 40).

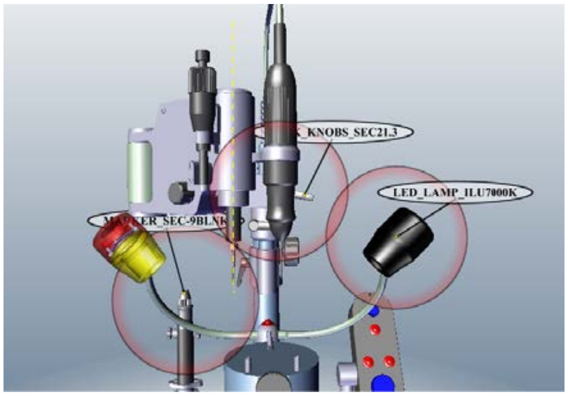


Figure 39: 3D External annotations, during design phase, Model #1 [1].

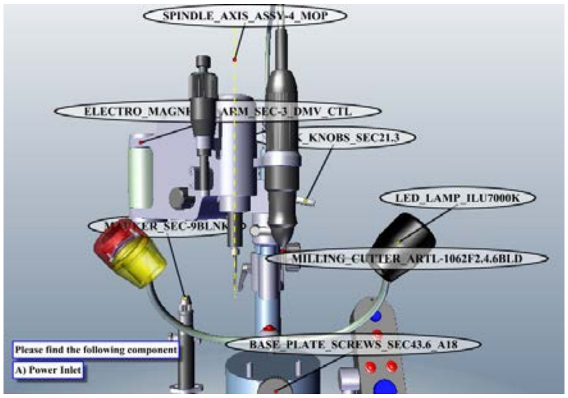


Figure 40: 3D External annotations, after design study prototype, Model #1 [1].

This approach ensured that the external annotation does not fall inside/intersect with other 3D components and/or 3D external annotations. Another important design aspect of our implementation of external annotations was that the textual details of the external labels were enclosed or bounded by an elliptical bubble with solid black border. This enclosure of textual details inside an elliptical bubble made the external annotation visually distinct from the rest of the 3D model. To improve the overall readability of the textual details inside external labels further we added a semi-transparency white background that highlighted the textual details making them very clear. This design aspect of our implementation of 3D external labels is again influenced from the learning experience we gained from designing the prototype and running the pilot, Gupta et al [22]. In addition, we kept a constant font size of the textual details in our implantation of external labels, relative to the user screen (iPad form factor).

3.1.2.3 Box Style Annotations:

Box Style Annotations in our research were simply an extension of external annotations where the amount of textual content contained in the annotation is much greater than for a typical external annotation. This additional detail provides more insight and knowledge about the component, its structure, how it is installed or how it is connected with the neighboring components, etc. Hence, Box style annotations require more space on screen and occlude components falling under their shadow/foot print. To reduce occlusion, we added transparency to the solid background of the annotation boxes thus making the parts of the 3D model that fall under/below the annotation boxes partially visible. This is similar to the approach taken with intersecting roads (made transparent) in a 3D map that are blocked by the various building structures, Vaaraniemi et al [54]. We evaluated the effect of adding 50% transparency to the background of the annotation boxes over readability of the displayed text in a pilot study, Gupta et al [22] with 12 participants and found that textual details inside annotation boxes were easily readable and participants were able to see the complete 3D model without any disconnects caused by the box style annotations with solid background (as shown in figure 41 below) at varying zooming levels. An approach similar to the design implementation of 3D external style annotations was adopted to implement box style annotations. However one design detail, the design of the connecting line was tweaked to suit the multiple lines of text in a box style annotation. In our implementation we switch the design of the connecting lines from a uniformly thick line to a thick gradient tooltip that had a darker shade at the anchor point and a lighter shade that spread into multiple lines, connecting an entire side of the annotation box. This was done to connect/link the multiple lines of text to refer to one single component rather one line of text referring to a single 3D component.

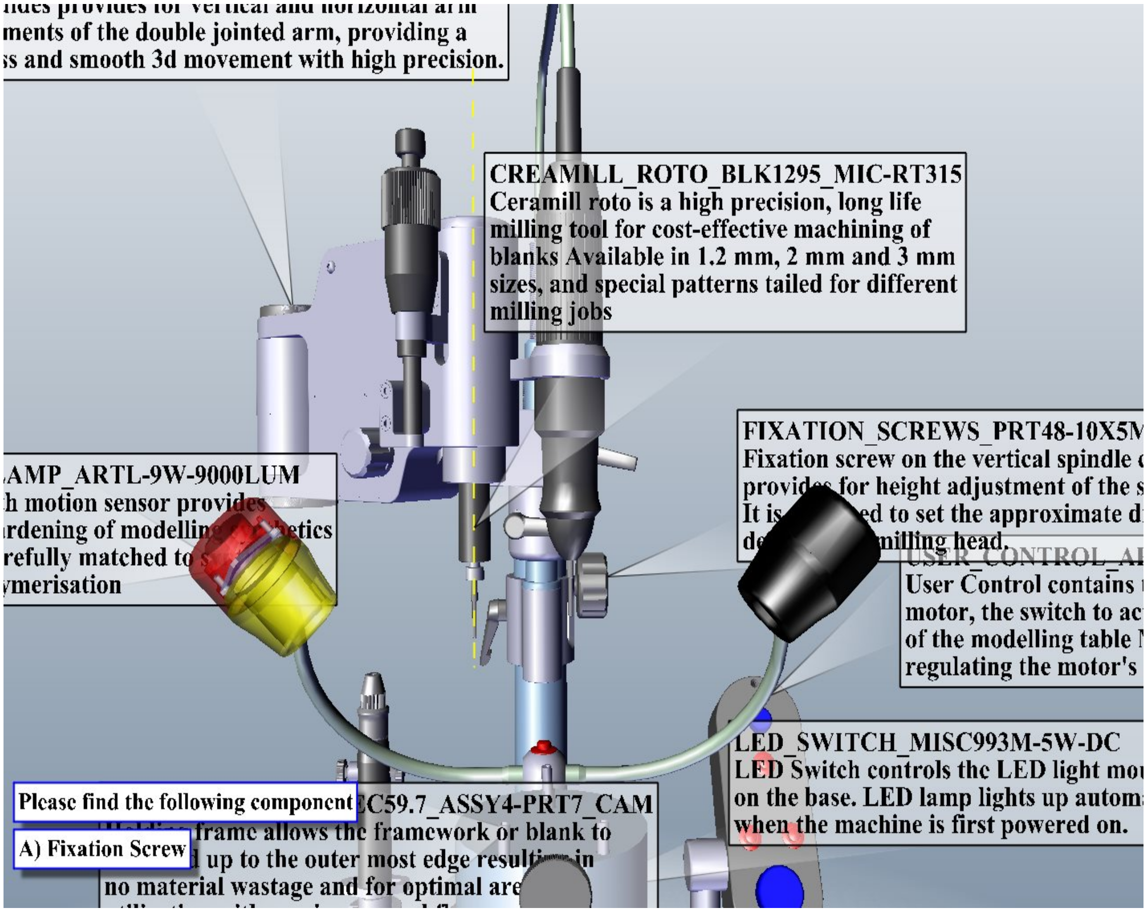


Figure 41: 3D Model #1 with box style annotations (3D component visible on screen).

3.1.3 Cameras

To achieve a uniform level of zoom across the three 3D models, we created 3 cameras (L1, L2 and L3 as shown in figure 42. below) for each zooming level and positioned them accordingly. We kept the aperture angle of the three cameras fixed to 45 degrees and calculated the distance of separation between the camera and the centre of the 3D object, making sure that our cameras are placed at an appropriate distance from the 3D object on the line of sight, and that this camera position was maintained across all 3D models for different zooming levels.

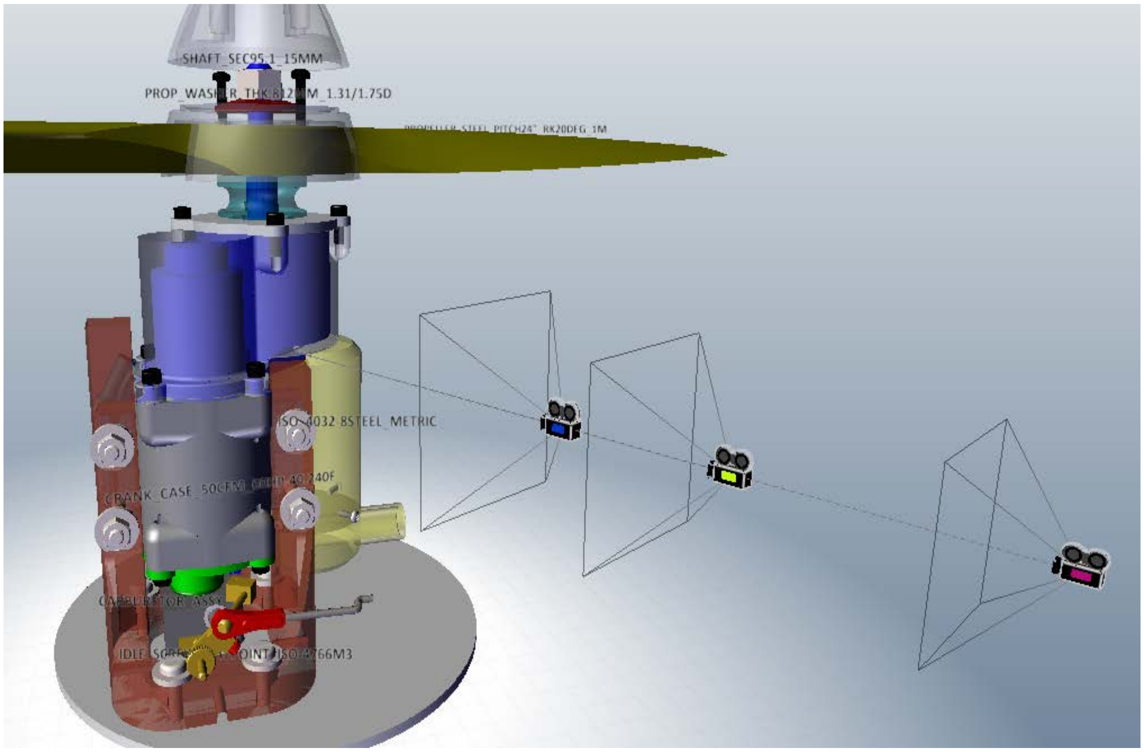


Figure 42: Three cameras provide participants with three levels of zoom.

3.1.4 3DVIA Composer and 3DVIA Player

We used 3DVIA Composer V6R2012s x64 bit Edition - Build 6.9.1.1850 software from Dassault Systems for designing the study prototype. A single user, floating academic license was purchased with one year of validity from Dassault Systems. 3DVIA Composer is 3D CAD Software that provided us with a neat interface to build interactive flows for our study prototype. It allowed us to create custom views, provided us with design features such as explode and merge to tweak various parts of the 3D models used in the study. It enabled us to define zooming levels by setting up cameras. The tool made it easy for us to alter the complexity of the existing 3D models and to modify properties of the collaborative actors (parts, assemblies, and components that make up the 3D model) and geometry actors (markup, annotations, measurements, and cutting planes). It enabled us in creating textual annotations and in adding images, buttons and colors to the 3D models. It facilitated us in creating animations and defining task flows. Once the study prototype was ready, an executable package of the study prototype was created in 3DVIA Composer which was later ported on to lab machine that ran it via 3DVIA Player.

CHAPTER 4 METHODOLOGY

4.1 Research Question

The goal of our study is to compare the three types of textual annotation styles (internal annotation style, external annotation style and box style annotations) at varying zooming levels, for three community of users (expert users, intermediate users and novice users) and to measure the impact of these factors on (a) performance (efficiency and accuracy) when searching for components inside an annotated 3D model, (b) learning (in supporting learning by measuring recall for components and their location) and, (c) user preference in interacting with the 3D model.

4.2 Study Design

We have a 3 x 3 x 3 mixed factorial design approach with following factors: (a) expertise; participants prior experience in interacting with 3D models and software with three levels (expert users, intermediate users, and novice users), (b) level of zooming with three levels (level 1, 3D object covers 80% of the screen size; level 2, 3D object covers 150% of the screen size and level 3, 3D object covers 270% of the screen size), and (c) annotation styles/techniques with three levels (internal annotation style, external annotation style and box style annotation). The independent variable "user expertise" serves as the between subjects control variable to split the total participant base into 3 groups and the independent variables "annotations styles/techniques" and "zooming levels" serve as the within-subjects variables. This is similar to the mixed study design approach used in some of the previous research such as [32], [52] and [51], where the participants did not see a single component set being annotated thrice by each of the three annotation styles in some order, rather saw three different component sets of a 3D model annotated with a separate annotation style, where the order of annotation styles used to annotate the three component sets (Set A, Set B, and Set C) were rotated among participants. For example, if the first participant saw the three component sets (Set A, Set B, and Set C) annotated with internal, external and box style annotations, then the second participant saw these three component sets (Set A, Set B, and Set C) annotated with external, box and internal style annotations (see Table 5). The within-subject design enabled us to measure the performance, recall and user preference for the three annotation styles at the three levels of zoom for every participant and also control for learning and order effects.

4.3 Independent Variables

Our first variable, "user expertise", the subject variable is a nominal variable with three levels. User expertise divides the participant population into three user groups: "expert users" (with the highest level of expertise in interacting with 3D models and 3D software), "intermediate users" (with some previous experience with 3D models and 3D software) and "novice users" (with no or very little previous experience with 3D models and 3D software),

We administered a pre-test questionnaire to measure participant's knowledge about the 3D models used in the study and user expertise in interacting with the 3D models and software. For the pre-test, we provided the participants with the un-annotated versions of the three 3D models used in the study and asked them to tag as many components as they know or possibly can. Participants with good prior knowledge about the 3D models used in the study were excluded from the study (to avoid any biasness emerging from their previous knowledge about the 3D models used in the study). No participants were excluded from our study as they had minimal or no knowledge about the various parts of the 3D model. The components that were tagged frequently were "screw" (for different types of screws and nuts) and "fan" (for propeller and compressors). However, as the participants did not provide us with the correct names for these components (ISO part names for screw and nuts, and propeller, centrifugal compressor, stator compressor, and 2nd stage compressor for fan) this generic knowledge about components did not interfere with the study.

The level of participant's expertise in interacting with 3D models and software was measured by taking into account the number of 3D software participants have previously worked with and the frequency of their interactions with 3D models and software in last six months. Participant who interacted daily with 3D models using at least one of the listed 3D software were grouped under the "expert users" category and those who interacted less than 4 to 5 times a month were grouped under the "novice users" category. Participants who interacted 4 to 5 times a month or more and less than 12 - 15 times a month using at least one of the listed 3D software were grouped into the category of "intermediate users". For novice users the number of 3D software was not taken into account.

Our other two independent variables were "annotation techniques" and "zooming levels". These were nominal variables as well, each with three levels, "annotation techniques": internal annotation style, external annotation style, and box style annotation, and "zooming levels": zooming level 1, 3D object covers 80% of the screen size; zooming level 2, 3D object covers 150% of the screen size, and zooming level 3, 3D object covers 270% of the screen size).

Independent Variables	Variable Type	Levels of the variables
1) Expertise (Between Subjects)	Nominal	{Expert Users, Intermediate Users, Novice Users}
2) Annotation Styles (Within-Subjects)	Nominal	{Internal, External, Annotation Box }
3) Zooming Levels (Within-Subjects)	Nominal	{Level 1 (80%), Level 2 (150%), Level 3 (150%)

Table 1: List of IVs (Independent Variables).

The combination of the two within-subjects factors "annotation style" and "zooming level" produced nine cells or treatment conditions (see table2 below) with varying "annotation styles" and "levels of zoom" in each cell/condition. As these nine treatment cells were formed by the two within-subjects factors every participant in the three user groups experienced each of these nine treatment conditions.

User Groups	Zooming Levels	Textual Annotation Styles Display Sequence		
Expert users, Intermediate users, and Novice users		Internal Annotation Style	External Annotation Style	Box Style Annotation
	Zooming Level 1	1	2	3
	Zooming Level 2	4	5	6
	Zooming Level 3	7	8	9

Table 2: Nine Cells (Treatment Conditions) of the Study.

4.4 Dependent Variables

The first part of our research question aims to evaluate the overall performance of the three textual annotation styles (internal annotation style, external annotation style and box style annotation) when participants are searching for components inside a 3D model annotated with these three annotation styles at varying levels of zoom for three community of users (expert users, intermediate users and novice users).

This overall performance was measured in two parts (a) efficiency and (b) accuracy. To measure efficiency we recorded the time taken by the participants to complete the study task of finding three components in an annotated 3D model. To measure accuracy, we recorded the error count which was the number of incorrect selections made while searching for those three components. Hence our two dependent variables were (a) time: the time taken by the participants to complete the search task in the annotated 3D model and (b) error count: the number of errors participants made while completing this study task. Thus, a high performance annotation style will be the one with which participants took less time and made less errors.

The second part of the research question was designed to investigate the impact of textual annotation styles on a user's ability to learn and comprehend a 3D model and its components at different levels of zoom. To answer this part of the research question, we need to understand what role these three textual annotation styles play in facilitating on demand learning (i.e. learning on the job) for some previously unseen 3D model annotated with these three styles of textual annotations.

We wanted to evaluate whether the textual annotation styles overloads the short term memory of the user or whether they reduce the cognitive load making it easier for the participants to remember the details and develop a better understanding of the complex 3D model, thus facilitating learning. We measured the relative impact on learning via recall (retrieval of information from past), where participants were asked to recall the component names and their positions in a 3D model annotated with random numbers. For a textual annotation style that supports and facilitates learning, the participants should be able to recall more details (annotated components and their location) given the finite limits of the short term memory. Our third dependent variable, the "recall score" reflects the number of correctly recalled components of a previously shown annotated 3D model.

The third part of the research question was designed to investigate the user preference for the three textual annotation styles at varying zooming levels for three types of users (expert users, intermediate users and novice users). It is here that we try to develop a better understanding of user's preferences, that is which annotation style is visually more appealing and convenient to use and how does this preference change with the level of expertise users have in interacting with 3D models and with the level of zooming at which participant interacts with the annotated 3D model.

The fourth dependent variable of the study was user preference ranks given by the participant to the each annotation style at the three zooming level. Participants were asked to rank the three annotation styles without ties based on their interactions with the annotated 3D model in the nine study treatments (cells), where a rank of "1" was given to the most preferred annotation style and a rank of "3" was given to the least preferred annotation style. In addition participants rated these three annotation styles, on a Likert scale of 1 to 5, on four user preference factors (a) readability of annotations, (b) ease of usage, (c) look and feel, and (d) satisfaction (see Appendix [G] - Post-task Questionnaire (part 1)). These ratings gave us the preliminary insights into the design aspects of the annotation styles as perceived by the participants during their interaction. A higher rating score (of 4 or 5) for a user preference factor (such as readability) would imply that participants were satisfied with the design of the annotation style implementing the details for that user preference factor (readability). At the end of the study, an exit interview was conducted, where we probed our participants to justify their rankings and preferences for annotation styles at various zooming levels and gained insights into the strengths and weakness of each annotation style as perceived by the participants (qualitative feedback) when interacting with the 3D model,

Construct	Dependent Variables	Variable Type	Unit of Variable Measurements
(a) Performance	1) Time 2) Error Count	Ratio Ratio	Measured in seconds Measured in whole numbers
(b) Learning	3) Recall	Ratio	Measured in whole numbers
(c)User Preference	4) Rank	Ordinal	Measured in natural numbers

Table 3: List of DVs (Dependent Variables).

4.5 Research Hypotheses

We provide here the list of hypotheses that were tested in our study. However before listing the hypotheses we first explain our expectations from the study data, speculating the relationship between the independent and dependent variables and then list the framed null (H_o) and alternate (H_a) hypotheses accordingly for each of the three independent variables in our study.

4.5.1 Performance

4.5.1.1 Expectations from the Research Data

The first part of the research question was designed to investigate participant's overall performance when searching for components in an annotated 3D model. This overall performance was measured in two parts first by measuring the time taken by participants to complete the search task of finding three components in an annotated 3D model for efficiency and second by measuring the error count (the number of incorrect component selections made while searching for those three components) for accuracy.

Our expectations from the study data were that expert users with the highest level of expertise in interacting with 3D models and software will be the fastest in searching for components in an annotated 3D model and will have the lowest count for errors (incorrect component selections) when compared with intermediate and novice users.

Moreover, we believed that with the increase in the level of zoom the time taken to complete the search task will increase linearly as the participants will consume more time to uncover the zoomed in hidden surfaces of the 3D model and the error count (number of incorrect component selections) will drop linearly as the components at higher zooming level would be more clearly visible and easy to select.

In addition, we believed that since each of the three annotation style were equally efficient and accurate in supporting users at the task of searching for components, the performance of the three annotation styles will be similar.

4.5.1.2 Research Hypotheses for Performance

The Research Hypotheses for the first part of the research question were:

H_{a1}: Efficiency when searching for components in an annotated 3D Model will vary significantly with the level of expertise.

H_{o1}: Efficiency when searching for components in an annotated 3D Model does not vary significantly with varying level of expertise.

H_{a2}: Accuracy when searching for components in an annotated 3D Model will vary significantly with the level of expertise.
H_{o2}: Accuracy when searching for components in an annotated 3D Model does not vary significantly with varying level of expertise.

H_{a3}: Efficiency when searching for components in an annotated 3D Model will vary significantly with the style of annotations used to annotate the 3D model.
H_{o3}: Efficiency when searching for components in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

H_{a4}: Accuracy when searching for components in an annotated 3D Model will vary significantly with the style of annotations used to annotate the 3D model.
H_{o4}: Accuracy when searching for components in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

H_{a5}: Efficiency when searching for components in an annotated 3D Model will vary significantly with zooming levels.
H_{o5}: Efficiency when searching for components in an annotated 3D Model does not vary significantly with zooming levels.

H_{a6}: Accuracy when searching for components in an annotated 3D Model will vary significantly with zooming levels.
H_{o6}: Accuracy when searching for components in an annotated 3D Model does not vary significantly with zooming levels.

4.5.2 Learning

The second part of the research question was designed to investigate the impact of the three textual annotation styles on participant's ability to learn and comprehend a 3D model. We measured the impact on learning via recall (retrieval of information from past).

4.5.2.1 Expectations from the Research Data

Our expectations from the study data were that user expertise in interacting with the 3D model and software will affect learning such that, expert users being more fluent in their interactions with 3D models have the upper hand, an advantage, to explore more details about the annotated 3D model in comparison to intermediate and novice users in a short span of time. Thus Expert users have the potential to score more on the recall test on account of their greater coverage about the 3D model.

In addition, we believed that with the increase in the level of zooming, the recall score will drop linearly as at higher levels of zoom the participants will see a smaller portion of the 3D model and will lose the overall context of the 3D model. Moreover, we expected that since each of the three annotation style were equally good in supporting learning, the recall scores of the three annotation styles will be very similar.

4.5.2.2 Research Hypotheses for Learning

The Research Hypotheses for the second part of the research question were:

H_{a7}: Impact on learning (Recall Score) in an annotated 3D Model will vary significantly with the level of expertise.

H_{o7}: Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with varying level of expertise.

H_{a8}: Impact on learning (Recall Score) in an annotated 3D Model will vary significantly with the style of annotations used to annotate the 3D model.

H_{o8}: Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

H_{a9}: Impact on learning (Recall Score) in an annotated 3D Model will vary significantly with zooming levels.

H_{o9}: Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with zooming levels.

4.5.3 User Preference

The third part of the research question was designed to investigate about user preferences for annotation styles, where participant ranked (without ties) and rated the three annotation styles on four user preference factors (a) readability, (b) look and feel, (c) ease of usage, and (d) satisfaction.

4.5.3.1 Expectations from the Research Data

Our expectations from the study data were that user preference for an annotation style will vary with “expertise”. Hence expert users will have a user preference different from that of intermediate and novice users who will also differ in their preferences for a favorite annotation style. Moreover, we believed that user preference for an annotation style will change with the level of zoom at which the user interacted with the annotated 3D model.

In addition, we expected that since each of the three textual annotation styles were equally good in supporting users in interacting with the 3D model, the split in user preference for the three annotation styles will be equal overall for all 27 participants.

4.5.3.2 Research Hypotheses for User Preference

The Research Hypotheses for the third part of the research question were:
H_{a10}: The user preference for an annotation style varies significantly with the level of expertise
H_{o10}: The user preference for an annotation style does not vary significantly with the level of expertise

H_{a11}: The user preference for an annotation style varies significantly with the level of zoom
H_{o11}: The user preference for an annotation style does not vary significantly with the level of zoom

H_{a12}: The split in the overall participant population for the user preference will vary for the three annotation styles

H_{o12}: The split in the overall participant population for the user preference will not vary (be equal) for the three annotation styles will be equal

4.6 Study Participants

Our study population for this research study comprises of people who may or may not have previous experience interacting with 3D models and 3D software. We recruited a total of 27 participants with varying level of user expertise in interacting with 3D models and software. The participant population comprised of 9 "expert users", 9 "intermediate users" and 9 "novice users".

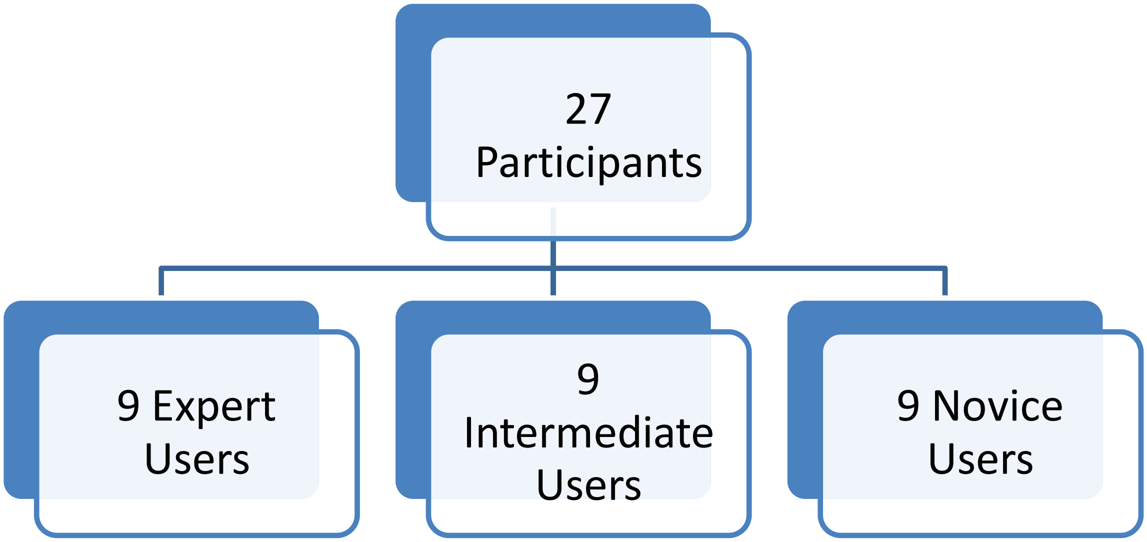


Figure 43: Structure of participant population

A total of 9 participants were recruited for each user group on account of the nine treatment conditions/cell combinations formed by the three levels of within-subjects factor "annotation styles" with the three levels of the other within-subjects factor "zooming levels" (3 zooming levels x 3 annotation techniques, please see Table 2), where we controlled for previous experience in interacting with 3D models and software, and implemented controls for counter balancing effects from learning and order.

4.6.1 Recruitment of Participants

In order to recruit participants for the study, I posted the recruitment script (see Appendix [B] - Recruitment Script) on the notice boards of various departments and faculties at Dalhousie University. In addition, I sent recruitment emails, requesting participants for a research study to all undergraduate Students, graduate students, post docs and staff at the Faculty of Computer Science, Dalhousie University (csall@dal.ca). Email announcement was also made via Dalhousie Notice Digest Emails (notice.digest@dal.ca).

There were no pre-requisites for participating in the study. Our participant population for this study comprised of students, faculty, and staff members at Dalhousie University, who were English language readers and speakers with varying levels of previous experience in interacting with 3D models and 3D software. All participant who participated in the study were rewarded an honorarium of $15 for their participation (see Appendix [J] - Participant Payment Receipt).

4.6.2 Protection of Human Subjects

The study was conducted from Jan 9, 2013 to Jan 24, 2013, and was approved by "The Social Science and Humanities Research Ethics Board (REB)" at Dalhousie University, Halifax, Nova Scotia, Canada. Ref# 1011671(see Appendix [A]: Dalhousie University Research Ethics Board's Letter of Approval, dated August 20, 2012).

All participants obtained and signed an informed consent form (see Appendix [C] - Informed Consent) at the beginning of the study. The informed consent form clearly outlined the purpose of the study, the risks and benefits associated with the study, the honorarium participants received, the participant's right to withdraw without consequence, and assurances of confidentiality and anonymity of personal data along with the email of the researcher if they have any questions later.

There were minimal risks associated with this study, with the primary risks being that participants may get tired, frustrated, or bored while participating in the study; or that they may feel embarrassed if having difficulty on the tests. To mitigate this risk, we provided training to the participants on a training model to make them familiar with the study software and to increase their comfort level before starting with the actual study. In addition, we included three mandatory breaks to ensure that participants did not get tired during the study and offered beverages (tea and coffee) and cookies during the breaks to reduce the effect of fatigue.

4.6.3 Participant Expertise in Interacting with 3D Models and Software

Out of 27 recruited participants, majority of the participants (22) indicated that they had interacted with 3D models and software at some point in the last six months prior to participating in the user study. Only few participants (4 novice users) reported that they had not interacted with any 3D models and/or software (including 3D games) in the last six months (please see table 4: User expertise in interacting with 3D models and software).

Expert Users	Intermediate Users	Novice Users
3D Games	3D Games	None
[Unity 3D]	3D Games and [Google Sketch up]	3D Games
3D Games and [Open GL]	3D Games	None
3D Games and [Google Sketch up]	3D Games	None
3D Games and [Blender, Unity 3D]	3D Games	None
3D Games and [Blender, Google Sketch up, Unity3D]	3D Games	None
3D Games and [Auto Desk]	3D Games	3D Games
3D Games and [Google Sketch up, Unity 3D]	3D Games	3D Games
3D Games and [Google Sketch up]	3D Games and [Unity 3D]	3D Games

Table 4: Participants user expertise in interacting with 3D models and software.

The data collected from the pre-test questionnaire (Appendix [D] - Pre-Test Questionnaire) revealed that all participants in the expert user group and intermediate user group had interacted with 3D models before and a majority of their interactions with 3D models were via playing interactive 3D games such as Xbox Games, Call of Duty, modern warfare, etc (see figure 44). We believe this was on account of the fact that most of our participants were either graduate or undergraduate students with a few post docs from Dalhousie University.

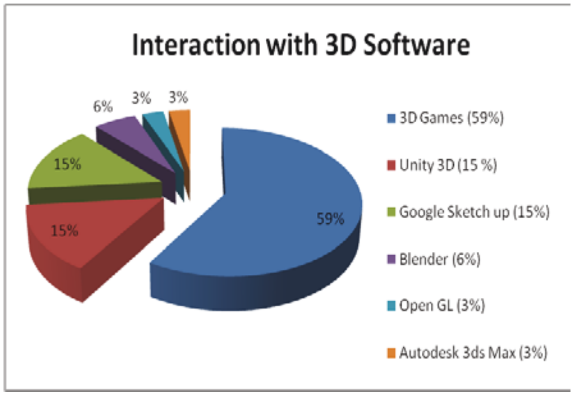


Figure 44: Interaction with 3D Software.

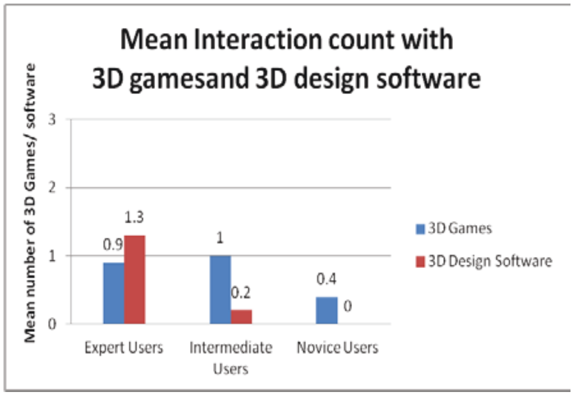


Figure 45: Mean Interaction count with 3D design software and 3D games.

We also found an interesting pattern about the average number of 3D software used by participants in interacting with 3D models. Study data revealed that on average, participants in the expert user group had interacted with 3D models via at least two ways, using one or more of the 3D design software (such as Google Sketch Up, Unity 3D, Blender, etc) and by playing interactive 3D games). For the intermediate user group, we found that on average participants interacted with 3D models mostly via interactive 3D games/gaming software and participants in the novice user group never interacted with any 3D software and only half of the participants in this group had some interaction with 3D model via interactive 3D games/gaming software (see figure 45).

We believe that we have covered the expertise bandwidth well for the novice user group as well as for the intermediate user group, where half of our participants in the novice user group were new users (having no exposure in terms of interacting with 3D models and software), and the other half interacted with 3D models sparsely (less than 4 to 5 times a month in the last six months) via 3D games/gamming software. Hence the participant population in our novice user group represented the overall general population of novice users (with either minimal or no experience at all in interacting with 3D models and software) well.

For our Intermediate user group, we found that all of our participants had interacted with 3D models via 3D games/gamming software with the exception of two participants who had also interacted with 3D models via 3D software and design tools such as Google Sketch up and Unity 3D. And that the frequency of their interactions with the 3D models varied widely from 4 to 15 times a month in the last six month. We believe that out sample of intermediate users in the research study was close to a perfect batch of intermediate users, where half of the participants in this group had interacted with 3D models via 3D games/gamming software and the other half via 3D software and design tools. Even though, few participants in this group had interacted with 3D models via 3D software. This did not matter much, as we provided training to all our participants to make them familiar with the 3D software setup and its operation, used to interact with the 3D models when performing the real study tasks, with a simple training 3D model. Hence, participants in our intermediate user group represented the overall general population of intermediate users (with some experience in interacting with 3D models and software) well.

We believe that our participant population in the expert user group covered the expertise bandwidth well, from the perspective of the general population of expert users of 3D models on mobile/tablet form factor who interact with 3D models and software on regular/daily basis. However we do acknowledge that the user expertise of our participants in the expert user group may not have covered the entire expertise bandwidth of the expert users. We believe this is on account of our participants, mostly being students and researchers coming from academia and not industrial user community. It would have been better to have some of the participants in this user group to be coming from the industry such as manufacturing, architectural, mechanical, auto, and aeronautical industry. As industry professionals (such as architects, CAD professionals, design engineers, manufacturing engineers, GIS professionals, etc) would have made our sample of expert users, well representative of the overall expert user community in the industrial as well as the general population of expert users in interacting with 3D models and software.

Hence, the impact of our findings apply well to the general population of users interacting with 3D models and software, however applying the result of this research directly to some industrial domain will require further evaluation by the specific industry experts. We have also addressed this limitation in the limitation section on the document.

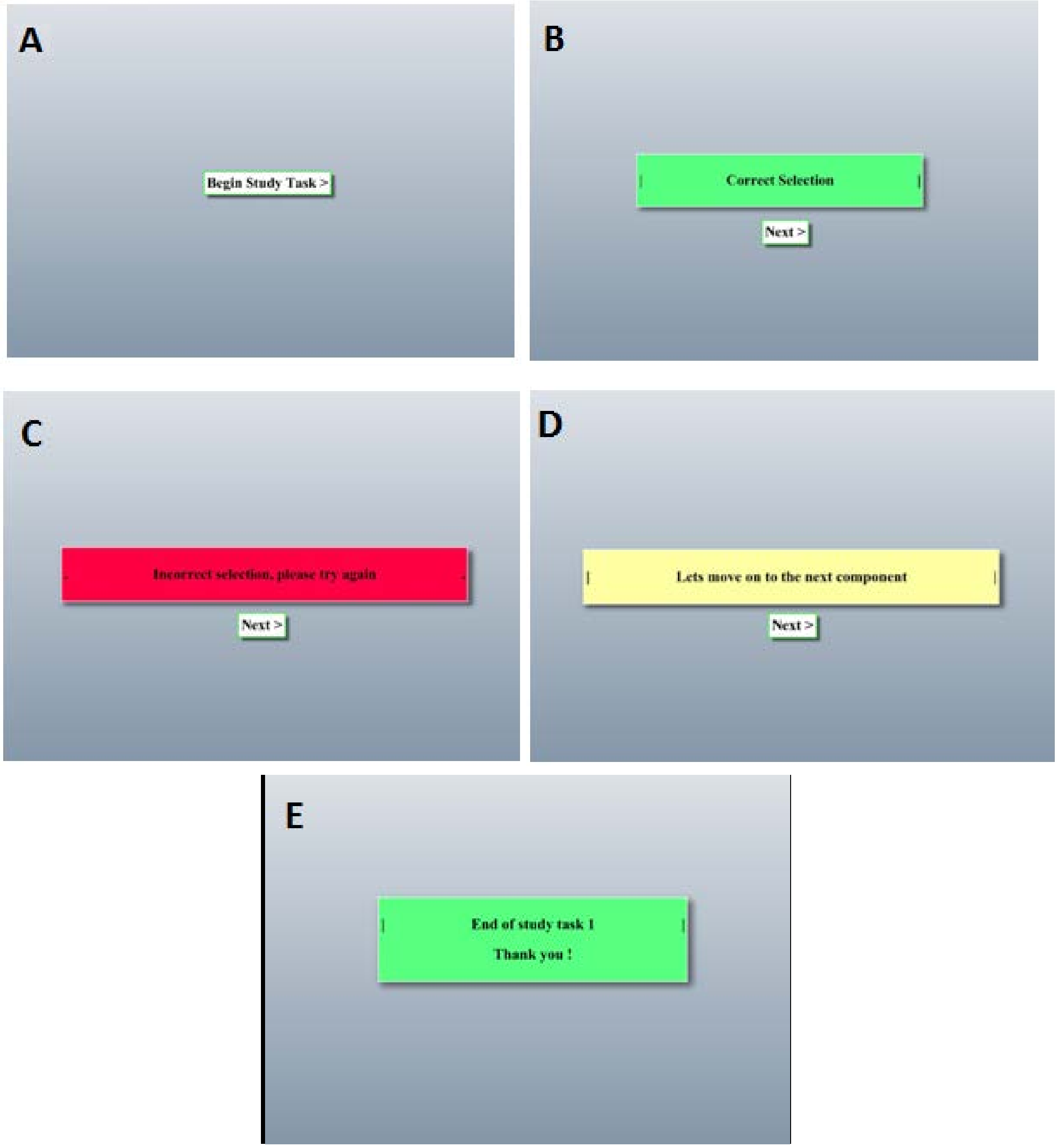
4.7 Study Tasks

In this study, we have two study tasks (search task and recall task) that are repeated by each participant nine times once for each of the various combinations of within-subjects factors “annotation styles” and “zooming levels”.

4.7.1 Search Task

The first study task is designed to address the first part of the research question, to investigate participant’s overall performance when searching for components in an annotated 3D model. This overall performance was measured in two parts (a) efficiency (time taken by participants to complete the study task) and (b) accuracy (the number of errors participants make).

At the beginning of this task, participants were provided with the initial prompt (figure 46.a), once the participant clicked this prompt (start study task button), a 3D model annotated with one of the three textual annotation styles considered in the study (internal, external and box style annotations) was presented to them at a zooming level. The job of the participant was to search for three components inside this annotated 3D model where a total of 9 unique components were annotated. The three components that participants searched for were placed in a way that only one of them was visible on the initial screen, the second component being searched for was partially visible on the initial screen, and the third component being searched for was hidden. This ensured that participants had to interact with the 3D model. The reason of tasking participants to search for three components was to ensure that we covered all possible locations where a component could be found with a ranging level of user interaction with the 3D model (please see figure 47 depicting the flow of search task). Once a participant felt that he/she has found the correct component, he/she left clicked on it to confirm the selection. On a correct component selection, a “correct selection” message was displayed (figure 46.b). Following that, the name of the next component to be searched for was presented. However, if an incorrect component selection was made, “an incorrect selection, please try again” message (figure 46.c) was displayed and the user’s view was reset to initial view. After three consecutive incorrect selections for a component the system displayed “Let us move on to the next component” message (figure 46.d) and took the participant to the next component in queue that had to be searched in the 3D model. At the end of the third component “end of study task” message (figure 46.e) was displayed completing the search task. In addition to the search prompts participants were provided with the study instructions on paper describing to them what they had to do in this task and the navigational controls (Appendix [E] Search Task Instructions).



Correct Selection

Incorrect selection, please try again

Lets move on to the next component

End of study task 1

Thank you !

Figure 46: Message Screens providing feedback to participants in Search Task (a) Initial Prompt, (b) Feedback upon correct selection, (c) Feedback upon incorrect selection (d) Feedback prompt after three consecutive incorrect selections, (e) End of task Prompt.

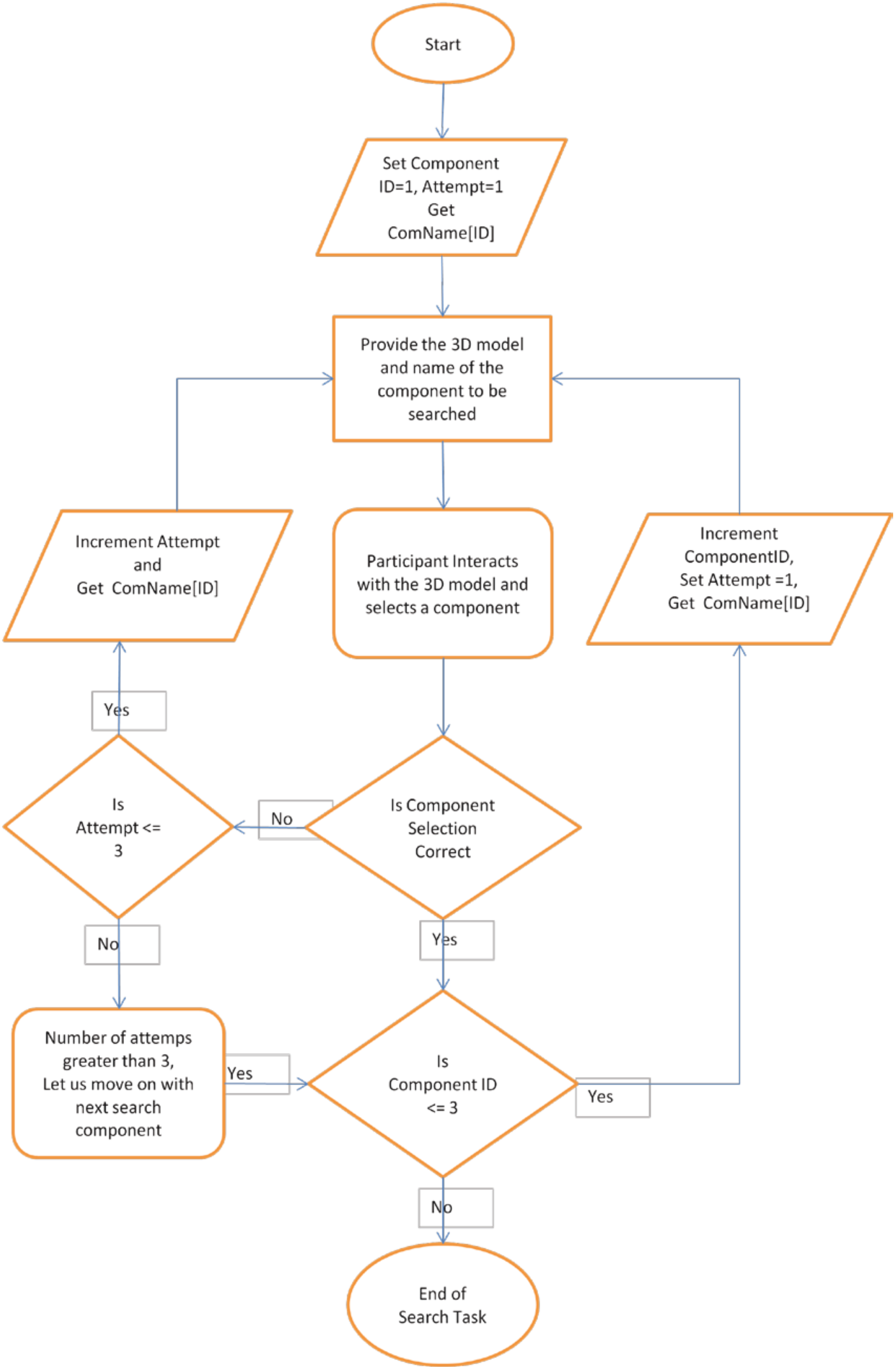


Figure 47: Flow of Search Task.

4.7.2 Recall Task

The second study task was designed to address the second part of the research question, to study the impact on learning. In this task, we provided the participants with recall sheets and engaged them in a recall test (recall: retrieval of information from past), where the participants were asked to recall the component names they saw in search task and match them on a recall sheet, see Appendix [F] - Recall Sheet, with their corresponding positions in a 3d model annotated with numbers randomly assigned to the annotated components (figure 48.). An annotation style that facilitates learning shall have a higher recall score as the participants will be able to recall more details of the 3D model (annotated components and their locations. A total of nine recall sheets were created for the three 3D models used in the study. The recall test was a timed test and participants were given a minute to complete this task. They completed the recall test after each search task.

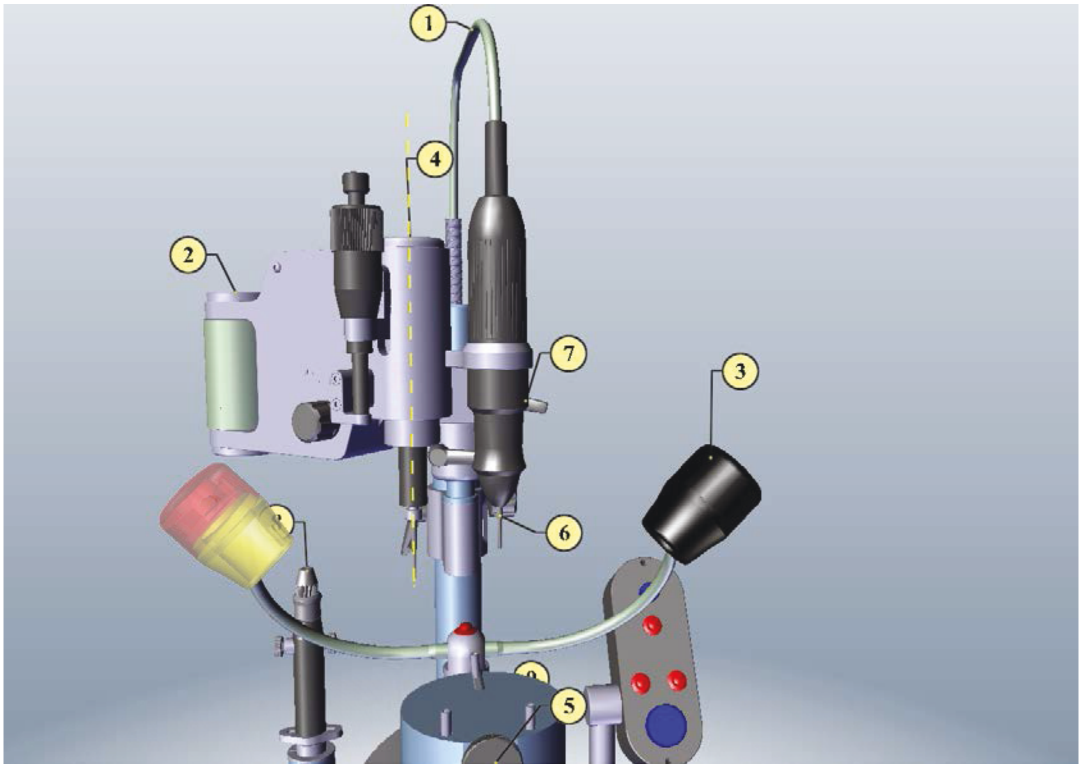


Figure 48: Un-annotated 3D model with components marked randomly from 1 to 9.

4.8 Study Instruments

We used the following research instruments in this study:

(a) A Pre-Test Questionnaire was administered to capture the knowledge about the 3D models used in the study and for measuring user experience in interacting with 3D models and software after the participants signed the informed consent form (Appendix [D] - Pre-Test Questionnaire).

(b) Recall Sheets were deployed to measure the recall score of participants for the three textual annotation styles at varying levels of zoom (Appendix [F] - Recall Sheet).

(c) Post Task Questionnaires were administered to collect ratings for annotation styles on four user preference factors (a) readability, (b) look and feel, (c) ease of usage, and (d) satisfaction on a 5 point Likert scale (Appendix [G] - Post-Task Questionnaire Part 1) and to collect rankings (without ties) given to the three annotation styles at the three zooming levels (Appendix [G] - Post-Task Questionnaire Part 2).

(d) An exit Interview was conducted to gain qualitative feedback, probing participants to gain more insights into the strengths and weakness of each annotation style as perceived by the participants (Appendix [I] - Exit Interview).

(e) Post-Test Questionnaire was administered at the end of the study to measure the gain in knowledge about the 3D models presented in the study (Appendix [H] - Post-Test questionnaire).

(f) Tobii Eye Tracker T-60 was used to capture participants gaze, user screen and user interactions (mouse clicks) while performing the study tasks.

However at the end of the study, when we started to analyze participant eye gaze plot with respect to the user interactions (rotation and panning motions) with the 3D models, we found that the eye tracker, tracked participant's eyes in two dimensional rather than in three dimension mode. This was on account of the fact that the eye tracker we used (Tobii Eye Tracker T-60) created 2D gaze plots on the captured user screen instead of creating gaze plots on the 3D model.

Later, we found that in order to perform the data analysis of the eye tracker data such as gaze plot analysis for scanning search paths or interaction trajectories and establishing

AOI/ROI (areas/regions of interest, formed by clustering of the fixation data/gaze plots) to determine which regions were looked at more than others, required the content inside the captured user screen to remain static. This limitation of not being able to analyze dynamically changing data such as in case of a video or animation, (or in our case interactive 3D models) was documented as one of the limitations in the Tobii Eye Tracker T-60 manuals that we downloaded from the vendors (Tobii) website. For example, when we were analyzing our participants eye tracker data, we found that when a participant interacted with the 3D model via a pan or a rotation motion, the content inside the AOIs/ROIs would change and the component which earlier was lying inside this AOIs/ROIs, drifted outside of AOIs/ROIs scope. Hence we were not able to analyze any gaze plots or AOI/ROI Data.

4.9 Study Protocol

At the beginning of the study an informed consent form was provided to all participants. After signing the informed consent form participants were quickly briefed about the complete study setup and the study tasks they had to perform. Following that a quick testing of the eye tracker setup was done with every participant to ensure that eye tracker could capture the eyes of all participants. Participants had to sit on a non-rotatable chair to prevent them from moving too much during the experiments. The lighting in the lab was kept under control. Before starting with the actual study, pre-test questionnaire was administered to capture their knowledge about the 3D models used in the study and interaction experience with 3D software. Participants with good prior knowledge about the 3D models used in the study were then given their honorarium and were excluded from participating in the study. Other participants with no or minimal knowledge about the 3D models used in the study were then allotted participant IDs depending upon their frequency of interaction (in the last six months) with 3D models and software. Hence the total participant base was split into three categories expert users, intermediate users, and novice users. Later training was provided to participants on a training model (rk-62 rifle) to make them familiar with the 3D software and annotation styles used in the study. Three mandatory breaks were included in the study to reduce the fatigue effects. After training participants started with the actual study, where they performed search task followed by recall task followed by a post task questionnaire capturing feedback on user preference for annotation styles. The two study tasks and post task questionnaire were repeated eight more times in the study. After this an exit interview was conducted, followed by the post-test questionnaire. The participants were then debriefed and an honorarium of $15 was given for their participation.

4.10 Pilot Study

In March 2012, we ran a pilot study with 12 participants and obtained initial user feedback on annotation style types and research methods [22]. We had a 3x3 within subjects study design with two factors being (a) annotation style (internal, external and box style annotations) and (b) zooming levels (level 1: 3D object covers 80% of the screen size; level 2: 3D object covers 150% of the screen size and level 3: 3D object covers 270% of the screen size), and measured the impact of these two within-subjects factors on participants efficiency (time taken) to complete the search task of locating 5 components in an annotated 3D model and user preference. In addition we captured participant feedback on the readability of box style annotations to evaluate the impact of introducing transparency on the readability of the textual details displayed inside the annotation boxes (figure 49.a).

The prototype deployed was a 3D model (red sports car) with 27 annotated components displayed all at once on the user screen (as shown in figure 49.b, where the 3D model was annotated with 27 external annotations and figure 49.c with 27 internal annotations). We used 3DVIA Composer student trial version (with limited functionalities) for designing the pilot prototype. Our participant population for the pilot study were 12 graduate students at Dalhousie University; who may or may not have previous experience interacting with 3D models.

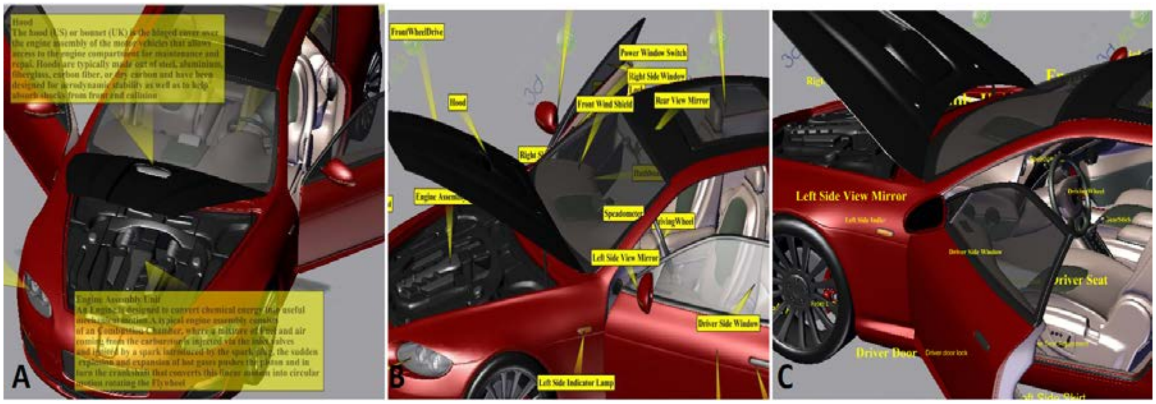


Figure 49: Pilot study prototype annotated with (a) semi transparent annotation boxes, (b) external annotations, and (c) internal annotations.

The learning and feedback obtained from running the pilot were incorporated in this study. Some of the important points taken from running the pilot were:

(a) To balance for learning effect from using the same 3D model at the three zooming levels. Results from the pilot study reflected that participants became faster at search task as they approached the end of the study (as by the end of the study participants had already seen this model many times before and were familiar with its construction).

(b) To check for prior knowledge about the 3D models used in the study and exclude those participants who have good knowledge about the 3D models. When running the pilot study we encountered 3 participants who had a good prior knowledge about the 3D model used in the study, as a result the data from these three individuals were dropped as they introduced many outliers in the pilot study data.

(c) To control for order effects. When running the pilot study the order of the zooming levels were fixed where the participant saw annotated 3D model at zooming level 1 first, then at zooming level 2 and finally at zooming level 3. As a result the participants were overall faster at zooming level 3 when compared to their performance at zooming level 1 and 2 (see figure 50).

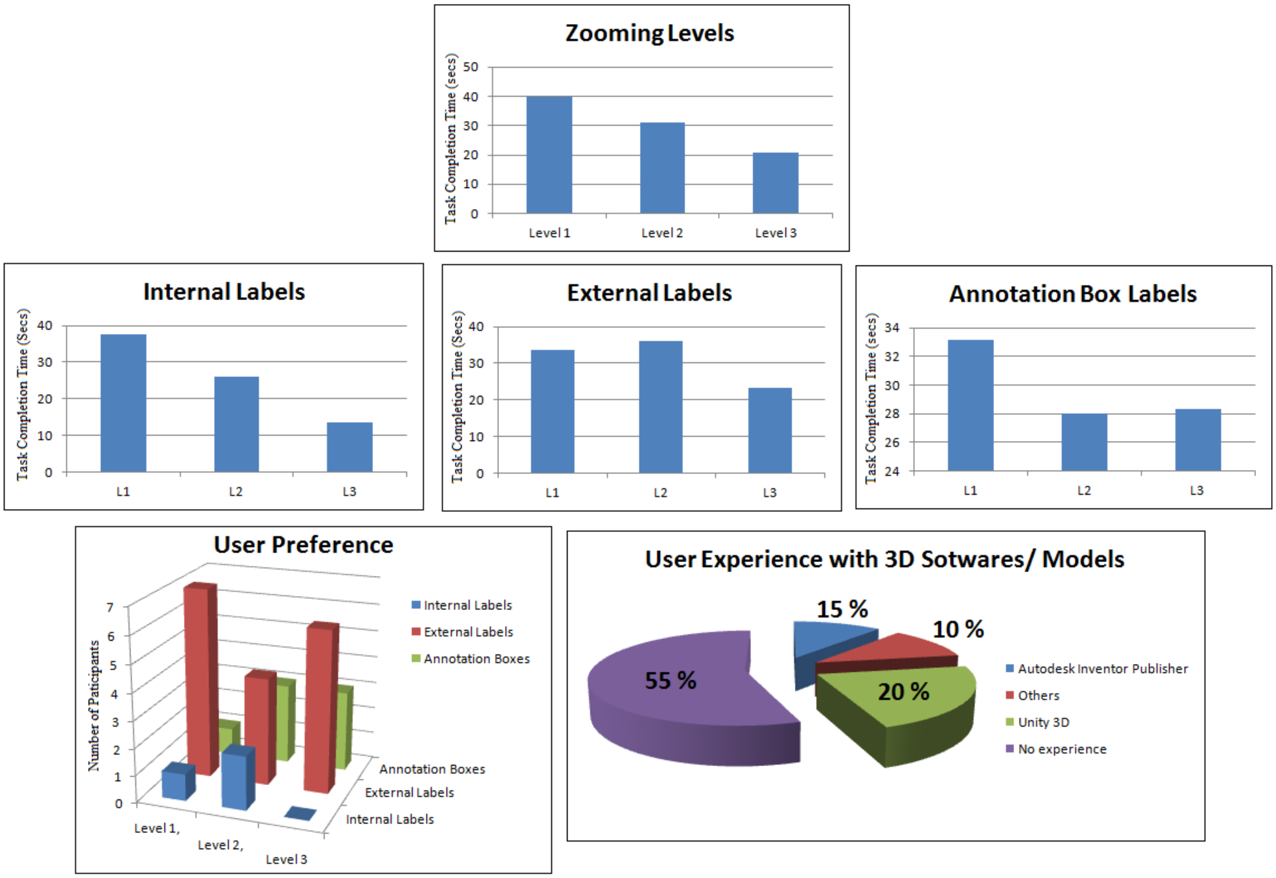


Figure 50: Pilot Study Results.

4.11 Study Controls

4.11.1 Counter Balancing for Learning Effects

In our study, to control for learning effect, we presented participants with a different 3D model at each zooming level. This implied that every participant would see a unique annotated 3D model at each of the three zooming levels. For example, participant P1 is presented with annotated 3D model #1 at zooming level 1, annotated 3D model #2 at zooming level 2, and annotated 3D model #3 at zooming level 3 (see figure 52). This control ensured that the gain in knowledge about a 3D model and learning on account of interacting with that 3D model three times one for each of the three annotation styles at a single level of zoom will not influence the performance of participants on similar study tasks for subsequent levels of zoom (the other two zooming levels) in the study.

4.11.2 Counter Balancing for Order Effects

In this study we have counter balanced (rotated) the order of the zooming levels as well as the order of annotation styles, as search task and recall task were performed nine times by a single participant to gather data for the nine different treatment conditions created by the varying levels of the two within-subjects factors “annotation styles” and “zooming levels”.

The sequence of the annotation styles/techniques (for example internal annotations first followed by external annotations and then annotation boxes) were rotated to counter balance for the any improvement in performance on account of the order in which annotation styles/techniques were presented.

Along similar lines, the order of zooming levels were counter balanced (rotated) to ensure that the participants improved performance at the last seen zooming level is distributed among the three zooming levels, such that every zooming level (level 1, level 2, and level 3) gets an equal chance of being the last seen zooming level.

Hence, in this study we fully counter balanced the order of zooming levels and annotation styles to control for order effects.

We also counter balanced the order of the three components participants had to find in the search task (completely visible, partially visible, and not visible on the initial screen). We rotated the order to ensure that the three components occurred equally often in the first, second, and final positions in the order in which they were presented to the participants. For example, participant P1, P4, and P7 were all presented 3D model#1 at zooming level 1, however, the order of the three components (8, 1, and 6) was rotated (see figure 52).

4.11.3 Need for 27 Unique Components per 3D Model

In the search task, where we provided the participants with an annotated 3D model that had a set of 9 unique annotated objects, annotated with a certain annotation style. We annotated nine unique components as previous research has shown that nine is the upper limit of numbers (7 ± 2), the number of objects an average human can hold in the working memory [35]. Now, in order to compare the efficiency of the three annotation styles we need to annotate the same 3D model thrice (once for each annotation style) so that we can measure the time taken by participant to complete the search task when the 3D model is annotated by internal annotations, then when the same 3D model is annotated by external annotation style and then when it is annotated with box style annotations. However, we cannot use the same set of 9 unique annotated components again so needed two more sets of 9 new and unique components. This is necessary to guard against learning effects as once the participant completes the task with one annotation style; they have now become familiar with the name and position of these nine tagged objects. Hence we need three sets of 9 unique components (raising the count to 27 unique components per 3D model) to compare the efficiency of the three textual annotations.

Another important issue that needs to be addressed is the rotation of the three component sets among the three annotation styles. As explained above we need three sets of 9 unique components, where each component set maps to an annotation style and is used to measure the time taken by participants to search for components annotated with that annotation style in the 3D model. However, this association or mapping of a component set to an annotation style needs to be broken very cautiously (need to be rotated) as we can compare the efficiency of the three annotation styles only when we have the efficiency data for a component set that has been shown to the participant once for each annotation style. Table 4 below, shows the rotation of the three component sets (Set A, Set Band Set C) each comprising of 9 unique components.

Participant ID	Internal Annotation Style	External Annotation Style	Box Style Annotation
P1	Set A (9 unique components)	Set B (9 unique components)	Set C (9 unique components)
P2	Set B (9 unique components)	Set C (9 unique components)	Set A (9 unique components)
P3	Set C (9 unique components)	Set A (9 unique components)	Set B (9 unique components)
Study Data	Internal Annotations {Set A, Set B, Set C}	External Annotations {Set A, Set B, Set C}	Box Style Annotations {Set A, Set B, Set C}

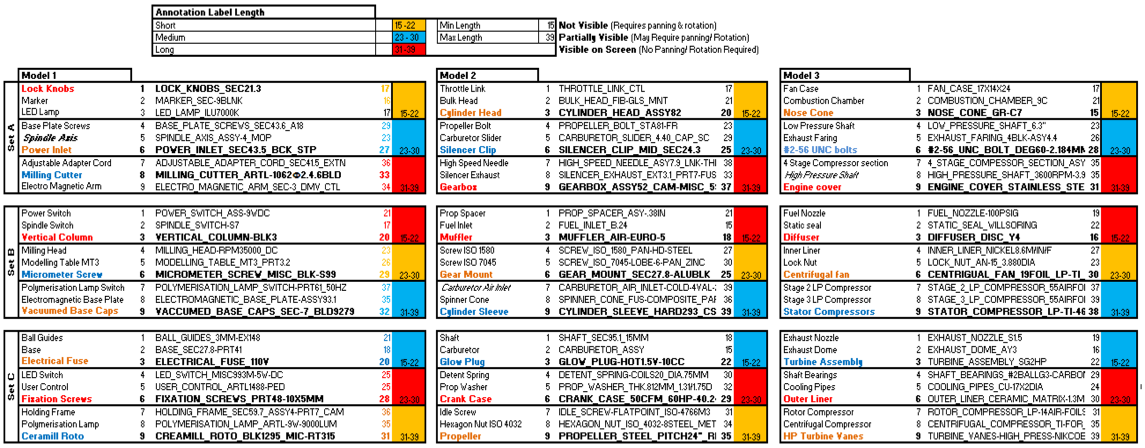
Table 5: The number of Component Sets required for comparing the three Annotation Styles.

4.11.4 Need for Three 3D Models

In our study we are comparing the three types of textual annotation styles (internal annotation style, external annotation style and box style annotation) at three levels of zoom. Since the within-subjects factor "zooming levels" has three levels (level 1, level 2 and level 3) we need to repeat the configuration shown in Table 4 two more times, once for zooming level 2 and then for zooming level 3, raising the number of component sets (Set A, Set B and Set C) from three to nine. This led us to design the 3D model to provide participants with two new sets of 27 components (raising the count to 81 selectable components for a single 3D model). It is difficult to design 81 unique selectable components on a single 3D model. To solve this issue, we added two new 3D models providing participants with two new sets of 27 components each, hence achieving the count of 81 unique parts but via three 3D models as shown in figure 51. These three 3D models were similar in the 3D complexity and size as measured by our 3D software tool

(3DVIA composer) with different components (see figure 51 below for the list of components).

The technical names of the 81 components in 9 component sets for the three 3D model were of varying length (see figure 51) and had three levels of annotation label length short (ranging 15 to 22 characters), medium (ranging 23 to 30 characters), and long annotation label length (ranging 31 to 39 characters). The length of the textual annotation was also rotated within each component set with respect to the visibility order (see figure 51) in which the three components to be searched for (from a single component set comprising of nine components) inside the annotated 3D model were presented to the participants in search task. In addition, the three component sets (Set A, Set B and Set C) in each of these three 3D models {Model #1, Model #2, and Model #3} were rotated to allow us to compare the three annotation styles at each zooming level as shown in Table 5.



Annotation Label Length	
Short	15 -22
Medium	23 - 30
Long	31 -39

Min Length	15
Max Length	39

Not Visible (Requires panning & rotation)
Partially Visible (May Require panning/ Rotation)
Visible on Screen (No Panning/ Rotation Required)

Model 1

Set A	**Lock Knobs**	**1**	**LOCK_KNOBS_SEC21.3**	**17**	15-22
	Marker	2	MARKER_SEC-9BLNK	16	
	LED Lamp	3	LED_LAMP_ILU7000K	17	
	Base Plate Screws	4	BASE_PLATE_SCREWS_SEC43.6_A18	29	23-30
	Spindle Axis	5	SPINDLE_AXIS_ASSY-4_MOP	23	
	Power Inlet	**6**	**POWER_INLET_SEC43.5_BCK_STP**	**27**	
	Adjustable Adapter Cord	7	ADJUSTABLE_ADAPTER_CORD_SEC41.5_EXTN	36	31-39
	Milling Cutter	**8**	**MILLING_CUTTER_ARTL-1062Φ2.4.6BLD**	**33**	
	Electro Magnetic Arm	9	ELECTRO_MAGNETIC_ARM_SEC-3_DMV_CTL	34	
Set B	Power Switch	1	POWER_SWITCH_ASS-9WDC	21	15-22
	Spindle Switch	2	SPINDLE_SWITCH-S7	17	
	Vertical Column	**3**	**VERTICAL_COLUMN-BLK3**	**20**	
	Milling Head	4	MILLING_HEAD-RPM35000_DC	23	23-30
	Modelling Table MT3	5	MODELLING_TABLE_MT3_PRT3.2	26	
	Micrometer Screw	**6**	**MICROMETER_SCREW_MISC_BLK-S99**	**29**	
	Polymerisation Lamp Switch	7	POLYMERISATION_LAMP_SWITCH-PRT61_50HZ	37	31-39
	Electromagnetic Base Plate	8	ELECTROMAGNETIC_BASE_PLATE-ASSY93.1	35	
	Vacuumed Base Caps	**9**	**VACCUMED_BASE_CAPS_SEC-7_BLD9279**	**32**	
Set C	Ball Guides	1	BALL_GUIDES_3MM-EX148	21	15-22
	Base	2	BASE_SEC27.8-PRT41	18	
	Electrical Fuse	**3**	**ELECTRICAL_FUSE_110V**	**20**	
	LED Switch	4	LED_SWITCH_MISC993M-5W-DC	25	23-30
	User Control	5	USER_CONTROL_ARTL1488-PED	25	
	Fixation Screws	**6**	**FIXATION_SCREWS_PRT48-10X5MM**	**28**	
	Holding Frame	7	HOLDING_FRAME_SEC59.7_ASSY4-PRT7_CAM	36	31-39
	Polymerisation Lamp	8	POLYMERISATION_LAMP_ARTL-9W-9000LUM	35	
	Ceramill Roto	**9**	**CREAMILL_ROTO_BLK1295_MIC-RT315**	**31**	

Model 2

Set A	Throttle Link	1	THROTTLE_LINK_CTL	17	15-22
	Bulk Head	2	BULK_HEAD_FIB-GLS_MNT	21	
	Cylinder Head	**3**	**CYLINDER_HEAD_ASSY82**	**20**	
	Propeller Bolt	4	PROPELLER_BOLT_STA81-FR	23	23-30
	Carburetor Slider	5	CARBURETOR_SLIDER_4.40_CAP_SC	29	
	Silencer Clip	**6**	**SILENCER_CLIP_MID_SEC24.3**	**25**	
	High Speed Needle	7	HIGH_SPEED_NEEDLE_ASY7.9_LNK-THI	38	31-39
	Silencer Exhaust	8	SILENCER_EXHAUST_EXT3.1_PRT7-FUS	33	
	Gearbox	**9**	**GEARBOX_ASSY52_CAM-MISC_5:**	**37**	
Set B	Prop Spacer	1	PROP_SPACER_ASY-.38IN	21	15-22
	Fuel Inlet	2	FUEL_INLET_B.24	15	
	Muffler	**3**	**MUFFLER_AIR-EURO-5**	**18**	
	Screw ISO 1580	4	SCREW_ISO_1580_PAN-HD-STEEL	27	23-30
	Screw ISO 7045	5	SCREW_ISO_7045-LOBE-6-PAN_ZINC	30	
	Gear Mount	**6**	**GEAR_MOUNT_SEC27.8-ALUBLK**	**25**	
	Carburetor Air Inlet	7	CARBURETOR_AIR_INLET-COLD-4VAL-:	39	31-39
	Spinner Cone	8	SPINNER_CONE_FUS-COMPOSITE_PAI	36	
	Cylinder Sleeve	**9**	**CYLINDER_SLEEVE_HARD293_CS**	**39**	
Set C	Shaft	1	SHAFT_SEC95.1_15MM	18	15-22
	Carburetor	2	CARBURETOR_ASSY	15	
	Glow Plug	**3**	**GLOW_PLUG-HOT1.5V-10CC**	**22**	
	Detent Spring	4	DETENT_SPRING-COILS20_DIA.75MM	30	23-30
	Prop Washer	5	PROP_WASHER_THK.812MM_1.31/1.75D	32	
	Crank Case	**6**	**CRANK_CASE_50CFM_60HP-40.2·**	**29**	
	Idle Screw	7	IDLE_SCREW-FLATPOINT_ISO-4766M3	31	31-39
	Hexagon Nut ISO 4032	8	HEXAGON_NUT_ISO_4032-8STEEL_MET	34	
	Propeller	**9**	**PROPELLER_STEEL_PITCH24"_RI**	**35**	

Model 3

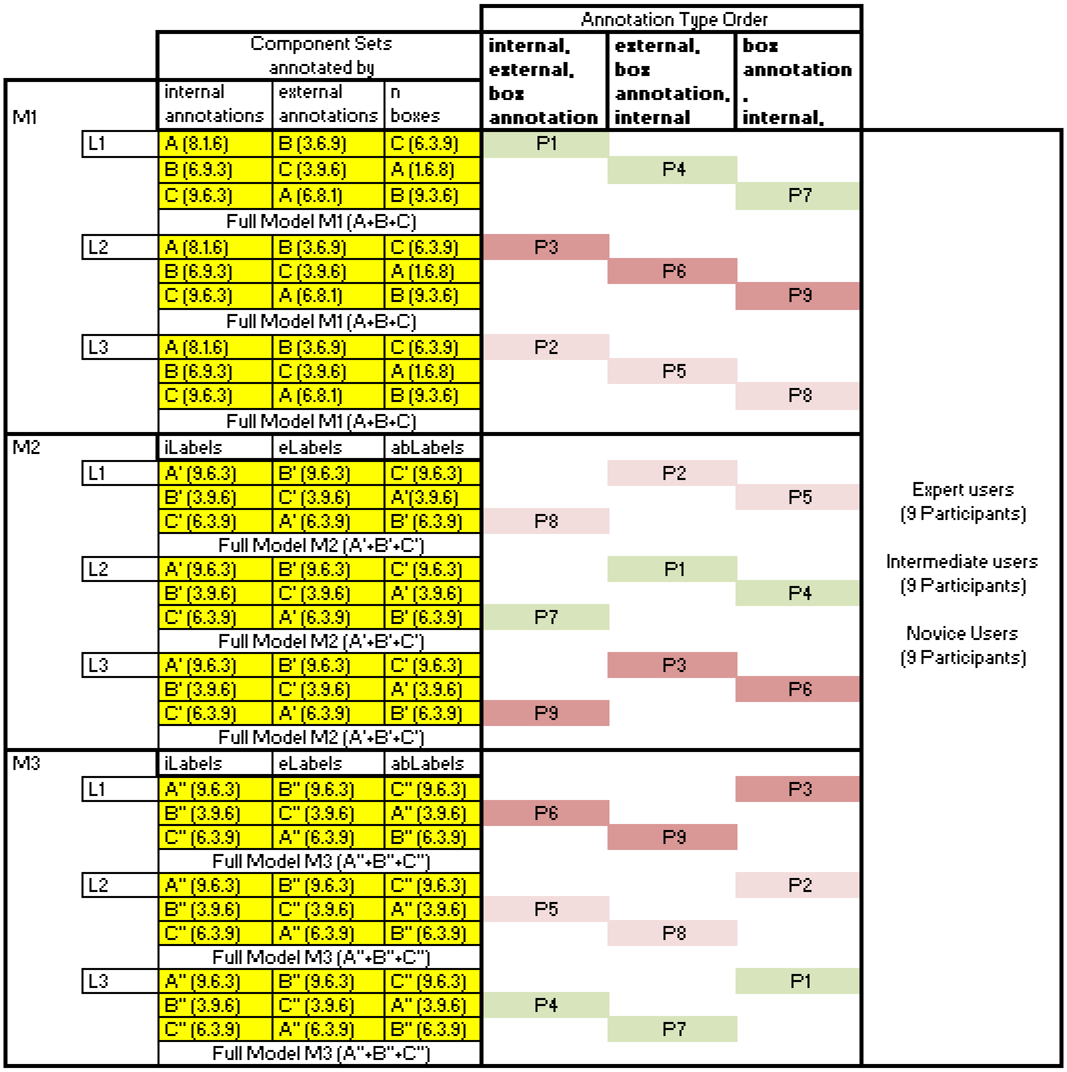
Set A	Fan Case	1	FAN_CASE_17X14X24	17	15-22
	Combustion Chamber	2	COMBUSTION_CHAMBER_9C	21	
	Nose Cone	**3**	**NOSE_CONE_GR-C7**	**15**	
	Low Pressure Shaft	4	LOW_PRESSURE_SHAFT_6.3"	23	23-30
	Exhaust Faring	5	EXHAUST_FARING_4BLK-ASY4.4	26	
	#2-56 UNC bolts	**6**	**#2-56_UNC_BOLT_DEG60-2.184MM**	**28**	
	4 Stage Compressor section	7	4_STAGE_COMPESSOR_SECTION_ASY	35	31-39
	High Pressure Shaft	8	HIGH_PRESSURE_SHAFT_3600RPM-3.9	35	
	Engine cover	**9**	**ENGINE_COVER_STAINLESS_STE**	**31**	
Set B	Fuel Nozzle	1	FUEL_NOZZLE-100PSIG	19	15-22
	Static seal	2	STATIC_SEAL_WILLSORING	22	
	Diffuser	**3**	**DIFFUSER_DISC_Y4**	**16**	
	Inner Liner	4	INNER_LINER_NICKEL8.6M/IN/F	27	23-30
	Lock Nut	5	LOCK_NUT_AN-15_3.880DIA	23	
	Centrifugal fan	**6**	**CENTRIGUAL_FAN_19FOIL_LP-TI_**	**30**	
	Stage 2 LP Compressor	7	STAGE_2_LP_COMPRESSOR_55AIRFOI	37	31-39
	Stage 3 LP Compressor	8	STAGE_3_LP_COMPRESSOR_55AIRFOI	39	
	Stator Compressors	**9**	**STATOR_COMPRESSOR_LP-TI-46**	**38**	
Set C	Exhaust Nozzle	1	EXHAUST_NOZZLE_S1.5	19	15-22
	Exhaust Dome	2	EXHAUST_DOME_AY3	16	
	Turbine Assembly	**3**	TURBINE_ASSEMBLY_SG2HP	22	
	Shaft Bearings	4	SHAFT_BEARINGS_#2BALLG3-CARBOI	29	23-30
	Cooling Pipes	5	COOLING_PIPES_CU-17X2DIA	24	
	Outer Liner	**6**	OUTER_LINER_CERAMIC_MATRIX-1.3M	30	
	Rotor Compressor	7	ROTOR_COMPRESSOR_LP-14AIR-FOILS	31	31-39
	Centrifugal Compressor	8	CENTRIFUGAL_COMPRESSOR_TI-FOR_	35	
	HP Turbine Vanes	**9**	TURBINE_VANES-HIGH_PRESS-NIKCOE	39	

Figure 51: List of components names for the 3D models.

Models	Participant ID	**Internal Annotation Style**	**External Annotation Style**	**Box Style Annotation**
3D Model #1 at Zooming Level 1	P1	Set A (9 unique components)	Set B (9 unique components)	Set C (9 unique components)
	P2	Set B (9 unique components)	Set C (9 unique components)	Set A (9 unique components)
	P3	Set C (9 unique components)	Set A (9 unique components)	Set B (9 unique components)
Model #1		{Set A, Set B, Set C}	{Set A, Set B, Set C}	{Set A, Set B, Set C}
3D Model #2 at Zooming Level 2	P1	Set A (9 unique components)	Set B (9 unique components)	Set C (9 unique components)
	P2	Set B (9 unique components)	Set C (9 unique components)	Set A (9 unique components)
	P3	Set C (9 unique components)	Set A (9 unique components)	Set B (9 unique components)
Model #2		{Set A, Set B, Set C}	{Set A, Set B, Set C}	{Set A, Set B, Set C}
3D Model #3 at Zooming Level 3	P1	Set A (9 unique components)	Set B (9 unique components)	Set C (9 unique components)
	P2	Set B (9 unique components)	Set C (9 unique components)	Set A (9 unique components)
	P3	Set C (9 unique components)	Set A (9 unique components)	Set B (9 unique components)
Model #3		{Set A, Set B, Set C}	{Set A, Set B, Set C}	{Set A, Set B, Set C}

Table 6: The Order of 9 Component Sets in the Study.

In addition the order of the zooming levels and the order of the annotation technique were also rotated for each user group as shown in figure 52.



		Component Sets annotated by			Annotation Type Order		
M1		internal annotations	external annotations	n boxes	internal, external, box annotation	external, box annotation, internal	box annotation , internal,
	L1	A (8.1.6)	B (3.6.9)	C (6.3.9)	P1		
		B (6.9.3)	C (3.9.6)	A (1.6.8)		P4	
		C (9.6.3)	A (6.8.1)	B (9.3.6)			P7
		Full Model M1 (A+B+C)					
	L2	A (8.1.6)	B (3.6.9)	C (6.3.9)	P3		
		B (6.9.3)	C (3.9.6)	A (1.6.8)		P6	
		C (9.6.3)	A (6.8.1)	B (9.3.6)			P9
		Full Model M1 (A+B+C)					
	L3	A (8.1.6)	B (3.6.9)	C (6.3.9)	P2		
		B (6.9.3)	C (3.9.6)	A (1.6.8)		P5	
		C (9.6.3)	A (6.8.1)	B (9.3.6)			P8
		Full Model M1 (A+B+C)					
M2		iLabels	eLabels	abLabels			
	L1	A' (9.6.3)	B' (9.6.3)	C' (9.6.3)		P2	
		B' (3.9.6)	C' (3.9.6)	A'(3.9.6)			P5
		C' (6.3.9)	A' (6.3.9)	B' (6.3.9)	P8		
		Full Model M2 (A'+B'+C')					
	L2	A' (9.6.3)	B' (9.6.3)	C' (9.6.3)		P1	
		B' (3.9.6)	C' (3.9.6)	A' (3.9.6)			P4
		C' (6.3.9)	A' (6.3.9)	B' (6.3.9)	P7		
		Full Model M2 (A'+B'+C')					
	L3	A' (9.6.3)	B' (9.6.3)	C' (9.6.3)		P3	
		B' (3.9.6)	C' (3.9.6)	A' (3.9.6)			P6
		C' (6.3.9)	A' (6.3.9)	B' (6.3.9)	P9		
		Full Model M2 (A'+B'+C')					
M3		iLabels	eLabels	abLabels			
	L1	A" (9.6.3)	B" (9.6.3)	C" (9.6.3)			P3
		B" (3.9.6)	C" (3.9.6)	A" (3.9.6)	P6		
		C" (6.3.9)	A" (6.3.9)	B" (6.3.9)		P9	
		Full Model M3 (A"+B"+C")					
	L2	A" (9.6.3)	B" (9.6.3)	C" (9.6.3)			P2
		B" (3.9.6)	C" (3.9.6)	A" (3.9.6)	P5		
		C" (6.3.9)	A" (6.3.9)	B" (6.3.9)		P8	
		Full Model M3 (A"+B"+C")					
	L3	A" (9.6.3)	B" (9.6.3)	C" (9.6.3)			P1
		B" (3.9.6)	C" (3.9.6)	A" (3.9.6)	P4		
		C" (6.3.9)	A" (6.3.9)	B" (6.3.9)		P7	
		Full Model M3 (A"+B"+C")					

Expert users
(9 Participants)

Intermediate users
(9 Participants)

Novice Users
(9 Participants)

Figure 52: Order of annotation styles and zooming levels for 27 participants.

4.12 Data Collection

4.12.1 Time

Time taken to search for three components in an annotated 3D model was measured by the eye tracking software as part of the screen recording facility of the software system. Eye tracker software inserted events (flags) automatically in this recorded screen for all user interaction events such as mouse left clicks, right clicks, etc.

Later, the time difference between two related events such as the time elapsed between the mouse event corresponding to the starting screen when the component name and the annotated 3D model was presented to the participant (after left clicking the initial prompt). And the event that marked the end of search for this component (the correct component selection screen), was calculated manually and inserted in an excel sheet for each of the three components for the search task.

4.12.2 Error Count

The error count or the number of incorrect component selections was captured by the eye tracking software as part of the screen recording. A count of the number of incorrect selection screens for each of the three component for search task was then done manually and entered into an excel spreadsheet.

4.12.3 Recall Score

Recall scores were computed manually in response to the answers provided by participants on the recall sheets. Participants matched the component names with numbers that corresponded to the component's position in a 3D model annotated with numbers randomly assigned to the annotated components. These numbers were later compared to the correct answers to compute the recall score for each of the nine conditions.

4.12.4 User Preference

User preference ratings were collected from the participant on following user preference factors (a) readability, (b) look and feel, (c) ease of usage, and (d) satisfaction on a 5 point Likert scale on user preference sheets. In addition participant also ranked the three annotation styles at each zooming level without ties. These rating and ranks were then transferred to an excel sheet for each of the nine conditions.

4.12.5 Qualitative Feedback

Exit interviews were conducted to gain qualitative feedback from participants. These interviews probed them for insights such as the strengths and weaknesses of each annotation style, as perceived by them. And on the reasons for their preferences for different annotation styles at varying zooming levels. Participants answered the questions provided on the exit interview sheet and further discussion points were captured on paper and at the back of the exit interview sheet by the researcher. At the end of the exit interview all provided feedback was shared with the participant to confirm that the captured qualitative feedback was a true reflection of the participant's views and opinions.

4.13 Statistical Tests for Data Analysis

Data analysis for this study was all done in SPSS. We first transferred the collected data from the excel sheets to SPSS and then ran statistical tests and procedures to accept or reject the null hypothesis of the study.

4.13.1 Performance

To evaluate the research hypotheses for performance (H_{o1}, H_{o3}, and H_{o5} for efficiency, and H_{o2}, H_{o4}, and H_{o6} for accuracy), we performed a split plot ANOVA with a between-subjects factor being the user "expertise" and two within-subjects factors being "annotation styles" and "zooming levels". With "time" taken to complete the search task and "error count", the number of incorrect attempts as the dependent variables.

4.13.2 Impact on Learning

To evaluate the research hypotheses (H_{o7}, H_{o8}, and H_{o9}), we performed a 3x(3x3) split plot ANOVA, with a between subject factor being the user "expertise" and two within-subjects factors being "annotation styles" and "zooming levels" with participant's "recall score" as the dependent variable.

4.13.3 User Preference

To evaluate the research hypotheses (H_{o10}, H_{o11}, and H_{o12}), we first analyzed the impact of "expertise" (between-subjects factor) on user preference ranks via Kruskal-Wallis H nonparametric test. We then analyzed the impact of varying zooming levels (repeated-measures factor) on user preference ranks given to the three annotation styles via Friedman non parametric test (the Friedman two-way analysis of variance of ranks).

Lastly, we evaluated the split in the participant population for the user's preference towards a favorite annotation style with the Pearson's Chi Square test.

To determine the impact of expertise on the user preference ratings for the four usability factors (readability, look and feel, ease of usage, and satisfaction), we performed Kurskal-Wallis H test (non parametric test) on our ordinal data (user preference ratings). Here we used expertise (the between subjects factor) as the independent variable. And later, we performed Friedman two-way analysis of variance of ranks with zooming levels (the within-subjects factor) as the independent variable to determine the impact of varying zooming levels on the user preference ratings for the four usability factors.

We then summarized user preference ratings for the three annotation styles into three main categories (agree, neutral, and disagree), where we merged the two negative categories (disagree and somewhat disagree) into one category "disagree". And merged the two positive categories "agree" and "somewhat agree" into one category "agree", to generate a simple and meaningful 3 column visualizations. For each of the four usability factors (readability, look and feel, ease of usage, and satisfaction) considered in this study.

CHAPTER 5 DATA ANALYSIS

In this chapter, we present the results of our data analysis for each of the twelve research hypotheses. We have grouped these by performance (section 5.1), impact of learning (section 5.2) and user preference (section 5.3)

5.1 Performance

5.1.1 Efficiency

Null Hypothesis# 1: (H_{o1}): Efficiency when searching for components in an annotated 3D Model does not vary significantly with varying level of expertise.

5.1.1.1 Analysis for Expertise

The results of performing a one way ANOVA with "expertise" as the between subjects factor and "time" taken to complete the search task as the dependent variable revealed that the differences in mean time taken to complete the search task for the three user groups varying in levels of expertise were statistically not significant. As observed from the collected data (see figure 53), the mean time taken to complete the search task were M=23.317 sec, SD= 1.88 sec for expert users, M=23.317 sec, SD=1.88 sec for intermediate users, and M=28.947 sec, SD=1.88 sec for novice users.

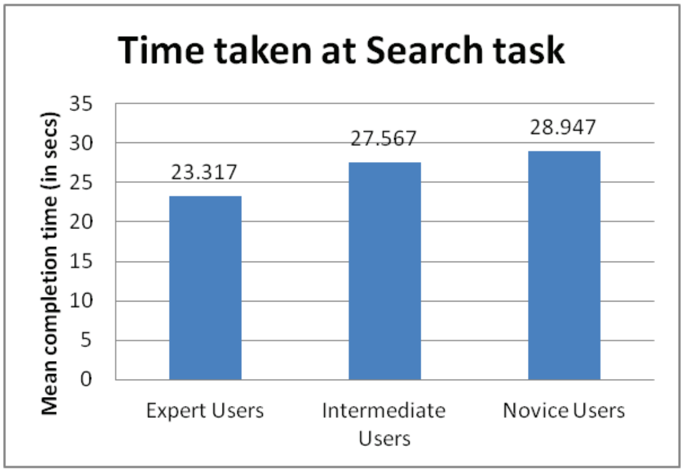


Figure 53: Efficiency (time taken to complete the search task) for the three user groups.

Result: Null Hypothesis# 1: (H_{o1}) was not rejected.

5.1.1.2 Analysis for Annotation Styles

Null Hypothesis# 3: H_{o3}: Efficiency when searching for components in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

As no main effects for the between subject factor expertise were observed, we shifted our attention to evaluate whether the participants as a whole differ in overall performance (time) when searching for components in an annotated 3D model for varying levels of annotation styles and zooming levels. We performed a two-way repeated measures ANOVA with the two within-subjects factors being "annotation styles" and "zooming levels" and "time" taken to complete the search task as the dependent variable.

The results revealed a statistically significant main effect for the within-subjects factor "annotation styles" (an F (1.559, 40.54) = 23.240, *p*=0.0000012, ηp2=.472; computed at an alpha value of 0.05). Since the results of Mauchly's test of sphericity revealed that the sphericity assumption was not met at significant level of .05, the degrees of freedom of the ANOVA test were adjusted using Greenhouse-Geisser procedure. The effect size (partial eta-square) of ηp2 = .472 indicated that on average the annotation styles (internal, external and annotation box style) had a very large effect on the overall performance (time taken to complete the search task) of the 27 participants.

Performing a post hoc analysis, a pair wise comparison with Bonferroni adjustment between the three levels of the within-subjects factor annotation styles, statistically significant differences between internal annotation style and external annotation style (*p*=.0000008), between external annotation and box annotation style (*p*=.00018) and between internal annotation style and box annotation style (with *p*=.038) were observed.

The mean completion time at search task with external annotations was significantly lower than the mean completion time with internal annotations (Mean Difference = -

14.771), and with box style annotations (Mean Difference = -7.662), thus making external annotation the fastest among the three textual annotations considered in the study (see figure 54).

Comparing the mean completion time for search task between internal annotation and box style annotation results reflected that participants overall were slower (took more time to complete the search task) with internal annotations as compared to box style annotations (Mean Difference = 7.049, see figure 54).

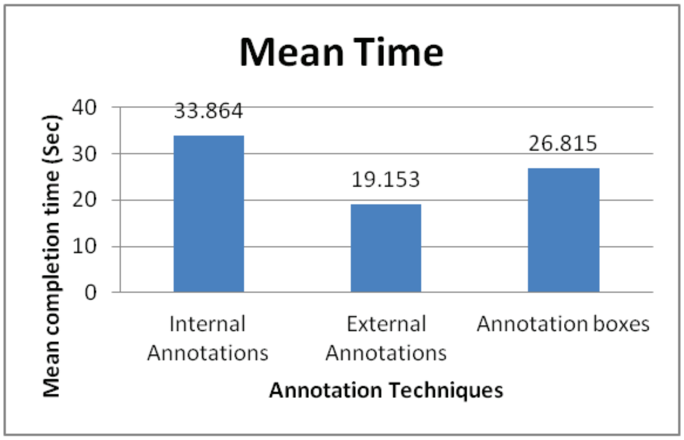


Figure 54: Efficiency (time taken to complete the search task) with varying annotation styles.

Result: We **rejected** the Null Hypothesis# 3: (H_{o3})

5.1.1.3 Analysis for Zooming Levels

Null Hypothesis# 5: H_{o5}: Efficiency when searching for components in an annotated 3D Model does not vary significantly with zooming levels.

The results our data analysis indicated that there was no significant main effect of the within-subjects factor “zooming levels”. This implied that the time taken by our (27) participants to complete the search task was overall the same for the different levels of zoom. As observed from the collected data (see figure 55), the mean completion time for search task at the three zooming levels were very similar (zooming level 1: M = 26.613, SD = 1.645; zooming level 2: M = 26.247, SD = 1.463; zooming Level 3: M = 26.971, SD = 1.712).

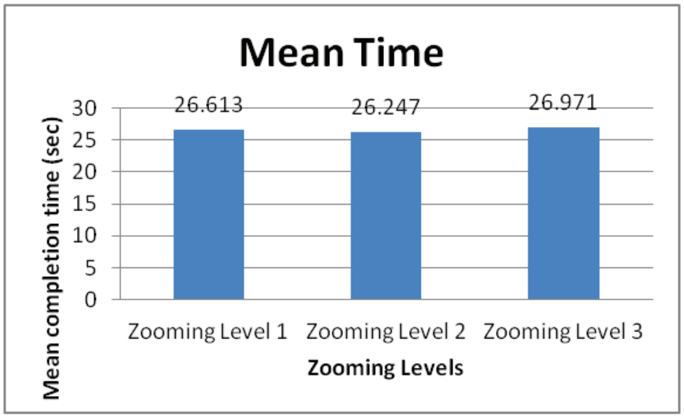


Figure 55: Efficiency (time taken to complete the search task) with varying levels of zoom.

In addition the results from our data analysis revealed no significant two way interactions among the two within-subjects factor “annotation styles” and “zooming levels” (see figure 56).

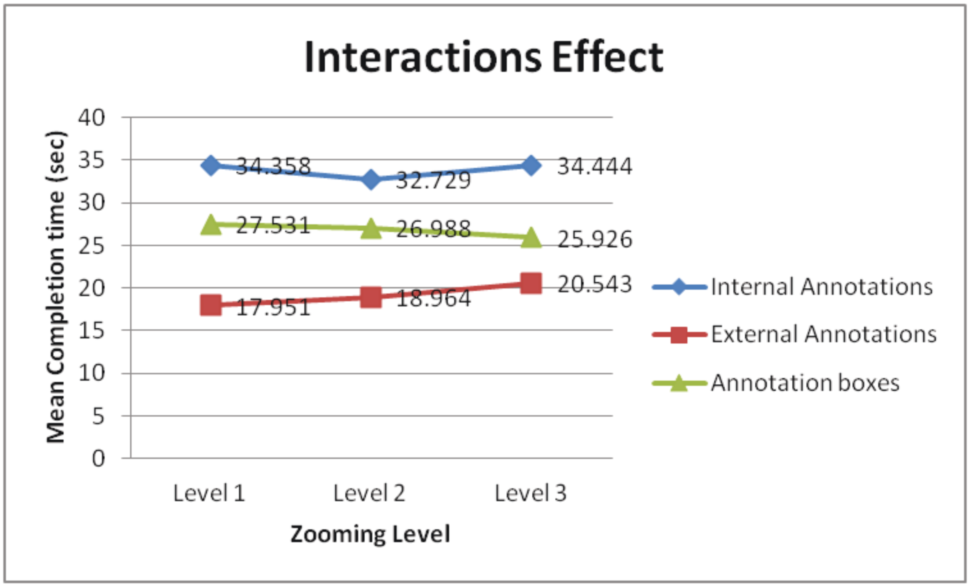


Figure 56: Interactions Effect between annotation styles and zooming levels.

Result: Null Hypothesis# 5: (H_{o5}) was not rejected.

5.1.2 Accuracy

5.1.2.1 Analysis for Expertise

Null Hypothesis# 2: (H_{02}): Accuracy when searching for components in an annotated 3D Model does not vary significantly with varying level of expertise.

The results of performing a one way ANOVA with expertise as the between subjects factor and the "number of incorrect component selections (error count)" made while completing the search task as dependent variable revealed that the differences in the mean incorrect selections were statistically not significant. As observed from the recorded data, (see figure 57), we found that intermediate users had a lower error count (21) when compared to expert users (35) and novice users (34), at searching for components inside an annotated 3D model. The Estimated marginal means was as follows expert users (0.432), intermediate users (0.259) and novice users (0.42) with a standard deviation of (0.111) for 81 component selections per user group.

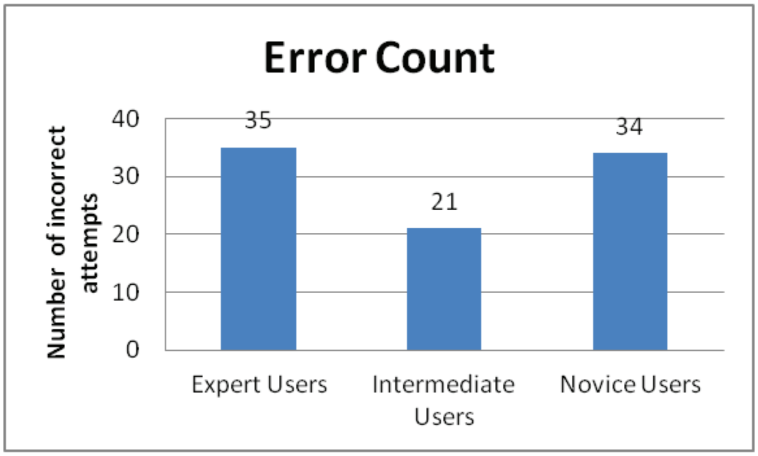


Figure 57: Accuracy with varying levels of expertise.

Result: Null Hypothesis# 5: (H_{o5}) was not rejected.

5.1.2.2 Analysis for Annotation Styles

Null Hypothesis# 4: H_{o4}: Accuracy when searching for components in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

As there was no main effect for the between subject factor "expertise", we evaluated whether all 27 participants as a whole differed in overall accuracy when searching for components in an annotated 3D model at varying levels of annotation styles and zooming levels. We performed a two way repeated measures ANOVA with the two within-subjects factors being annotation styles and zooming levels and error count (the number of incorrect attempts) as the dependent variable.

The results our data analysis revealed a statistically significant main effect for the within-subjects factor "annotation styles" (an $F(2, 52) = 10.905$, $p=0.0001$, ηp2=.295; computed at an alpha value of 0.05). The effect size (partial eta-square) of ηp2 = .295 indicated that on average the three annotation styles (internal, external and annotation box style) had a very large effect on the overall accuracy of the 27 participants.

Performing a post hoc analysis, a pair wise comparison with Bonferroni adjustment between the three levels of the within-subjects factor "annotation styles", statistically significant difference between internal annotation style and external annotation style (with $p= .0006$) and between external annotation and box style annotation (with $p=.045$) were observed.

The mean error count of the external annotations was significantly lower than the mean error count of internal annotations (Mean Difference = 0.543) and the mean error count for box style annotations (Mean Difference = 0.273) for n=243 component selections with 27 participants (see figure 58 and 59). Suggesting external style annotation the most accurate annotation style among the three textual annotation styles considered in the study, (external annotations: M = 0.099, SD =0.039; internal annotations: M = 0.642, SD =0.127; annotation box annotations: M = 0.37, SD = 0.09).

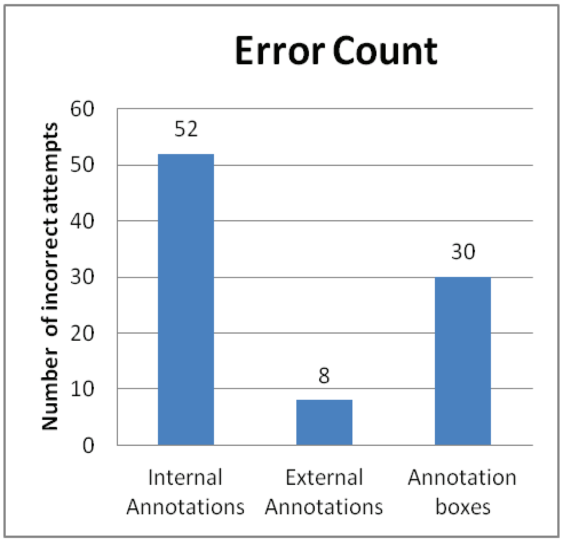


Figure 58: Accuracy (total error count) for the three annotation styles.

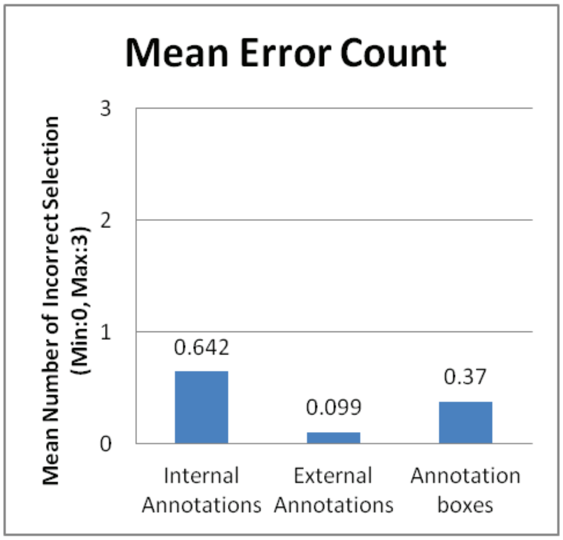


Figure 59: Accuracy (mean error count) for the three annotation styles.

Result: Null Hypothesis# 4: (H_{o4}) was rejected.

5.1.2.3 Analysis for Zooming Levels

Null Hypothesis# 6: H_{o6}: Accuracy when searching for components in an annotated 3D Model does not vary significantly with zooming levels.

As observed in the collected data (see figure 60) the total number of incorrect selections as we move from lower to higher levels of zoom were zooming level 1(34), zooming level 2 (33) and zooming level 3 (23).

The results our data analysis revealed no significant main effects of the within-subjects factor "zooming levels" for our (27) participants.

The mean error count (see figure 61) for the three zooming levels for (243) component selections with 27 participants were (zooming level 1: M = 0.420, SD = 0.130; zooming level 2: M = 0.407, SD =0.101; annotation box annotations: M = 0.284, SD = 0.066).

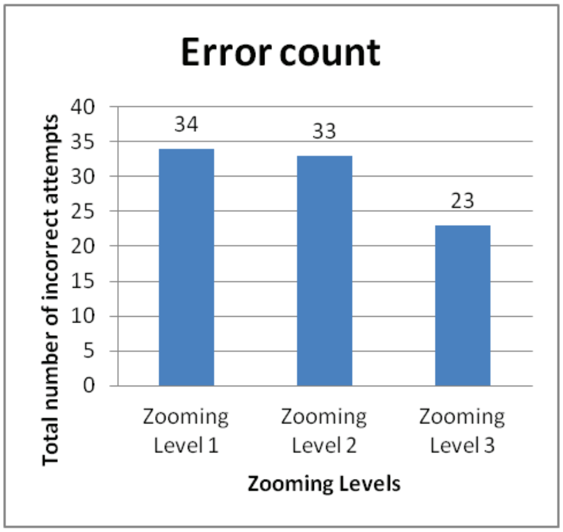


Figure 60: Accuracy (total error count) at the three zooming levels.

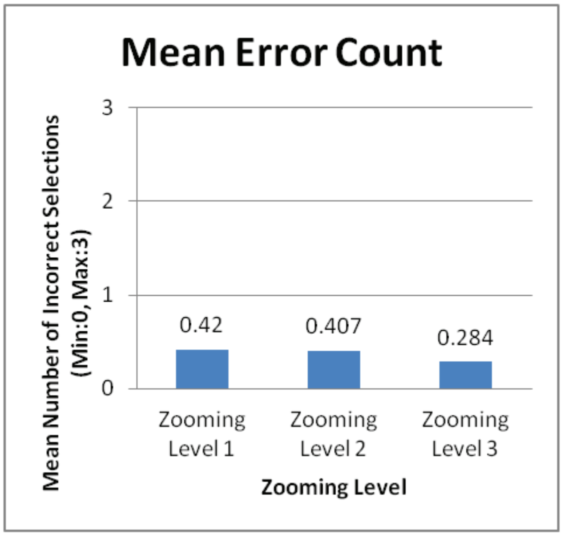


Figure 61: Accuracy (mean error count) at the three zooming levels.

In addition, the results from our data analysis revealed no significant two way interactions among the within-subjects factors “annotation styles” and “zooming levels” (see figure 62).

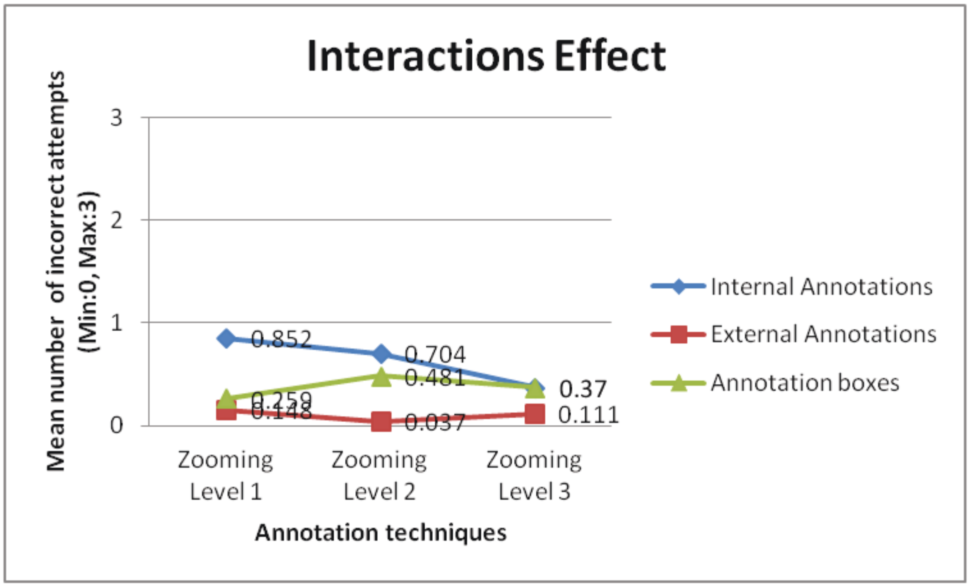


Figure 62: Interactions Effect between annotation styles and zooming levels for Error Count

Result: Null Hypothesis# 6: (H_{o6}) was not rejected.

5.2 Impact on Learning

5.2.1 Analysis for Expertise

Null Hypothesis# 7: (H_{o7}): Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with varying level of expertise.

The results of performing a split plot ANOVA with a between subject factor “expertise” and two within-subjects factors “annotation styles” and “zooming levels” with “recall score” as the dependent variable) revealed a statistically significant difference between the mean recall scores of the three user groups expert users, intermediate users and novice users (a F (2, 24) = 4.238, p<.027, ηp2 = .261; computed at an alpha value of 0.05).

Performing a post hoc analysis, a pair wise comparison with Bonferroni adjustment between the three levels of expertise (expert users, intermediate users and novice users), statistically significant difference between mean recall scores of expert user group and novice user group (*p*= .025) was found. The mean recall score for expert users was higher than the mean recall score for naive users with a mean difference of (1.543) for n=162 observations with 18 participants (9 expert users and 9 novice users), see figure 63. The means recall score for the three user groups wee expert users (M = 3.975, SD =0.38), intermediate users (M = 3.42, SD =0.38) and novice users (M = 2.432, SD = 0.38).

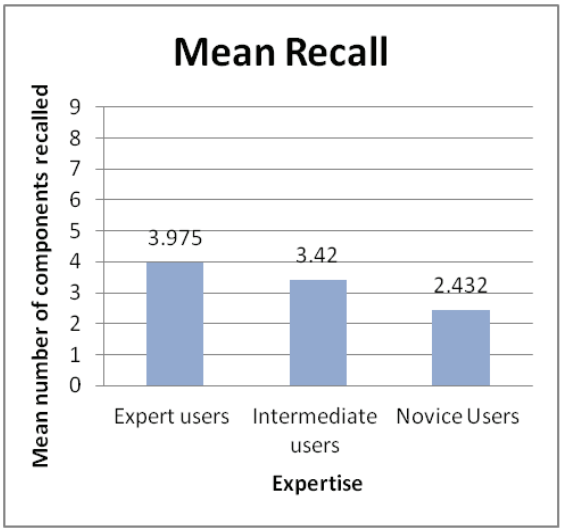


Figure 63: Mean Recall Score for the three user groups.

Result: Null Hypothesis# 7: (H_{o7}) was rejected.

Analysis for Annotation Styles and Zooming levels

Null Hypothesis# 8: (H_{o8}): Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with style of annotations used to annotate the 3D model.

Null Hypothesis# 9: (H_{o9}): Impact on learning (Recall Score) in an annotated 3D Model does not vary significantly with zooming levels.

Since a main effect for the between-subjects factor expertise was observed, we performed a separate within-subjects analysis for expert users, intermediate users and novice users to understand how does the recall score varies with the varying levels of the within-subjects factors annotation styles and zooming levels for each user group. To perform this analysis we split our data file of 27 participants on user expertise and perform a two way repeated measure ANOVA for each user group with the within-subjects factors being annotation styles and zooming levels and recall score as the independent variable.

5.2.1.1 Recall Analysis for Expert Users

5.2.1.1.1 Recall Analysis for the Nine Annotated Components

As observed from the collected data (see figure 64), the mean recall score for the three textual annotation styles were internal annotations (M = 3.926, SD = 0.293), external annotations: (M = 4.370, SD = 0.517), and box style annotations (M = 3.630, SD = .435) for n=81 components. However, the results of the data analysis revealed no significant main effect of the within-subjects factor "annotation style" on the recall scores of the expert users.

As observed from the collected data (see figure 65) the mean recall score for expert users at the three levels of zoom were zooming level 1 (M = 4.630, SD = 0.489), zooming level 2 (M = 3.778, SD = 0.289), and zooming level 3 (M = 3.519, SD = .524) for n=81 components. However, the results of the data analysis revealed no significant main effect of the within-subjects factor "zooming levels" on the recall scores of expert users.

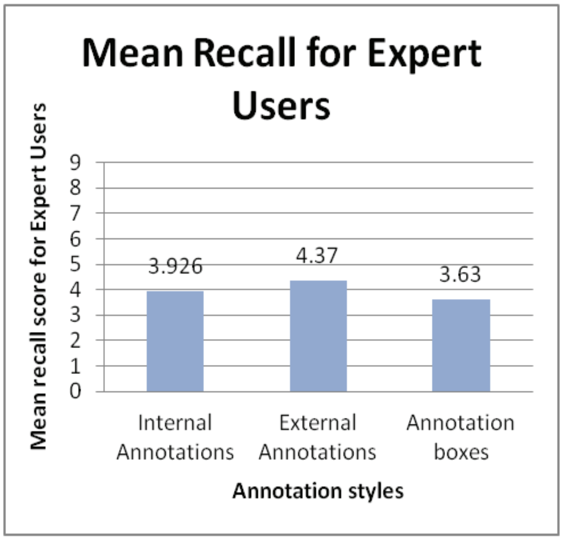


Figure 64: Mean Recall Score of expert user group for the three annotation styles.

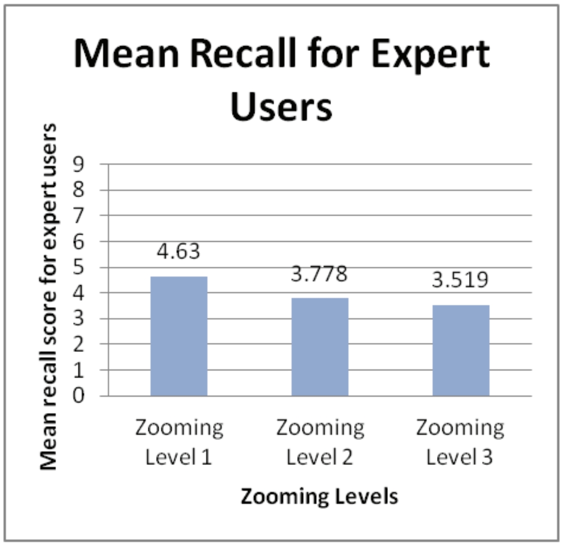


Figure 65: Mean Recall Score of expert user group at the three zooming levels.

In addition, the results revealed no significant two way interactions among the within-subjects factors annotation styles and zooming levels for the expert user group, (see figure 66).

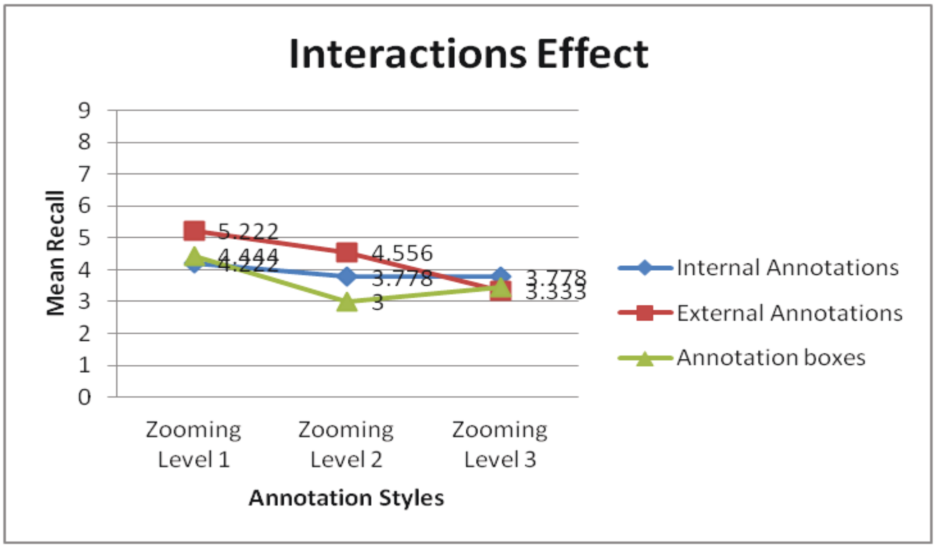


Figure 66: Interactions Effect between annotation styles and zooming levels for expert user group.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for expert users.

We later performed the non parametric tests (Friedman two way analyses of ranks) on the recall scores for the two component sets (the three search components that participants explicitly searched for in the search task and the other six components that served as distractions while performing the search) as the normality assumption of the data was not met with 9 expert participants.

5.2.1.1.2 Recall Analysis for Three Searched Components

As observed from the collected data (see figure 67 and 68), the mean recall score for the three annotation styles were internal style annotations (2.3), external style annotations (2.4), and box style annotations (1.9). Similarly, the mean recall score at the three levels of zoom were zooming level 1 (2.3), zooming level 2 (2.1), and zooming level 3 (2.2). Overall expert users were able to recall at least two of the three components the searched in the annotated 3D model successfully. However the mean recall score for the expert users in recalling the three components they explicitly searched in the annotated 3D model didn't vary significantly neither with the three annotation styles nor with the variation in levels of zoom.

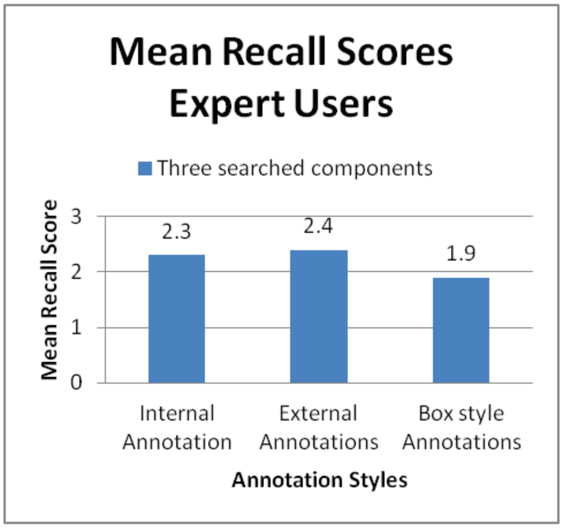


Figure 67: Mean Recall Score of expert users for the three searched components with varying styles of annotation.

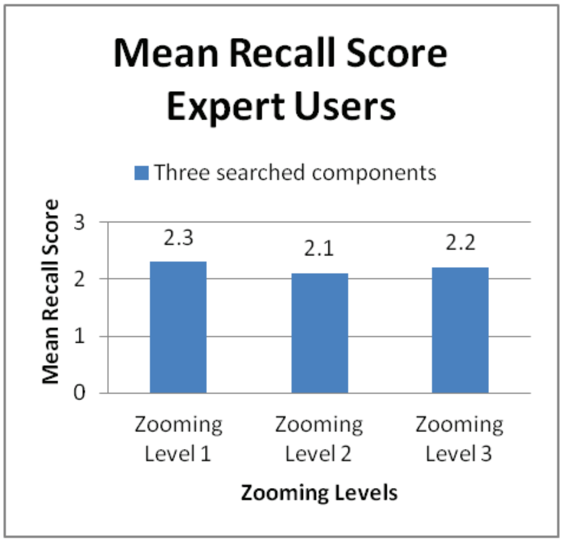


Figure 68: Mean Recall Score of expert users for the three searched components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the three components searched explicitly by expert users.

5.2.1.1.3 Recall Analysis for Six Distraction Components

As observed in the collected data (see figure 69 and 70) the mean recall score for the three textual annotation styles were internal style annotations (1.63), external annotation styles (1.96), and box style annotations (1.7). Similarly, the mean recall score at the three levels of zoom were zooming level 1 (2.3), zooming level 2 (1.67), and zooming level 3 (1.33). However, the results of the data analysis revealed that for the six distraction components the recall scores of expert users did not vary significantly, neither with the three annotation styles nor with the variation in levels of zoom.

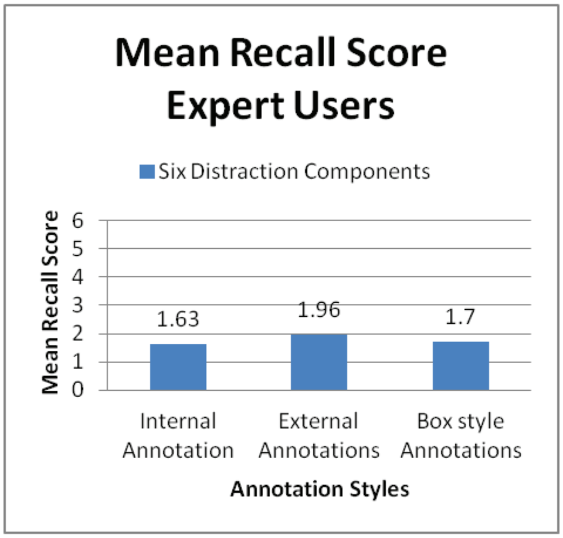


Figure 69: Mean Recall Score of expert users for the six distraction components with varying styles of annotation.

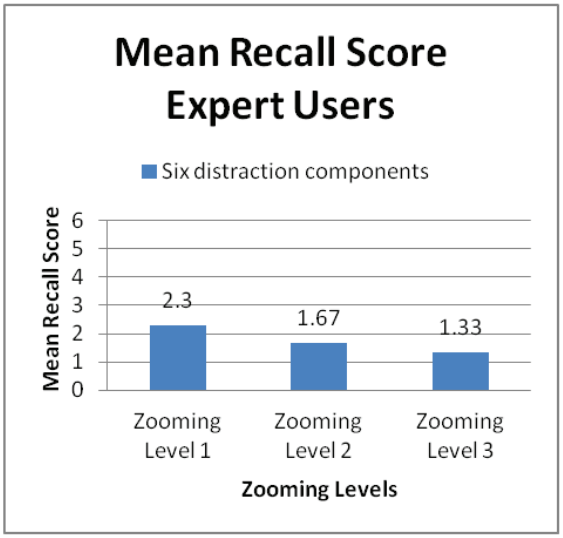


Figure 70: Mean Recall Score of expert users for the six distraction components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the six distraction components that expert users saw in search task.

5.2.1.2 Recall Analysis for Intermediate Users

5.2.1.2.1 Recall Analysis for the Nine Annotated Components

As observed from the collected data (see figure 71), the mean recall score for the three textual annotations were internal style annotations (M = 3.370, SD = 0.504), external style annotations (M = 3.407, SD = 0.509), and box style annotations (M = 3.481, SD = .547) for n=81 components. However, the results of the data analysis (two-way repeated measures ANOVA analysis) revealed no significant main effect of the within-subjects factor “annotation style” on the recall scores of the intermediate users.

Similarly, the mean recall score as observed from the collected data (see figure 72) at the three zooming levels were zooming level 1 (M = 3.63, SD = 0.605), zooming level 2 (M = 3.259, SD = 0.523), and zooming level 3(M = 3.370, SD = .483). However, the results of the data analysis revealed no significant main effect of the within-subjects factor “zooming level” on the recall scores of the intermediate users.

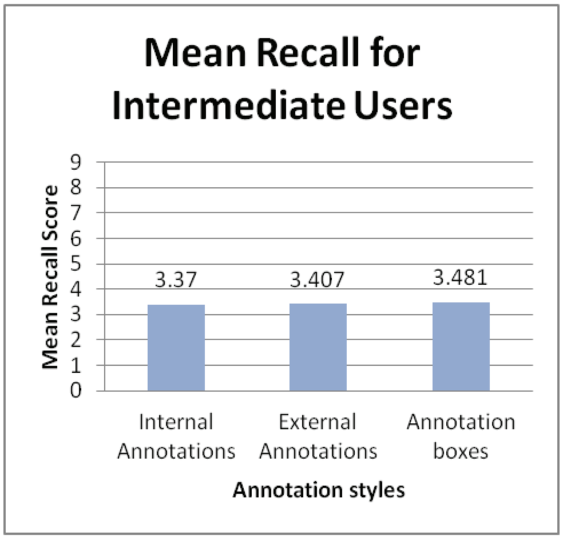


Figure 71: Mean Recall Score of intermediate user group for the three annotation styles.

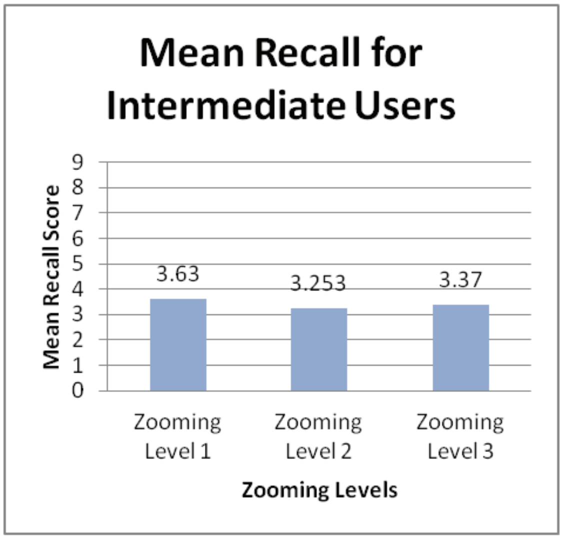


Figure 72: Mean Recall Score of intermediate user group at the three zooming levels.

In addition the results revealed no interactions effects for the two within-subjects factors "annotation styles" and "zooming levels", (see figure 73).

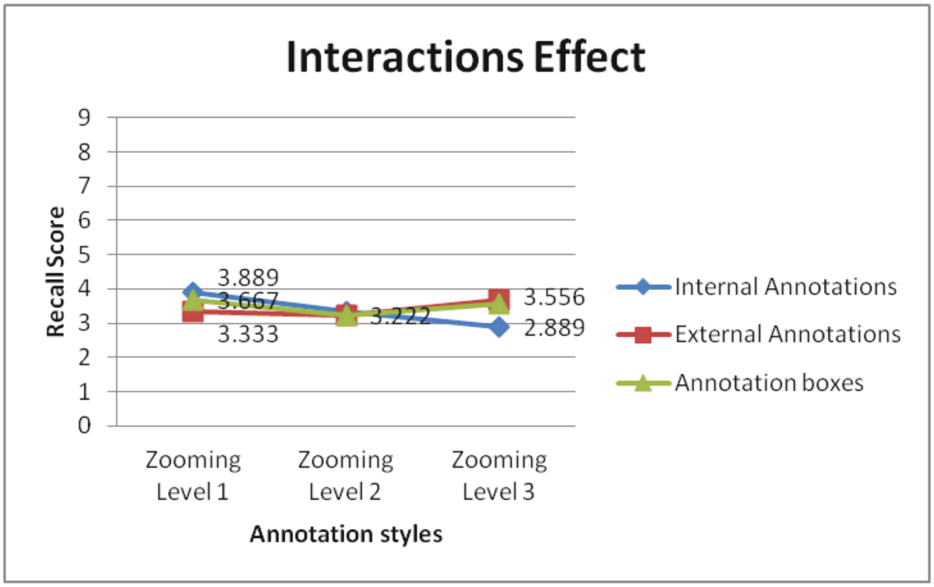


Figure 73: Interactions Effect between annotation styles and zooming levels for intermediate users.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for intermediate users.

We then performed the non parametric tests (Friedman two-way analyses of ranks) on the recall scores for the two components sets (the three search components that participants explicitly searched for in the search task and the other six components that served as distractions while performing the search). As the normality assumption of the data was not met with 9 participants in the intermediate user group.

5.2.1.2.2 Recall Analysis for the Three Searched Components

As observed from the collected data (see figure 74 and 75), the mean recall score for the intermediate users in recalling the three search components with the three textual annotation styles were internal style annotations (2.26), external style annotation styles (2.3), and box style annotations (2.3). Similarly, the mean recall score at the three zooming levels were zooming level 1 (2.4), zooming level 2 (2.19), and zooming level 3 (2.26). Overall intermediate users (like the expert users) were also able to recall at least two of the three components the searched in the annotated 3D model successfully. However, the mean recall score for the intermediate users in recalling the three search components did not vary significantly neither with the three annotation styles nor with the variation in levels of zoom.

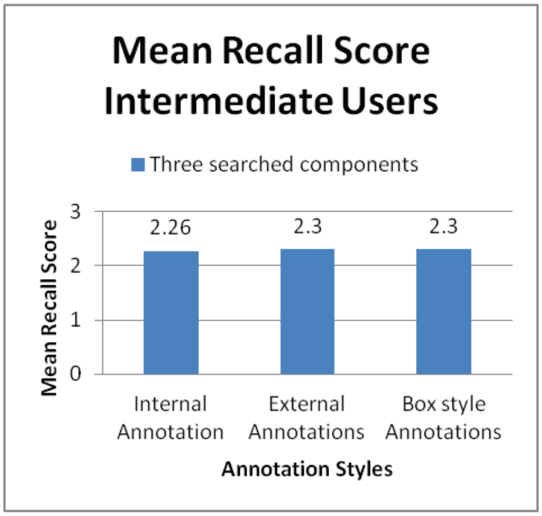


Figure 74: Mean Recall Score of intermediate users for the three searched components with varying styles of annotation.

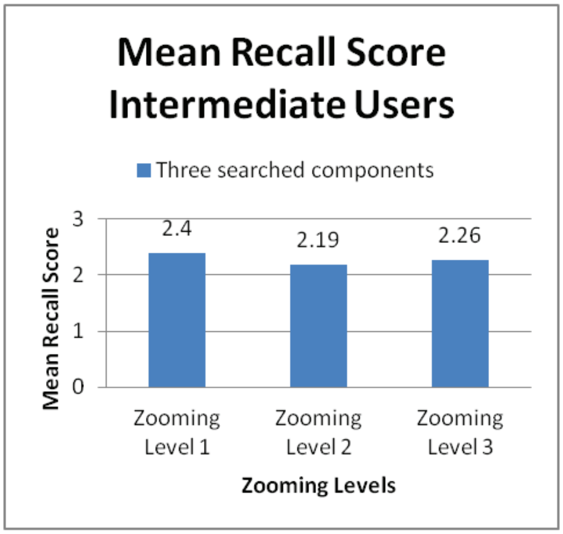


Figure 75: Mean Recall Score of intermediate users for the three searched components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the three components searched explicitly by expert users.

5.2.1.2.3 Recall Analysis for the Six Distraction Components

As observed from the collected data (see figure 76 and 77), the mean recall score for the intermediate users in recalling the six distraction components presented with the three textual annotations were internal style annotations (1.11), external style annotations (1.11), and box style annotation (1.87). Similarly, the mean recall score at the three zooming levels were zooming level 1 (1.22), zooming level 2 (1.07), and zooming level 3 (1.11). However, the results of the data analysis revealed that for the six distraction components the recall scores of intermediate users did not vary significantly, neither with the three annotation styles nor with the variation in levels of zoom.

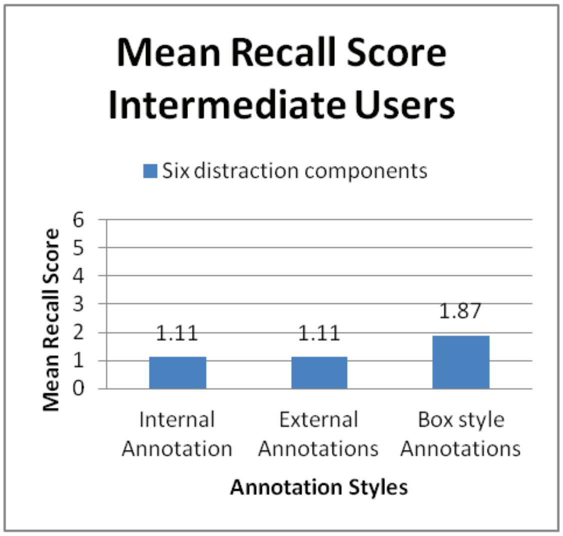


Figure 76: Mean Recall Score of intermediate users for the six distraction components with varying styles of annotation.

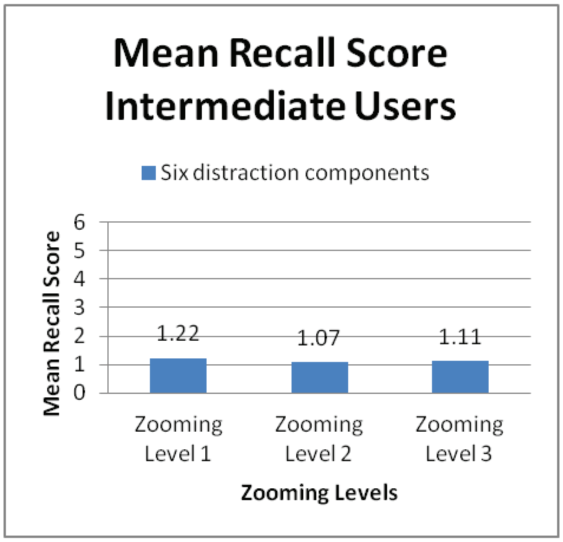


Figure 77: Mean Recall Score of intermediate users for the six distraction components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the six distraction components that expert users saw while searching for the three search task components.

5.2.1.3 Recall Analysis for Novice Users

5.2.1.3.1 Recall Analysis for the Nine Annotated Components

As observed from the collected data (see figure 78), the mean recall scores for the three textual annotations were internal annotations (M = 2.185, SD = .320), external annotations (M = 2.556, SD = 0.294), and box style annotations (M = 2.556, SD = 0.294), for n=81 components. However, the results of the data analysis (two-way repeated measures ANOVA analysis) revealed no significant main effect of the within-subjects factor “annotation style” on the recall scores of the novice users.

Similarly the mean recall score as observed from the collected data (see figure 79) for novice users at the three zooming levels were zooming level 1 (M = 2.185, SD = 0.338), zooming level 2 (M = 2.593, SD = 0.368), and zooming level 3 (M = 2.519, SD = .216). However, the results of the data analysis revealed no significant main effect of the within-subjects factor “zooming level” on the recall scores of the novice users.

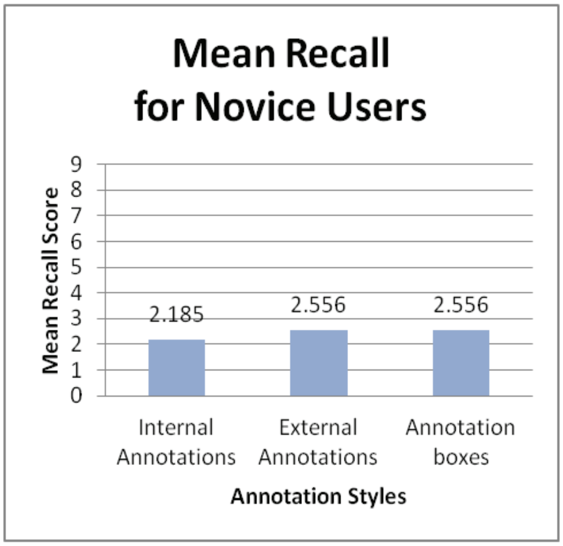


Figure 78: Mean Recall Score of novice users for the three annotation styles.

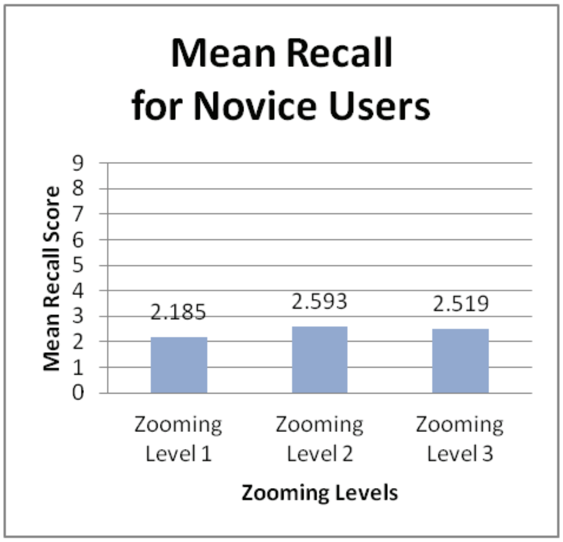


Figure 79: Mean Recall Score of novice users at the three zooming levels.

In addition the results revealed no interactions effects for the two within-subjects factors “annotation styles” and “zooming levels”, (see figure 80).

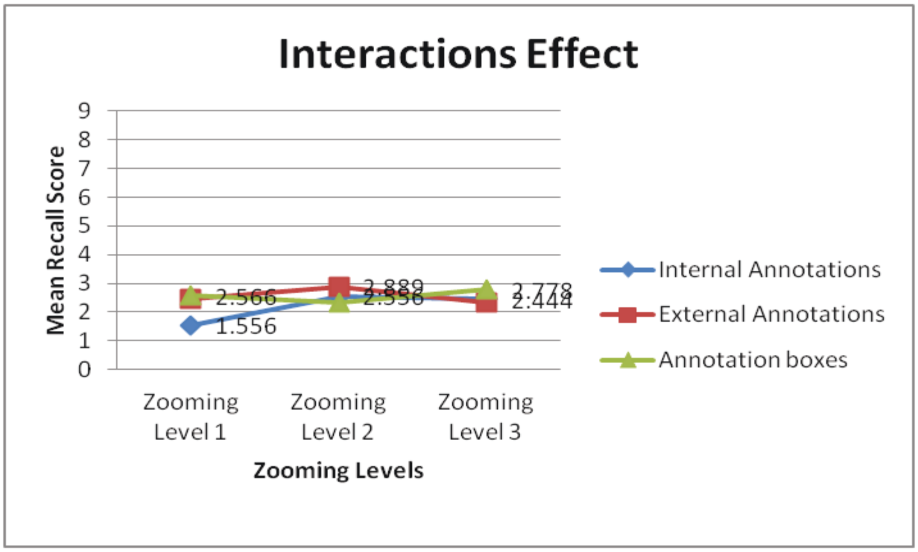


Figure 80: Interactions Effect between annotation styles ad zooming levels for novice users.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for novice users.

We then performed the non parametric tests (Friedman two way analyses of ranks) on the recall scores for the two component sets (the three search components that participants explicitly searched for in the search task and the other six components that served as distractions while performing the search), as the normality assumption of the data was not met with 9 participants in the novice user group.

5.2.1.3.2 Recall Analysis for the Three Searched Components

As observed from the collected data (see figure 81 and 82), the mean recall score for the novice users in recalling the three search components with the three textual annotation styles were internal style annotations (1.63), external style annotations (2), and box style annotations (1.92). Similarly, the mean recall score at the three levels of zoom were zooming level 1 (1.52), zooming level 2 (2.03), and zooming level 3 (2). Overall novice users (like the expert users) were also able to recall at least two of the three components the searched in the annotated 3D model successfully. However, the mean recall score for the novice users in recalling the three search components did not vary significantly neither with the three annotation styles nor with the variation in levels of zoom.

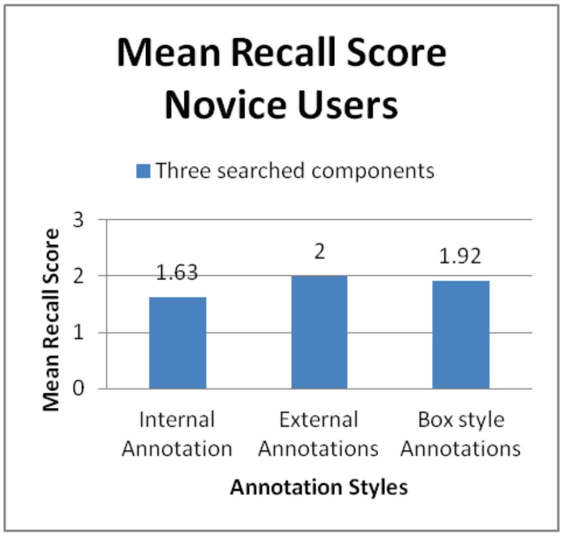


Figure 81: Mean Recall Score of novice users for the three searched components with varying styles of annotation.

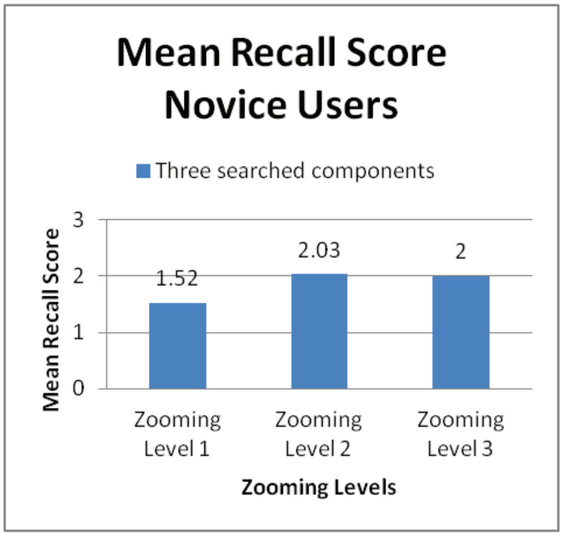
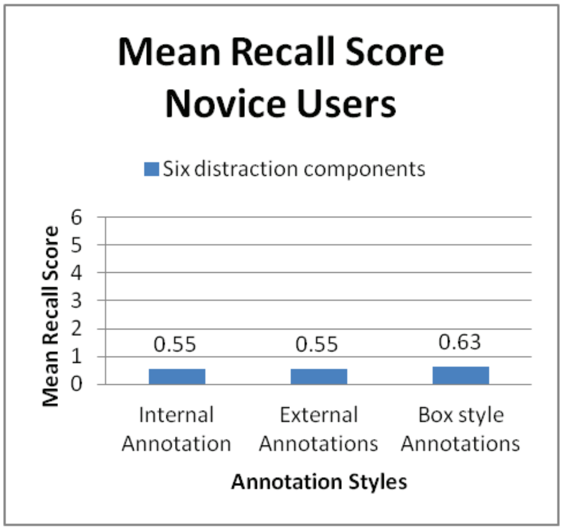


Figure 82: Mean Recall Score of novice users for the three searched components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the three components searched explicitly by expert users.

5.2.1.3.3 Recall Analysis for the Six Distraction Components

As observed from the collected data (see figure 83 and 84), the mean recall score for the novice users in recalling the six distraction components presented with the three textual annotation styles were internal style annotations (0.55), external style annotations (0.55), and box style annotation styles (0.63). Similarly, the mean recall score at the three zooming levels were zooming level 1 (0.67), zooming level 2 (0.55), and zooming level 3 (0.52). However, the results of the data analysis revealed that for the six distraction components the recall scores of intermediate users did not vary significantly, neither with the three annotation styles nor with the variation in levels of zoom.



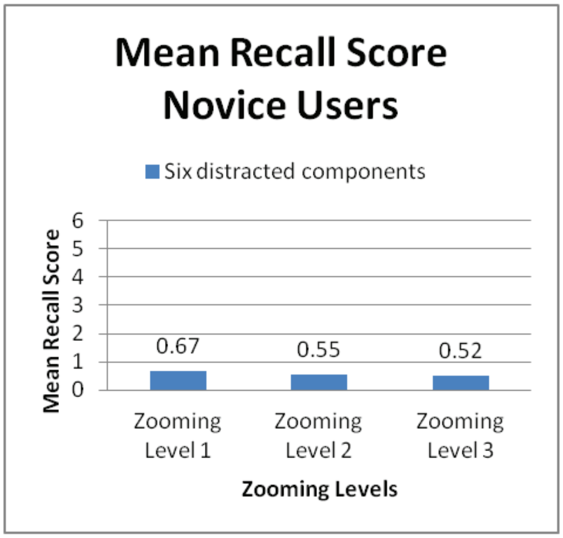


Figure 83: Mean Recall Score of novice users for the six distraction components with varying styles of annotation.

Figure 84: Mean Recall Score of novice users for the six distraction components with varying levels of zoom.

Result: Null Hypothesis# 8: (H_{o8}) and Null Hypothesis# 9: (H_{o9}) were not rejected for the six distraction components that expert users saw while searching for the three search task components.

5.3 User Preference

5.3.1 User Rating Analysis

5.3.1.1 Readability Ratings

The result of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and "readability" ratings as the dependent variable) revealed that the user preference ratings for the usability factor "readability" of the three annotation styles did not vary significantly with the variation in levels of expertise. Similarly, the data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and readability ratings as the dependent variable for each annotation style) also revealed that the user preference ratings for the usability factor "readability", for each of the three annotation styles did not vary significantly with the variation in levels of zoom.

However, as observed from the collected data (see figure 85 below) the user preference ratings for the usability factor "readability" did vary with the annotation style, where external style annotations received the highest levels of agreement (25) among 27 participants.

In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with annotation styles as the within-subjects factor and "readability" ratings as the dependent variable) revealed significant differences in the "readability" ratings for the three textual annotation techniques ($\chi^2(2) = 26.843$, $p= 0.000001483$) for 27 participants.

Performing a post hoc analysis, a pair wise comparison with "Wilcoxon signed rank test" for the three annotation styles with Bonferroni corrections, resulting in the adjustment of significance level to $p=0.0167$ (0.05/3). Results revealed a statistically significant difference in the "readability" ratings between external style annotation and internal style annotations ($Z = -4.3$, $p= 0.000017$), and between external style annotation and box style annotation ($Z = 3.923$, $p= 0.000017$) but not between internal style annotation and box style annotations. As observed from the collected data (see figure 85) the overall "readability" ratings for external style annotations were significantly better than the overall "readability" ratings of internal and box style annotations.

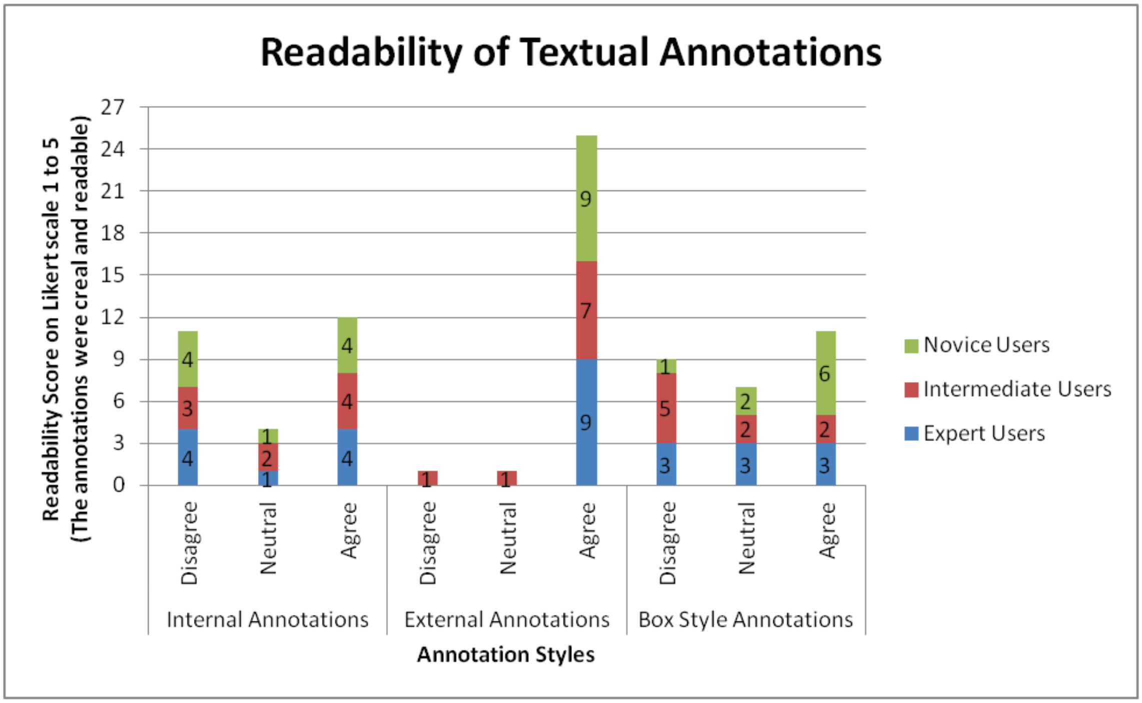


Figure 85: Readability ratings for the three annotation styles.

5.3.1.2 Look and Feel Ratings

The result of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and the "look and feel" ratings as the dependent variable) revealed that the user preference ratings for the usability factor "look and feel", for the three annotation styles did not vary significantly with the variation in levels of expertise. Similarly, the data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and the "look and feel" ratings as the dependent variable for each annotation style) also revealed that the user preference ratings for the usability factor "look and feel" for each of the three annotation styles did not vary significantly with the variation in levels of zoom.

However, as observed from the collected data (see figure 86) the user preference ratings for the usability factor "look and feel" did vary with the annotation style, where external style annotations received the highest levels of agreement (23) among 27 participants.

In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with annotation styles as the within-subjects factor and the "look and feel" ratings as the dependent variable) revealed significant differences in the "look and feel" ratings for the three textual annotation techniques ($\chi^2(2) = 36.5$, $p= 0.000000012$) for 27 participants.

Performing a post hoc analysis, a pair wise comparison with "Wilcoxon signed rank test" for the three annotation styles with Bonferroni corrections, resulting in the adjustment of significance level to $p=0.0167$ (0.05/3). Results revealed a statistically significant difference in the "look and feel" ratings between external style annotation and internal style annotations ($Z = -4.46$, $p= 0.000008$), and between external style annotation and box style annotation ($Z = 4.10$, $p= 0.000041$) but not between internal style annotation and box style annotations. As observed from the collected data (see figure 86) the overall "look and feel" ratings for external style annotations were significantly higher than the overall "look and feel" ratings of internal and box style annotations.

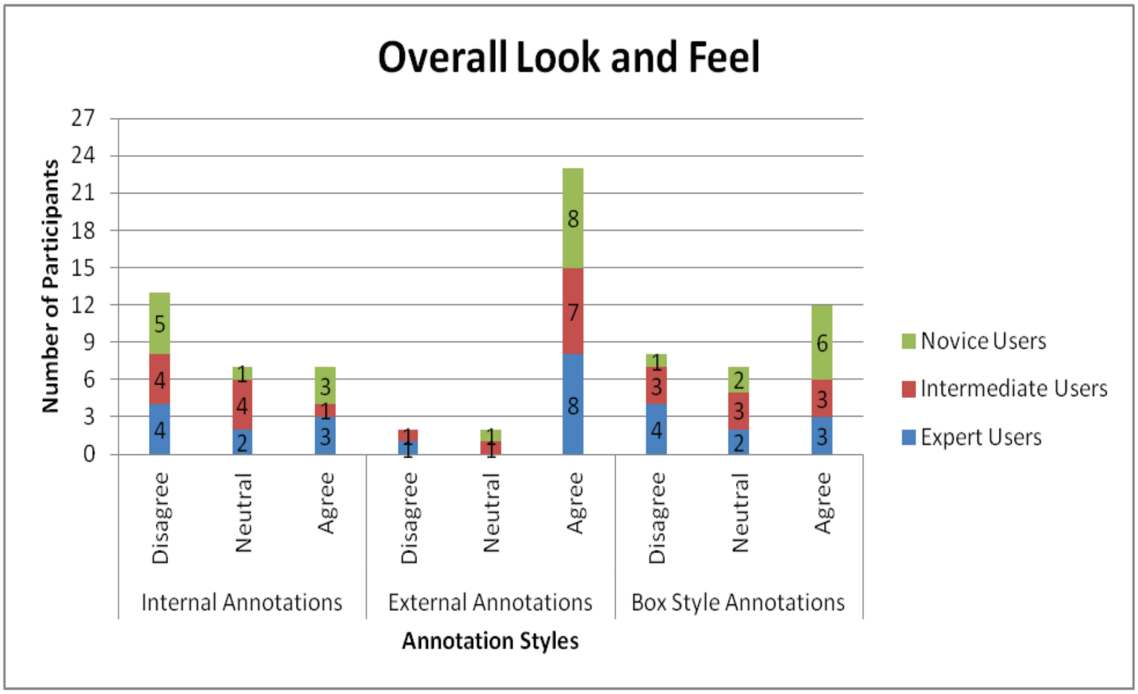


Figure 86: Look and Feel ratings for the three annotation styles.

5.3.1.3 Ease of Usage Ratings

The result of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and "ease of usage" ratings as the dependent variable) revealed that the user preference ratings for the usability factor "ease of usage" for the three annotation styles did not vary significantly with the variation in levels of expertise. Similarly, the data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and "ease of usage" ratings as the dependent variable for each annotation style) also revealed that the user preference ratings for the usability factor "ease of usage" for each of the three annotation styles did not vary significantly with the variation in levels of zoom.

However, as observed from the collected data (see figure 87) the user preference ratings for the usability factor "ease of usage" did vary with the annotation style, where external style annotations received the highest levels of agreement (22) among 27 participants.

In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with annotation styles as the within-subjects factor and "ease of usage" ratings as the dependent variable) revealed significant differences in the "ease of usage" ratings for the three textual annotation techniques ($\chi^2(2) = 20.931$, $p = 0.000028$) for 27 participants.

Performing a post hoc analysis, a pair wise comparison with "Wilcoxon signed rank test" for the three annotation styles with Bonferroni corrections, resulting in the adjustment of significance level to $p=0.0167$ (0.05/3). Results revealed a statistically significant difference in the "ease of usage" ratings between external style annotation and internal style annotations ($Z = -4.28$, $p = 0.000018$), between external style annotation and box style annotation ($Z = 3.5$, $p = 0.000041$), and between internal style annotation and box style annotation ($Z = 2.61$, $p = 0.009$). This implied that the overall "ease of usage" ratings for the three annotation styles differed significantly from each other. As observed from the collected data (see figure 87) the "ease of usage" ratings for external style annotations were significantly better than internal and box style annotations, followed by the "ease of usage" ratings for box style annotations which were significantly better than the "ease of usage" ratings for internal style annotations.

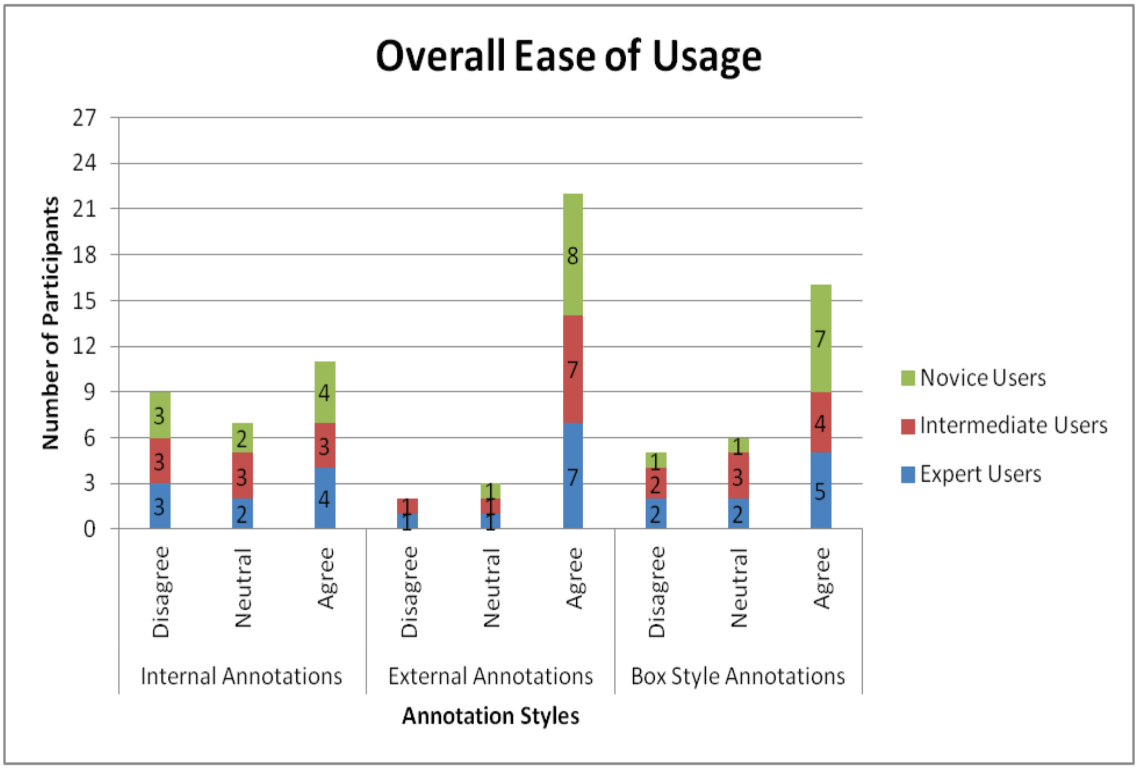


Figure 87: Ease of usage ratings for the three annotation styles.

5.3.1.4 Satisfaction Ratings

The result of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and "satisfaction" ratings as the dependent variable) revealed that the user preference ratings for the usability factor "satisfaction" for the three annotation styles did not vary significantly with the variation in levels of expertise. Similarly, the data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and "satisfaction" ratings as the dependent variable for each annotation style) also revealed that the user preference ratings for the usability factor "satisfaction" for each of the three annotation styles did not vary significantly with the variation in levels of zoom.

However, as observed from the collected data (see figure 88) the user preference ratings for the usability factor "satisfaction" did vary with the annotation style, where external style annotations received the highest levels of agreement (21) among 27 participants.

In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with annotation styles as the within-subjects factor and “satisfaction” ratings as the dependent variable) revealed significant differences in the “satisfaction” ratings for the three textual annotation techniques ($\chi^2(2) = 38.72$, p= 0.000000004) for 27 participants.

Performing a post hoc analysis, a pair wise comparison with “Wilcoxon signed rank test” for the three annotation styles with Bonferroni corrections, resulting in the adjustment of significance level to p=0.0167 (0.05/3). Results revealed a statistically significant difference in the “satisfaction” ratings between external style annotation and internal style annotations (Z = -4.55, p= 0.0000054), between external style annotation and box style annotation (Z = 3.79, p= 0.000147), and between internal style annotation and box style annotation (Z = 2.83, p= 0.005).This implied that the overall “satisfaction” ratings for the three annotation styles differed significantly from each other. As observed from the collected data (see figure 88) the “satisfaction” ratings for external style annotations were significantly higher than internal and box style annotations, followed by the “satisfaction” ratings for box style annotations which were significantly better than the “satisfaction” ratings for internal style annotations.

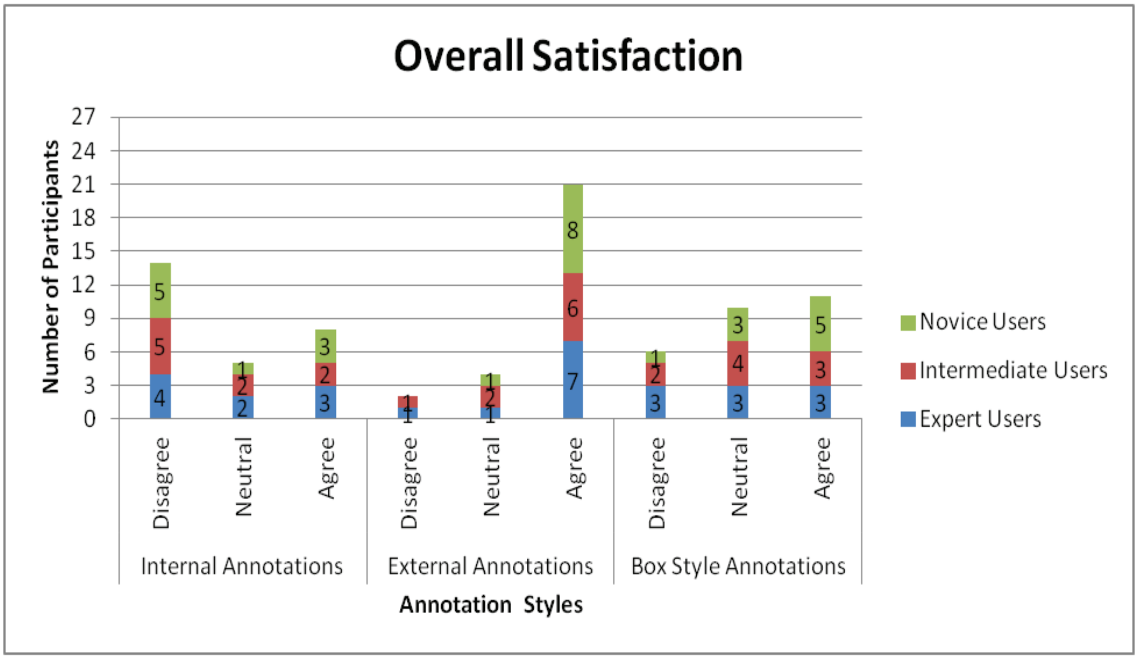


Figure 88: Satisfaction ratings for the three annotation styles.

5.3.2 Rank Analysis

5.3.2.1 Analysis for Expertise

Null Hypothesis# 10: (H_{o10}): The user preference for an annotation style does not vary significantly with the level of expertise.

5.3.2.1.1 Rank Analysis for Internal Annotation Style

As observed from the collected data (see figure 89, participant# 14) the median user preference rank of the 27 participants varying in levels of expertise for internal annotation style were expert users "3", intermediate users "3", and novice users "3", where a rank of "1" was given to the most preferred annotation style and a rank of "3" was given to the least preferred annotation style. In addition, the results of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to internal annotation style with varying levels of user expertise.

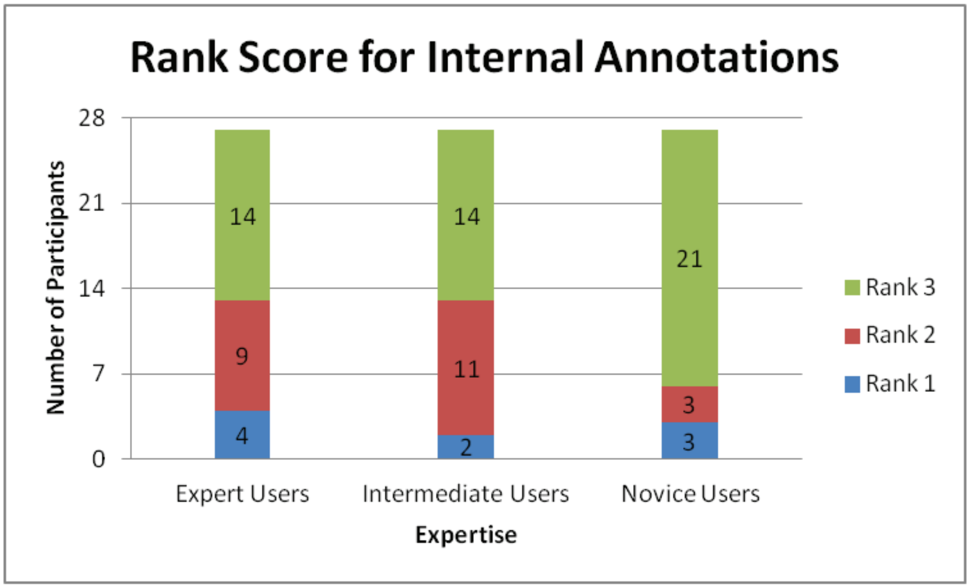


Figure 89: User preference ranks for internal annotation style with varying levels of expertise.

Result: Null Hypothesis# 10: (H_{o10}) was not rejected for internal annotation style.

5.3.2.1.2 Rank Analysis for External Annotation Style

As observed from the collected data (see figure 90, participant# 14) the median user preference rank of the 27 participants varying in levels of expertise for external annotation style were expert users ”1”, intermediate users ”1”, and novice users ”1”, where a rank of “1” was given to the most preferred annotation style and a rank of “3” was given to the least preferred annotation style. In addition, the results of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to external style annotation with varying levels of user expertise.

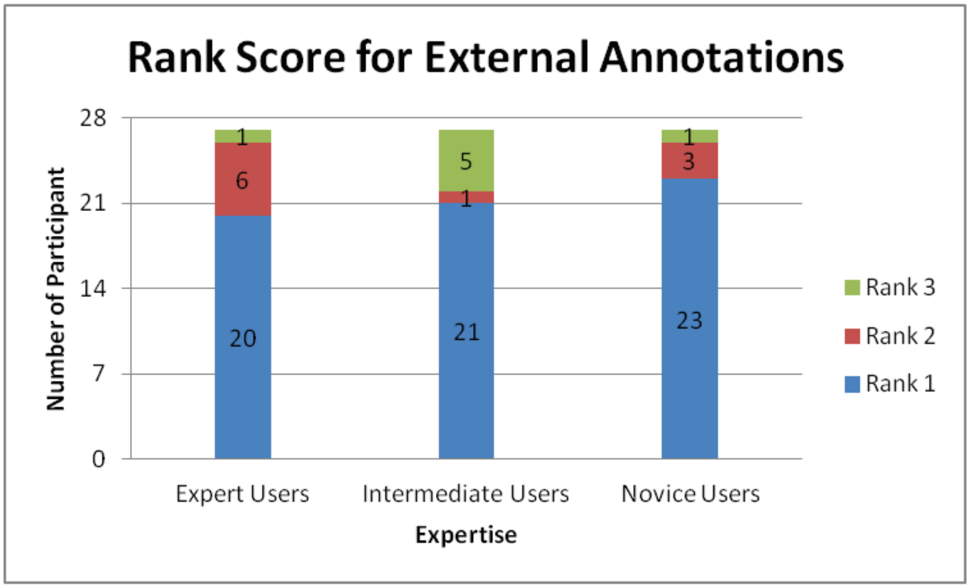


Figure 90: User preference ranks for external annotation style with varying levels of expertise.

Result: Null Hypothesis# 10: (H_{o10}) was not rejected for external annotation style.

5.3.2.1.3 Rank Analysis for Box Style Annotation

As observed from the collected data (see figure 91, participant# 14) the median user preference rank of the 27 participants varying in levels of expertise for box style annotations were expert users ”2”, intermediate users ”2”, and novice users ”2”, where a rank of “1” was given to the most preferred annotation style and a rank of “3” was given to the least preferred annotation style. In addition, the results of our data analysis (Kurskal-Wallis H test with expertise as the between subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to box style annotations with varying levels of user expertise.

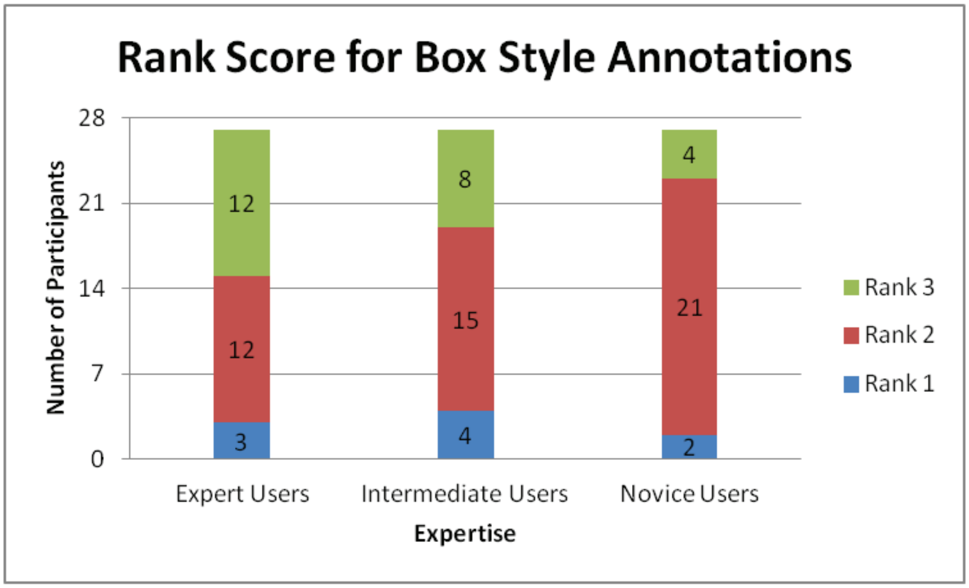


Figure 91: User preference ranks for box style annotations with varying levels of expertise.

Result: Null Hypothesis# 10: (H_{o10}) was not rejected for box style annotations.

5.3.2.2 Analysis for Zooming Levels

Null Hypothesis# 11: (H_{o11}): The user preference for an annotation style does not vary significantly with the level of zoom.

5.3.2.2.1 Rank Analysis for Internal Annotation Style

As observed from the collected data (see figure 92, participant# 14) the median user preference rank assigned to internal style annotations by 27 participants at the three zooming levels were zooming level 1 ”3”, zooming level 2 ”3”, and zooming level 3 ”3”, where a rank of “1” was given to the most preferred annotation style and a rank of “3” was given to the least preferred annotation style. In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to internal style annotations at the three zooming levels.

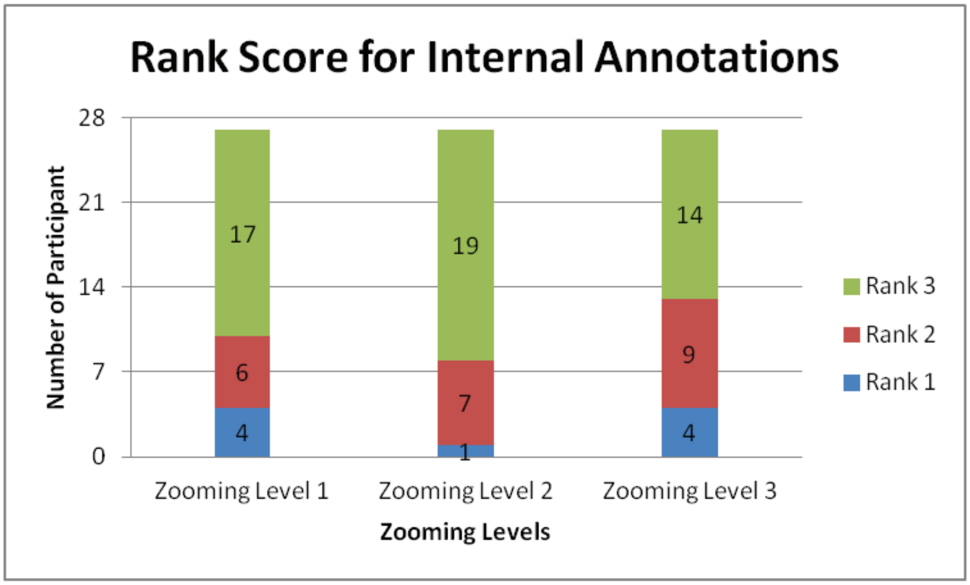


Figure 92: User preference ranks for internal annotation style at the three zooming levels.

Result: Null Hypothesis# 11: (H_{o11}) was not rejected for internal annotation style.

5.3.2.2.2 Rank Analysis for External Annotation Style

As observed from the collected data (see figure 93, participant# 14) the median user preference rank assigned to external style annotations by 27 participants at the three zooming levels were zooming level 1 ”1”, zooming level 2 ”1”, and zooming level 3 ”1”, where a rank of “1” was given to the most preferred annotation style and a rank of “3” was given to the least preferred annotation style. In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to external style annotations at the three zooming levels.

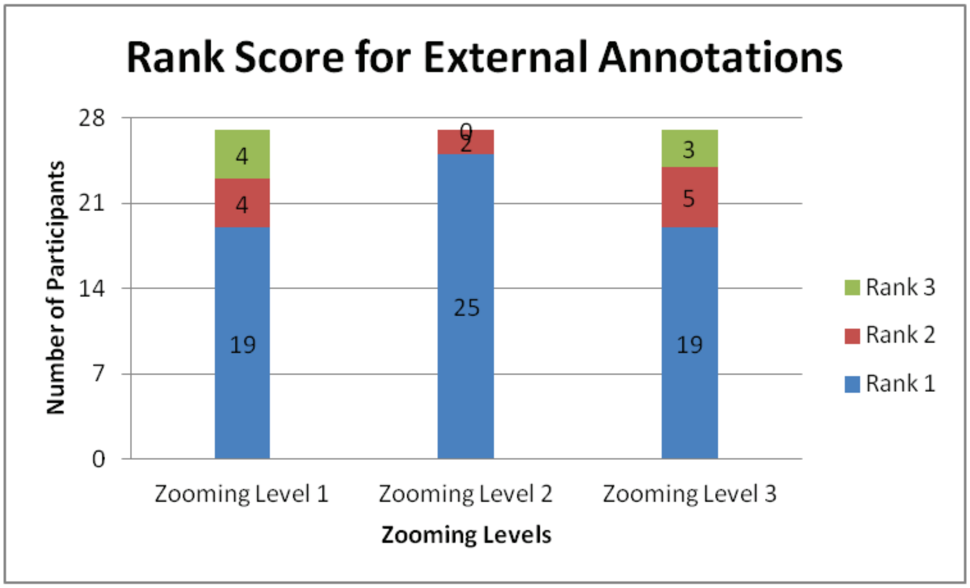


Figure 93: User preference ranks for external annotation style at the three zooming levels.

Result: Null Hypothesis# 11: (H_{o11}) was not rejected for external annotation style.

5.3.2.2.3 Rank Analysis for Box Style Annotation

As observed from the collected data (see figure 94, participant# 14) the median user preference rank assigned to box style annotations by 27 participants at the three zooming levels were zooming level 1 ”3”, zooming level 2 ”2”, and zooming level 3 ”2”, where a rank of “1” was given to the most preferred annotation style and a rank of “3” was given to the least preferred annotation style. In addition, the results of our data analysis (Friedman two-way analysis of variance of ranks with zooming levels as the within-subjects factor and user preference ranks as the dependent variable) revealed no significant differences in the ranks assigned to box style annotations at the three zooming levels.

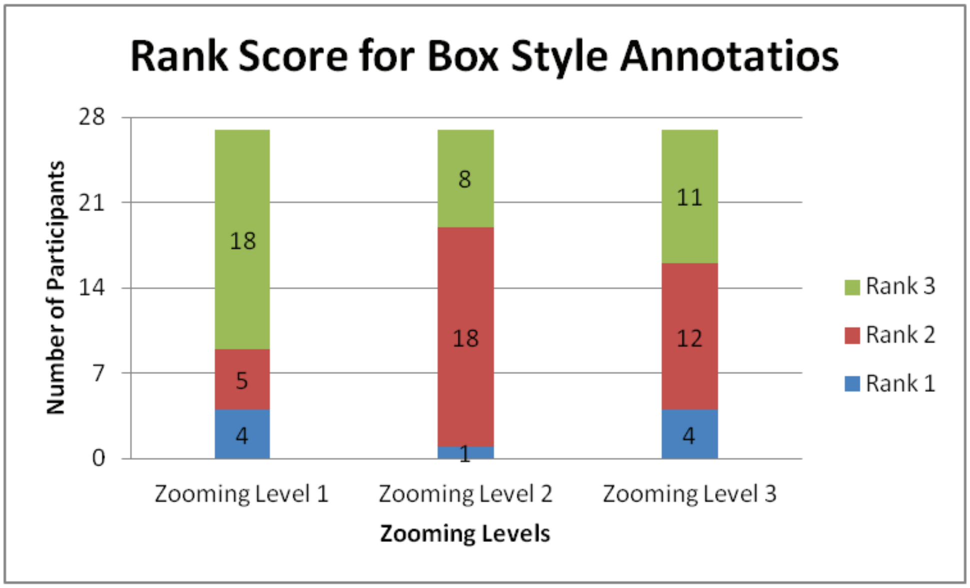


Figure 94: User preference ranks for box style annotation at the three zooming levels.

Result: Null Hypothesis# 11: (H_{o11}) was not rejected for external annotation style.

5.3.2.3 Analysis for Annotation Style

Null Hypothesis# 12: (H_{o12}): The split in the overall participant population for user preference will not vary (be equal) for the three annotation styles.

5.3.2.3.1 Chi-Square Analysis for Annotation Styles

As observed from the collected data (see figure 95) the three textual annotation styles were not equally popular, the data reflected that overall participants preferred external style annotations more than internal and box style annotations. In addition, the results of our data analysis (Pearson's Chi-square test also known as chi-square goodness-of-fit test) revealed significant differences in the preferences for the three textual annotation styles, the split in the participant population base was significantly different from the hypothesized equal split population $\chi(2) = 32.7$, $p = 0.000000081$.

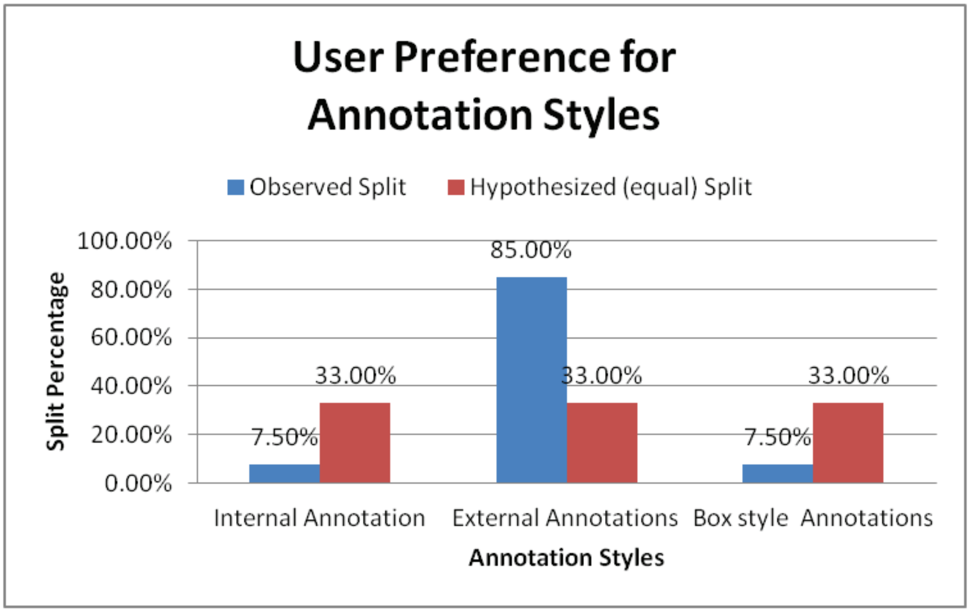


Figure 95: Split in participant population for the three annotation styles.

Result: Null Hypothesis# 12: (H_{o12}) was rejected.

5.4 Qualitative Data Analysis

The result of our quantitative data analysis is further substantiated by the qualitative feedback received from the participants in the interview session conducted at the end of the study where they reflected on the strengths and weaknesses of the three textual annotations used in the study.

5.4.1 External Annotation Style

(a) Participants reported that with external style annotations, the textual details were very clear and readable as these were highlighted against a semi-transparent white background.

(b) The presence of a line, connecting the text bubble with the 3D component made it easy for the participant to establish the visual link between the annotation and the annotated component.

(c) Participants reported that with external annotation they were quick and sure of their component selection as the anchor point, end point of the connecting line ending at the component side, pin pointed the exact part in the 3D model.

(d) Participants reported that external style annotations were visually appealing and easy to spot as they were not residing on the surface of the 3D model rather were floating like balloons on the 3D surface and had (clear and visible) connecting lines linking the textual annotations with their relevant parts,

5.4.2 Box Style Annotation

(a) Participants reported that external style annotations had just enough text to complete the search task and box style annotations on the other hand too much information, most of which was redundant with respect to the search task. Participants did appreciate the detailed content as it provided them with better explanation of the component for learning but felt that it was not required and the details should be shown on demand.

(b) Displaying many box style annotations (with a lot of textual content) at once on the screen made box style annotation look complex and overwhelming to the participants.

(c) Box style annotations created a lot of visual clutter on screen which became worse at lower levels of zooming where the screen was so full of text boxes that collided often as participants (rotated) interacted with the 3D model.

(d) Participants reported that the text inside the box style annotations were clear and readable except in cases where the annotations collided.

5.4.3 Internal Style Annotations

(a) The text inside internal style annotations was not as clear as it was with external and box style annotation where the font size of the text did not vary with the distance of the annotation from the user screen.

(b) At times, the text of the internal annotations would merge with the background annotated objects where the dark grey or black shade/color of the 3D objects would make it harder for participants to read the annotations.

(c) Novice users reported that with internal style annotations they were forced to interact with the 3D model in order to bring the far away annotated parts closer to the screen to be able to read the annotations clearly, which was not convenient. Whereas this was not the case with external or box style annotations as they font size remained the same throughout their interactions.

(d) Participants reported that with internal style annotations in general it was difficult to establish the visual connection between the textual annotation and the part it was annotating, as there were no connection lines. This became more difficult when the length of the internal annotations were longer and span multiple components. Participants reported, they had to interact (rotate) a lot with the 3D model to determine which component of the 3D model was annotated by the internal style annotations.

The qualitative feedback provided by participants, as listed above reflected that external annotation style had an overall better look and feel, were readable and convenient to use. Moreover they supported participants at the task of searching for components, and in exploring and interacting with the 3D models.

5.5 Summary of Research Hypotheses

Research (Alternate) Hypotheses	Null Hypotheses	Result
Efficiency at task of searching for components in an annotated 3D Model varied significantly with varying level of expertise.	Null Hypothesis# 1: (H_{o1})	Not Rejected
Accuracy at task of searching for components in an annotated 3D Model varied significantly with varying level of expertise.	Null Hypothesis# 2: (H_{02})	Not Rejected
Efficiency at task of searching for components in an annotated 3D Model varied significantly with style of annotations used to annotate the 3D model.	Null Hypothesis# 3: (H_{o3})	Rejected
Accuracy at task of searching for components in an annotated 3D Model varied significantly with style of annotations used to annotate the 3D model.	Null Hypothesis# 4: (H_{o4})	Rejected
Efficiency at task of searching for components in an annotated 3D Model varied significantly with zooming levels.	Null Hypothesis# 5: (H_{o5})	Not Rejected
Accuracy at task of searching for components in an annotated 3D Model varied significantly with zooming levels.	Null Hypothesis# 6: (H_{o6})	Not Rejected
Impact on learning (Recall Score) in an annotated 3D Model varied significantly with varying level of expertise.	Null Hypothesis# 7: (H_{o7})	Rejected
Impact on learning (Recall Score) in an annotated 3D Model varied significantly with style of annotations used to annotate the 3D model.	Null Hypothesis# 8: (H_{o8})	Not Rejected
Impact on learning (Recall Score) in an annotated 3D Model varied significantly with zooming levels.	Null Hypothesis# 9: (H_{o9})	Not Rejected
The user preference for an annotation style varied significantly with the level of expertise.	Null Hypothesis# 10: (H_{o10})	Not Rejected
The user preference for an annotation style varied significantly with the level of zoom.	Null Hypothesis# 11: (H_{o11})	Not Rejected
The split in the overall participant population for user preference will vary for the three annotation styles	Null Hypothesis# 12: (H_{o12})	Rejected

Table 7: Summary of the Research Hypotheses.

CHAPTER 6 RESULT SUMMARY AND CONCLUSION

6.1 Results Summary

As reported in Chapter 5, the majority of our findings (research hypothesis) revealed no significant differences (were not rejected), however we did get significant results for the annotation styles used in the study (please see section 5.5 Research Hypotheses Result Summary).

6.1.1 Performance

1) The results from our study suggested that the participant performance in the task of searching for components inside a 3D model did not vary significantly with the varying levels of expertise and zooming levels. This implied that participant performance in the search task was independent of the level of expertise (in interacting with 3D models and software) and the level of zoom at which the user interacts with the 3D model (see Null Hypothesis #1, 2, 5, and 6 in section 5.5 Research Hypotheses Result Summary).

2) The results from our study also suggested that the participant performance in the task of searching for components inside a 3D model varied significantly with the annotation styles used in the study. As this performance was measured in two parts (a) efficiency and (b) accuracy, we found that both efficiency and accuracy varied significantly with the annotation styles used with the 3D model (see Null Hypothesis # 3 and 4 in section 5.5 Research Hypotheses Result Summary). We found that both efficiency (time) and accuracy (error count) varied in a high-high and low-low pattern with the varying levels of annotation style. This implied that an annotation style either improved participant's overall performance with high efficiency and high accuracy score (participants went faster and with less errors at the search task) or reduced their performance (participants took more time and made more errors, incorrect component selections at the search task).

6.1.2 Impact on Learning

1) The results from our study revealed that the difference in the recall scores did not vary significantly with the variation in the levels of zoom and annotation styles for the three user groups (expert users, intermediate users and novice users). This implied that the participant's recall scores (the number of recalled components) in the three user groups were independent of the level of zoom at which participants interacted with the 3D models and were also independent of the three textual annotation styles used in the study (see Null Hypothesis #8 and 9 in section 5.5 Research Hypotheses Result Summary).

2) The results of the study also revealed that the impact of learning varied significantly with the level of expertise in interacting with 3D models and software. We found that the recall score of participants varied in a high-high, low-low relationship with respect to a variation in the levels the expertise. This implied that participants in the expert user group with the highest level of expertise in interacting with 3D models and software had a significantly higher recall scores in comparison to participants in the novice user group with the lowest level of expertise in interacting with 3D models and software. The mean recall score of the intermediate users with an intermediate level of expertise (greater than that of novice users but less than that of expert users), was greater than the mean recall score of novice users and less than the mean recall score of expert users (see Null Hypothesis #7 in section 5.5 Research Hypotheses Result Summary).

6.1.3 User Preference

1) The results of our study reflected that the user preference ranks assigned to the three annotation styles (internal annotation style, external annotation style and box style annotation), where a rank of "1" was given to the most preferred annotation style and a rank of "3" was given to the least preferred annotation style, (with no ties) at each zooming level, did not vary significantly with the varying levels of expertise and varying levels of zoom. This implied that participant's preference towards a certain annotation style was independent of the level of expertise (in interacting with 3D models and software) and was independent of the variation in the zooming levels at which the user

interacted with the 3D model (see Null Hypothesis #10 and 11 in section 5.5 Research Hypotheses Result Summary).

2) The results of our study also revealed that the split in the participant population for the most preferred annotation style among the three textual annotation styles considered in the study (internal annotation style, external annotation style and box style annotation) were significantly different. This implied that participants in our study did have a strong preference towards a certain annotation style and that all annotation styles were not equally preferred. We found that participants had a strong liking for external style annotations over internal and box style annotations when interacting with annotated 3D models.

6.2 Discussion

6.2.1 Performance

The results from our study suggest that participant's performance (both efficiency and accuracy) at the task of searching for components inside a 3D model varied significantly with the style of annotations used to annotate a 3D model. We found that the external style annotations provided the best performance results for both efficiency and accuracy among the three textual annotation styles considered in this study. The results of our data analysis revealed that participants were faster when searching for components inside an annotated 3D model with external style annotations followed by box style annotations, followed by internal style annotations. Similarly, the results revealed that participants made the least number of errors (incorrect selections) when searching for components inside a 3D model with external style annotations followed by box style annotations, followed by internal style annotations.

We believe that this is on account of the superior design characteristics of the external style annotations where the participants found the textual annotations to be clear and readable at all zooming levels. The font size in our implementation of the external style annotations was kept fixed (did not change with change in zooming level) and this font size was set relatively with respect to the screen size (iPad tablet form factor). This design attribute of the external annotations made a big difference in term of readability of the textual labels and was appreciated by participants in their qualitative feedback and in the readability ratings as well. Hence, we recommend this design aspect (of fixed font size relative to the user screen) of our implementation of external labels to fellow researchers, when designing or experimenting with annotation styles.

In addition to readability, participants also reported that it was easy to spot the external style annotations as they were floating on the 3D model rather than residing on/close to the surface of the 3D components as with internal style annotations. In our implementation of external style annotations we implemented fixed length external labels, where the length of the label was set relative to the dimensions of the 3D model. This design characteristic ensured that all external labels were at an equal and moderate distance, neither too close nor too far from the annotated components in the 3D model.

Participants also reported that it was easy to select the annotated component/part when annotated with external style annotations, as there were connecting lines and anchor points that pin pointed the exact annotated part, reducing their chances of making incorrect component selections. This design attribute of having fixed length connecting lines with anchor points pinpointing the annotated 3D components made the participant search for components faster and efficient. Our quantitative data analysis (search performance and error count data) and the qualitative feedback received from our participants, confirms the gravity of this design characteristic as well. Hence, we recommend this design aspect (of having fixed length external labels relative to the dimensions of 3D models) of our implementation of external labels as well, to the research community developing new annotation styles.

6.2.2 Impact on Learning

The results from this study indicate that the impact on learning varied significantly with the levels of expertise in interacting with the 3D models and software. We found that expert users who had the highest level of expertise in interacting with 3D model and software, had the highest recall scores and novice users who had the lowest level of expertise in interacting with the 3D models and software had the lowest recall scores.

This variation in the recall score was in line with our expectations. We speculated that expert users being the most fluent in interacting with the 3D models have the inherent advantage of exploring more details and an opportunity to learn more about the 3D model. Compared with intermediate and novice users who are not that fluent in interacting with the 3D model, and their attention is divided between learning (exploring the 3D model) and controlling the flow of their interactions with the 3D model.

In addition, we found that the recall scores of the participants in the three user groups (expert user group, intermediate user group and novice user group) were very similar for the three search components participants searched explicitly in the 3D model. Hence the variation in style of the annotation labels did not matter much as participants were focused and paid attention to the three search components of the search task and recalled them correctly. However, it was the recall score for the six distraction components that varied significantly with expertise. We found that participant in the expert user group had the highest recall score in correctly recalling the names of the six distraction components, followed by participants in the intermediate user group, and finally the participants in the novice user group.

Although the difference in recall scores did not vary significantly with the variation in the style of the textual annotations (internal annotation style, external annotation style and box style annotations) for the three user groups (expert users, intermediate users and novice users). The trend in our data reflected that expert users had a relatively higher recall score with external style annotations when compared with box style and internal annotations.

We believe that this relatively higher recall score with external labels was on account of the small size and limited content capacity of the external style annotations. Participants in the expert user group reported that the limited text (2 to 3 words) in external labels it was easy to remember and recall the information. Comparing this design aspect of external annotations with box style annotations, participants reported that the content of displayed information was a lot more and made it overwhelming for participants to read all that detail and then remember component names. Expert users recommended that additional details should be provided on demand instead of displaying that much content on screen at once. For internal style annotations, participants in the expert user group reported that it was difficult to establish the visual link between the component and the internal annotations as internal labels at times would span multiple components.

On the other hand, participants in the intermediate user group had a relatively higher recall score with the box style annotations when compared with external and internal style annotations. However this recall score was lower that the recall score of the participants in the expert user group.

We believe this is on account of the reduced and less fluent interactions with the 3D models of intermediate users when compared with expert users, where their attention is divided into two streams, one learning about the 3D model and controlling their user interactions with the 3D model.

Participants in the intermediate user group reported that the content inside box style annotations provided them with a better understanding of the component and its purpose thus helping them to recalling component names correctly.

And for participants in the novice user group, we found they had a relatively higher recall score with external and box style annotations (tie) when compared with internal annotations.

Hence, we recommend the limited content capacity design aspect of our implementation of external style annotations, in improving recall and supporting user learning. We also encourage fellow researchers to experiment with different ways of displaying details on demand to understand its impact on user learning.

6.2.3 User Preference

The results from our study revealed that external annotation style was the most preferred annotation style among the three textual annotation styles considered in this study. In addition, we found that participant's preference towards external annotation style was independent of the level of expertise in interacting with 3D models and software and the variation in the zooming levels at which the user interacted with the 3D model. The result form our quantitative data analysis revealed that external style annotations received the highest user preference ratings on all the four usability factors, such as readability, overall look and feel, ease of usage, and satisfaction. The qualitative feedback received from participants also reflected the same. For example participants reported that external annotations were clear and readable at all times. They were visually appealing, their overall look and feel was pleasant, and supported participants in interacting with the 3D model. Participants found external style annotations to be convenient and supported them at the task of searching for components.

We believe that this strong user preference for external style annotation is on account of its superior design characteristics. For example being smaller in size and floating on the 3D model with fixed length connecting lines, external annotation did not block user's view while they were interacting with the 3D model and did not create visual clutter. In addition, very few annotation collisions were experienced by participants in comparison to box style annotations when interacting (rotating) with the 3D model. The textual details displayed inside external style annotations were just enough to interact and explore the 3D model and for completing the search task. Compared with box style annotations, that had a lot of content, displayed all at once, making them look complex and overwhelming.

In comparison with internal style annotations, external style annotations had a fixed font size that did not vary with the distance from the user screen and were enclosed inside a semi-transparent bounding element (an ellipse). This bounding element, an elliptical bubble, separated the textual details from merging with components of the 3D model and highlighted the textual details the semi-transparent white background.

Hence, we recommend the small size, fixed length, ellipse bounded external annotation style with a semi-transparent white background (that highlights the inside textual details), design aspect of our implementation of external annotations, in improving the usability of textual annotations with 3D models.

We also found that many participants reported two common problems when interacting with our implementation of internal style annotations which we believe was responsible for the overall poor performance of internal annotations in the study. First, participants reported that they faced a lot of difficulty in establishing the visual connection between the annotated part and its internal annotation. And second, they reported that internal annotations that were away from the user screen were tiny and hard to read. To complete the study tasks, they first had to bring the annotated parts far from the user screen, closer to the user screen to read the component names, and then decide their next course of actions. This was very discomforting and was one of the main reasons for low user preference rating on the four usability factors. We believe that these problems were caused on account of the inferior design characteristics of our implementation of internal style annotations. In our implementation, we annotated smaller 3D components such as screws and nuts with internal annotations that were larger and longer in size/dimensions than the annotated component itself. In addition the font size of the internal annotation changed with the distance from the user screen similar to real life where bill boards and road signs away from the user are hard to read and the ones that are closer to the user can be read easily. This approach in designing internal style annotations did not work well in our study. In addition our internal labels became internal labels with close proximity to the annotated 3D part and spanned multiple components, creating confusion.

Hence, we do not recommend these design approaches for implementing internal style annotations. In fact, we recommend to, not annotate small sized components for which the internal annotations become bigger than the component being annotated. In other words internal annotations should only be used when they can remain 100% internal to the annotated component.

6.3 Limitations

1) The results of this study are based on the interactions with three annotated 3D models deployed on a tablet (iPad) screen size that were similar in 3D complexity. Varying the 3D complexity of the annotated 3D models was outside the scope of this study. Hence the results of this study are applicable only to those 3D models that have a complexity comparable to the 3D models used in our study

2) In this study we had considered three zooming levels, zooming level 1 providing 80% zoom, zooming level 2 providing 150% of zoom and zooming level 3 providing 270% of zoom. These three zooming levels were only representative zooming levels for a normal interaction with a 3D model. These zooming levels did not cover all possible operational zooming ranges which can vary depending on the size and complexity of the 3D model.

3) As the current technology (software) does not supports rendering of an annotated 3D model on a tablet hardware (due to the limited CPUs and GPUs processing capabilities) the annotated 3D models were deployed on a Lab Machine and were presented to the users on a reduced screen size that of a tablet (iPad) on a LCD monitor. Hence the results of this study are based on the simulated rendering of annotated 3D Models on a tablet screen and not on an actual tablet.

4) To interact with the 3D model participants in the study made use of a mouse (left click to select a component, right click and drag to rotate the 3D model, and scroll wheel press and drag to pan) instead of a touch screen. Hence the results of this study are based on user interactions with the 3D model using a mouse and not with touch screen gestures.

5) The results of this study are based on the specific implementation of the three textual annotation styles considered in this study. These were just one of the several potential implementations of internal, external and box style labels that were chosen by the

researcher. For example the length of the external labels was fixed and internal labels were only “internal” for a small portion of the time. In addition the annotation styles were implemented with the help of 3DVIA Composer software from Dassault Systems. Hence the results of this study are applicable in cases where 3D models are annotated using 3DVIA Composer design platform only.

6) Participants in this research study were mostly students and researchers from academia. Hence it was not possible to cover the entire higher side of the expertise scale including industrial professionals such as architects, CAD and design engineers, etc. The results of this study are hence applicable to the general population of 3D models and software only. Applying the result of this research directly to an industrial domain such as mechanical or aeronautical domain may require industrial evaluation and/or some customization by industry specific experts.

7) In this study, we did not evaluate user comprehension of the annotation labels as this was out of scope and would require our participants to have the ability to comprehend the coded technical information in our textual annotations. In addition this would also require us to construct realistic technical study tasks that will engage participants in performing part of some installation process that would evaluate participant’s comprehension of the presented technical textual annotations.

CHAPTER 7 CONCLUSION

7.1 Conclusion

In this thesis we explored annotation styles for use with 3D models within an information system that integrates relevant information needed by aircraft maintenance engineers in doing the jobs of repairing, assembling and installing parts on an airplane correctly, in form of textual annotations, with the 3D models of the aircraft parts and components. We researched with three different styles/types of textual annotations to explore which annotation style best facilitates users in searching /identifying objects/components inside a 3D model, at different zooming levels. We evaluated these textual annotation styles to determine which textual annotation style provides a better support for user learning, helping users to remember more information. We evaluated user's preference for these annotation styles to determine the most preferred annotation style, and to gain a better understanding of the design aspects of annotation styles that are preferred or appreciated by users.

We built a medium fidelity prototype making use of three 3D models (aircraft engine turbo-jet assembly, webra 2-stroke internal combustion engine and gear assembly, and a dental milling machine) with the help of 3DVIA Composer software, a 3D CAD design tool that allowed us to create, add and control the format of our designed annotations.
In addition, it allowed us to define the flow of our study tasks and provided our participants with an interface to interact with the annotated 3D model with interaction mechanisms such as selecting components, zooming, panning, and rotating, to view the various components and structure of the 3D model from multiple viewing angles.

In order to annotate our prototype (three 3D models) we used the three most commonly used annotating techniques found in the literature (internal annotation style, external annotation style and box style annotations) and tweaked these to improve their overall look and feel (a result of running the pilot study to gather user feedback on annotation styles and research methods). We designed two basic study tasks (a search task and a recall task) to measure the ability of these annotation styles in supporting users at their tasks at hand with the help of this system. In order to simulate the industry use of this system we added annotations that were coded with component names, technical details and manufacturing information as used in the aircraft industry. We received a list of aircraft component names from Boeing and based on that we created textual annotations for our models that varied in length and style as it would in an industry setting). We added colors to our 3D models to replicate the way these are used in an industrial scenario.

We then tested our prototype in a lab setting, where we ran a user study with 27 participants, comprising of students and staff at Dalhousie University with varying level of expertise in interacting with 3D model and software. We collected the quantitative and qualitative data via various study instruments (please see section 3.8 Study Instruments) and performed data analysis in SPSS (IBM - PASW v18) [38].

We found that of the three textual annotation styles considered in this research (internal style annotation, external style annotation and box style annotations) external style annotation was the most preferred annotation style. It received the highest ratings for all four usability factors (readability of the text, overall look and feel, ease of usage, and satisfaction) considered in this study (please refer to ISO definition of usability [29]). Results of our user study also revealed that external style annotations improved the participant's performance in searching for components inside a 3D model for both efficiency (time taken to complete the search task) and accuracy (the number of incorrect component selection made during the search task). We also found that with external style annotations participants were able to recall more components correctly than with the other two annotation styles. This implied that the overall design of the external style annotation reduced the cognitive load of our participants given the finite limits of short term memory when interacting with a previously unseen 3D model.

Our finding suggest that of the three textual annotation styles considered in this research external style annotation is the best annotation style to use with a 3D model and hence we recommend product designers to use external style annotation in their designs.

7.2 Future Work

We hope that our fellow researchers in HCI would take this research further and extend it by taking into account the varying levels of 3D model complexity of the 3D models, exploring the different parameters associated with annotation styles responsible for positive or negative impact on learning, and experimenting with other 2D, 3D annotation styles such as flags, pins and their format (such as size, color, etc). Some of the recommendations for future work in this research area are as follows:

(a) We would like extend this research by improving the design of internal style annotations and annotation boxes to reflect on the suggestions (qualitative feedback) received from our participants. For internal style annotations we would like to make the following design changes (a) display the textual details of internal labels in a rectangle box against a semi-transparent white background to fix the issue of merging text with background objects of similar font color or invert the font color of the internal labels with respect to the color of the background 3D objects they might overlap with, and (b) provide internal annotations with a supporting 3D object (such as a pin or nail) that pin points the internal annotation text plate to the annotated component in the 3D model. For annotation boxes we would like to make the following change, addition of maximize (+)/minimize (-) button to display the details on demand.

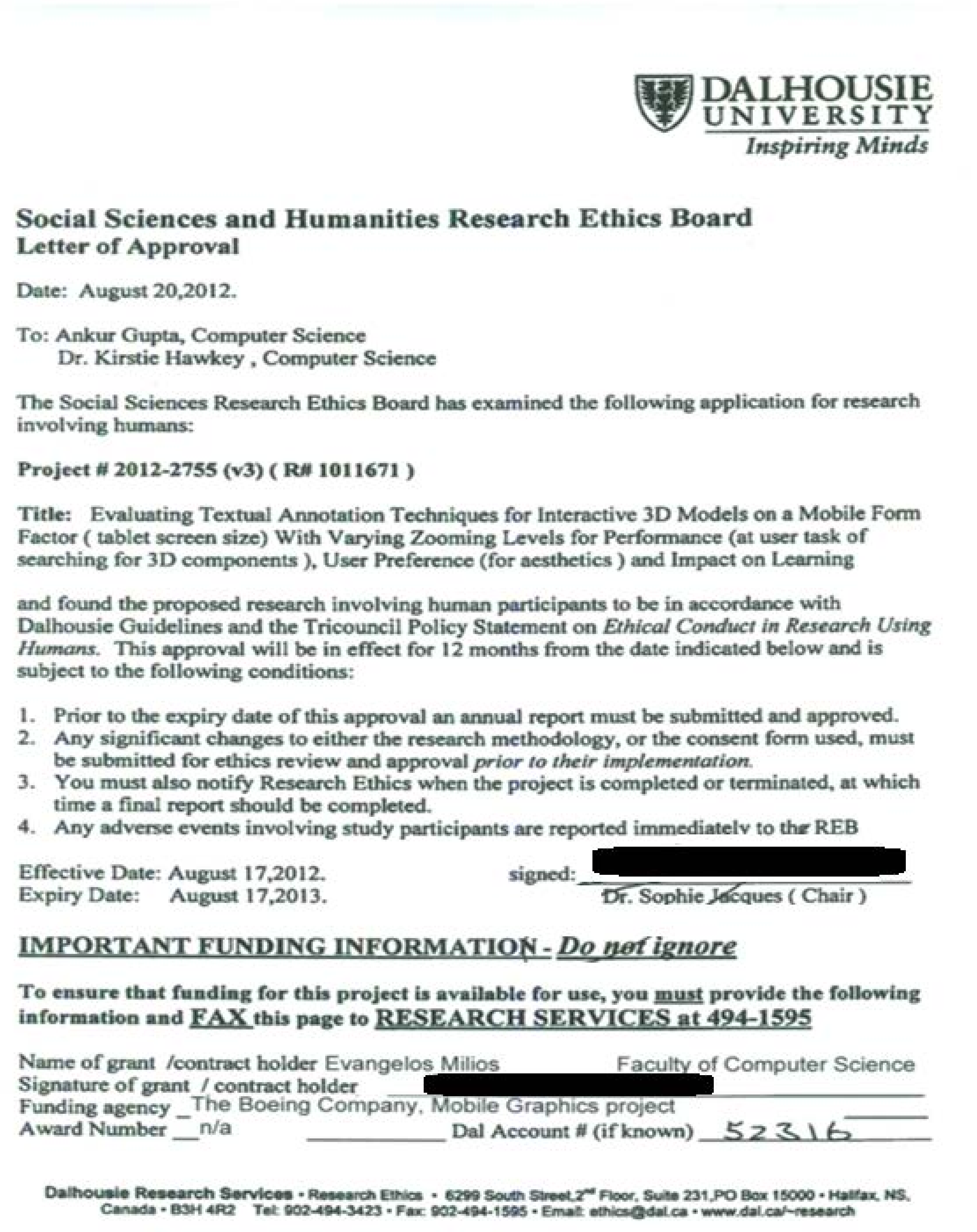
(b) We would like to extend this research further by varying the number of annotations with the complexity of the 3D models to explore the impact of these variables on user learning. Here we would like to explore the threshold/maximum cap for the number of annotations that can be applied on a 3D model with a given 3D complexity, before we hit the breaking point in supporting users with the annotated 3D model.

(c) In addition we would like to improve the way collisions between annotations are handled. We will assign priority to the annotation that is closest to the user such that the text of the textual annotation closest to the user is displayed over the text of other colliding annotations. This will serve as an improvement from its current implementation where the text in both the collided annotations becomes scrambled or grainy on user screen.

(d) We would extend this research further by including the evaluation of user comprehension in addition to just user learning. This will include designing realistic technical study tasks with help of domain experts and recruiting industry professionals such as aircraft mechanics, architects, and manufacturing engineers as participants for the study. This way the results of our study will be very pragmatic and industry centric.

APPENDICES

Appendix [A] - Dalhousie Research Ethics Board Letter of Approval



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Social Sciences and Humanities Research Ethics Board
Letter of Approval

Date: August 20,2012.

To: Ankur Gupta, Computer Science
Dr. Kirstie Hawkey , Computer Science

The Social Sciences Research Ethics Board has examined the following application for research involving humans:

Project # 2012-2755 (v3) (R# 1011671)

Title: Evaluating Textual Annotation Techniques for Interactive 3D Models on a Mobile Form Factor (tablet screen size) With Varying Zooming Levels for Performance (at user task of searching for 3D components), User Preference (for aesthetics) and Impact on Learning

and found the proposed research involving human participants to be in accordance with Dalhousie Guidelines and the Tricouncil Policy Statement on *Ethical Conduct in Research Using Humans*. This approval will be in effect for 12 months from the date indicated below and is subject to the following conditions:

1. Prior to the expiry date of this approval an annual report must be submitted and approved.
2. Any significant changes to either the research methodology, or the consent form used, must be submitted for ethics review and approval *prior to their implementation*.
3. You must also notify Research Ethics when the project is completed or terminated, at which time a final report should be completed.
4. Any adverse events involving study participants are reported immediately to the REB

Effective Date: August 17,2012. signed: [redacted]
Expiry Date: August 17,2013. Dr. Sophie Jacques (Chair)

IMPORTANT FUNDING INFORMATION - *Do not ignore*

To ensure that funding for this project is available for use, you must provide the following information and FAX this page to RESEARCH SERVICES at 494-1595

Name of grant /contract holder Evangelos Milios Faculty of Computer Science
Signature of grant / contract holder [redacted]
Funding agency The Boeing Company, Mobile Graphics project
Award Number n/a Dal Account # (if known) 52316

Dalhousie Research Services • Research Ethics • 6299 South Street,2nd Floor, Suite 231,PO Box 15000 • Halifax, NS, Canada • B3H 4R2 Tel: 902-494-3423 • Fax: 902-494-1595 • Email: ethics@dal.ca • www.dal.ca/~research

Appendix [B] - Recruitment Script

Dear All,

We invite you take part in a research study that investigates the effect of using textual annotation techniques with interactive 3D models, study conducted under the supervision of Dr. Kirstie Hawkey at the Faculty of Computer Science, Dalhousie University.

We invite people from all backgrounds to take part in this study irrespective of their previous experience or knowledge about 3D models and/or with 3D software. There are no prerequisites, except that all participants must be English language readers and speakers.

Before starting the study you will be presented with an informed consent form. A researcher will always be available to explain to you the study, the tasks you will be performing, and to answer any questions you may have or address any problems that you may experience while performing the study.

The study will take about 60 minutes and there is an honorarium of $15 for taking part in this research. If you are interested in participating in this study, please contact Ankur Gupta by email: Gupta@cs.dal.ca

Warm Regards,
Ankur Gupta

Appendix [C] - Informed Consent Form

Study Title:	Evaluating textual annotations with interactive 3D models at different zooming Levels
Principal Investigators:	Ankur Gupta, Faculty of Computer Science Kirstie Hawkey, Faculty of Computer Science
Contact Person:	Ankur Gupta, Faculty of Computer Science, Gupta@cs.dal.ca

Introduction

We invite you to take part in our research study at Dalhousie University. Your participation in this study is voluntary, there is a $15 compensation for participating in this study, and you may withdraw from the study any time. Neither your academic nor your employment performance evaluation will be affected by whether or not you participate. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study might not benefit you directly, but we might learn things that will benefit others. You may discuss any questions you have about this study with Ankur Gupta at any time through e-mail, phone or in person (before, during or after the study).

Purpose

The purpose of the study is to assess the effect of using textual annotations with interactive 3D models at different zooming Levels

Study Design

At the beginning of the study, you will meet with a researcher in an agreed upon location in the Mona Campbell building at the Faculty of Computer Science, Dalhousie University, to brief you about the overall study and the specific tasks that you will perform.

After you sign the informed consent, we will administer a pre-test, to measure your knowledge about the 3D models used in the study and on for prior experience in interacting with 3D models and software. After this we will provide you with a basic training on how to operate the 3D software used in the study with the help of a sample 3D model.

There are two study tasks that you need to perform. In study task #1, you will search for three 3D components in an annotated 3D model and in study task #2, you will be presented with an un-annotated version of the 3D model you just saw and be asked to tag as many 3D components as possible. You will then be provided with a post-task questionnaire to gather feedback on your interaction experience and user preferences.

The two study tasks and post task questionnaire will be repeated a total of 9 times during the study sessions. There will be three short 1 min breaks for some tea and cookies. At the end of the study you will complete a post-test questionnaire (measuring your increase in knowledge about the presented 3D models in the study) and complete an exit questionnaire.
The entire study will take about 60 minutes and a researcher will always be available to answer any questions or address any problem that you may experience during the study. This study involves 27 participants.

Inclusion Criteria
All Participants must be English language readers and speakers, such as Canadian high school pass outs or international students/professionals with IELTS score of 6.5 or above

Possible risks and Discomforts
There is a low risk of fatigue, frustration and boredom associated with the study. Some participants may get frustrated or bored while completing the study tasks or post task questionnaires.

Possible Benefits
There are no direct benefits for participants taking part in this study, aside from the opportunity of becoming aware of the 3D models, software and annotation techniques used in the study and being exposed to new research questions, and contribution to research that may benefit others.

Anonymity and Confidentiality
We are not collecting any information in this study that could be used to identify you. We will destroy your contact details one week after the study. This consent form will be kept in a locked cabinet in the PI's supervisor's office. Your responses will be identified with a randomly-generated ID and will be kept anonymous. All research data will be kept confidential and secured for five year after the end of this school term, after five years this data will be destroyed.

A researcher is always available during the study session to answer any questions you ma y have or address any problems that you may experience while performing the study. Should you have any further problems or issues related to the study, you may please contact the researcher Ankur Gupta by email at Gupta@cs.dal.ca

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University's Office of Human Research Ethics for assistance: phone: (902) 494 - 1462, email: catherine.connors@dal.ca.

Informed Consent Form

Study Title: Evaluating textual annotations with interactive 3D models at different zooming Levels

☐ "*I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I hereby consent to take part in the study. However, I understand that my participation is voluntary and that I am free to withdraw from the study at any time.*"

Participant	***Researcher***
Name: ________________	Name: ________________
Signature: ________________	Signature: ________________
Date: ________________	Date: ________________

☐ *"I agree to let you directly quote any comments or statements made in any written reports without viewing the quotes prior to their use and I understand that the anonymity of textual data will be preserved by using pseudonyms."*

Participant	***Researcher***
Name: ________________	Name: ________________
Signature: ________________	Signature: ________________
Date: ________________	Date: ________________

☐ Provision of results to participants: If you are interested in seeing the results of this study, please check below and provide your email address. We will contact you with publication details that describe the results.

"I would like to be notified by email when results are available via a publication"

[If this option is chosen, please include a contact email address: _________________________

Appendix [D] - Pre-test Questionnaire

Participant ID: ____

1. Have you interacted with any 3D computer graphics software or games?

   Yes ☐
   No ☐

   If your answer is yes, please answer the following two sub-questions

   1(a) Please provide the name of the 3D software used.

   Autodesk 3ds Max ☐ Unity 3D ☐ CATIA ☐
   3DVIA Composer ☐ Autodesk Inventor Publisher ☐
   Solid works ☐ Google Sketch up ☐ Blender ☐

   3D Games ☐
   (World of Warcraft, etc)

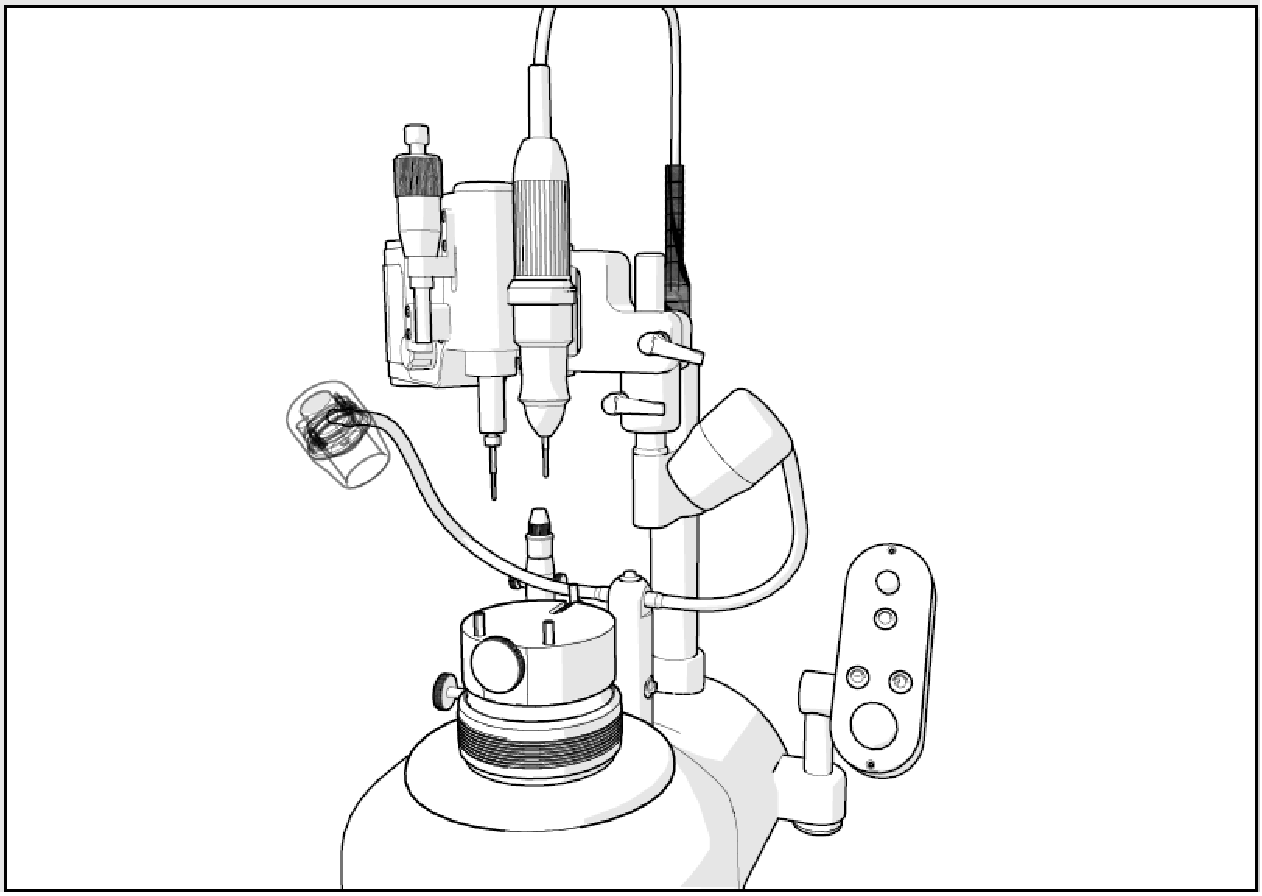
   Others ☐
   Please Specify: ________________________________
   ____

   1(b) How **frequently** have you interacted with 3D computer graphics software in the **past six months**?

   Daily ☐
   2 to 3 times in a week ☐
   4 to 5 times in a month ☐
   Less than 4-5 times a month ☐

Participant ID: ____

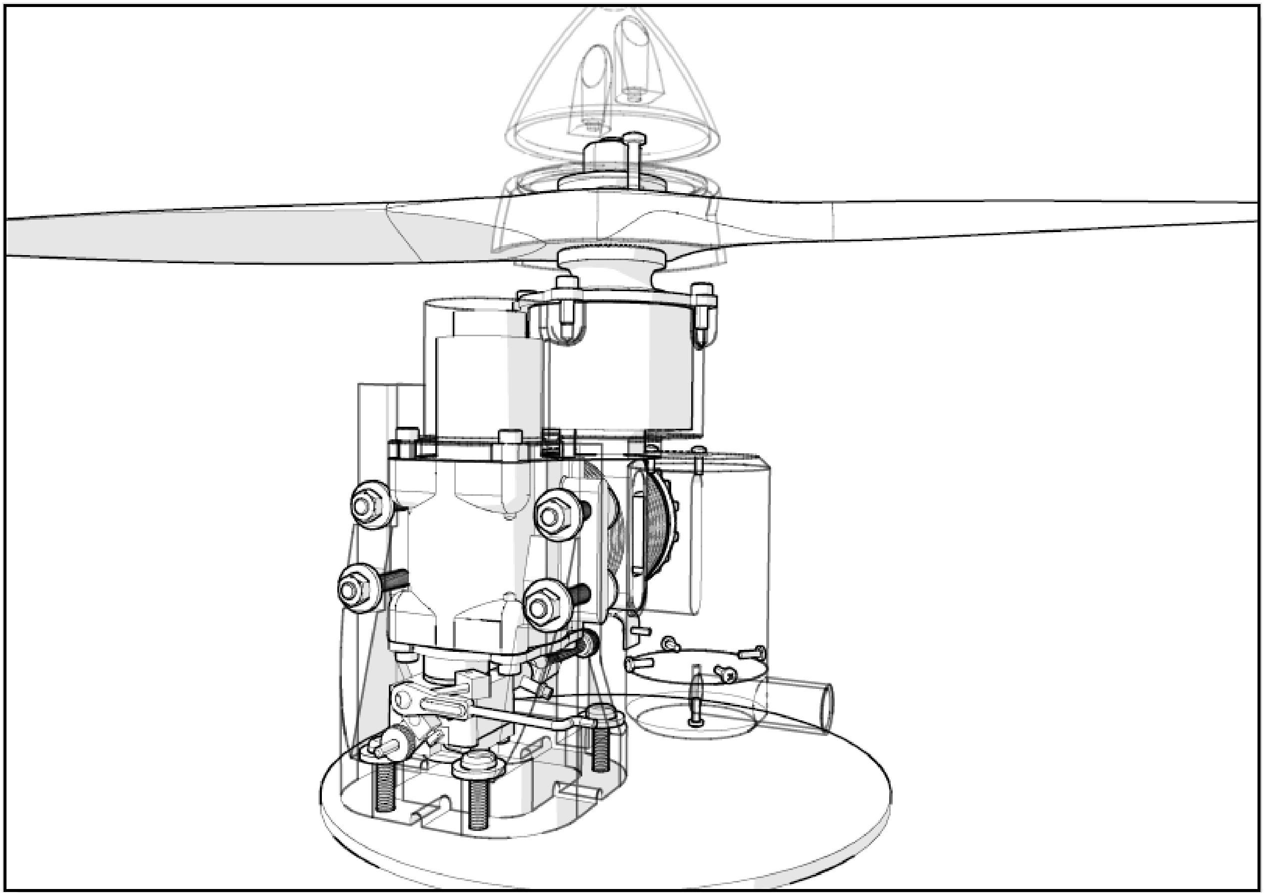
2) Please label as many components as possible for the following model.



1. ____________________ 2. ____________________
3. ____________________ 4. ____________________
5. ____________________ 6. ____________________
7. ____________________ 8. ____________________
9. ____________________

Participant ID: ____

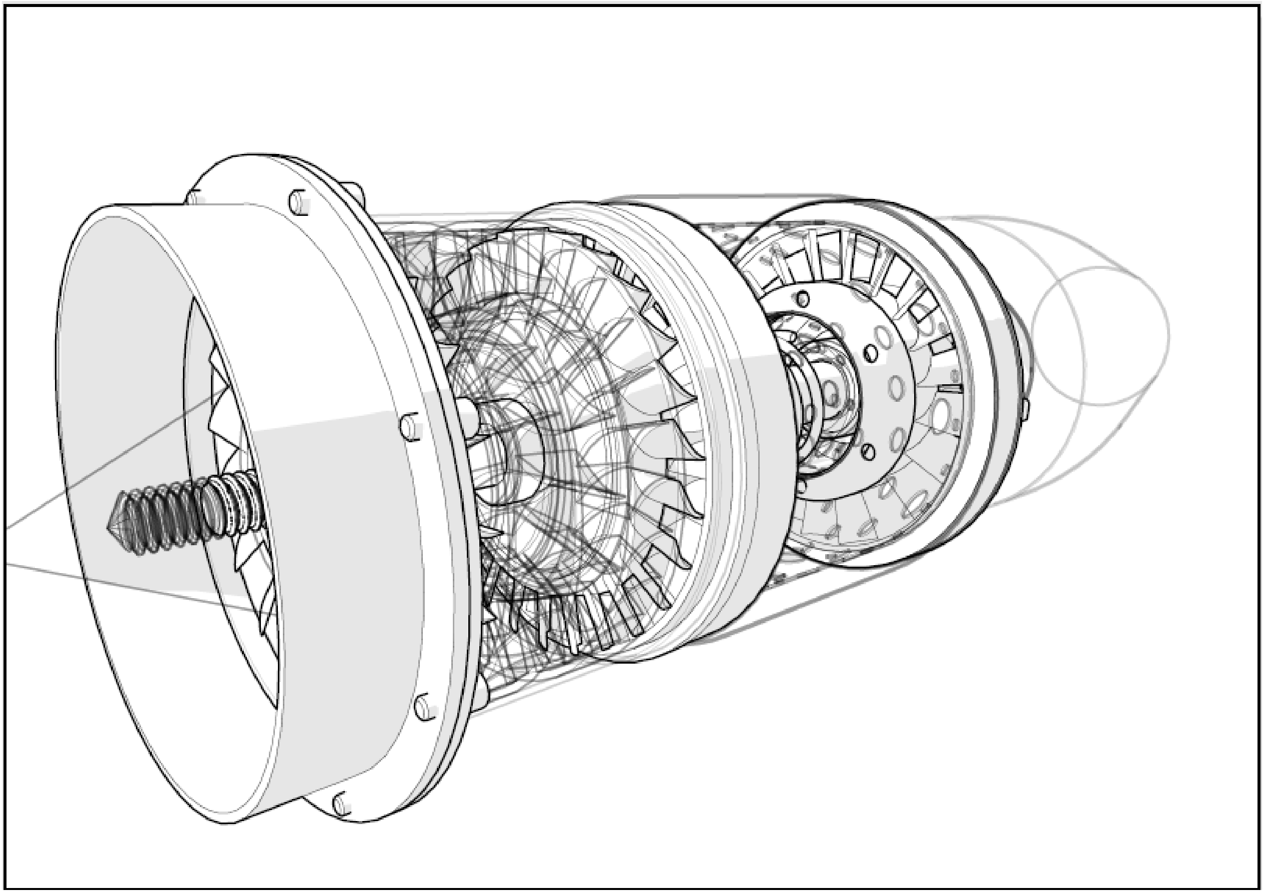
3) Please label as many components as possible for the following model.



1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________
6. ____________________
7. ____________________
8. ____________________
9. ____________________

Participant ID: ____

4) Please label as many components as possible for the following model.



1. ______________________
2. ______________________
3. ______________________
4. ______________________
5. ______________________
6. ______________________
7. ______________________
8. ______________________
9. ______________________

Appendix [E] - Instructions for Study Task #1

You will be presented with an annotated 3D model

Your task is to search and identify for three components within this annotated 3D model as they appear on screen,

To navigate through the 3D model with the mouse, use mouse scrolling wheel for panning (press scroll wheel and drag) and the mouse right click button for rotating the 3D model (press right click button and drag)

When you think you have found the correct component, left click on it,

If you were incorrect, a message would be displayed on the screen and the view will be reset, please try again,

The task will complete once you have correctly searched for the three components

Mouse Controls
Selecting Components: Mouse Left click
Rotating 3D model: Press right click button and drag
Panning 3D model: Press scroll wheel and drag

Appendix [F] - Recall Sheet

Participant ID: ____

Model No: 1, Component Set A, Study Task [1 to 9]: ____

For the un-annotated 3D model shown on your screen, please identify the various components (marked with number 1 to 9) on this 3D model, in the table below,

Component	Annotation Label	Position (Number)
Adjustable Adapter Cord	ADJUSTABLE_ADAPTER_CORD_SEC41.5_EXTN	
Base Plate Screws	BASE_PLATE_SCREWS_SEC43.6_A18	
Electro Magnetic Arm	ELECTRO_MAGNETIC_ARM_SEC-3_DMV_CTL	
LED Lamp	LED_LAMP_ILU7000K	
Lock Knobs	LOCK_KNOBS_SEC21.3	
Marker	MARKER_SEC-9BLNK	
Milling Cutter	MILLING_CUTTER_ARTL-1062F2.4.6BLD	
Power Inlet	POWER_INLET_SEC43.5_BCK_STP	
Spindle Axis	SPINDLE_AXIS_ASSY-4_MOP	

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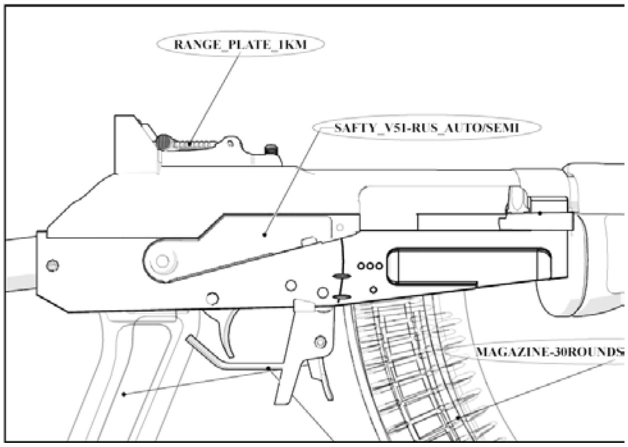
Appendix [G] - Post-task Questionnaire (part 1 and part 2)

Participant ID: ____ **Part 1**

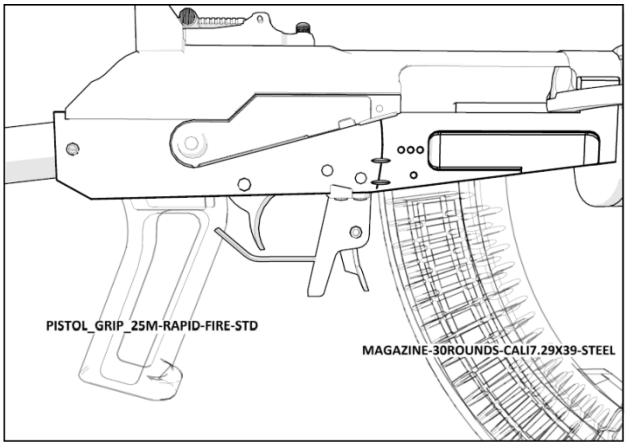
Annotation Type : Zooming Level :	**Disagree**	**Somewhat Disagree**	**Neutral**	**Somewhat Agree**	**Agree**
	(1)	(2)	(3)	(4)	(5)
1. Readability of Annotation Labels: The annotation labels **were clear and readable**	○	○	○	○	○
2. Look and feel of the annotations:					
(a) The annotation labels **create a visual clutter (too much text/too many labels)** on the rendered 3D model	○	○	○	○	○
(b) The annotation labels **were blocking (occlusion) parts of the 3D model**	○	○	○	○	○
(c) The annotation labels **were placed accurately**	○	○	○	○	○
(d) The overall **display** format **of annotation labels** was **appealing** and **pleasant**	○	○	○	○	○
3. Perceived Ease of use of annotation labels					
(a) The annotation labels **were easy to use** /operate	○	○	○	○	○
(b) The annotation labels **were easy to understand** (minimize cognitive load)	○	○	○	○	○
(c) The annotation labels **supported me in searching for components** inside a 3D model	○	○	○	○	○
(d) The annotation labels **facilitated me in learning about the 3D model**	○	○	○	○	○
(e) The annotation labels **supported me in exploring and navigating** through the 3D model	○	○	○	○	○
4. Satisfaction					
(a) I would **recommend this annotation label for search tasks**	○	○	○	○	○
(b) I would **recommend this annotation label for facilitating learning**	○	○	○	○	○

Participant ID: ____ Part 2

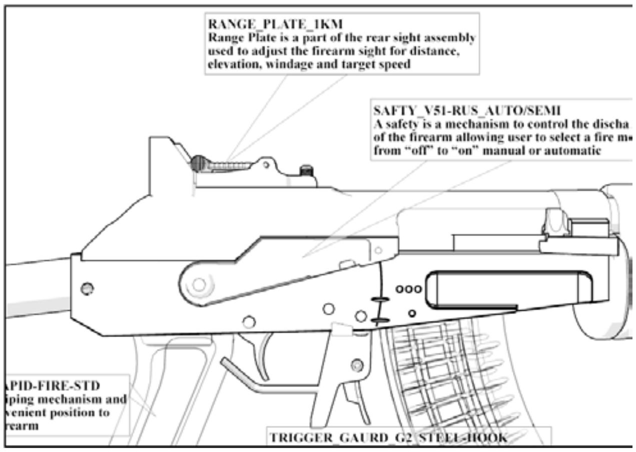
Zooming Level: 1 / 2 / 3



(a) External Annotation Labels



(b) Internal/Proximity Annotation Labels



(c) Box Annotation Labels

1) Which Annotation label type do you prefer the most at this zooming level?

Rank 1 to 3 with no ties [1 best, 3 least]

Label type	Rank
Internal annotation labels	
External annotation labels	
Box annotation labels	

2. Did you face any problems with the textual annotations used at this zooming level?

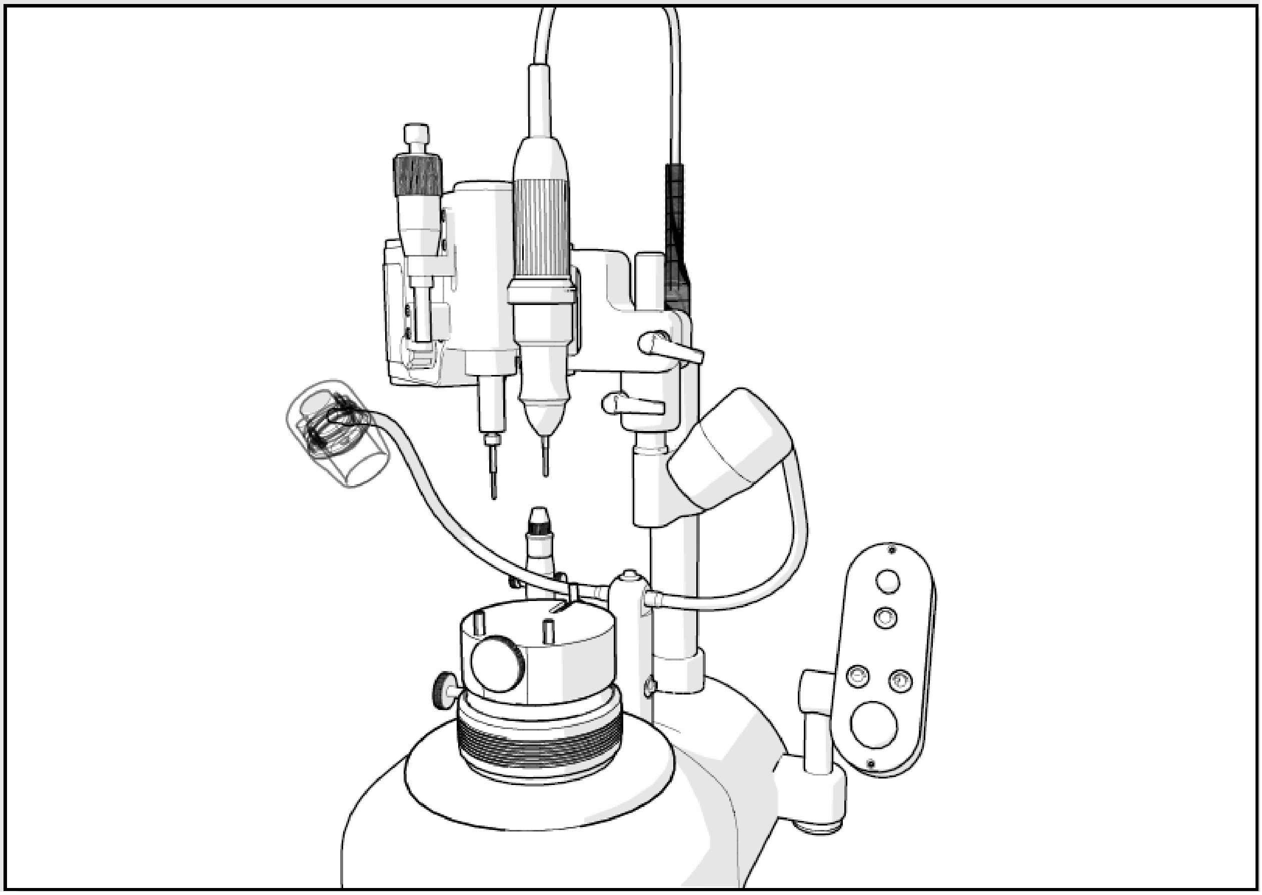
Internal Annotations		**External Annotations**		**Box Annotations**	
No problems	☐	No problems	☐	No problems	☐
Minor problems	☐	Minor problems	☐	Minor problems	☐
Major problems	☐	Major problems	☐	Major problems	☐

3 Please provide the details of the problems you experienced, if any?

Appendix [H] - Post-test Questionnaire

Participant ID: ____

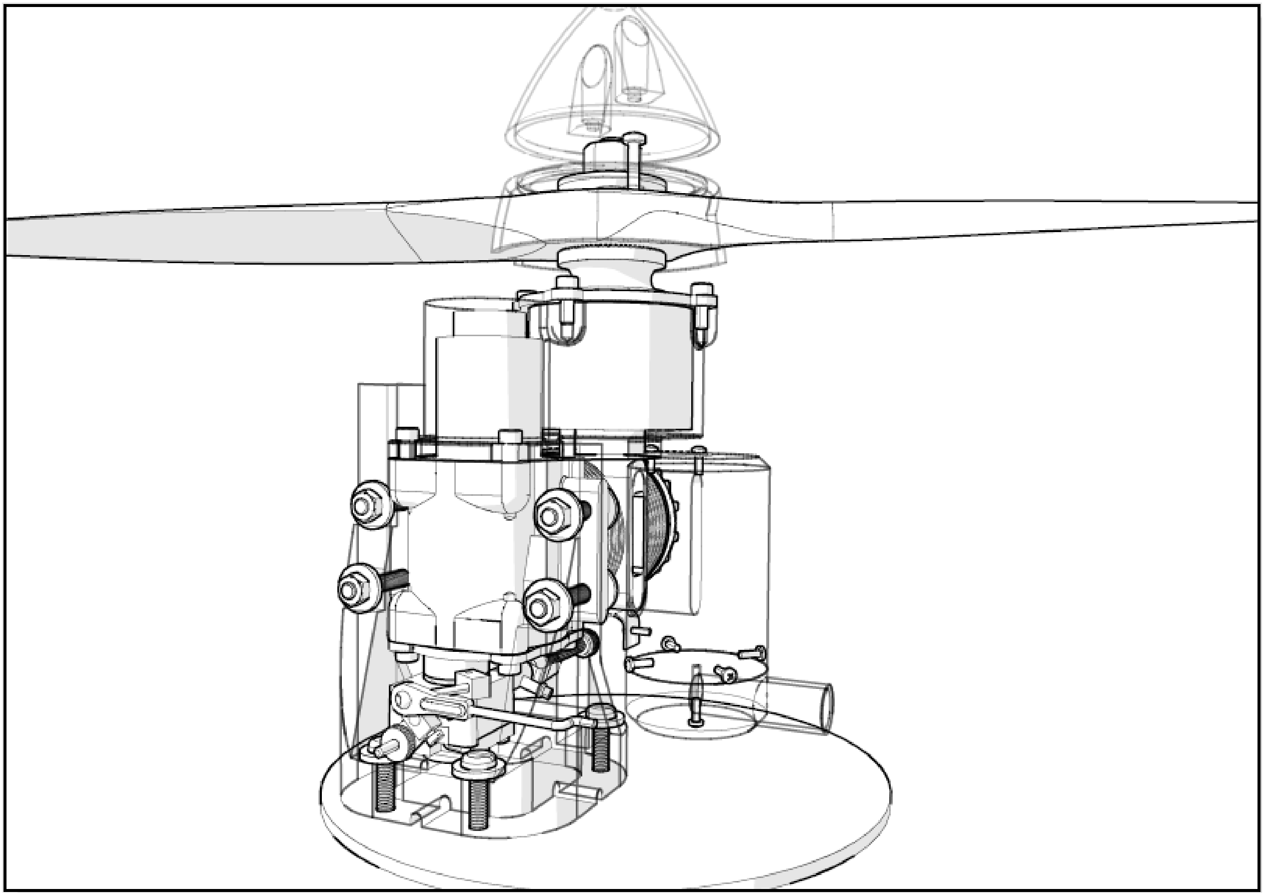
1) Please label as many components as possible for the following model.



1. ____________________ 2. ____________________
3. ____________________ 4. ____________________
5. ____________________ 6. ____________________
7. ____________________ 8. ____________________
9. ____________________

Participant ID: ____

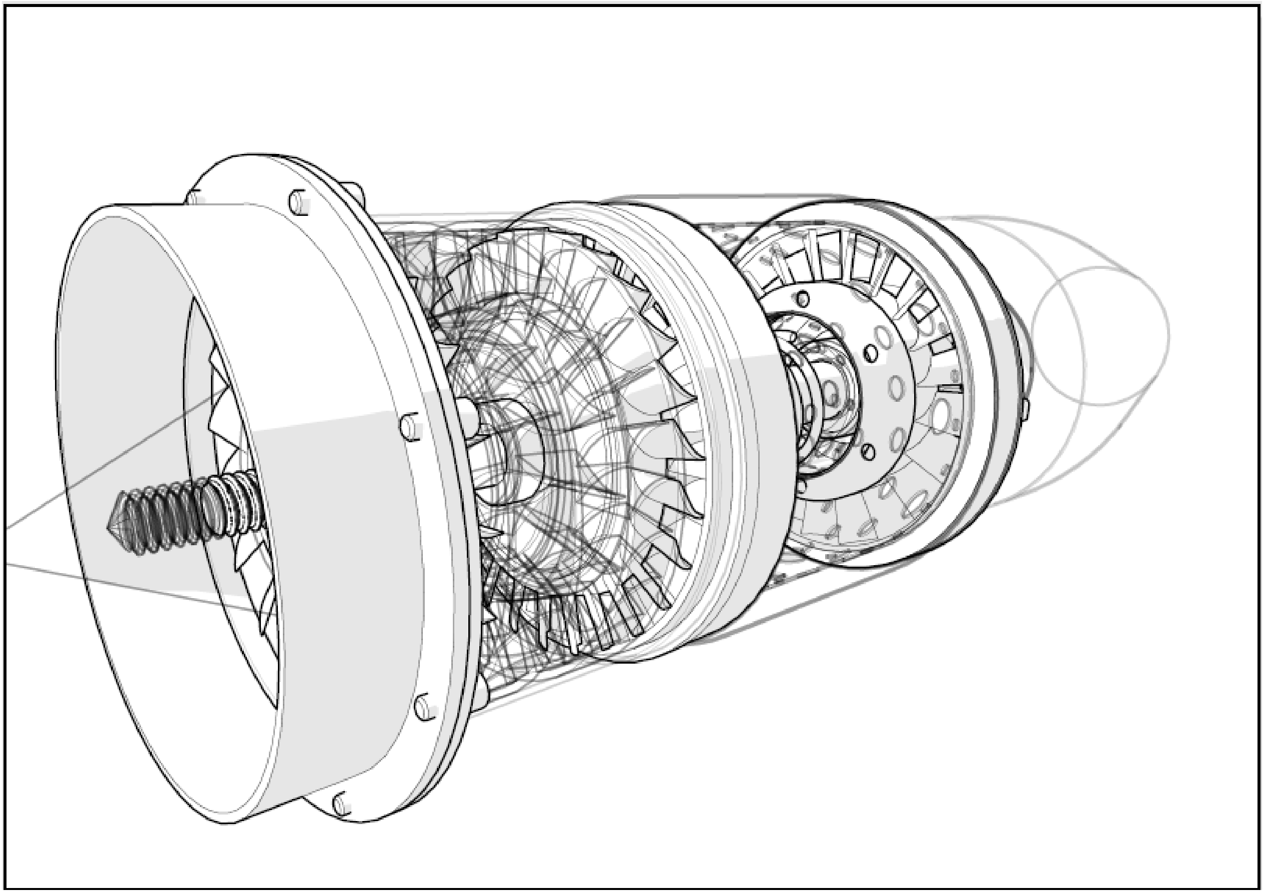
2) Please label as many components as possible for the following model.



1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________
6. ____________________
7. ____________________
8. ____________________
9. ____________________

Participant ID: ____

3) Please label as many components as possible for the following model.



1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________
6. ____________________
7. ____________________
8. ____________________
9. ____________________

Appendix [I] - Exit Interview Questions

Participant ID: ____

1. In your opinion do you think the number of zooming levels were enough to interact with the annotated 3D models?

Yes ( ) No ( )

If no, (please justify/provide reasons)

2. In your opinion, do you think there are other textual annotation styles that should be considered for identifying components/parts of a 3D model? If yes, please elaborate

3. In your opinion, do you think there are any other textual annotation styles that should be considered that would facilitate user's learning process and interaction with the 3D model?

4. Do you have any other comments, criticisms or suggestions

Thank you for your time and feedback

Appendix [J] - Participant Payment Receipt

My signature below confirms that I have received CAD $ 15 cash from researcher Mr. Ankur Gupta as an honorarium payment for participating in the user study titled “Evaluating textual annotations with interactive 3D models at different zooming Levels”

I understand that this honorarium is taxable income and it is my responsibility to claim it on my income tax, as Dalhousie University will not be issuing a T4A form for this payment.

Name (please print): ____

Signature: ____

Date: ____

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