RVDT: A Design Space for Multiple Input Devices, Multiple Views and Multiple Display Surfaces Combination

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ABSTRACT

We study interaction combination performed using a table-top device, a mouse, and/or a six Degrees Of Freedom (DOF) input device in a system combining a 2D flat (map-kind) view presented horizontally and a 3D perspective vertical view of the same virtual environment. The design of such a 2D/3D interface relies on the RVDT model and its design space that allow easy high-level combined interactions to achieve spatial tasks. RVDT integrates the relations between physical and numerical DOFs and applies to any graphical user interface in which multiple views, multiple display surfaces and multiple input devices are combined. The user study shows that experimented users prefer table-top/6DOF input device interaction combination with a maximal number of elementary tasks performed with both devices.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*graphical user interfaces*; H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—*artificial, augmented, and virtual environment.*

General Terms

Design, human factors, experimentation.

Keywords

Multiple input devices, multiple views, multiple display surfaces.

1. INTRODUCTION

The mouse is widely used for desktop applications but there is no perfect input device for 3D graphical user interfaces suitable for all applications [24]. Each existing 3D input device has its advantages and drawbacks (e.g. lack of intuitivity, fatigue, precision, ease of use, etc.) and none fulfills all application and user requirements.

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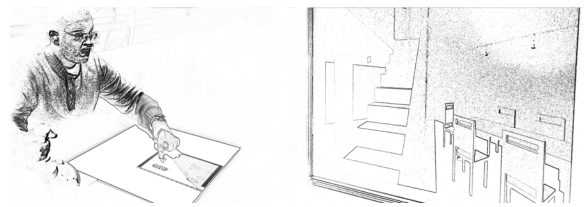

Figure 1: A user interacting through a 2D view displayed on a table-top device and through a 3D complementary view of the same virtual environment using a joystick.

The research on table-top devices is in continuous expansion. This expansion is explained by the multiple advantages of table-top devices such as collaboration aspects. Moreover, the physical input/output co-location of table-top devices offers intuitive gesture interactions [20]. Nevertheless, some drawbacks of table-top devices exist such as occlusion, imprecision, and lack of Degrees Of Freedom (DOF).

Every input device has a preferred set of data (e.g. keyboard for text and numerical values, mouse for 2D spatial information, etc.). Mouse and table-top devices target the same 2D spatial information and can be seen as concurrent. Table-top has also proven to be suitable for 2D and more DOFs interactions (e.g. horizontal translations and rotations) but however fails to offer an easy and efficient interface for 6 DOFs control. The combination of a table-top device with another input device (e.g. a mouse, a multiple DOFs input device) in a complementary way in order to cover 6 DOFs is an interesting combination. In comparison with existing research works combining multiple input devices and multimodal input, the contribution of our study is to focus on the combination of multiple views with different dimensions each and displayed on distinct surfaces. For this purpose, we combine interactions performed through a 2D view projected on a table-top device and interactions performed through a 3D view projected on a vertical display of the same virtual environment. Such an interface combines multiple views, multiple display surfaces, and multiple input devices (see Figure 1).

This type of interaction combination requires the consideration of physical and numerical DOFs, dimensions, and input/output coupling. Our study presents the Real/Virtual-Device/Task (RVDT) model and its high-level design space for the design of such a multimodal/multi-view interface. The model as well as the design space bind input devices to elementary spatial tasks and integrate physical and numerical DOFs as well as the input/output coupling.

We first present the related works in multimodal interface design models, multi-view and multi-device interfaces, and more specifically the combination of a table-top device with a companion vertical screen. We then present the RVDT model and a user study comparing six setups designed within our design space. Last, we conclude this paper and present our future works.

2. RELATED WORK

2.1 Multimodal Concepts and Platforms

Several definitions of a modality, a mode, and a media exist in literature. In our research work, we consider the definition given by Teil and Bellik [21] of these terms. A communication mode refers to the sensory communication channel (e.g. visual mode), "*a modality is a particular form of a communication mode*", and a media is defined as the data support.

Martin [17] develops the TYCOON (TYpes and Goals of COOperatioN) framework that characterizes existing relations between the different modalities. The considered properties are: transfer, equivalence, specification, redundancy and complementarity. Coutaz and Nigay [9] define the CARE properties to define existing relations between modalities within four properties: Complementarity, Assignment, Redundancy, and Equivalence. The aim of these properties is to guide designers in the conception process of multimodal interfaces.

Inspired by CARE properties, ICARE [7] is a platform for designing multimodal interactions by defining existing relations between modalities. Flippo and his colleagues [13] develop a framework for the design of mulimodal input fusion. The multimodal input design is separated from the multimodal output design. Other research works [3] [11] focus on graphical multimodal output design. These works address the problems of coordinating visual output modalities. Rousseau and his colleagues [19] develop another platform for multimodal output specification. This platform integrates the life cycle of multimodal data presentation with the WWHT model. All these platforms (as well as other platforms) separate input from output. When combining multiple input devices that act on distinct surfaces and views, and when input/output coupling is important, input and output modalities should be studied jointly as will be presented in this paper through the RVDT model.

2.2 Multiple Views

Roberts [18] advocates the use of multiple views in a visualization system because "*a user may understand the information through different perspectives, overcome possible misinterpretations and perform interactive investigative visualization through correlating information between views*". He highlights essential elements that must be considered when combining multiple views such as consistency and coupling multiple views. These elements are also important when combining interactions performed through multiple views displayed on multiple surfaces.

Baldonado and her colleagues [5] develop eight rules to respect when combining multiple views: diversity, complementarity, decomposition, parsimony, space/time resource optimization, self-evidence, consistency, and attention management. The authors underline the negative and the positive contribution of each rule (e.g. learning and computational overhead). Even though this research work does not take into account multiple display surfaces, these rules can still be applied in our context.

2.3 Multiple Input Devices

The combination of multiple input devices is studied in various domains and at different levels. iStuff [6] is developed for the combination of multiple devices for ubiquitous computing environments. The iStuff devices classification according to the number of dimensions that they integrate in input and output seems interesting. However, DOFs are not integrated but only dimensions are considered. In another research work, ICon [10] is a system that manages multiple input devices. It allows to build interactive applications with easily reconfigurable input(s). Kobayashi et al. [15] develop a framework for multimodal and multiple input device systems. This framework is divided into three parts: the input widget, the service component, and the binding conductor that manages the connections between the first two parts. ICon and the framework developed by Kobayashi and his colleagues bind the input devices to tasks in the system. They can integrate numerical data acquired from input devices DOFs. Nevertheless, real world dimensions and real world input device DOFs are not considered in these research works. Real world dimensions are essential in our work because of multiple view presentation of a virtual environment on distinct display surfaces. Since the type of interface considered in our work uses multiple input devices that have different DOF characteristics, DOFs are also essential notions in our work.

2.4 Combining a Table-top Device and a Companion Vertical Display

Wigdor et al. [22] study the effects on user performance and preference of a control space orientation on the table-top device and the vertical display orientation. The results show that user's preferences are not correlated with her/his performance but are mostly related to her/his comfort. Moreover, users orient the control space slightly in the same direction as the vertical screen. The vertical screen placement behind the user is inappropriate.

[2], [4], [12], and [16] study the combination of a 2D view displayed on a table-top device and a 3D view displayed on a vertical screen. In [12] and [16] a top-down (map-kind) view of a virtual scene is displayed on the table-top device and a 3D first person view on the vertical display. This mapping seems interesting because of the correspondence between real world and virtual dimensions. However, in all these systems, interactions are only performed by using the table-top device. In [14], a table-top device is combined with several vertical displays and interactions can be performed using the table-top device and/or a TabletPC. In [23], authors display on the table-top device a miniature version of the displayed information on the vertical displays. The presentation of multiple patterns on the vertical displays and the table-top device facilitates users understanding of existing relations between the multiple views. All the research works presented here do not allow to perform interactions directly through the vertical display which is the essential element of our study. We present in the next section the RVDT model and its design that allow high-level interaction combination performed through multiple views displayed on distinct display surfaces and using multiple input devices.

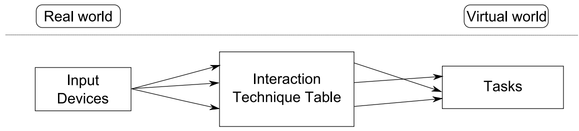

Figure 2: RVDT model.

3. DESIGN SPACE

Dimensions, real and virtual DOFs, and the relation between views are the main elements that should be considered when combining interactions performed through a 2D and a 3D view of the same virtual environment and displayed on distinct display surfaces. Existing models do not consider all these elements when designing multiple views or multimodal interfaces. In this section, we present a model called RVDT and a design space that allow a high-level design of such interactions.

3.1 RVDT Model

RVDT aims at modelling interactions performed using multiple input devices on multiple views displayed on distinct display surfaces. It is composed of three components (see Figure 2): input device, interaction technique table, and task. Each input device possesses appropriate interaction techniques (e.g. Drag And Drop for the mouse). These interaction techniques are integrated in the second component of the RVDT model. Each interaction technique specifies the DOF(s) used in the real world. The task component encloses elementary tasks divided according to virtual DOFs. The RVDT model binds input devices to tasks like in [7], [10], and [15].

ICon [10] and Kobayashi et al. framework [15] map input device data to system tasks and allow to modify this data flow (e.g. calibration, fusion, etc.). However, they do not consider how interactions are performed in the real world. In comparison with these works, the RVDT model is developed for a higher level of interaction design. It offers the possibility to design interaction techniques by examining the relation between real world and virtual DOFs. Since the numerical data flow is not explicitly represented in the RVDT model, its modification is not considered (e.g. calibration).

3.2 Design Space

In this section we describe the design space of the RVDT model into five steps: task definition, views and display surface definition, input device choice, interaction technique table definition, and interaction technique table/task binding. We consider the combination of interactions performed through a 2D view projected on a table-top device and a 3D view using a mouse as an example to illustrate this design space. We call this example $TT + M$ as for Table-Top and Mouse.

3.2.1 Task Definition

Tasks are decomposed into multiple elementary tasks. Beside selection, each elementary task integrates required virtual DOFs. For example an application requires the following transformations on virtual 3D objects: 3D translations, 3D scales, and a rotation around the vertical axis. The result of task definition in $TT + M$ is illustrated in the right part of Figure 3.

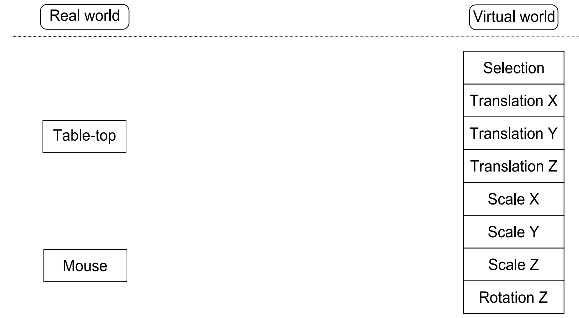

Figure 3: Task and input device components definition. Left: input device component definition. Right: task component definition.

3.2.2 Views Definition

The second step consists in defining the number of views, their layout in the real world, the view type (subjective or objective), and the dimensions presented on each view. Inspired by [5] and [18], the view definition must consider that:

- A high number of views increases the complexity for users to understand the structure of the virtual scene but allows to overcome occlusion problems.
- The presentation of a global view of the virtual scene facilitates the user understanding of its structure.
- Displaying different dimensions on different views increases complementarity between views.
- Preserving real world and virtual world dimension coupling can facilitate user's understanding of the virtual scene structure. Hence, view dimension definition should be defined according to its layout in the real world.
- Reduce numerical transformations existing between views. The translation and scale are acceptable but rotations should be reduced because of their cognitive cost.

In $TT + M$ we combine a view projected horizontally on a table-top device and a view displayed vertically. In order to respect the preceding rules, the view projected on the table-top device displays a global 2D horizontal (map-kind) view of the virtual scene. The vertical view displays a 3D subjective view of the virtual world preserving the relation between virtual and real dimensions. The existing transformations between both views are translations and scales only. This view disposal is similar to the ones in [12] and [16].

3.2.3 Input Device Choice

The choice of input devices must consider existing complementarity between input devices such as DOFs and precision. An input device that offers fast but inaccurate interactions is complementary to an input device that allows accurate but slow interactions. The number of input devices should be reduced because of learning and the switch between input devices drawbacks. At last, reduce the DOFs number when possible to facilitate interaction [8, p.180-181].

The input/output coupling is essential for some input devices such as table-top devices. Interactions performed using these input devices are related to information presentation (for example when performing selection). Hence, each input device presenting an input/output coupling characteristic should be connected to one of the views defined previously. Connecting input devices to distinct views increases complementarity. The table-top and the mouse are the two input devices that we choose in $TT + M$ (see left part of Figure 3). The table-top device is connected to the 2D view and the mouse is related to the 3D view.

3.2.4 *Interaction Technique Table Definition*

The RVDT interaction technique table defines each interaction technique with the real world DOFs that the user must perform (e.g. real world DOFs of a mouse drag and drop are horizontal translations). In $TT + M$ the table offers pointing, x and y translation using one finger direct manipulation, and horizontal scale using two finger manipulations. For the mouse, pointing is done by direct manipulation whereas drag and drop uses x and y translations.

3.2.5 *Interaction Technique Table/Task Binding*

The three RVDT components being defined, the number of connection possibilities between the interaction technique table and task component is high. We define five rules for interaction technique table/task binding that rely on logical or perceptual constraints and that help us to discard invalid bindings. We list them in order of increasing priority:

- $R1$: Respect user's preferences when expressed.
- $R2$: Preserve the correspondence between real world and virtual DOF types. Hence, a rotation realized in the real world corresponds to a rotation in the virtual world.
- $R3$: Reduce the number of transformations between real world and virtual DOFs through the view related to the input device. This rule might be in contradiction with the first rule (e.g. drag and drop for a mouse corresponds to translations in a real world horizontal plane and numerical translations in a vertical plane parallel to the view projection plane). Therefore, user's preferences must be favored or a user test must be conducted to assess which of both possibilities end users prefer.
- $R4$: Assign one interaction technique to each elementary task.
- $R5$: Respect task coverage. Each task of the RVDT task component must be binded to at least one interaction technique. If this is not possible, more interaction techniques must be defined via the interaction technique table. Adding new interaction techniques must consider occlusion problems (e.g. when adding a manipulator or graphical buttons). Interaction techniques that integrate physical DOFs should be favored.

3.2.6 *Binding Rules Usage*

In $TT + M$ the table-top device is related with the 2D view. In order to respect $R1$, $R2$, and $R3$ we bind respectively Pointing, TranslationX, TranslationY, ScaleX, and ScaleY from the interaction technique table (connected to the table-top device) to Selection, Translation X, Translation Y, Scale X and Scale Y (see Figure 4). The mouse is bound to the 3D view displayed vertically and therefore the cursor is displayed on

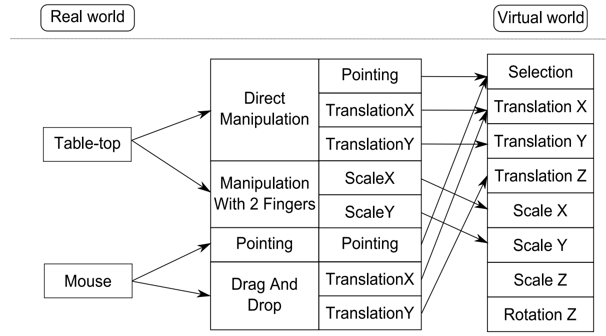

Figure 4: Binding interaction techniques table to tasks. Elementary tasks are not fully covered.

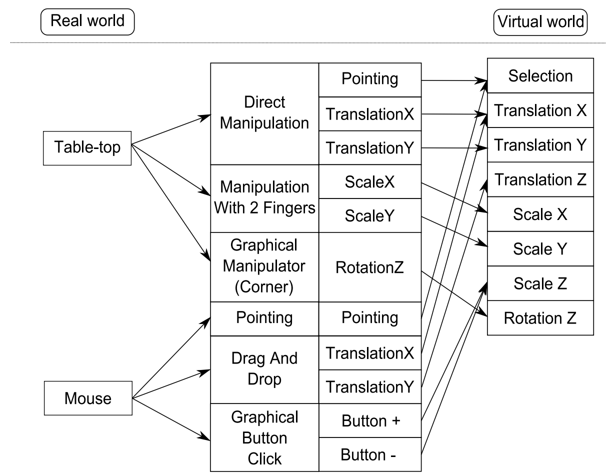

Figure 5: Complete RVDT representation respecting elementary task coverage.

the 3D view. We assign the mouse pointing from the interaction technique table to the elementary selection task. To respect $R2$ and $R3$ rules we bind respectively TranslationX and TranslationY (connected to the mouse) from the interaction technique table to Translation X and Translation Y of the task component. This binding does not respect $R1$ because users are forced to move graphical objects in the projection plane using a mouse input device. Therefore, in order to respect this rule, we bind TranslationY from the interaction technique table to Translation Z in the task component. The resulting interaction technique table/task binding leads to the RVDT representation illustrated in Figure 4. This setup respects $R4$.

Rotation around the z axis and vertical scale are not covered in the RVDT representation of Figure 4. Therefore, $R5$ is not respected and a graphical manipulator is defined in the 2D view to perform rotations around the z axis and two graphical buttons are defined in the 3D view to allow vertical scale. Mouse wheel could be used for vertical scale but we choose to avoid it in case the wheel is not integrated in the mouse. The resulting RVDT representation with the full interaction technique table/task bindings is illustrated in Figure 5. This setup respects $R1$, $R2$, $R4$, $R5$, and partially $R3$.

3.3 Advantages and Limits

RVDT model and its design space allow a high-level easy design of setups and interactions combining multiple display surfaces, multiple views, and multiple input devices. The main contribution of the design space (when compared to existing models and design spaces) is its focus on the input interactions while considering the output physical and numerical properties. It integrates real world DOFs, virtual DOFs and their relation in the design phase. Moreover, it allows to visualize the CARE [9] assignment (i.e. when an elementary task is connected to only one interaction technique) and equivalence (i.e. when an elementary task is connected to multiple interaction techniques) properties at the task level.

The number of binding possibilities between interaction technique table and task component is high. This high number of possibilities allows designers to explore and imagine new interaction techniques. Examples of such techniques are binding real world two-finger scaling with the table-top device to virtual object vertical or horizontal translation in $TT + M$. Virtual object vertical translation with two fingers would refer to a pinching (to move upward) and releasing (to move downward) metaphor. Binding the two-finger scaling to horizontal translation would refer to displace a virtual object by squeezing it. The five rules we define aim at reducing the binding possibilities but are not restrictive.

The main drawback of the RVDT model and its design space are their specificity to spatial tasks. Indeed, the RVDT advantage is the consideration of dimensions and DOFs that are central for spatial tasks. Moreover, the second limit is the integration of only graphical output modalities. The model and the design space are also more suitable for input devices presenting DOF characteristics. Nevertheless, they can be applied to multiple application domains such as computer aided design, 3D games, molecular docking, room acoustic visualization [1], etc.

4. EXPERIMENTATION

In this section we present an evaluation combining interactions performed through a 2D view projected on a table-top device and interactions performed through a 3D view projected on a vertical display. The aim of the evaluation is to compare six setups designed with the RVDT model and its design space in a docking task. The input devices are a table-top device connected to the 2D view, a mouse connected to the 3D view, and a 6DOF input device (i.e. similar to a spacemouse) connected to the 3D view. First, we explore the various configurations by considering all the possible connections between devices and tasks. Then we apply the rules given above to discard cognitively or logically invalid possibilities or to complement partial setups through additional interaction techniques. In the case of the docking task, we end up with only six valid configurations.

4.1 Six Setups

The docking task is divided into selection, 3D translations, and 3D scales of a virtual object. The first three setups integrate each only one of the three possible input devices. The fourth one combines interactions using the table-top device and the mouse. The last two setups combine interactions performed through the table-top device and using the 6DOF input device. All six setups display the 2D view on the table-top device and the 3D view on the vertical display.

The first setup (that we call *SetupT*) allows to perform interactions using the table-top device only. The initial interaction technique table/task binding does not cover vertical transla-

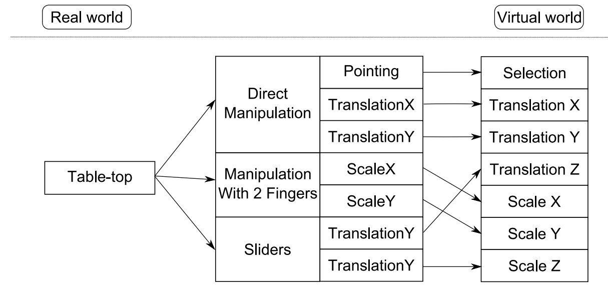

Figure 6: RVDT representation of *SetupT* (table-top only).

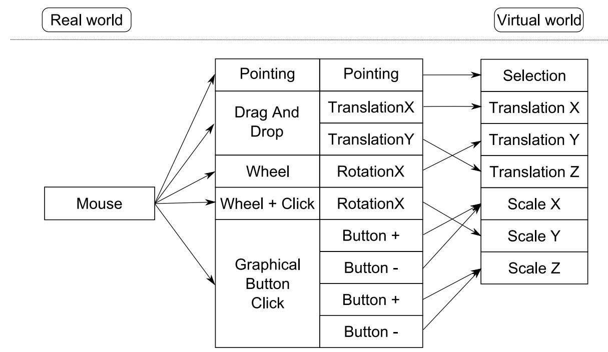

Figure 7: RVDT representation of *SetupM* (mouse only).

tion and scale, and therefore rule R5 is not satisfied. We add two sliders to cover these elementary tasks. The resulting RVDT representation is illustrated in Figure 6.

For the setup using the mouse as the only input device the initial interaction technique table/task binding does not allow to cover all tasks (R5 not respected). Hence, we add to this setup the usage of the mouse wheel and graphical buttons to cover the seven elementary tasks. The resulting RVDT representation of this setup that we call *SetupM* is illustrated in Figure 7.

The 6DOF input device integrates three translations and three rotations. We bind respectively each rotation from the interaction technique table to a scale in the task component. This binding does not satisfy rule R3 but allows to address some tasks without adding supplementary tasks. The six elementary tasks for translation and scale are covered but not the selection task. Therefore, we add a graphical sphere that represents a 3D cursor. The user translates in 3D this sphere towards the desired object and when an intersection between the sphere and this virtual object occurs, the object is selected. We call this setup *SetupSt* with respect to the input device called SpaceTraveler.

The combination of interactions performed through the table-top device and using a mouse does not cover the vertical scale task. Therefore, we add four graphical buttons on the 3D view to allow object scaling in the projection plane. We block the mouse wheel usage since corresponding elementary tasks are covered by table-top interactions. We call the resulting setup *SetupTM*.

The selection is the only missing task that is not directly covered by the 6DOF input device. Therefore, when combining the table-top device with the 6DOF input device, the selection is covered by the table-top device. We call this setup that allows only to perform selection using the table-top de-

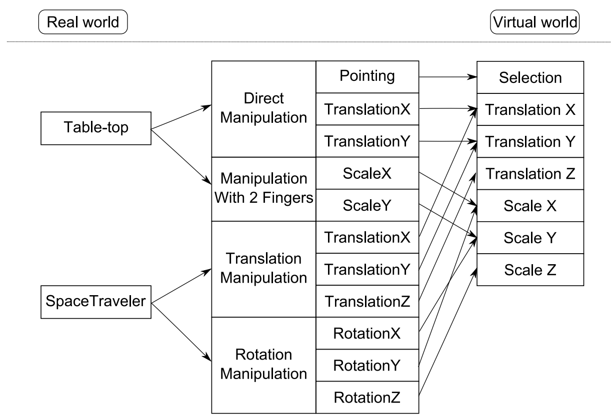

Figure 8: RVDT representation of *SetupTSt*2 (table-top and 6DOF input device).

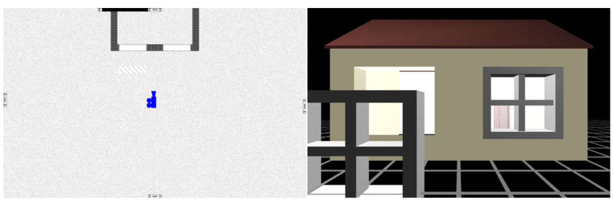

Figure 9: Left: 2D global view of a virtual scene displayed on the table-top device. Right: 3D view of the same virtual scene displayed on the vertical surface.

vice $SetupTSt_1$. In order to enhance the existing complementarity between the table-top device and the 6DOF input device, we develop the sixth setup that we call $SetupTSt_2$. This setup combines basic table-top interaction techniques and the 6DOF input device interaction techniques. The resulting RVDT representation of $SetupTSt_2$ is illustrated in Figure 8. The $SetupTSt_1$ RVDT representation is similar to Figure 8 but the connections related to table-top translations and scales are deleted.

4.2 Experimentation Procedure

Twelve users (eight men and four women) with different education backgrounds participate in our evaluation. We focus on choosing users with various levels of experience in 3D interactive computer graphics and 3D games. Each participant is seated in front of the table-top device and the vertical display is situated directly in front of her/him. A 2D global view of a virtual scene as well as a camera icon that represents the 3D point of view are displayed on the table-top device (see Figure 9 left). A 3D subjective view of the same scene is displayed on the vertical surface (see Figure 9 right). The task users are asked to accomplish is a docking task requiring a virtual object selection, its 3D translation, and 3D scale.

At the beginning of the evaluation, each user has five minutes to test freely the six setups. During evaluation, users are asked to dock a virtual 3D window into a house opening (see Figure 9) as fast as possible. Users freely indicate the end of the interaction when they consider that the result is satisfying. For each setup users have three tasks to perform with different initial characteristics (with respect to desired final object state): different position, different scale, and different position and scale. The setups order is alternated between users as well as initial characteristics between setups to avoid any bias. The objective analysis is performed on the time needed for task accomplishment and precision according to each setup. The experiment lasts approximately 30 minutes.

Users are asked to answer a questionnaire during and at the end of the evaluation process. Questions focus on users preferences for selection and object manipulation. Users are also asked to rate between 1 (totally negative) and 7 (totally positive) the ease, satisfaction, intuitivity, and efficiency of interaction of each setup. These questions offer us the possibility of a subjective user feedback comparison between the different setups.

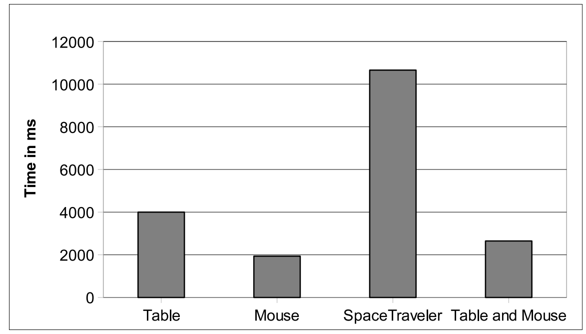

Figure 10: Average time in ms needed for virtual window selection.

4.3 Results and Analysis

In this section, we present at first the results of the selection and then those of object manipulation in our evaluation. Afterwards we present the results of the overall (selection and object manipulation) and we finish by discussing obtained results.

4.3.1 Selection

In $SetupTSt_1$ and $SetupTSt_2$, selection is only made by using the table-top device. Therefore, only four selection modes exist in our evaluation: Table, Mouse, SpaceTraveler, and Table and Mouse. Times needed for the virtual window selection are illustrated in Figure 10. The needed selection time using the SpaceTraveler is approximately 4.5 times higher than the mouse. Both the mouse and the SpaceTraveler are related to the 3D view and therefore this time difference is justified by the difference between the numbers of input device DOFs.

The time needed to select the virtual window using the table-top device is the double of the time needed using the mouse. Two reasons justify this difference that are input/output space ratio difference between input devices and object/view ratio difference between the 2D and 3D view. The input/output space ratio is one for the table-top device whereas it is a lot smaller for the mouse. Object/view ratio depends on the object position and dimensions in the view. For example, object/view ratio of the virtual window (see Figure 9) in the 3D view is approximately 0.260 whereas the one for the 2D view is approximately 0.005. These aspects justify clearly the different selection times between the mouse and the table-top device.

The subjective selection results show that 75% of users prefer the table-top device. Fast selection and the "*haptic* "aspect

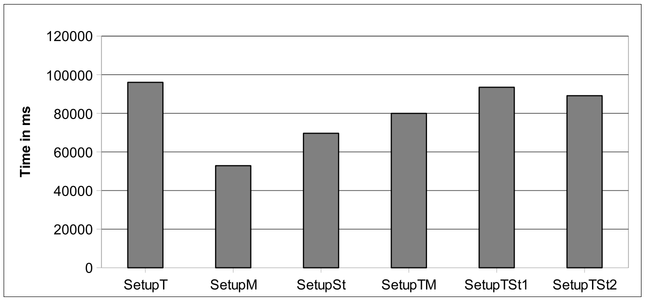

Figure 11: Average time in ms needed for virtual window manipulation according to the six setups.

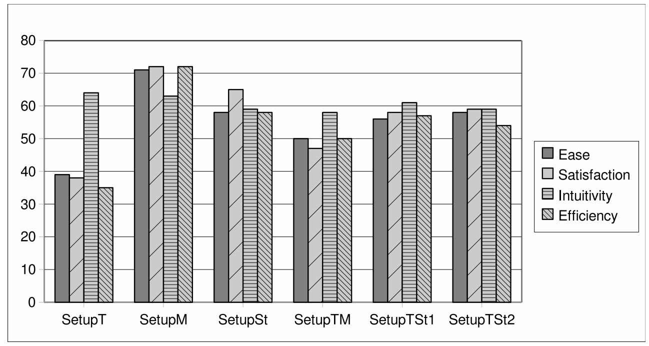

Figure 12: User overall grading of the six setups by ease, satisfaction, intuitivity, and efficiency.

are the main reasons that users present to defend the table-top choice. Two users choose the mouse as the preferred selection device because of its ease and intuitive aspects. One user only chooses the SpaceTraveler because it is "*fun*".

4.3.2 Manipulation

Manipulation time needed for task accomplishment of object manipulation shows that *SetupM* has the best time and *SetupT* has the worse time (see Figure 11). The setups combining two input devices have nearly the same manipulation time results. Moreover, precision results show a higher imprecision of *SetupT* when compared with other setups.

Users' setup preferences for object manipulation are more mixed than for selection. 43% of users choose *SetupM* as their preferred setup whereas 33% choose $SetupTSt_2$. Users who favor *SetupM* justify their choice by their experience of using a mouse. Users that prefer $SetupTSt_2$ justify their choice by the possibility of performing easier interactions for rough horizontal translations using the table-top device and the "*intuitivity*"of the 6DOF input device. *SetupT* is not chosen by any of the participants and the other three setups are chosen by one participant each.

4.3.3 Overall (Selection and Manipulation)

The average manipulation time is significantly higher than average selection time and thus the overall time results are similar to manipulation time results. As shown in the previous section, *SetupM* has the best average time for task accomplishment.

Users' ratings of ease, satisfaction, intuitivity, and efficiency (see Figure 12) show that users consider *SetupM* as the easiest, most satisfying, and most efficient whereas *SetupT* is the worst for these characteristics. No significant difference exists for intuitivity rating results. Moreover, 59% of users choose *SetupM* as their preferred setup followed by *SetupTSt*2 (25%). Only one user choose *SetupT* and another one *SetupTSt*1. Participants justify the *SetupM* choice by their experience and the ease, precision, and fast aspects of interactions using the mouse. Most of the participants who choose the *SetupTSt*2 have a good experience in 3D interactive computer graphics and/or 3D computer games.

4.3.4 Experimentation Discussion

The six interaction setups of the experimentation are developed with the RVDT model and its design space. The design space allows to explore the interaction combination possibilities exhaustively. The five binding rules allow to eliminate uninteresting combinations and to focus on attractive solutions. The aim of the experimentation is to evaluate the solutions generated by our model. Therefore, the resulting design space allows exhaustive interaction combination with restrictive selection among these combinations and a final validation through experimentation.

Even though the evaluation results show that the mouse has the best subjective and objective results, it produces other interesting results. The 2D selection is definitely preferred to 3D selection. Moreover, the table-top device is suitable for selection tasks and rough positioning tasks but not for tasks where precision is essential. The combination of a 6DOF input device with a table-top device for spatial tasks is promising. The comparison between $SetupTSt_1$ and $SetupTSt_2$ shows that equivalence between interaction techniques for task accomplishment is important for users. Most of the users who choose this combination have a regular practice of video games. Therefore, with some learning and for experimented users, the combination of a table-top device with a 6DOF device could become the best combination when compared to other input device combination possibilities.

5. CONCLUSION

This paper has presented the RVDT model and its design space for high-level interaction design combining multiple input devices and multiple views displayed on multiple surfaces. This design space integrates real and virtual input DOFs and output dimensions at the design phase. It allows to explore the possible interaction combinations exhaustively and to eliminate uninteresting solutions through five rules. The evaluation has compared six possible combinations of a table-top device, a mouse, and a 6DOF input device for combining interactions performed through a 2D horizontal view and a 3D vertical view of the same virtual environment. The combined interactions have been designed with the RVDT model and its design space. The results show the mouse is the fastest, most precise, and the preferred input device for users. Nevertheless, results show that combining a table-top device with a 6DOF input device is suitable for experienced users.

We plan to develop a framework based on the RVDT model that allows software design and concurrency management. Concurrency is a key issue in our work because of the possibility to perform interactions on multiple representations of the same virtual object and using distinct input devices. We also plan to apply the RVDT model to navigation tasks. The aim is to compare different interaction navigation possibilities in the same context as the evaluation we presented in this paper. Last, we plan to develop with the RVDT model and its design space "*exotic*" cross task interaction techniques. An example of such techniques is the manipulation of a camera icon, displayed on one view and that represents a second view, simultaneously with a virtual object manipulation displayed on the second view. The aim of developing these kind of exotic interactions is to study their usability with end users.

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