Detecting Interaction Variables in a Mixed Reality System for Maxillofacial-guided Surgery

Daniela G. Trevisan[1,3], Luciana P. Nedel[2], Benoit Macq[1], Jean Vanderdonckt[3]

[1]Communications and Remote Sensing Laboratory
Université catholique de Louvain (UCL)
Place du Levant 2, Bat. Stevin, 1348 – Louvain-la-Neuve – Belgium

[2]Instituto de Informática – Universidade Federal do Rio Grande do Sul (UFRGS)
Caixa Postal 15.064 – 91.501-970 – Porto Alegre – RS – Brazil

[3]Belgium Laboratory of Human Computer Interaction
Université catholique de Louvain (UCL)
Place de Doyens 1, 1348 – Louvain-la-Neuve – Belgium

{trevisan,macq}@tele.ucl.ac.be, nedel@inf.ufrgs.br

vanderdonckt@isys.ucl.ac.be

Abstract. *To establish a relation between the user preferences and accuracy while using a VR or MR system and the set of components (technical, functional and perceptual) used in the system conception is yet a challenge. In this work we study the user reaction in relation to image guided surgery applications using different kind of visualization and guidance. Our goal is to identify practical basis that explains how mixed reality interfaces might provide support and augmentation for interactive applications. To accomplish that, we propose a model that allows the identification of the contribution of each independent variable in the final user interaction. The contribution rates were identified by applying user tests.*

1. Introduction

One of the most challenging aspects on the new interactive systems development lies on the ability to integrate computer-based information into the real world. These kind of systems, so called mixed reality (MR) systems, are promising since they are capable of overlaying and registering digital information on the user's workspace in a spatially meaningful way. This characteristic allows MR systems to be an extremely effective operating medium, once it is based on monitoring the state of the user and/or the environment in real time, and adapting or augmenting the computational interface to significantly improve the user performance on the task execution. When applied to the medical surgery domain, MR systems allow users to keep their environmental perception while having intuitively access to more contextual information, such as the incisions location, regions to be avoided, diseased tissues, and so on.

Human-computer interaction (HCI) research usually focuses on the design, implementation and evaluation of interactive systems in the context of a user's task and work [Dix et al. 1998]. Concerning medical applications, the generic design of human-computer interfaces for image-guided surgery (IGS) should deal with pre and intra-operative images displayed in the surgical environment to provide surgeons with some kind of guidance [Trevisan et al. 2003]. In this typical application of MR systems, the virtual world involves the pre-operative information (i.e. information acquired before surgery), while the real world corresponds to the intra-operative live information (i.e. information acquired during the surgery). Both should be correctly aligned and displayed in real time. This scenario highlights the description of user interfaces for image-guided systems is not a trivial task.

In this work we are studying the user reaction in relation to IGS applications using different kind of augmentation. Our main objective with this usability test is to identify theoretical and practical basis that explains how mixed reality interfaces might provide support and augmentation for interactive applications. To accomplish that, we are using the results provided by user tests to find a model that allows the identification of the contribution factor of each independent variable in the final user interaction. With that other interactive mixed systems designed with the same variables can be described by the proposed model, reducing the time for user interaction estimation.

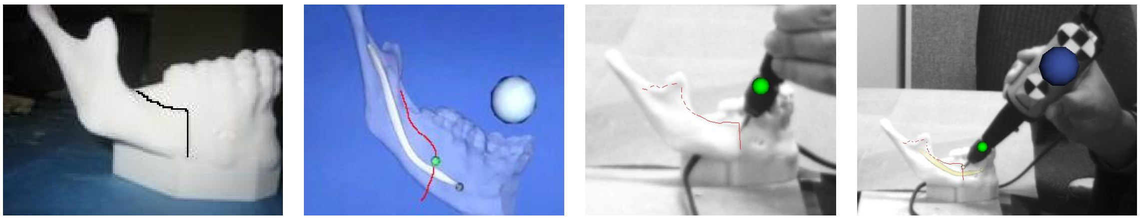
The paper is organized as follows. In Section 2 we presented the testbed application developed to carry on the evaluation method proposed, as well as the method proposed by us to measure the system accuracy. In Section 3 we present all the aspects needed to proceed with the system usability evaluation and in Section 4 we describe our experiment preparation. In Section 5 we present our results and the discussion. Finally, in Section 6 we make final comments and about our on-going research.

2. Testbed Application

2.1. System design

In collaboration with the *Service de Stomatologie et Chirurgie Maxillo-faciale at Saint Luc Hospital*, in Brussels, we proposed the development of an application using a mixed reality interface to guide surgeons in a maxillofacial surgery. The goal of this application is to increase the first surgery success, avoiding a second intervention. To achieve this objective, we are mixing real and virtual images by projecting a virtual guidance path-line on the patient mandible live video images. Then, the surgeon should cut the patient mandible paying attention to follow this path-line and avoiding touching the dental nerve. The time involved in this procedure is not important, but the accuracy is mandatory.

Two main scenarios are explored in this study, considering virtual and augmented guidance. The virtual guidance scenario provides the 3D visualization (in the screen) of the tool trackers and the reconstructed mandible. The interactive task consists in cutting the mandible following, as best as possible, the path-line shown in the screen. When the surgeon touches the good position (over the real object), the virtual representation of the surgical tracked tool becomes green (see Figure 1(b)). Another dynamic sphere attached to the tracked tool indicates the distance from the tool to the dental nerve. Additional information, such as, where is located the internal structure (dental nerve), are provided by using transparency visualization effects. Manipulations with the virtual object such as rotation, scale and zooming are allowed at any time. The augmented guidance scenario provides the visualization (in the screen) of the 3D elements superposed to live video images. This scenario presents two alternatives according to which information are displayed in the scene. In the first variant, the path-line is projected over the video image. When the user touches the correct position (over the real object), a sphere representing the tracked tool becomes green (Figure 1(c)). To indicate if the tool is in front of or behind the mandible mock-up we change the intensity of the green sphere. If the tracking tool is behind the mock-up and, consequently, occluded in the viewed image, the visualization of a semi-transparent sphere guarantees a kind of depth guidance for the user. The same principle is used in relation to the path-line. As shown in Figure 1(c) and (d), the draw representing the path-line is dotted when it indicates an occluded area (behind the visible real surface). This kind of representation was suggested by the surgeon, once dotted lines have been currently used in other procedures such as pre-operative planning.



(a) (b) (c) (d)

Figure 1. Four scenarios for a maxillofacial surgery system: with no guidance, just showing the cutting line in a printed piece of paper (a); using a virtual representation of the maxillar, the dental nerve, the tool and the cutting line (b); considering augmented visualization and guidance where the representation of a cutting line and a tracking indicator (green sphere) are shown super posed to live video (c); also with augmented visualization and guidance, but adding more information - the representation of the dental nerve and an indicator (blue sphere) of the distance between the tool and the dental nerve (d).

The second variant of the augmented guidance scenario considers two more additional information: an indicator of the distance between the tool and the dental nerve; and the visualization of the dental nerve over the live video images. When the marker is recognized by the system, two spheres are displayed in the screen: one attached to the tool; and other, bigger, displayed in the middle of the tool (see Figure 1(d)). The big one indicates the distance between the tool and the dental nerve using three colors: gray means go ahead; blue means pay attention (i.e., you are less than 3mm from the nerve); red means stop (i.e., you will probably touch the nerve).

2.2. Apparatus

In mixed reality applications, as well as in virtual reality ones, the characteristics of the input and output devices used affect the user performance during the execution of a task [MacKenzie 1995], [Poupyrev 1997].

Our tests were performed in a PC computer with 3.0Ghz processor, 1GB of RAM memory and a nVidia GeForce graphics card. For the visualization, we have used a 19' LCD screen, and to capture the interaction of the user with the mock-up, a live video capture system based on a stereo camera from Claron Technology, model S60. The tool used to cut the mock-ups is a mini-driller with controlled speed (Figure 2(d)), while the mock-ups used in the experiments are two: a simple one, representing a 3D "L" shape (Figure 2(b)) and a more complex, the printed 3D mandible (Figure 2(c)). Both include a wire passing inside (simulating the dental nerve), were built with the same material (gypsum), and were printed using a 3D printer [1]. To detect if the user touched the dental

[1]Z-corp Website: http://www.zcorp.com

nerve or not during the experiment, we have developed an electronic circuit (Figure 2(a)) connecting the wire and the tool. It produces a sound alarm and a visual feedback (using a LED) when the tool touches the wire.

Figure 2. Experimental scenario tools

2.3. Accuracy measurement

A huge problem involved in the evaluation of virtual and mixed reality system is the number of constraints imposed by its components and the dependencies identified among these components [Azuma 1997]. Trying to minimize the intervention of each component of the system in the final evaluation, we calculated our system performance by estimating the global and local errors.

The local error (e_l) is calculated by computing the sum of the error estimation for all factors that can insert noise in the system: the tracker (e_{tr}), the user interaction (e_{ui}), the registration (e_{reg}) and the printed model (e_{pm}).

$$e_l = e_{tr} + e_{ui} + e_{reg} + e_{pm} \tag{1}$$

The global error (eg) is provided by calculating the distance from the points picked by the user to the registered object. We can say that global error is approximately equal to the local error estimation.

Error estimation for our system is calculated as follows.

2.3.1. Tracking error

A relevant factor for the tracked object accuracy relates to the way we dispose the markers. Due to the lever effect, the farther apart the Xpoints (Figure 3) at the ends of a vector, the lower the error in measuring the vector's orientation in space, and, therefore, the lower the error in extrapolating object positions of interest, such as the tool used by us to cut the jaw. The drawing in Figure 3 demonstrates this effect by showing a tool position error range for two different placements of the Xpoints. To minimize extrapolation error, one end of the longer vector should be placed as close to the tool tip as possible, and the other as further away from it as possible. We have tested two designs of markers for our tracked tool. We have computed 1000 poses for each design and the RMS errors for the tracked tool tips positions are depicted in Table 1.

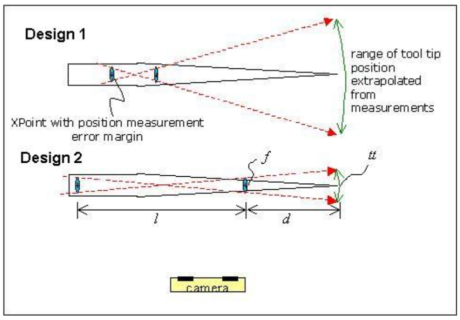


Figure 3. Relating the tool tip definition accuracy and the markers placement

Table 1. Tool tip precision error for 1000 poses

Design	$l(mm)$	$d(mm)$	e_f	e_{tt}	RMSE for the tool tip tracked poses
1	60.55	118.91	0.17	0.5564	0.5680
2	117.1933	58.5695	0.20	0.3470	0.3620

If d is small relative to l, the tip error is dominated by the Xpoint error (roughly, calibration error + jitter, typically in the range $0.2mm$ to $0.4mm$ RMS[2]). If d is large relative to l, the error is dominated by the ratio d/l. As a rule of thumb, to ensure that RMS error at the tip is sub-millimeter, keep $l \geq d$. Analyzing the Table 1, we verify that the marker configuration for the Design 2 is most accurate then the one used for Design 1 fitting the expected range ($0.2mm$ to $0.4mm$). We have used such design for our tests.

2.3.2. User interaction error

We call user interaction error, the imprecision of the user while interacting with the system and is directly related to the dexterous ability of each user. To evaluate the precision of such interaction we have performed a sequence of 15 tests with 15 users that provide us the RMS and the standard deviation for the user interaction error. The test consists in picking the 4 corners of one of the faces of the L mock-up. As the real distance and angles between these points are known, we can compare it with the distances and angles given by the acquired 3D points. Table 2 shows the RMS error and standard deviation computed from 15 users essays. As these points were acquired by the users while using the tracking system and the tracking error (e_{tr}) is known, the user interaction error (e_{ui}) should be the values collected during the experiments, minus the tracking error, or yet $0.048mm$. If the user that will operate the system performs such calibration procedure before the registration procedure, the system will be able to compute a personalized performance for this user.

[2]Information given by the manufacter.

Table 2. RMS error and standard deviation for distances and angles calculated from the points picked by the users to the real corners positions.

	RMSE	STD
Distances (mm)	0.41	0.66
Angles (radians)	0.06	0.025

2.3.3. Printed model error

The final printed object were scanned (with a laser scanner) and compared with the initial 3D model using the Inspector Software to align and register the models. For the "L"shape, virtual and real mock-ups are overlapped with a precision of $0.20mm$.

2.3.4. Registration error

For the registration between virtual and real objects we are using the method described in [Quentin et al. 2004]. While using such algorithm we should pay attention to three parameters that influence the accuracy of the method: the number of points one should acquire to characterize the object surface, the pattern along which those points should be acquired, and the resolution needed for the Euclidean distance map. For the resolution, we assume the values found by [Quentin et al. 2004], where a resolution similar to the internal slice resolution of the image yields good results. Improving the distance transformation resolution further does not benefit to the accuracy. For the number of points and which pattern to consider we have performed a sequence of tests and found 20 points along the contour of the mandible and 12 points on the corners of the "L" has produced acceptable registration matching. We can verify it comparing the global error estimation with the sum of the local errors. As a result of the registration step we are able to compute the global error by calculating the distance from the points picked by the user to the registered object. Then using equation (1) we can find the registration error

$$e_{reg} \approx e_g - e_{tr} - e_{ui} - e_{pm} \tag{2}$$

We have found global registration error from 0.8mm to 1.5mm which give us a filtered registration error from $0.24mm$ to $0.94mm$. Such results seem to fit the range error of $0.17mm$ to $0.38mm$ previously computed in simulations [Quentin et al. 2004].

3. Evaluating the System Usability

Many new interaction techniques are emerging from 3D and virtual technologies looking for more natural interactions. However, the same problems regarding the 3D visualization are still there in addition to other specific factors. We can resume the different results found in experiments regarding evaluation of 3D interactions in VR worlds [Poupyrev 1997], [Forsberg et al. 1996], [Bowman et al. 2002], [Nedel et al. 2003] by saying that the 3D visualization could help the user interaction if the dominant perceptual cues (i.e. depth cues involving motion parallax, shadows, transparency, etc.) are identified and adapted for each application. In the next section we describe how we designed our scenarios for usability tests.

Table 3. Scenarios used in the tests sessions. The numbers in the "kind of guidance" column correspond to: (1) no guidance; (2) visualization of the path-line with distance indicator; (3) visualization of the path-line with its distance indicator and the internal structure (dental nerve) visualization with its distance indicator.

Scenario	Kind of visualization	Kind of guidance	Kind of display
1	none	(1)	—-
2	virtual	(3)	screen
3	augmented	(2)	screen
4	augmented	(3)	screen

3.1. Scenarios considered

For the evaluation tests, we considered 4 different scenarios: (1) no guidance and no visualization scenario; (2) virtual guidance and visualization scenario; (3) augmented guidance and visualization scenario; (4) augmented guidance and visualization scenario with feedback about the contact with the dental nerve.

In the no guidance scenario none computer guidance is provided to the user. Three different views of the path-line (as seen in Figure 1(a)) are shown to the user in a piece of paper and the user should cut the mock-up just checking this piece of paper. This scenario corresponds to the real currently situation and will serve as reference scenario to measure the value added by the guidance provided by the other scenarios. The other 3 scenarios were previously explained in Section 2.1. Table 3 summarizes the 4 proposed scenarios. For technical limitations, at this stage of the work we are just considering the "L" mock-ups. Despite we also made some tests using mandible mock-ups, these are not yet sufficient to correctly evaluate interaction in our system.

3.2. Independent and dependent variables

Independent variables are the experiment variables that are manipulated to generate different conditions to compare. In this mixed reality experience, we established the kind of guidance and visualization as independent variables. Dependent variables are the measures taken as the performance indicative or level of acceptance of the technique by the users. The dependent variables used in our experiment were: precision on task execution (we measure the user precision by calculating the distance between the path-line and the line drawn by the user); time to perform the task; task performance (Precision/Time); workload (based on the result given by the subjective NasaTLX post-test [Hart and Staveland 1988]).

4. The Experiment

4.1. Task description

The task is always the same for the 4 considered scenarios and consists in cutting the mock-up reproducing as best as possible the indicated trajectory without touching the internal hidden structure (dental nerve). There is no limit time to accomplish the task. Before starting the main task execution, the user has free time for training. The training consists in performing sub-tasks that allow the user to understand how the system will provide guidance in each scenario. We proposed two sub-tasks: user perception calibration and motor calibration.

In the perception calibration task the user should select arbitrary points over the mock-up surface. These points are indicated in the virtual or augmented scene. This task is done once without guidance (i.e., the user perceives the point in the virtual or augmented scene and then performs the task) and then with guidance (i.e., when the user is pointing the good position, a small sphere representing the tracked tool tip becomes green). This task is performed in the virtual and augmented scenarios. In the augmented scenarios, the tracked tool tip becomes transparent and the path-line visualization is dotted if the surface is occlusion. Time and precision (i.e., performance) for the user task accomplishment are computed.

In the motor calibration procedure, the user should cut a trajectory drawn over the mock-up surface. In this case, the mock-up resistance is the same used to execute the main task. Time and precision (i.e., performance) for the user task accomplishment are computed.

4.2. Subjects and procedure

Sixteen users volunteered for experience the tasks: 14 males and 2 females, with a mean age of 24 years. Each participant tested only one of the designed scenarios to avoid the learning effect. Each scenario was tested 4 times. Before each session, the mock-up should be calibrated and registered. Session length varied according to the index of difficulty given by the kind of guidance, kind of visualization, and the level of the individual motor coordination of each user. The subjects were tested individually. Considering the virtual 3D scenario, users were carefully informed how to use the manipulation commands (i.e. translation, rotation and zoom), but they were left free to use it or not during experimental trial. At the end of the test, each user was asked to answer the NasaTLX questionnaire [Hart and Staveland 1988].

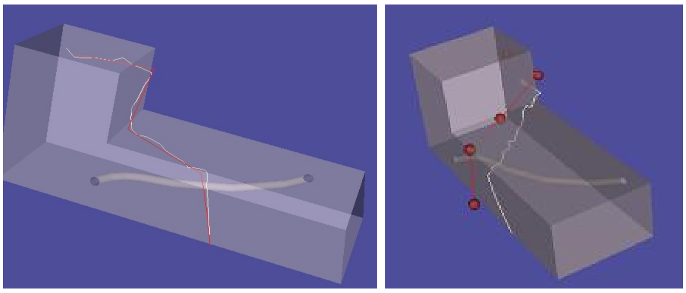
5. Results and Discussion

We are not interested just in find a number representing the final user performance; we want to be able to decompose such result by identifying all parameters involved in the final performance. The goal of such model is to assist in the design of future user mixed interfaces as well as to predict the performance of operators avoiding to apply series of usability user tests.

Some known metrics has been used to compute performance and movement time in many experiments. For instance, the Fitts' law [Fitts 1954] is an effective method of modeling rapid, aimed movements, where one appendage (like a hand) starts at a specific start position, and moves to rest within a target area. However, Fitts' law predicts movement in just one dimension. Fitts' original experiments tested human performance in making horizontal moves toward a target. Both the amplitude of the move and the width of the terminating region were measured along the same axis. It follows that the method is inherently one-dimensional. So, when dealing with two or three dimensional target acquisition tasks, new interpretations of target width must be considered. Another major deficiency is the absence of a consistent technique for dealing with errors.

5.1. Computing precision

For each tested scenario, the Euclidean distance between the reference and the final path-line performed by the user were calculated, providing the final user precision. Both path-lines (i.e. reference and final, Figure 4) were acquired in the same way, i.e., digitalizing points over the surface trajectory with the tracked tool. The task accomplishment involves the cutting of the real mock-up. However, to calculate the Euclidean distance between the reference and the user performed path-lines, we are first projecting the line designed by the user on the mock-up surface to fit the requirements of the reference line, also designed on the mock-up surface.



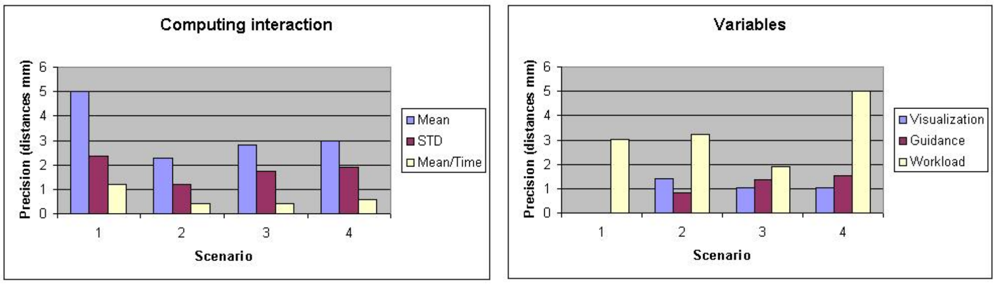
(a) (b)

Figure 4. Result of user interaction for variables configuration given by scenario 2 (a), and by scenario 1 (b). Red line represents the ideal suggested path while the white line represents the final user interaction.

Our results are expressed in terms of the mean distance and standard deviation calculated for each scenario. We are not considering the time variation because the precision of the task is more important than time for our tests. Smaller is the distance, better will be the interaction technique (Figure 5(a)). As we are not using all functionalities that could be provided by AR systems, such as the use of a head mounted display, we are not interested in a comparison between 3D visualization and AR. Instead, we are more interested in identifying how the independent variables involved in these two types of techniques (3D and AR) are influencing the interaction. Despite the 3D visualization offers better spatial perception, AR visualization presents more realistic representation of the real scene by projecting virtual objects over the video live images. Once the final user performance was calculated for each scenario, we can compare the scenarios 2, 3 and 4 with the scenario 1 (neither guidance nor visualization) and extract the performance gain of each one. Such gain is attributed to the influence of the guidance and visualization on the task accomplishment.

The performance gain given by the visualization can be deduced from the assessed perception calibration task (Section 4.1). We assume that the remaining performance gain is divided between user motor performance and guidance. User motor performance was assessed during the motor calibration tests (Section 4.1) and we assume it is constant for all scenarios. We found a mean of $1.31mm$ with a deviation standard of $0.47mm$.

Concerning the workload we obtained that the higher workload rating coincide with the kind of guidance 3, where the user has more guidance information. The workload rating was normalized to be plotted together with the other two assessed variables (Figure 5(b)).



(a) (b)

Figure 5. Precision of the user interaction in the four proposed scenarios (a), and independent variables influence in each scenario (b).

As the users were not experts in the application domain and very poor information was provided in scenario 1, users were not very aware about the path to follow and less mental effort was spent for the task execution in this scenario. It reflects the low workload level found in scenario 1 (Figure 5(b)).

5.2. Defining the model

Once we have created our data set we want to identify how the captured variables are related. To do that we have used the Spearman's test where significant correlation was found between precision and visualization ($p = 0.0241$), and between precision and guidance ($p = 0.0306$). No significant correlation was found between visualization and guidance.

Based on such analysis the user interaction can be expressed by the following expression:

$$I \approx \alpha V_i + \beta G_j + \gamma + \epsilon \tag{3}$$

where the indexes i, j represent the values that the variables V_i (kind of visualization with i= 1, 2, 3), G_j (kind of guidance with j= 1, 2, 3), γ (constant for the user motor calibration), α and β (contribution factors for the final interaction I), and ϵ (error factor) can assume.

To solve such linear system we applied a SVD (Singular Value Decomposition) method which uses the least squares and pseudo-inverse computation [Peters and Wilkinson 1970]. Least square is a mathematical optimization technique that attempts to find a best fit to a set of data by attempting to minimize the sum of the squares of the ordinate differences (called residuals) between the fitted function and the data.

In mathematical terms, we want to find a solution for the equation

$$\left[\underline{A}^T\ \underline{A}\right] C = \underline{A}^T I \tag{4}$$

where $\underline{A}$ is an m-by-n matrix of variables (with $m > n$) and C and I are n-respectively (vector of constants α, β,γ) m-dimensional (vector of final user interactions) column vectors.

We have found α = 0.6, β = 0.5 (for visualization and guidance respectively), γ = 1.31 (value previously measured in Section 4.1).

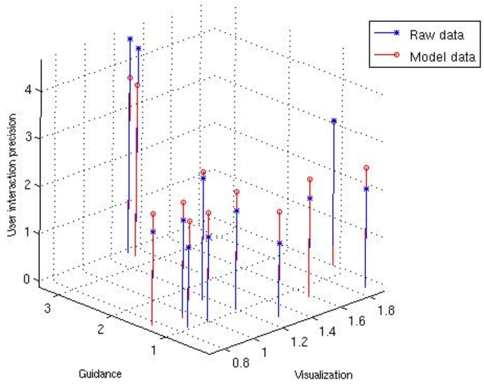


Figure 6. Approximation given by the proposed model

By plotting the data set (Figure 6) we observe a good approximation with the proposed model. As a preliminary result we observe that visualization has more influence than guidance for our experiment. It reinforces the results shown in Figure 5(a), where the virtual visualization with the same amount of guidance has provided better precision.

6. Conclusions and Future Work

In this paper we presented the strategy we developed to evaluate the usability of mixed reality systems, precisely, the use of mixed reality in surgery. First of all, we briefly presented the problem we are trying to solve and the application developed to be used as a testbed application. Then, we explained how we have calculated the errors inherent from the computer system, devices used and user interaction. That is used for measuring the overall accuracy. The experiment was described in detail and the method we used to evaluate the system interaction presented. By analyzing the interaction between our assessed variables, it is apparent that the workload augments according to the amount of guidance provided. As the workload index was measured with very subjective tests, more concrete and objective evaluation should be envisaged to assess such influence. For instance, analysis of biological signals to capture user' state (such as stress) could be combined with the NasaTLX results.

On the other hand, the precision of the interaction technique varies according to the guidance and visualization choices. In this way a model to describe the final user interaction based on such variables influence was proposed. As a result, future interactive mixed systems can use such model to estimate interaction at early stages of system development or adapt the model to better fit your own system variables.

At the moment we have just tested our model taking into account the error factor found to best fit our first data set. In our on-going work we are doing the user tests with the mandible mock-up, what will augment our results reliability. Then, we will tabulate the tests results and extract our conclusions related to the index of task difficulty. With this procedure, we intend to highlight the influence of each system component (kind of visualization, kind of guidance, and kind of mock-up) in the final user performance. The results obtained from this evaluation will be then combined with the suggestions proposed by the use of DesMiR [Trevisan et al. 2004] design space.

Acknowledgements

We gratefully acknowledge the support from the MERCATOR project under contract WALEO 21/5129 and SIMILAR Network of Excellence (FP6-507609), CNPq (Brazilian Council for Research and Development) projects number 478721/2003-0 and 306099/2004-7, and the Brazilian Education Ministry (MEC-CAPES) for financial support. We also thank all the colleagues that participated as subjects in the experiments.

References

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, 6(4):355–385.

Bowman, D., Gabbard, J., and Hix, D. (2002). A survey of usability evaluation in virtual environments: Classification and comparison of methods. *Presence: Teleoperators and Virtual Environments*, 11(4):404–424.

Dix, A., Finlay, J., Abowd, G., and Beale, R. (1998). *Human Computer Interaction*. Prentice Hall Europe.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47:381–391.

Forsberg, A., Herndon, K., and Zeleznik, R. (1996). Effective techniques for selecting objects in immersive virtual environments. In *Proc. ACM UIST'96 Symposium on User Interface Software and Technology (UIST)*. ACM Press.

Hart, S. G. and Staveland, L. E. (1988). *Development of NASA-TLX (Task Load Index): results of empirical and theoretical research*. Elsevier Science, North-Holland.

MacKenzie, I. (1995). *Virtual Environments and Advanced Interface Design*. Oxford University Press, NY.

Nedel, L. P., Freitas, C. M. D. S., Jacob, L. J., and Pimenta, M. (2003). Testing the use of egocentric interactive techniques in immersive virtual environments. In *Interact 2003*, pages 471–478. IFIP.

Peters, G. and Wilkinson, J. H. (1970). The least squares problem and pseudo-inverses. *Comput. J.*, 13:309–316.

Poupyrev, I. e. a. (1997). A framework and testbed for studying manipulation techniques for immersive vr. In *ACM Symposium on Virtual Reality Software and Technology*, Lausanne, Switzerland. ACM.

Quentin, N., Matthieu, F., Yves, V., Etienne, O., Benoit, M., and Olivier, B. (2004). Registration and real-time visualization of transcranial magnetic stimulation with 3-d mr images. *IEEE Transactions on Biomedical Engineering*, 51:1994–2005.

Trevisan, D., Vanderdonckt, J., Macq, B., and Raftopoulos, C. (2003). Modeling interaction for image-guided procedures. In *Proceedings of International Conference on Medical Imaging SPIE2003 (San diego, 15-20 February 2003), K. Hanson, C.-T. Chen, E.L. Siegel (eds.)*, volume 5029, pages 108–118. International Society for Optical Engineering.

Trevisan, D. G., Vanderdonckt, J., and Macq, B. (2004). Conceptualizing mixed spaces of interaction for designing continuous interaction. *Virtual Reality Journal*, 8(2):83–95.