

Perceived Quality of Simplified Polygonal Meshes: Evaluation using Observer Studies

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Abstract

The complexity of a polygonal mesh model is usually reduced by applying a simplification method, resulting in a similar mesh having less vertices and faces. Although several such methods have been developed, it is not yet clear how the choice of a given method, and the level of simplification achieved, influence the quality of the resulting mesh, as perceived by the final users. Following on work carried out by the authors, but only for mesh models of the lungs [SSSMF05, SSFM05], a comparison among the results of three mesh simplification methods, for a few generic models and two simplification levels, was performed through a controlled experiment involving 65 observers. The goal was to ascertain whether the main findings previously obtained for lung models, through a study with 32 subjects, could be generalized to other types of models and confirmed for a larger number of observers. This was verified through the analysis of the data collected from the experiment, which shows that, regarding perceived quality, users are indeed sensitive to the mesh simplification method used and that this sensitivity varies with the simplification level.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Object Modeling; Visualization

1. Introduction

Polygonal meshes are widely used for modeling different kinds of objects and structures in many application areas (e.g., Medicine [JSG03], Cultural Heritage [GFDS*05], etc.). Sometimes, due to insufficient memory or processing power, low screen resolution or reduced network bandwidth (e.g., in a mobile device), the number of faces defining a mesh has to be reduced by applying a simplification method, resulting in a similar and more manageable, less complex model and allowing interactive visualization. Although several such simplification methods have been developed and are reported in the literature (see the survey in [Lue01]), they have been the subject of only a few evaluation studies [WFM01] and it is not yet clear how the choice of a given method, and the level of simplification achieved, influence the quality of the resulting mesh, as perceived by the final users. Clearly, for interactive applications, the perceived quality of any mesh model is of paramount importance and

should be taken into account when choosing a particular processing method, i.e., not just for mesh simplification.

We have previously evaluated three mesh simplification methods, for two simplification levels, by investigating the characteristics of simplified meshes of the lungs regarding their original reference models with two different approaches: i) developing a within subjects experimental methodology (i.e., each subject performed under each different condition) to assess model quality as perceived by users, performing an observer study involving 32 subjects, who classified simplified models by assigning preferences and ratings, and analysing the collected data [SSSMF05]; ii) computing quality indices to describe the geometric distance between a simplified mesh and its original, as well as to compare the respective sets of normal vectors, and analysing the resulting data, as well as comparing this data with the findings of the observer study [SSFM05].

As a result of the data analysis carried out, we were able

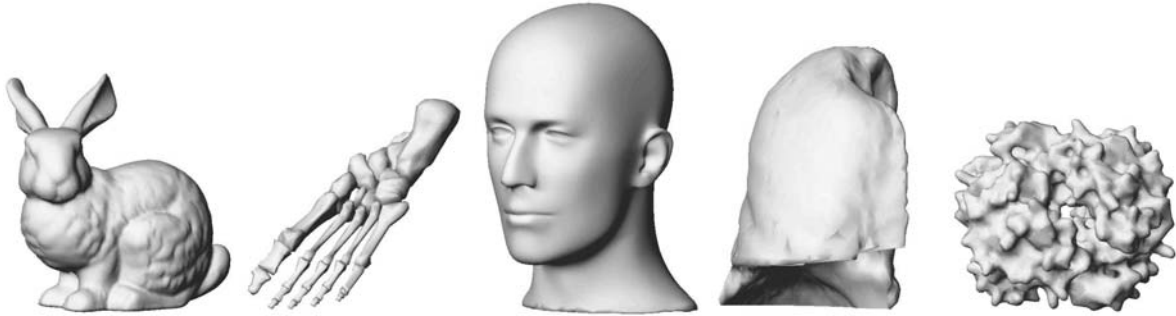


Figure 1: Original models used. From left to right: Bunny, Foot, Head, Lung and Strange

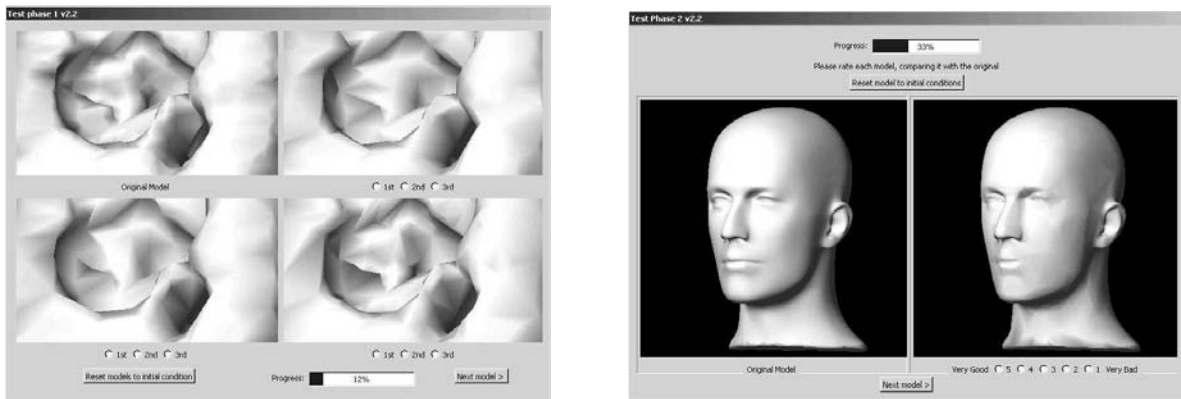


Figure 2: First phase (on the left): the original model (upper left) and three simplified versions are presented and preferences are asked. Second phase (on the right): the original model (left) and one simplified version are presented and a rating is asked.

to draw some conclusions, for the particular lung models and simplification methods used, in particular: two distinct methods were identified as providing a better perceived model quality for each one of the simplification levels [SSSMF05], and two distinct quality indices seemed to behave as estimators of the users preferences (i.e., of the model quality perceived by them), again for each one of the simplification levels [SSFM05].

To ascertain whether the findings of that controlled experiment do generalize to other model types, and are indeed confirmed for more observers, thus becoming useful guidelines for practitioners, a second similar study — now using a different set of five mesh models as references and having the help of 65 observers — was performed and is reported here. In order to compare outcomes, test models were generated using the same methods and simplification levels as before, and the same experimental methodology was followed.

In the following sections, we detail the main aspects of the observer study carried out and the most important results from the analysis of the collected data. Afterwards, a comparison is made between those findings and the ones that

had been obtained for lung models. Finally, we present some general conclusions and ideas for future work.

2. Observer Study

The observer study — whose main features, as well as the experiment, are presented in what follows — was set up and carried out exactly as it had been done before for the study using lung models: see [SSSMF05] for a thorough description of the objectives, context, framework, experimental methodology and data analysis of that former study.

Note that the former observer study was a suitable testbed to confirm that the developed experimental design and protocol allowed perceived quality evaluation, as well as to establish the methods for the statistical analysis of the collected data.

2.1. Main features

We intended to compare three mesh simplification methods — the widely used *QSlim* [GH97] and two other methods provided by the *OpenMesh* [BSBK02] library (one using error quadrics, the other additionally using a normal flipping

First Phase	Second Phase
Preferences (first, second, third)	Ratings given to each model
Order of presentation of the test data sets	Order of presentation of the simplified versions of the models
Number of interactions with each test data set	Number of interactions with each simplified model
Time taken to order each data set	Time taken to rate each simplified model

Table 1: Type of data collected on both experiment phases.

criterion) — regarding the “perceived quality” of the resulting meshes, for a set of five reference models of different kinds (see Fig. 1), and for two simplification levels: severe (to 20% of the original number of mesh faces) and average (to 50%).

Model sets were built from the set of five reference models: for each model and for each simplification level (20% and 50%) three simplified models were created using the three simplification methods. This resulted in a total of 10 test sets, each composed by the original and the three simplified models (five sets for each simplification level).

Note that the five models chosen are different from each other and have different numbers of vertices and faces. The lung model used was taken from the model set of the previous observer study, in order to verify if the results obtained for it were similar in both experiments.

Starting from the hypothesis that distinct mesh simplification methods have different effects on the model quality perceived by human observers, possibly varying with the simplification level and other factors, we assessed that by asking for the observers’ preferences and ratings, which are widely used to obtain relative judgements from observers and are probably the most adequate indices of fidelity [WFM01].

With preferences, each observer assigned to the three simplified models in a test set an ordering according to their perceived quality, regarding the original reference model. With ratings, each observer classified each simplified model regarding the reference model, according to its perceived quality. For each of these tasks, the time taken to reach a decision and the number of interactions (performed on each model before deciding) were also recorded, since they seemed to be related to the degree of difficulty observers encounter in performing the preference and rating tasks.

To allow an easy implementation of the experimental protocol, as well as an easy storage and management of the collected data, the same software application that had been developed for the former lung models study was used [SSSMF05]. Note that, with this application, observers were freely allowed to interact with a model, by changing its position, orientation and scaling factor, and choose the viewpoints they wished to analyse a model from, which is a more realistic and less limitative setting than the one used by Watson et al. in a similar study [WFM01].

2.2. The experiment

A within subjects experimental design was used, i.e., each observer performed under each different condition. Due to the possible influence of learning effects, nervous behaviour in the first task or fatigue in the last, all test sets were presented randomly to each observer and, for each observer, the order of presentation of the models, within each set, was randomly chosen.

For each observer, the experiment was divided into two phases (see Fig.2):

In the first phase — preference task —, an observer was sequentially presented with each one of the 10 test sets and asked to assign a first, second and third place to each of the simplified models, according to their perceived quality regarding the original.

In the second phase — rating task —, an observer was sequentially presented with an original model and one of its simplified versions, taken from one of the test sets, and asked to rate the simplified model using a five level Likert scale [Bar03] from 1 (very bad) to 5 (very good), once again based on its perceived quality.

Sixty-five engineering students and lecturers, aged between 18 and 55 years (the majority, 45 subjects, was between 18 and 25 years), participated in the experiment (57 men and 8 women). Forty-one subjects declared to have experience in viewing/manipulating 3D models. For each observer, the collected data for each experiment phase is listed on Table 1. Since the gender, age or experience with 3D object manipulation of an observer might influence the results, this information was used to characterize the profile of each observer.

3. Results

In this section the main results obtained from the analysis of the data collected from the observer study are presented.

First, an Exploratory Data Analysis (EDA) [HMT83] was performed on the collected data, which provided general information on the structural relations, showing the amplitudes, asymmetries, localizations, outliers, etc. As the collected data concerning preferences and ratings are ordinal, decision times are quantitative and the number of interactions is measured in a quantitative but discrete scale, we have used different methods adequate for each type of data

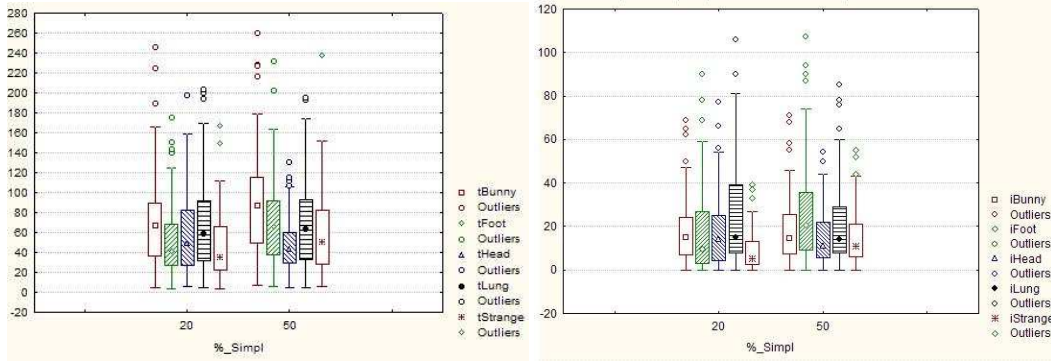


Figure 3: Preferences: box-plots corresponding to the decision times (left) and number of interactions (right) for all models, after removing severe outliers and categorized by simplification level (20% and 50%).

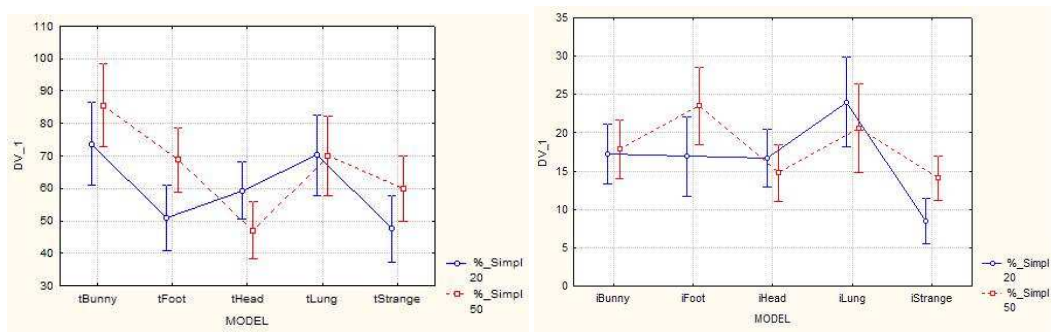


Figure 4: Decision times (left) and number of interactions (right) as a function of model and level of simplification.

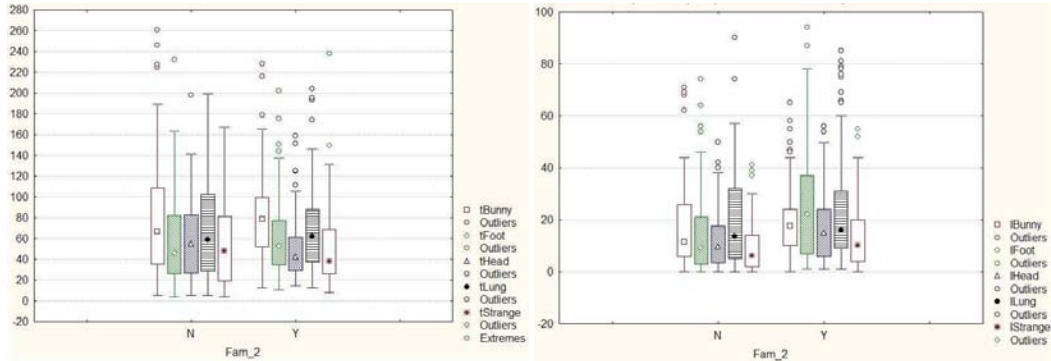


Figure 5: Decision times (left) and number of interactions (right) categorized by familiarity (experience in viewing and manipulating 3D models).

	1 st place	2 nd place	3 rd place
QSlim_20%	144	123	58
OMeq_20%	85	132	108
OMeqnf_20%	97	91	137

	1 st place	2 nd place	3 rd place
QSlim_50%	103	162	60
OMeq_50%	80	98	147
OMeqnf_50%	166	90	69

Table 2: Contingency table corresponding to preferences for the two simplification levels: 20% and 50%.

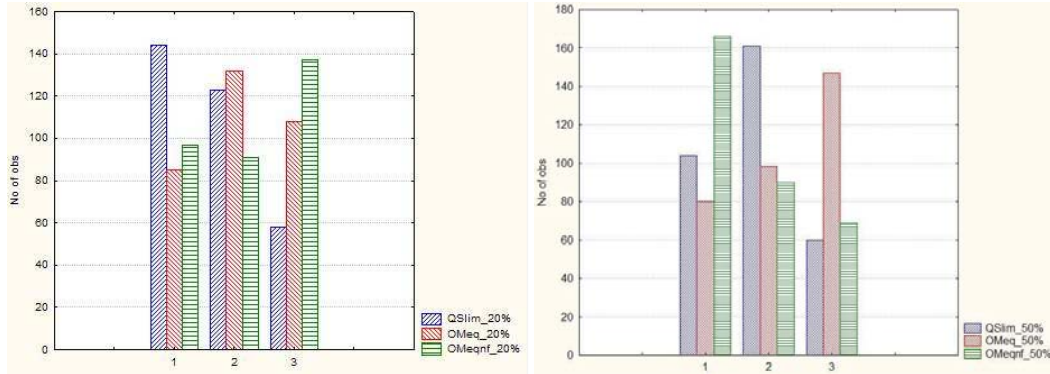


Figure 6: Preferences corresponding to the two simplification levels: 20% (left) and 50% (right).

[Alt99]. All the presented results were obtained using STATISTICA [Sta06].

3.1. First Phase: Preferences

The first variables analysed were the decision time and the number of interactions. After a preliminary Exploratory Data Analysis (EDA) using box-plots, we decided to remove all severe outliers and maintain the moderate ones. Figure 3 shows, on the left, the box-plots corresponding to decision times and, on the right, the box-plots corresponding to the number of interactions, both categorized by the simplification level (20% and 50%).

Concerning decision times, a two-way ANOVA (figure 4, on the left) rejected the equality hypothesis in relation to the factor model ($F(4,119)=14.9$, $p=0.00$), and between the model and the simplification level ($F(4,476)=4.22$, $p=0.002$). As to the number of interactions, using again a two-way ANOVA (figure 4, on the right), we reached the same conclusion, based on the following values, $F(4,116)=12.2$, $p=0.00$ for the factor model and $F(4,464)=3.30$, $p=0.01$ for the interaction between the model and the simplification level.

Finally, and in order to investigate other possible influences on these variables, due for instance to any profile characteristics of the users, we studied decision times and number of interactions categorized by gender and familiarity in viewing/manipulating 3D models. Regarding the gender it was possible to verify that men were faster than women for a simplification level of 20%. In the box-plots of figure 5, we can observe (on the left) a smaller variability in decision times for users with 3D familiarity. On the right it is possible to verify that users with 3D familiarity in general interacted more with the models.

Concerning the preferences, as a first step, we produced bar charts showing the number of first, second and third places obtained by each simplification method for the two simplification levels, as shown in figure 6 (20% on the left

and 50% on the right). The bar-chart on the left seems to reveal a tendency of the observers to prefer the simplified versions using *QSlim* (larger number of first places), then the versions simplified using *OpenMesh* and, in third place, the versions simplified using *OpenMesh* with normal flipping. The bar-chart on the right of figure 6 seems to reveal that the observers prefer the simplified versions using *OpenMesh* with normal flipping, followed by *QSlim* and *OpenMesh*.

In order to confirm the statistical significance of the above-mentioned tendency, contingency tables were used and independency hypothesis were tested. The independency between the simplification method and the observers' preference was rejected for both simplification levels, with $\chi^2 = 57,57 \gg 9,49$ ($\chi^2(4d.f.;\alpha=0.05)$) for 20% and $\chi^2 = 110,54 \gg 9,49$ ($\chi^2(4d.f.;\alpha=0.05)$) for 50%. These results suggest that observers are indeed responsive to the simplification method used, although they react in a different way according to the simplification level; for 20% *QSlim* obtains the best results, while for 50% it is *OpenMesh* with normal flipping that obtains most of the first places.

The results obtained by the contingency tables can be visualized using a Correspondence Analysis [Joh98]. Figure 7 shows the factorial planes corresponding to the contingency tables for both simplification levels. In these projections we can observe that, for the simplification level of 20% each simplification method is clearly associated to a type of preference (first place for *QSlim*, second place for *OpenMesh* and third place for *OpenMesh* with normal flipping). A different and even stronger association appears for the simplification level of 50%: *OpenMesh* with normal flipping is associated with the first place, *QSlim* with the second and *OpenMesh* with the third place.

To conclude the analysis of the data collected in the first phase of the experiment, we used Cluster Analysis [Joh98], another Multivariate Analysis. This technique allowed studying the similarity between simplification methods, in the scope of observers' preferences. Figure 8 (on

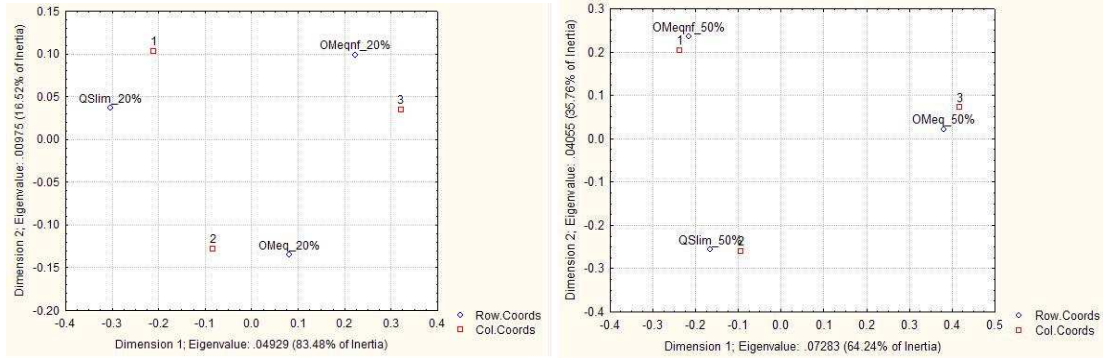


Figure 7: Correspondence Analysis (where simplification methods are in rows and preferences in columns) for the two simplification levels: 20% (left) and 50% (right).

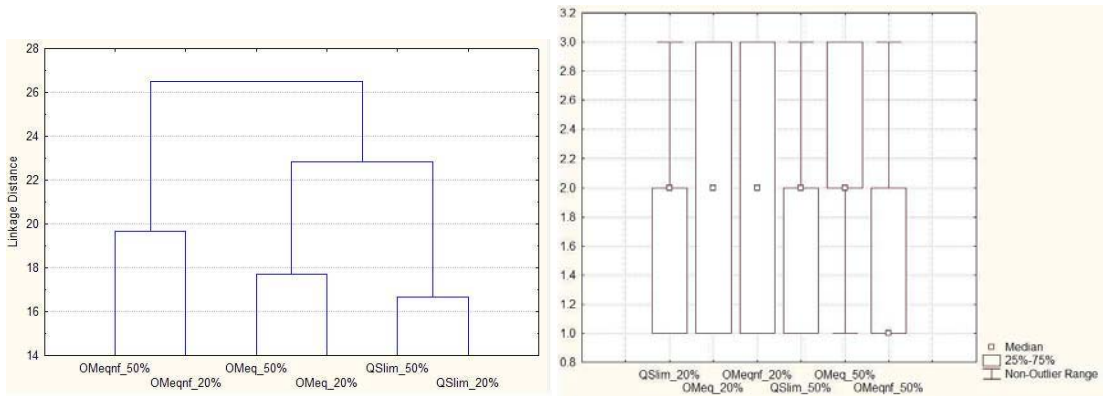


Figure 8: Dendrogram and box-plots for the preferences obtained with all simplification methods at the two simplification levels.

the left) shows the dendrogram using Complete Linkage as proximity measure; reading the diagram from the lower distance values (bottom-up), we observe that preferences are first associated by simplification method, *OpenMesh* is associated to *QSlim* and *OpenMesh* with normal flipping is farther away. On the right side of figure 8 we have the box-plots corresponding to the preferences for the three simplification methods at the two simplification levels; notice the improvement in the obtained results by *OpenMesh* with normal flipping from 20% to 50%, and the opposite effect for *OpenMesh*. This confirms the results previously obtained using Correspondence Analysis.

3.2. Second Phase: Ratings

In this second phase, decision times and the number of interactions were also the first variables analysed. As in the previous phase, after a preliminary EDA using box-plots, all severe outliers were removed and the moderate ones were kept. Figure 9 shows, on the left, the box-plots corresponding to decision times categorized by the simplification level

(20% and 50%); on the right we have the box-plots corresponding to the number of interactions.

Concerning ratings, as a first step, we produced bar charts showing the number of marks (1 – very bad, to 5 – very good) obtained by each simplification method for the two simplification levels as shown in figure 10 (20% on the left and 50% on the right). The bar-chart on the left seems to reveal a tendency of the observers to rate poorly all the simplification methods, specially the simplified versions using *OpenMesh* with normal flipping (larger number of ones), then the versions simplified using *OpenMesh* and *QSlim*. It must be noted that almost nobody rated above 4, and even for this mark the number of observations is very low. On the other hand, there is a visible increase on the rating, when the level of simplification decreases (50% simplification level). The bar-chart on the right shows a majority of marks ranging from 3 to 5. All the three methods seem equally well rated, perhaps with a slight advantage (larger number of fives) of the *OpenMesh* with normal flipping, which was considered the worst on the 20% simplification level. This result is con-

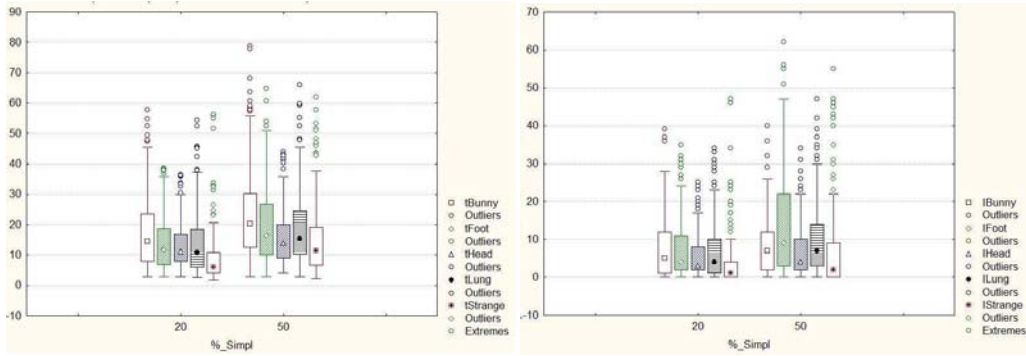


Figure 9: Ratings: box-plots corresponding to the decision times (left) and number of interactions on all models (right), after removing severe outliers and categorized by simplification level (20% and 50%).

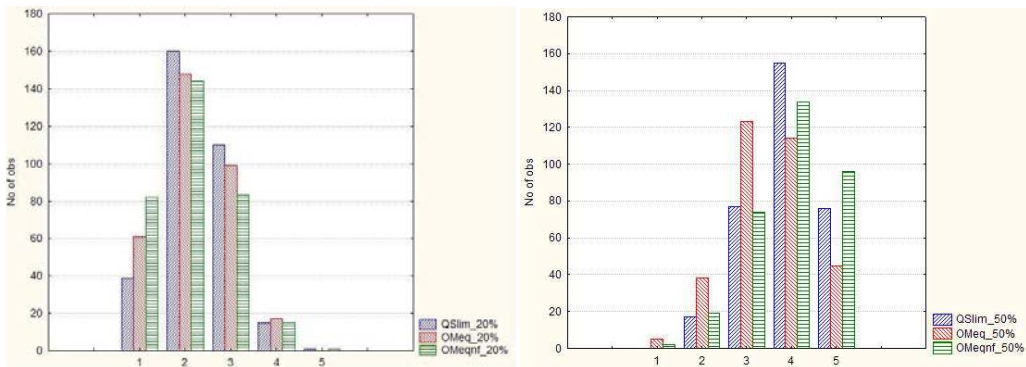


Figure 10: Ratings corresponding to level of simplification: 20% (left) and 50% (right).

	1	2	3	4	5
QSlim_20%	36	154	106	16	3
OMeq_20%	61	148	99	17	0
OMeqnf_20%	82	144	83	15	1

	1	2	3	4	5
QSlim_50%	0	17	77	155	76
OMeq_50%	5	38	123	114	45
OMeqnf_50%	2	19	74	134	96

Table 3: Contingency table corresponding to the ratings for the two simplification levels: 20% and 50%.

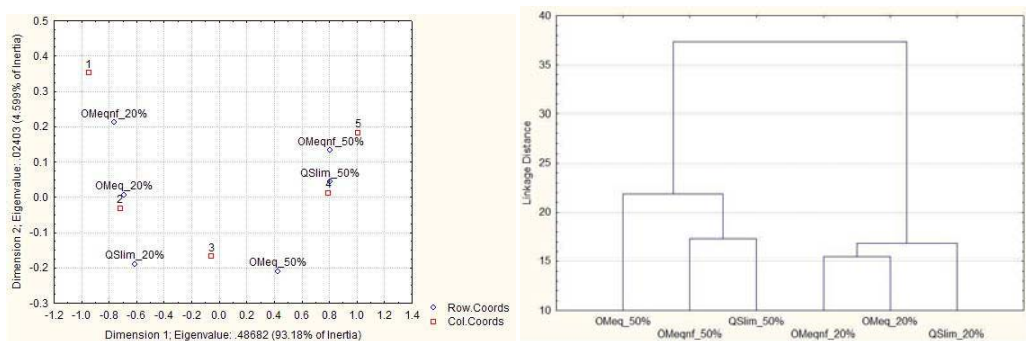


Figure 11: Correspondence Analysis (where simplification methods are in rows and ratings are in columns) for the two simplification levels: 20% and 50%, and dendrogram.

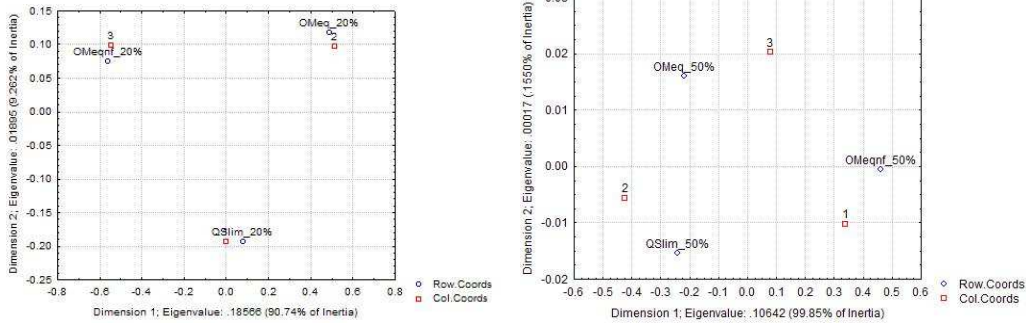


Figure 12: Cluster Analysis for the first phase of our previous study, using lung models, presented in [SSSMF05].

sistent with the one previously obtained from the preferences.

As in the first phase, in order to confirm the statistical significance of the above-mentioned tendency, contingency tables were used (table 3) and independency hypothesis were tested. The independency between the simplification method and the observers' ratings was rejected for the 20% simplification level, with $\chi^2=24,57 > 15,5$ ($\chi^2(8d.f.;\alpha=0.05)$), as well as for 50%, $\chi^2 = 1013,54 \gg 31,41$ ($\chi^2(20d.f.;\alpha=0.05)$) for 50%. These results suggest that, for this task as for the preferences task, observers are responsive to both simplification method and simplification level.

The visualization of the contingency tables using a Correspondence Analysis (figure 11 on the left) shows that for the simplification level of 50% all methods obtain similar ratings and higher than the obtained for the simplification level of 20%. On the other hand, the dendrogram (figure 11 on the right) shows that observers' ratings are first associated by simplification level not simplification method as the preferences (figure 8). Moreover, while *QSlim* is associated first to *OpenMesh* with normal flipping and then to *OpenMesh* for 20% a different association appears for a simplification level of 50%.

4. Results Comparison

A brief comparison between the results obtained in our previous study [SSSMF05] using lung models and the results presented above is done in what follows.

4.1. First Phase - Preferences

Comparing figure 7 with figure 12, showing the Correspondence Analysis for the first phase of both studies, we verify that, for each simplification level, the associations between method and place are the same. However, while in figure 7 we notice a stronger association for the 50% simplification level, in figure 12 it is the simplification level of 20% which exhibits a stronger association.

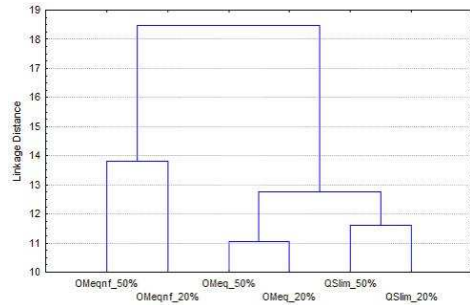


Figure 13: Dendrogram for the first phase of our previous study presented in [SSSMF05].

Comparing figure 8 with figure 13, showing the Dendrograms for the first phase of both studies, they present the same kind of behavior, i.e., preferences are first associated by simplification method, then *QSlim* is associated with *OpenMesh* and finally with *OpenMesh* with normal flipping.

4.2. Second Phase - Ratings

Comparing the Correspondence Analysis on the left side of figures 11 and 14 it is possible to verify that *OpenMesh* with normal flipping for a simplification level of 20% is associated with the lowest rate and *QSlim* and *OpenMesh* with normal flipping for a simplification level of 50% are associated with the higher rates. The association for the other methods and simplification levels is not so clear in figure 11 as in figure 14 with the method *OpenMesh*, for the simplification level of 50% close to a rate of 3.

Comparing the Dendrograms on the right side of figures 11 and 14, both show that observer ratings are first associated by simplification level. Only a slight difference can be noted: figure 14 shows a first association of *QSlim* with *OpenMesh* for the 20% simplification level, while figure 14 shows a first association between *OpenMesh* and *OpenMesh* with normal flipping, for this same level of simplification.

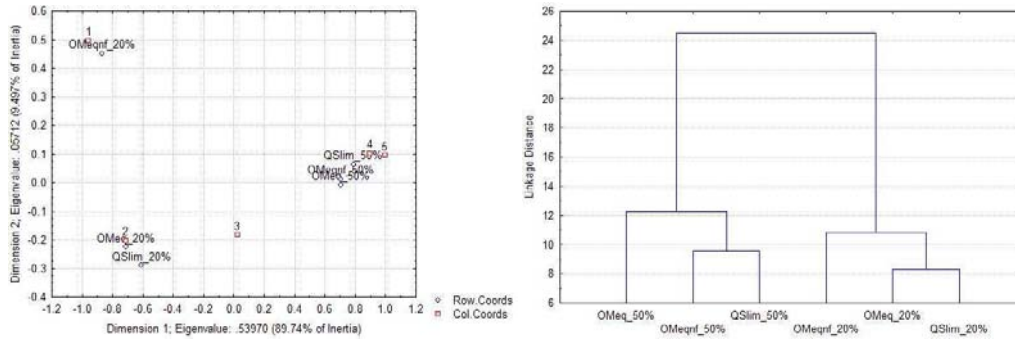


Figure 14: Cluster Analysis and Dendrogram for the second phase of our previous study presented in [SSMF05].

5. Conclusions and Future Work

In this paper we describe an experiment with 65 human observers, performed in order to compare different mesh simplification methods at different simplification levels. We intended to study if any of the methods allowed a better perceived quality for the same simplification level and if the results obtained in a previous study [SSMF05] could be generalized. With this purpose, an experiment with five different models simplified using three simplification methods and two levels of simplification was performed. A within subjects design was used and all participants could interact with each model at all experimental conditions, although in a different order. Observers' preferences, ratings, decision times and number of interactions were collected.

Results obtained from the analysis of the collected data suggest that the simplification level has in fact an influence on the observers' decision times, as we expected from the onset of the experiment. Observers seem to make faster decisions at the higher simplification level (20%), which might be related to the fact that they have less information on which to base their decisions and be a phenomenon similar to the distillation effect mentioned by Watson et al. [WFM01].

Results concerning preferences, consistently confirmed applying different statistical methods, suggest that observers are indeed responsive to the simplification method used, although they react in a different way according to the simplification level: for 20% *QSlim* obtains most of the first places, while for 50% it is *OpenMesh* with normal flipping that obtains the best results. This might be due to the fact that, as we pointed out in the other observer study, the normal flipping method represents areas of greater detail using more triangles than the other methods (i.e., preserving them better). When a model is represented by a reasonable number of faces (e.g., with a simplification to 50%), there are still enough faces available that are assigned to mesh areas with less detail, but when a severe simplification is needed (e.g., with a simplification to 20%), the number of faces assigned to less detail areas is small, entailing a worse result than with the other methods.

Results concerning ratings seem to imply that observers' performance, in this type of task, is more influenced by the simplification level than by the simplification method, as it seemed to happen for the preferences task. This brings out the issue of the difference between those tasks: in fact, we expected that preferences might express a relative measure of perceived quality of the simplified versions of the models, whereas ratings would produce an absolute measure. Thus, results concerning the former task should help to discriminate between methods (which would be more important in situations of lack of information), while results concerning the latter would express the "intrinsic value" of each method.

A closer look on the results for each model (not presented here due to space limitations) reveals that the head model obtained, in general, results which contradict the tendencies of the remaining models. For example, the decision times and number of interactions were larger for the simplification level of 20% and smaller for the simplification level of 50%. This is an interesting result which requires further analysis: is this related with the way the human brain processes information regarding faces [Gre98] or is it a consequence of the curvature properties of the model?

The results obtained in this experiment confirm those presented in [SSMF05] (using only lung models), i.e., the simplification methods obtained similar preferences and ratings in both experiments, for each used simplification level. The different nature of the models did not seem to affect the results in a significant way as it is suggested in the study by Watson et al. [WFM01].

The lung model used in this experiment was taken from the model set of the previous study. This will allow us to verify if the results for this model are similar in both studies, or if context influenced them.

We intend to use the data collected in both observer studies to perform an analysis using a wider range of automatic measures (e.g., curvature, saliency, etc.) than that used in our previous study (geometric and normal deviation) [SSFM05],

in order to continue looking for metrics that can be used as estimators of user perceived quality. To do this we developed a tool, called PolyMeCo [SMS05] which provides an integrated environment where polygonal meshes can be analysed and compared using several metrics.

These first observer studies dealt with the perceived global quality of polygonal models, after simplification. It is now important, using the knowledge and experience obtained, to step into studies which deal both with the perceived local quality of mesh models, as well as evaluate models resulting from other usual mesh processing operations (e.g., smoothing).

Based on further results we expect to produce some guidelines to help practitioners choose among mesh processing methods, as well as to explore automatic measures that can be used to estimate perceived quality in specific conditions.

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