

Interactive Visualisation for Surface Proximity Monitoring

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Abstract

We consider tasks that require users to be aware of the proximity of two 3D surfaces and where one or both of these surfaces is changing over time. We consider situations where users need to quickly and accurately assess when and where the two surfaces approach each other and eventually intersect. Because occlusion in 3D visualisations remains an issue in the perception of such data, a complete, simultaneous perception of the proximity of two such surfaces could be helpful. We propose and implement a new, interactive, visualisation technique, “Proximity Map Projection” (PMP), to provide this assistance to users and describe a user study to investigate the effectiveness of PMP in a static scenario. This study found that PMP enabled faster and more accurate identification of regions of nearest proximity and greatest protrusion. As well as affirming the potential benefits of PMP, this study motivates several areas of further investigation of the technique.

Keywords: user interfaces, Proximity Map Projection (PMP), interactive visualisation, surface proximity perception, real-time MRI-guided thermal therapy

1 Introduction

We envision interactive tasks where users need to carefully monitor two 3D surfaces whose proximity is changing over time. We consider situations during which users must perform such tasks in order to identify when and where the two surfaces approach and/or intersect. An example of such a task, which is a primary motivation for this research, is the use of real-time magnetic resonance imaging (MRI) for the guidance of thermal therapy.[Marshall, 2014]

Three-dimensional MRI data has been commercially used to guide the thermal therapy of human brain tumours[Tyc and Wilson, 2010]. These systems require that a surgeon monitor the proximity of a growing treatment volume to the boundary of a tumour, while at the same time applying their expert judgment to make a critical decision about when to stop a thermal application. The real-time nature of such a task, and the potential impact of errors and inaccuracies on the patient, motivate an interactive visualisation that enables a quick and accurate exploration of the data. Such an interface should, ideally, allow the user to spend as much time as possible applying their expert domain knowledge, rather than consuming unnecessary time navigating to regions of interest within the data.

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Our investigation suggests a solution that offers surgeons a familiar “detail view”. In the case of MR-guided thermal therapy, this detail view is one or more 2D planes (or “slices”) of MR image data. Surgeons are commonly presented with an arrangement of such slices that may be either consecutive parallel slices or orthogonal slices and they develop significant expertise in appropriately interpreting them. A principal difficulty is being able to quickly and easily navigate to the correct 2D slices at any point in time during the process. In this paper, we propose a special overall visualisation of the two 3D surfaces - “Proximity Map Projection” (PMP).

Three-dimensional visualisation and 3D to 2D mapping are two categories of potential (computer visualisation) approaches to such a problem. In our research, we consider a 3D to 2D mapping solution. Numerous mapping techniques are possible. The mapping technique used in our prototype was selected for its low computational cost and expected familiarity to users. In a general sense, navigation and selection are also central features of such a solution.

In Section 2, we describe previous work on visualisation problems similar to ours, both in the medical domain and more generally. We then present a new technique, Proximity Map Projection (PMP), in Section 3. PMP provides complete simultaneous perception of surface proximity to the user. There are aspects of the more general problem (of monitoring and predicting when and where two 3D surfaces approach each other) that deserve investigation before attempting to apply a solution to the specific needs of surgeons. The user study described in Section 4 considered whether participants could more quickly and accurately select 2D “slices” of 3D data using PMP compared with a common current technique. (Currently, it is common for surgeons to be presented with one or more 2D “slice” views from a series of medical images.) The results of that study are described in Section 5 and discussed further in Section 6. Sections 7 and 8 conclude the paper and describe anticipated future work.

2 Background and Previous Work

The use of imaging intra-operatively has achieved increasing popularity over the past 20 years. MRI guided procedures have become well-established. One of these procedures, laser induced thermal therapy (LITT), is a primary motivation for the present paper. Fan et al. [1992] found that monitoring and control of LITT via magnetic resonance (MR) was a major advantage. Jolesz [1997] stated that the reduction of surgical morbidity was a compelling reason to use intraoperative image guidance. Lewin et al. [2004] found that interactive MR image-guidance enabled a high success rate with radio-frequency ablation (RFA) treatment. Carpentier et al. [2008] stated that LITT provides a new and efficient treatment for focal metastatic brain disease.

2.1 Map Projection

Map projection is the projection of data from one space into another space. Such projections are commonly performed in order to facilitate the perception of the data by users. Typically, the projection is onto a surface of lower dimensionality such as a two-dimensional plane. Although, in the general sense, these surfaces need not be in Euclidean space, this research is particularly concerned with surfaces existing in physical 3D space. A rectangle on a two-dimensional plane is easily visualised on a computer display, and is an efficient shape in a windowed environment.

There are, theoretically, an unlimited number of methods of projecting data. Snyder [1997] described more than 200 cartographic projections used between the 15th and 20th centuries. All projections necessarily have some distortion. Projections can be differentiated from each other by where they attempt to minimise distortion, as well as computational complexity. Figure 1 is an example of a basic cylindrical projection. We expected a simple projection such as this to have low computational cost and be familiar to users.

Previous work suggests that the use of map projection is becoming increasingly more common in medical software. Minoshima et al. [1995] used “Three-Dimensional Stereotactic Surface Projection” (of brain imaging data) in the diagnosis of alzheimer’s disease. Haker et al. [2000] developed the idea of virtual colonoscopy using projection of the colon onto a flat surface. Kanitsar et al. [2002] developed “Curved Planar Reformation” for displaying tubular structures projected onto a flat surface. Scheef et al. [2003] used a projection method for functional MR image data in order to preserve “the spatial relation of eloquent areas to lesions.” Uwano et al. [2008] used “Stretched Curved Planar Reformation” to provide a flat view of the brain surface.

Earlier research efforts all involved some method of projection, but did not involve dynamic inter-surface proximities and they have been predominantly related to the diagnosis stage. By contrast, PMP is intended to support the monitoring of dynamic surface proximities intraoperatively. The existing literature indicates that:

- The use of map projection with static medical images during the diagnostic stage is established [Minoshima et al., 1995, Haker et al., 2000, Kanitsar et al., 2002, Scheef et al., 2003, Uwano et al., 2008], and this would likely have a positive effect on the acceptance of an extension of such techniques to a dynamic scenario.
- The use of map projection to visualise dynamic proximity between two medical surfaces intra-operatively is a novel concept. In particular, it has not been applied in a real time environment to address the limitations of human response time.

2.2 General Visualisation Studies

The general visualisation problem that we are concerned with is the real time monitoring of two 3D surfaces where one or both is changing over time. In this subsection, we consider studies relevant to this problem from the general visualisation literature and how they compare with our PMP technique, detailed in the next section.

Gross et al. [1997] described a variation on the “spring-mass” model approach to identifying multidimensional data relationships. (originally proposed by Eades [1984]) One novel aspect of their system was the initialisation of the spring-mass components onto the inner of two concentric spheres for its ultimate visualisation on the surface of the outer sphere. Whereas this use of projection is relatively abstract, PMP’s use of a similar projection deals with surfaces in physical 3D space.

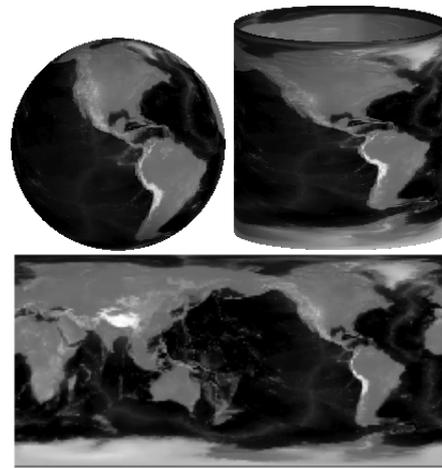


Figure 1: Basic Cylindrical Map Projection of the Earth - A simple projection of grey-scale encoded elevations is projected onto a cylinder, which is subsequently flattened into a 2D rectangle.

Ji and Shen [2006] have made contributions to the area of dynamic view selection where the data is changing with time. Their focus was on automatically creating animated sequences of views through a dynamic dataset in a way that maximises viewable information and smoothness. Their method and our PMP share some underlying attributes, such as the selection of a desirable view at a point in time. Whereas their technique involved the automatic-selection of appropriate views on dynamic data via post-processing, our PMP enables interactive selection of appropriate views on dynamic data in real-time.

Tory et al. [2006] described experiments using a range of 2D, 3D, and 2D-3D combination interfaces. They found that the choice of interface that performed best depended on the nature of the task. For example, some 3D interfaces allowed quicker task completion while some 2D interfaces facilitated greater accuracy. Similarly, we designed PMP to facilitate a specific category of tasks. It is designed to enable faster and more accurate decisions regarding the proximity (especially convergence) of two 3D surfaces.

Chen et al. [2009] used a combination of 3D and embedded 2D views of neural fibres to facilitate navigation/selection and examination of the fibres. Jianu et al. [2009, 2012] have also considered the interaction between 3D data and 2D embeddings. PMP also uses a 3D to 2D projection, but does so interactively and intraoperatively in real-time.

Dick et al. [2011] described a technique of viewing distance indicators *on* a 3D surface, with the purpose of guiding medical implant planning. This is similar to PMP’s computation of inter-surface proximities, prior to projection onto a 2D surface. By contrast, PMP is designed to be used with less predictable dynamic surfaces.

3 Proximity Map Projection (PMP)

3.1 Visualisation

The idea of PMP is to provide complete, simultaneous perception of the proximity of the two surfaces. PMP handles singular masses with no internal holes, or more more complexly shaped tumours that have been previously subdivided into individual treatment targets meeting those parameters. It achieves this by:

Proximity Calculation - For every point on the tumour surface, the proximity (Euclidean distance) to the nearest point on the treatment surface is calculated.

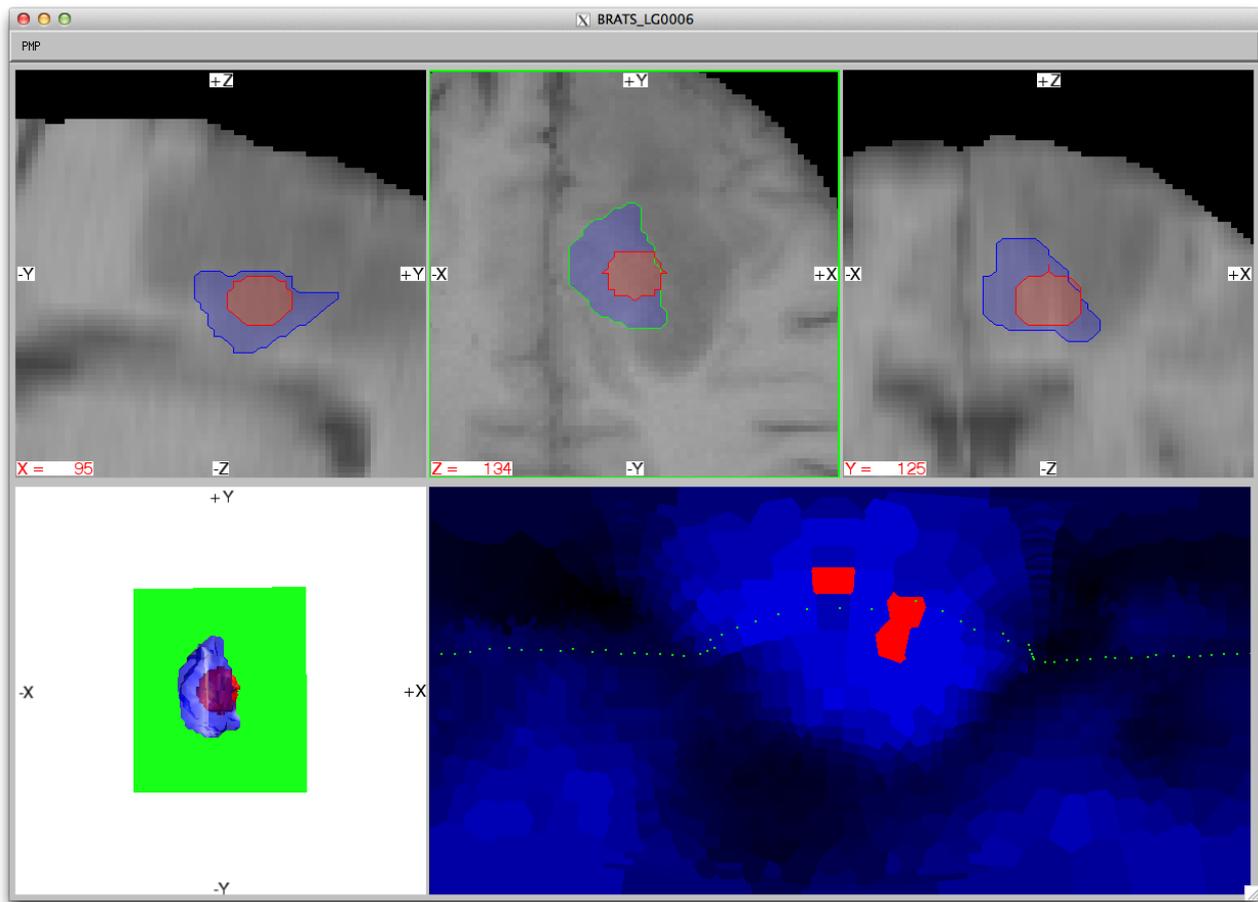


Figure 2: Experimental Software - A typical view of the PMP prototype is presented. The top row contains 2D slice views of the data. The selected slice view is highlighted with a green border and the plane of this selected slice is shown in the 3D volume visualisation at bottom-left. At bottom-right is the PMP view, with blue to red colour-encoded inter-surface proximity values and a green dotted line representing the tumour boundary. This proximity to colour scale is further described in Figure 3. (Best viewed in colour.)

Coordinate Conversion - The cartesian coordinates (x , y , z) of the tumour surface points are converted to spherical coordinates (r_{radius} , $\theta_{inclination}$, $\phi_{azimuth}$).

Projection to Sphere - The tumour surface points are projected onto a sphere, by setting r to a fixed distance.

Projection to Plane - The points on the sphere are projected onto a plane by mapping $x = \theta$ and $y = \phi$.

Colour Encode Points - Colour values are assigned to each mapped coordinate, using a scale varying from black (distant non-protruding points) through blue to white (converged points) to red (distant protruding points). This scale is non-linear, and provides greater contrast for proximities nearer to the tumour surface.

3.2 Use Scenario

The standard anatomical orientations of planes in medical imaging are “axial” (looking down through the top of the head), “coronal” (looking from the front at the face), and “sagittal” (looking from the side of the head). For the purpose of this discussion, this is how we will refer to the planes. For the benefit of non-expert user study participants, we labeled the prototype software with “x”, “y”, and “z” planes, as can be seen in Figure 2.

Figure 2 shows the experimental prototype with the Proximity Map Projection view (lower-right) enabled and the axial plane (top-middle) selected. It shows the most interesting visual aspects of the experimental software, which are the PMP view and its relationship with the other views. The scenario is for a tumour located in the brain

that is undergoing thermal treatment. The treatment volume is shown as a sphere inside the irregular tumour volume. Note that:

- The selected (top-middle) plane view is highlighted.
- The selected plane is displayed (in green) in the 3D volume view (lower-left).
- The boundary of the tumour in the selected slice is drawn on the PMP (lower-right). This relationship between the selected slice and the boundary shown in the PMP is further illustrated in Figure 4.

All of the data points on the surface of the tumour have 3D coordinates. All of the points on the PMP are also linked to a point on the surface of the tumour. Showing the perimeter of the tumour that falls on any given 2D slice is made simple by this link.

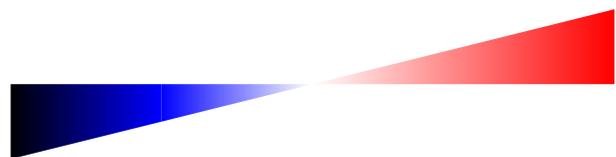


Figure 3: Proximity to colour scale mapping for the PMP view, as drawn in the bottom-right of Figure 2. Proximities of treatment surfaces are shown from most distant, non protruding, in black, through to most distant, protruding, in dark red. (Best viewed in colour.)

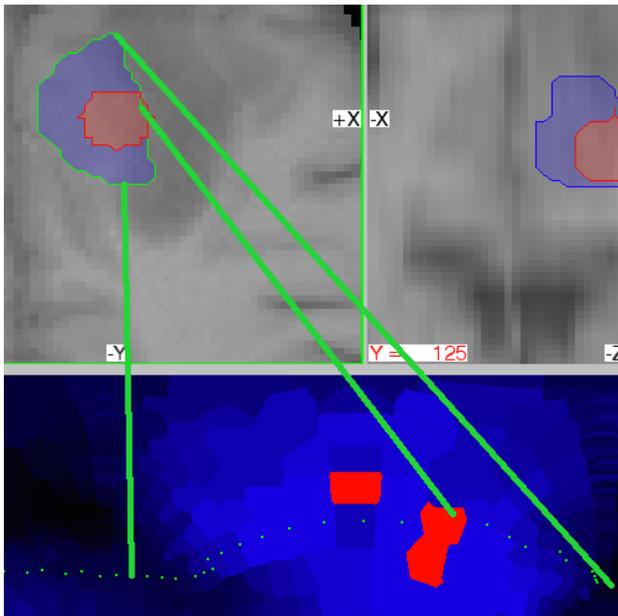


Figure 4: Tumour Boundary - The green dotted line in the PMP view represents the tumour boundary points on the selected 2D plane. Solid green lines highlight the link between top and bottom views, but are not present in the actual prototype. (Best viewed in colour.)

In the planar views of the figure (top row), tumour regions are represented in blue while treatment regions are represented in red. In the PMP view, darker regions indicate tumour surface points that are relatively further away from the treatment volume. Bright blue regions indicate points close to the treatment. Lighter red regions (towards pink) indicate points where the treatment volume protrudes beyond the tumour surface by a small amount. Darker red regions indicate points where the treatment protrudes by the greatest amount.

3.3 Interaction

Users are able to interact with the prototype software in the following ways:

Click on the PMP View - The user may click a point on the PMP. Every point on the PMP represents a point on the surface of the tumour. Selecting such a point updates the planar views to intersect at the selected point on the tumour surface as well as updating the plane shown in the 3D view and the boundary shown in the PMP.

Click on a Slice View - The user may click on any of the three planar views. Doing so updates the plane shown in the 3D view and the boundary shown in the PMP.

Press the Up or Down Arrow Keys - The user may press the up or down arrow keys on the keyboard. Doing so navigates up or down in the stack of images on the selected axis. Changing the selected slice also updates the position of the plane in the 3D view and the position of the boundary in the PMP.

Press the Enter Key - The user may press the enter key to start a task and to finish a task.

3.4 Implementation

We developed the PMP prototype, using version 8.2 of Interactive Data Language (IDL), provided by Exelis Visual Information Solutions. We chose IDL for developing the prototype due to its simple interface development and

its orientation towards visualisation. IDL has numerous graphical and matrix oriented routines that are useful in this context.

As implemented, the PMP prototype performs sufficiently well to study user interaction at common current MR thermometry refresh rates of six to eight seconds. IDL has the ability for its built-in functions to take advantage of multiple CPUs and General Purpose GPUs.

4 User Study

We performed a user study to investigate the effect of the presence or absence of the PMP interface and the protrusion or non-protrusion of the simulated treatment volume on the speed and accuracy of selection of 2D slices when the treatment volume was unchanging in time. We hypothesised that the use of a PMP interface would: increase selection accuracy; decrease selection time; and be easier and more satisfying for the participants to use.

Logging of keyboard and trackpad input was simplified by IDL's method of event-handling. We conducted the user study using:

- a Macbook Air with a 2.13 Ghz processor;
- 4 GB memory;
- an external 27-inch Apple LED Cinema Display;
- an external keyboard; and,
- an external trackpad.

4.1 Experimental Design

The basic design for the study was a within-group factorial experiment, using repeated measures ANOVA. We also performed post-hoc analysis of the effects, using multiple regression analysis and a paired-samples t-test.

We obtained brain tumour image data used in this study from the MICCAI 2012 Challenge on Multimodal Brain Tumour Segmentation (<http://www.imm.dtu.dk/projects/BRATS2012>) organized by B. Menze, A. Jakab, S. Bauer, M. Reyes, M. Prastawa, and K. Van Leemput. The challenge database contains fully anonymized images from the following institutions: ETH Zurich, University of Bern, University of Debrecen, and University of Utah.

We used ten of the MRI series and associated expert segmentations from the above MICCAI challenge. This provided a realistic context for the tasks that users performed, without requiring any medical expertise. The chosen MRI data provided a range of tumour surfaces from small (958 vertices) to large (8863 vertices) and simple to highly irregular topology. All of the selected tumours were singular masses containing no internal holes.

Sixteen adult individuals participated in this study. Participants included undergraduate and postgraduate students and other researchers. Participants were recruited via advertising the study in lectures, bulletin board posters, and "word-of-mouth". All participants had either normal or corrected-to-normal vision. Each individual received a standard briefing prior to the experiment, which included a familiarisation with the interface and an explanation of the tasks to be performed.

Half of the participants experienced a variation of the interface without PMP first, and the other half experienced the PMP variation first. When the PMP view was not available, the participants' ability to interact with other parts of the interface was unaltered. Prior to using each of the two interface variations, participants were allowed a brief (five minutes maximum) training period with that variation. During this period, participants were also allowed to ask basic questions. Discussion of strategies was

specifically avoided during the briefing and training, except where it followed a script delivered uniformly to all participants.

We assigned participants to one of these two orders of presentation in alternating fashion, after an initial random assignment of the first participant. With each of the two software variations (PMP and non-PMP), the participants performed 20 tasks using 10 tumours. Each tumour was seen once with a treatment volume that protruded through the tumour surface and once with a treatment volume that did not protrude.

In the case of a protruding treatment, the task was to select at least one 2D view in the top row that the participant believed to show the MRI data where the treatment protruded by the greatest distance.

In the case of a non-protruding treatment, the task was to select at least one 2D view in the top row that the participant believed to show the MRI data where the treatment was the closest to the tumour surface.

Within each grouping of 20 tasks (20 - PMP, 20 - non-PMP), the order that the tumour/treatment pairs were presented in was randomised. An example of this assignment of interfaces and tasks is provided in Table 1, for illustrative purposes. For example, “ T_{91} ” means tumour 9 with a protruding treatment while “ T_{80} ” means tumour 8 with a non-protruding treatment.

Subject	PMP Order	20 Tasks	20 Tasks
S_1	$0 \rightarrow 1$	$T_{21}, T_{50} \dots T_{91}$	$T_{80}, T_{30} \dots T_{21}$
S_2	$1 \rightarrow 0$	$T_{70}, T_{40} \dots T_{61}$	$T_{11}, T_{51} \dots T_{80}$
...
S_{16}	$1 \rightarrow 0$	$T_{11}, T_{20} \dots T_{71}$	$T_{31}, T_{10} \dots T_{91}$

Table 1: Study Design - An illustrative example of participants being assigned to tasks, where “ T_{91} ” means tumour 9 with a protruding treatment while “ T_{80} ” means tumour 8 with a non-protruding treatment.

During the participants’ interactions, all trackpad and keyboard inputs were logged by our software (including selection coordinates). Certain summary information was also logged at each task completion, especially the time taken and the accuracy of the final selection.

After the software interaction portion of each user session, the participants completed a brief questionnaire and discussed their experiences in a semi-structured interview. The interactions, during task performance, as well as interviews were video recorded. The video recordings were used to encode participant responses afterwards.

4.2 Study Variables

The following is a list of the independent variables:

Interface (factor, levels: PMP and non-PMP) - The PMP was either present or not present.

Treatment Extent (factor, levels: Protruding and non-Protruding) - The simulated treatment volume either did or did not protrude beyond the tumour surface.

The following is a list of the dependent variables:

Task Time (seconds) - Task Time was measured from the moment that the participant signalled (via keyboard) to start the task until they again signalled (via keyboard) that they were satisfied with their slice selection.

Task Accuracy (# slices from actual) - Task Accuracy was measured as the difference (in # of slices) between the nearest correct slice and the selected slice on any of the three axis.

The following is a list of other variables that were observed, but not controlled:

Task Sequence (1-40) - Each participant performed 40 tasks. Task Sequence, therefore, ranged from 1 to 40.

Tumour Vertices (#) - Tumours used for the tasks varied in size and complexity. The number of vertices comprising the tumour surface were recorded.

Correct Options (#) - With each task, there were one or more pairs of points having an equal least distance (non-protruding) or greatest distance (protruding) between them. In cases where there was more than one such pair of points, selecting any slice containing one of those points was “correct”. Task accuracy, therefore, was the distance between the selected slice and the nearest such “correct” slice.

4.3 Usage Strategies

The pre-task instructions to participants in our study were deliberately limited to describing how the systems could be used and giving general suggestions about usage strategies shared by both interface options. Most users, however, quickly discover that PMP allows them to focus on the most “interesting” areas of the data in their search for a detail view that shows the two surfaces coming closest or protruding by the greatest amount.

For users who choose to focus their strategy on navigating the detailed “slice” views via keyboard, the tumour boundary in the PMP view can be used to see if further scanning of the stack of slices is likely to provide any more useful information. As the tumour boundary moves towards darker areas of the PMP, it is an indication that there is unlikely to be a benefit in navigating further in that direction.

With more practice using PMP than was available to study participants, we expect that most users will realise the following: If it is difficult to discriminate between two colours in the PMP view, it will also be difficult to discriminate between the 2D proximities shown in the associated slice view.

5 Results

We show the data, in the order that it was gathered, in Figure 5 (Task Time) and Figure 6 (Selection Accuracy). Each participant completed 40 tasks.

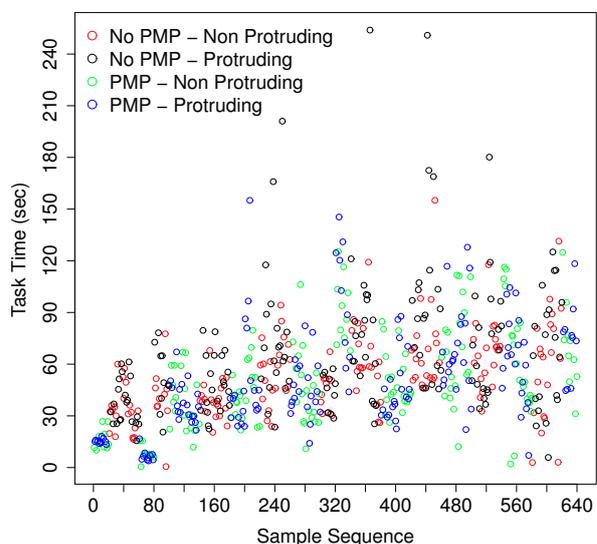


Figure 5: All Samples - Sequence is shown on the x-axis and time taken to complete the task is shown on the y-axis.

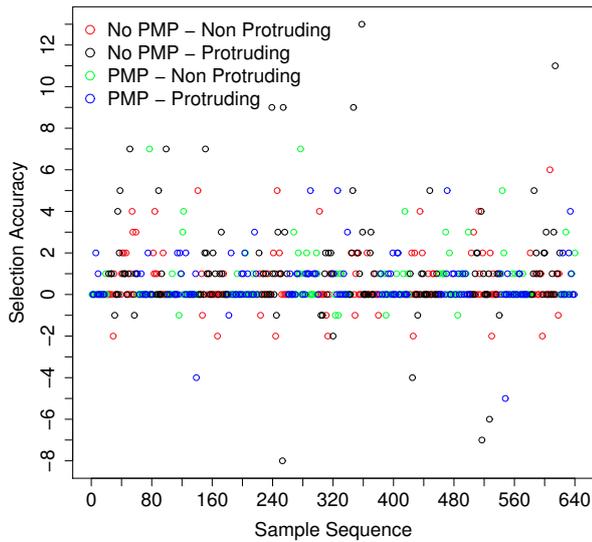


Figure 6: All Samples - Sample sequence is shown on the x-axis and accuracy of slice selection is shown on the y-axis. Tasks are categorised and colour-encoded according to the legend in red, black, green, or blue.

We used two-way repeated measures ANOVA, multiple regression, and a paired-samples t-test to analyse the results. We corrected p values on the three effects in 2x2 ANOVA results by using the Holm Sequential Bonferroni (HBonf) method, in order to address the potential for increased “Type 1” errors with multiple hypothesis testing. With Holm Sequential Bonferroni, the unmodified p values are first ordered from smallest to largest. If n is the number of effects and i is the index of the ordered p values, then: $p(HBonf)_i = (n - i + 1) \times p_i$

We used the t-test to compare the accuracy of initial and final selections when using PMP.

5.1 Assumptions for Parametric Methods

Certain assumptions are required for using these parametric methods. All of those assumptions (as noted below) were met, with the exception of homoscedasticity of variances for multiple regression on the selection accuracy data. Although we discuss multiple regression on the selection accuracy data, we do not therefore use it to draw further conclusions.

- Task time and accuracy are continuous variables that were approximately normally distributed.
- The two independent variables (PMP presence and treatment protrusion) consist of two categorical related groups.
- There are no significant outliers for task time or accuracy.
- Both independent variables have two levels, and the sphericity assumption is always met when a factor has only two levels.
- The variables used in the regressions are independent of each other.
- Each independent variable has a linear relationship with the dependent variable.
- The task time variances are homoscedastic.

5.2 Standard Effect Size

For Cohen’s f^2 :

- $f^2 \leq .02$ is “small”
- $f^2 \leq .15$ is “medium”
- $f^2 \leq .35$ is “large”

For the ANOVA, we report effect sizes as η_p^2 (partial eta-squared). η_p^2 is the ratio of the variance accounted for by an effect to that variance plus its associated error variance, as follows: $\eta_p^2 = \frac{SS_{effect}}{SS_{effect} + SS_{error}}$. η^2 can be converted to f^2 as follows: $f^2 = \frac{\eta^2}{1 - \eta^2}$

For η^2 :

- $\eta^2 \leq .01$ is “small”
- $\eta^2 \leq .09$ is “medium”
- $\eta^2 \leq .25$ is “large”

5.3 Completion Time

We analysed time taken to complete tasks by a two-way analysis of variance having two levels of interface (PMP and non-PMP) and two levels of treatment extent (protruding and non-protruding). The main effect of interface was significant, $F(1, 15) = 6.09$, $p(HBonf) = .03$, and had an effect size (η^2) = .05 (“small”). The main effect of treatment extent was significant, $F(1, 15) = 13.78$, $p(HBonf) = .004$, and had an effect size (η^2) = .02 (“small”). The interaction effect was significant, $F(1, 15) = 15.85$, $p(HBonf) = .004$, and had an effect size (η^2) = .02 (“small”). The presence of PMP decreased the time required for participants to complete the tasks. Protrusion of the treatment increased the time. The effect of PMP and protruding treatments in combination, however, decreased time. Although “small”, the effect size is apparent in Figure 7, which represents this data as a box plot.

Using a multiple regression analysis of the time taken to complete tasks, we found that task sequence, PMP presence, treatment protrusion, and number of tumour vertices

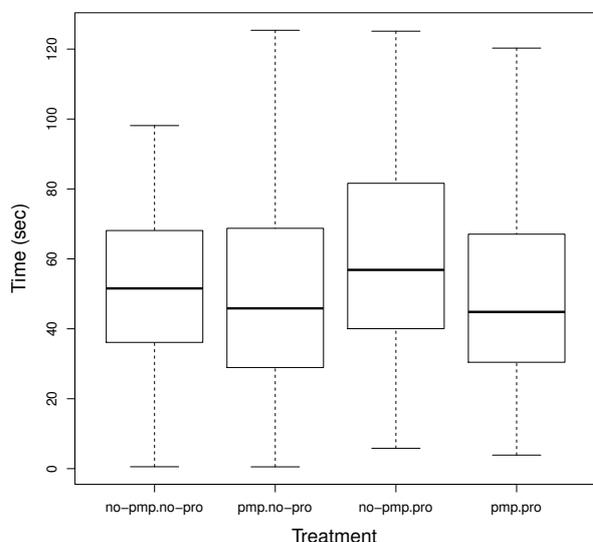


Figure 7: Completion Time by Condition - This box plot shows the “small” but significant effect of interface on selection time.

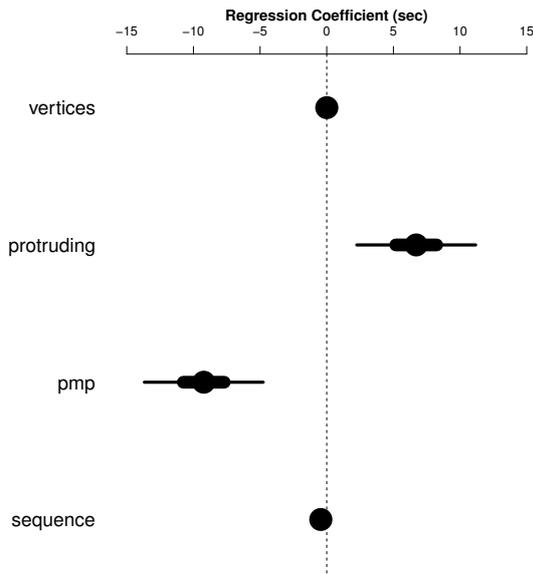


Figure 8: Completion Time - This coefficients plot for the regression model of completion time show the significant effect that PMP use and treatment protrusion had on task completion time. For example, the regression model predicts that using PMP will reduce task completion time by between five and fourteen seconds, for 95% of samples.

explained 18% of the variance ($R^2 = .18$, $F(4, 635) = 34.73$, $p < .001$). Task sequence ($\beta = -.16$, $p < .001$), PMP presence ($\beta = -.15$, $p < .001$), treatment protrusion ($\beta = .11$, $p = .003$), and number of vertices ($\beta = .35$, $p < .001$) significantly predicted the time taken to complete tasks. We represent this, in Figure 8, as a plot of the coefficients of the regression model.

5.4 Accuracy

We analysed the accuracy of completed tasks by a two-way analysis of variance having two levels of interface (PMP and non-PMP) and two levels of treatment extent (protruding and non-protruding). The main effect of interface was marginally significant, $F(1, 15) = 4.82$, $p(\text{HBonf}) = .09$, and had an effect size ($\eta^2 = .06$ (“small”). For a discussion of p-values and use of the term “marginally significant”, see [Gelman, 2013]. The interaction effect was marginally significant, $F(1, 15) = 7.26$, $p(\text{HBonf}) = .05$, and had an effect size ($\eta^2 = .05$ (“small”). The presence of PMP increased the accuracy with which participants completed the tasks. Protrusion of the treatment volume through the tumour surface amplified this effect of PMP presence. Figure 9 represents this data as a kernel density plot.

Using a multiple regression analysis of the accuracy of completed tasks, we found that PMP presence, number of tumour vertices, number of “correct” options, and variance of the PMP explained 13% of the variance ($R^2 = .13$, $F(4, 635) = 23.24$, $p < .001$). PMP presence ($\beta = -.09$, $p = .02$) and number of “correct” options ($\beta = -.11$, $p = .003$) significantly predicted the magnitude of the error in selection. We represent this, in Figure 10, as a plot of the coefficients of the regression model. This multiple regression must be considered with caution, as the residuals were heteroscedastic.

For tasks performed using the PMP version of the software, we used a paired-samples t-test to show that participants had a mean difference in error from first selection with the PMP to final selection of .23. (SD = 3.38), which was not significant at the .05 level. ($t = -1.18$, $p = .24$) Participants made marginally better first selections with the

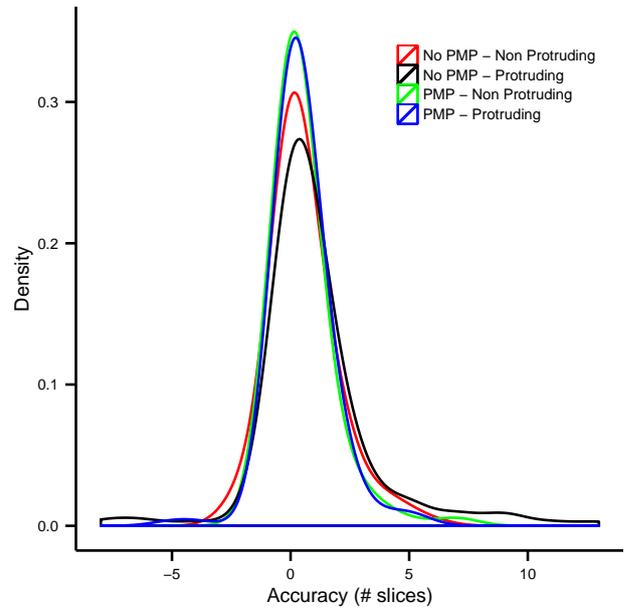


Figure 9: Accuracy by Condition - This kernel density plot shows the effect of interface on selection accuracy. The PMP conditions can be seen to higher “peak” (where the error is closer to zero, and shorter “tails” (where error is greater).

PMP than the final selections at the conclusions of tasks, but that difference was not significant.

5.5 Satisfaction and Ease-of-Use

Eleven of sixteen participants reported being more satisfied with PMP than non-PMP. Three were equally satisfied. Two were less satisfied with PMP than non-PMP. The most frequent satisfaction rating for PMP was “satisfying”. The most frequent satisfaction rating for non-PMP was “neutral”.

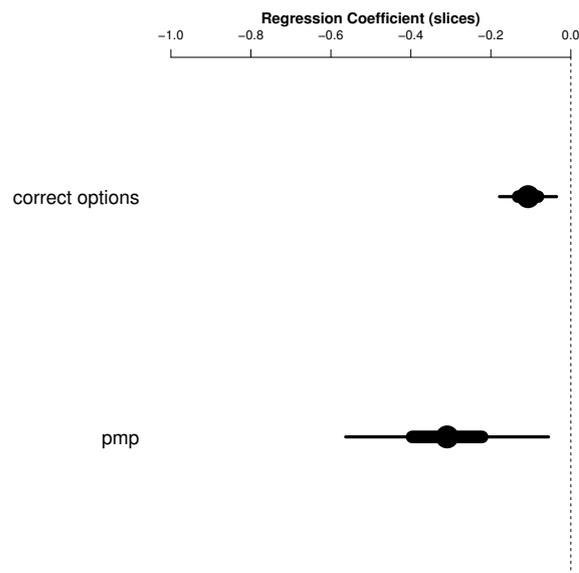


Figure 10: Accuracy - This coefficients plot for the regression model of accuracy show the significant effect that PMP use and the number of correct options had on selection accuracy. For example, the regression model predicts that using PMP will improve accuracy by between 0.1 and 0.6 slices, for 95% of samples.

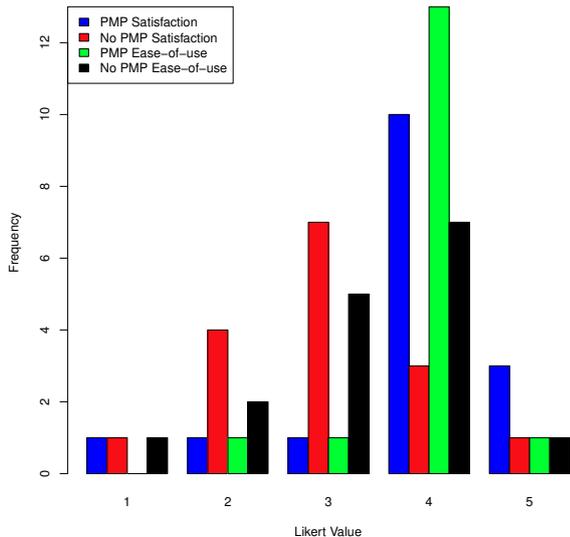


Figure 11: Satisfaction and Ease-of-Use - This frequency distribution graph shows that participants tended to rate PMP more favourably in terms of satisfaction and ease-of-use.

Eight of sixteen participants reported it being easier to use PMP than non-PMP. Five found it equally easy. Three found it more difficult to use PMP than non-PMP. The most frequent ease of use rating for PMP was “easy”. The most frequent ease of use rating for non-PMP was “easy”. We show these results in Figure 11.

5.6 User Feedback and Strategies

During post-session interviews, participants made 103 observations in response to being asked 4 questions about what had been easy, satisfying, difficult, and unsatisfying about either version of the software they had used. Participants typically did not differentiate between satisfaction and ease-of-use, so their observations were coded as positive (+) or negative (-). Some of the observations that were coded as negative were “wish list” issues, such as “I wish I could bookmark a slice.” Of the 103 observations: 74 (72%) concerned the PMP view (45+/29-), 23 (22%) concerned the 2D slice views (5+/18-), and 6 (6%) concerned the 3D volume view (1+/5-).

The most frequently reported positive thing about the PMP view (in various ways) was that it allowed participants to target interesting areas and navigate directly to those slices. The second most frequent positive observation was that the PMP view allowed participants to constrain their search to a smaller range of the 2D slices. The most frequent category of negative observations concerned perceived discrepancies between colour differences and the spatial differences in the 2D slices that were navigated to.

The most frequent negative observations about the 2D slices were a desire to have some form of “bookmarking” to facilitate switching between slices, and that it was difficult to compare proximities in two slices (especially two slices on the same axis).

The strategy that participants most frequently reported having used when there was no PMP view was an end-to-end scan of each axis of 2D slices. Some participants also used the 3D volume view to constrain their search.

The strategy that participants most frequently reported having used with the PMP view was to click in the PMP, navigating directly to interesting slices, and then performing a constrained scan of the 2D slices. Some participants also used the changing boundaries in the PMP view, as

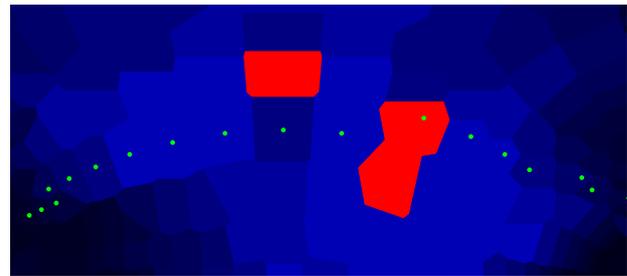


Figure 12: Tumour Boundary - This graphic shows a close-up view of the tumour boundary in the PMP view. It is represented as a green dotted line. (Best viewed in colour.)

shown in green in Figure 12, to constrain their key stroke navigation within the 2D slices.

6 Discussion

6.1 Assumptions for Parametric Methods

The dependent variables had linear relationships with the independent variables. Some of the independent variables, however, were observed in an attempt to take into consideration the overall “difficulty” of the task. In that sense, those variables were a proxy measure of difficulty. As the PMP technique is applied to different domains, we expect that the particular measures of difficulty in each domain may vary. Difficulty may have a non linear relationship with task time and/or accuracy. It will be useful to investigate the common indicators of difficulty shared between different domain applications of PMP, and how they may explain results.

6.2 Standard Effect Size

Although the effect size reported for ANOVA in terms of η^2 were considered to be “small”, the results still encourage further investigation. The prototype employed was an initial one. We expect that lessons learned from this investigation will help improve the PMP technique in an iterative fashion.

Some ways in which PMP may be improved, yielding a larger effect size, are: increased trust; increased time pressure; and, modification of the PMP tumour boundary lines to better suit the user strategies discovered during this study.

6.3 Task Completion Time

While the ANOVA showed PMP having a significant effect on the time taken to complete tasks, the multiple regression analysis revealed a more complex relationship between completion time and additional observed variables. Furthermore, multiple regression showed that other variables explained the variation in task time with greater significance than treatment protrusion. The number of tumour vertices, for example, could be considered as an indication of the size of the search problem.

It was apparent that the time allowed, during this study, for task completion was more than adequate for a high level of accuracy and user comfort with final slice selection. In other words, the tasks did not put a high amount of pressure on the participants. PMP was designed primarily for the dynamic task scenario. In the dynamic task scenario, users are constrained to making selections within limited time-frames. Examining user performance with PMP in the static scenario was a necessary precursor step for designing an appropriate study with dynamic tasks.

6.4 Task Accuracy

In order to draw any conclusions about the effects of various measures of tumour complexity on accuracy, further study will be required.

In the ANOVA analysis, we showed treatment protrusion to have a significant effect on task accuracy, while PMP had a marginally significant effect on task accuracy. As was the case with completion time, we used multiple regression analysis to reveal more complex relationships and observed variables that explained the variance in accuracy with greater significance than protrusion.

We used a multiple regression for predicting task time to show that the order in which tasks were performed had a small but significant effect, reducing the time taken. At the same time, using a multiple regression for accuracy, we did not show a significant effect of task order on accuracy. This could be a “fatigue” order-effect. If participants became fatigued and started making quicker decisions with time, it did not significantly impact on the accuracy of their decisions. Because of the effect of heteroscedasticity on the regression analysis, however, this will need to be verified in a further study.

Using a paired samples t-test, we showed that participants did not significantly improve the accuracy of their selections beyond their first selection in the PMP. *If participants had completed the tasks after their first selection in the PMP, the reduction in task completion time would have been dramatic. This appears to be further evidence that PMP can be used with even greater effectiveness than was demonstrated in this study.*

6.5 Satisfaction and Ease-of-Use

While achieving greater task speed and accuracy with PMP, a majority of participants found it was also easier and more satisfying to use. In addition to the subjective reports of ease-of-use and satisfaction, participants made several observations about what in particular was easy, difficult, satisfying, or unsatisfying.

6.6 User Feedback and Strategies

Participants focussed nearly three quarters of their observations on the PMP. Their positive observations about PMP outnumbered the negative by a ratio of approximately 3 to 2. Their negative observations about the 2D views outnumbered the positive by a ratio of approximately 3 to 1. Some of the negative observations that were of the “wish list” variety have solutions that could be easily implemented in a future version of the software.

The most frequently observed positive things about PMP were its ability to “target” and “constrain” searching of the data. These were intended to be strengths of the experimental software. Participants commonly reported some kind of discrepancy between the colour differences that they perceived and the 2D spatial differences that existed in the slices that were navigated to. This had been anticipated in the design of the experimental software. The chosen scaling of colour appears to have been only partially effective in addressing the issue.

In addition to the expected participant strategies of “targeting” in the PMP and scanning and bracketing in the 2D views, an additional strategy became apparent during this user study. A number of participants were also using the boundary shown in the PMP to observe the effects of their slice navigation in the 2D views. Participants reported doing this in order to help determine when they could stop searching the slices in a given direction.

Without being advised in the pre-task briefing to that effect, participants appeared to naturally develop a degree of trust that the tumour boundary in the PMP could be used effectively to constrain their searching in the 2D slices. It is possible that a modification to the pre-task briefing

could lead participants to such a strategy and trust level more quickly.

7 Conclusions

We have described a new visualisation technique, PMP, for interactively determining when and where two nested 3D surfaces approach each other. We developed the technique particularly for real-time medical applications where a thermal dosage is being applied to a tumour.

We have described a user study in a static scenario, which showed that PMP enabled faster identification of regions of nearest proximity and greatest protrusion, and may also increase the accuracy of such identification. It was, at the same time, more satisfying and easier to use than a 2D planar view.

We observed quantitative and qualitative indications that greater trust in the PMP interface could allow for quicker selections without significantly affecting accuracy.

We made qualitative observations that we expect to improve the effectiveness of PMP in its next revision.

8 Future Work

We hypothesise that PMP’s performance benefits will extend from the static task to a dynamic scenario. The next user study, therefore, will investigate the effect of PMP (present, not present) on accuracy with a dynamic task where the participant will attempt to be monitoring the correct slice at convergence while a simulated treatment volume is growing within a tumour. (Much as with the real-life surgical scenario.)

Observations of participant strategies during our study suggested that selections could be made even faster with PMP, without sacrificing accuracy, by having greater trust in the technique. Participants’ use of the tumour boundary shown in the PMP was more sophisticated than expected. Beyond its intended purpose of increasing a user’s spatial understanding of the data, participants employed the tumour boundary in the PMP as part of a strategy for constraining searches. In future studies, we will investigate the effect of boundary interactivity (clickable, not clickable) on PMP performance.

Participant feedback during the present study suggests that “bookmarking” and colour to proximity mapping scales are potentially interesting issues to investigate in a subsequent user study.

We identified the user’s trust of PMP as a critical factor in its successful future adoption as a tool for practical real-world tasks. Real-time MRI-guided thermal therapy has been the domain that provided the primary motivation for investigating PMP. Having demonstrated some important (but general) performance benefits of PMP, an appropriate next step in this research will be to conduct a series of semi-structured exploratory interviews with surgical experts who would potentially be motivated to use PMP. From such an investigation, one could learn what are the most important challenges to PMP being accepted and successfully employed as a tool in real-time MRI-guided thermal therapies (or other surgical techniques involving the real-time monitoring of surface proximity).

9 Acknowledgments

We would like to acknowledge Dr. Duncan Stevenson, and Dr. Hongdong Li for numerous helpful conversations.

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