Supplementary material: Use of visual analysis of in-silico hemodynamic indices for left atrial appendage occlusion preplanning

1. Image processing and simulations setup

Retrospective pre- and post-occlusion CT images of two non-valvular AF patients were provided by Hôpital Haut-Lévêque (Bordeaux, France), after approval from the ethical committee and informed consent of the patients. Cardiac CT studies were acquired on a 64-slice dual-source CT system (Siemens Definition, Siemens Medical Systems, Forchheim, Germany) and reconstructed into isotropic voxel sizes (0.37-0.5 mm range; 512x512x[270-403] slices).

Patient-specific geometrical information and simulated blood flow patterns were extracted from binary mask segmentations of retrospective pre- and post-occlusion CT images. To determine the real location of the LAAO device, two device positioning approaches were defined for the two analyzed patients. First, the LAAO device was manually segmented in the post-CT images. A fiducial registration technique using Meshlab v2021-07 was then employed to align the pre-and post-treated LAAO meshes, allowing the placement of the CT segmented device in the pre-occlusion mesh. The segmented device and the pre-CT left atrium (LA) mesh were subsequently uploaded into the VIDAA platform for simulation of the device deployment.

The device segmentation in the post-CT images provided information on the device's size, type, and location, which was used to select the appropriate model of the device for deployment in the pre-CT LA geometry. In the analyzed patients, the devices were implanted deep in the LAA, uncovering the pulmonary ridge (the lateral fold formed by the coalescence of the LAA and the left superior pulmonary vein). As a result, a second device positioning approach was evaluated, aiming for placement closer to the ostium (the interface between the LA main cavity and the LAA) and covering the pulmonary ridge. Within the VIDAA platform, the recommended LAAO device size for this second configuration was estimated based on anatomical measurements following the guidelines provided by device manufacturers.

To solve the fluid domain, tetrahedral volumetric meshes of 12x10x5 elements were generated with the LAAO devices deployed and LA geometry downloaded from VIDAA.

To establish the boundary conditions and setup for the simulations, generic clinical measurements obtained from a patient with AF were utilized. The boundary conditions were defined by imposing catheter pressure data in the pulmonary veins and echo-Doppler velocity profiles at the mitral valve. These boundary conditions were determined based on sensitivity analyses conducted on fluid models that were based on the LA.

In addition to the boundary conditions, the simulation incorporated LA wall motion. This was achieved by implementing a passive mitral valve annulus motion function derived from the study conducted by Veronesi et al [1]. To ensure motion diffusion throughout the LA wall geometry, a spring-based dynamic solution of the CFD solver was employed.

The simulations were conducted for two cardiac cycles, with a total of 176 time steps. The time step size was set at 0.01s. To avoid initialization inaccuracies, only the second cardiac cycle was analyzed.

The data modelling pipeline is shown in Figure 1.

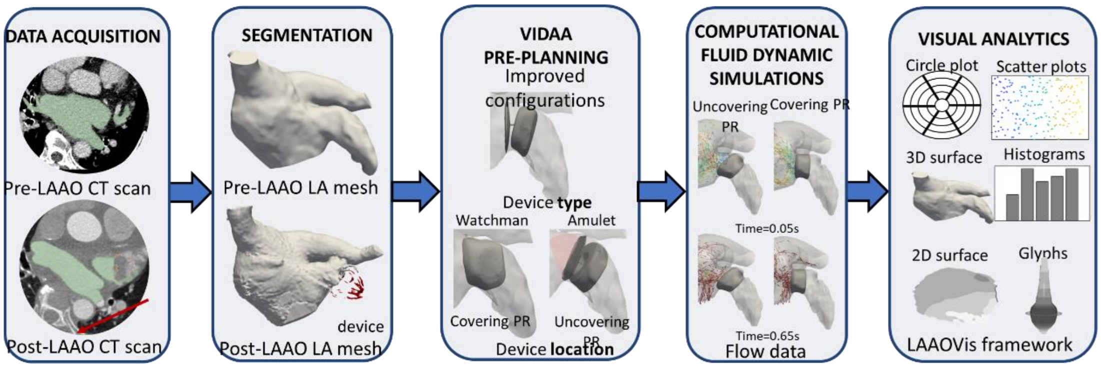


Figure 1: Computational pipeline for the visualization and analysis of in-silico hemodynamic indices for different left atrial appendage occluder (LAAO) device configurations, e.g., covering or not the pulmonary ridge (PR). CT: computed tomography images.

2. User interace of LAAOVis framework

The LAAOVis is an adapted version of the MuscaVis tool [2] that is designed with four linked views of LAAO data. These views facilitate the comparison of two cases that involve different device configurations. The link between the views and two device configurations ensures that the visualization remains consistent across all views as the data is observed over time. In the subsequent subsections, we provide a comprehensive description of each view and explain how they are interactively connected to enhance the user experience and analysis capabilities.

2.1 Data exploration using the circle plot

Multiple scalar fields can be extracted from the fluid simulations in each cardiac cycle. The bull's eye plot (BEP) is a commonly used tool in clinical settings to visualize quantitative functional data of the left ventricle. Since clinicians are already familiar with this tool it was adapted to represent possible correlations between parameters over time, as shown in Figure 2 right. The view is split into two parts, each containing a BEP representing a different case. Each BEP is divided into 30 equal parts, where each part represents every third time-step. Splitting a circle into 88 time steps would lead to unnecessary visual clutter since the change of a scalar field from one to another is negligible. Then, the circle is divided radially into three segments, where each segment represents one scalar field. A legend at the top left corner shows the order of parameters along the radius.

In the center of the plot, a 2D map is shown, which is subdivided into five colored regions. Regions are defined as radial split of LAA surface based on the length of the centerline, as depicted in **Figure 2:** Left: left atrial main cavity (grey) and regional division of the LAA, with five regions going from the ostium (orange) to the tip (purple) of the LAA. Right: Circle plots show temporal correlations of scalar fields within different LAA regions.. Each LAA vertex is assigned to one of them. The user can manually define a threshold for each parameter, such that if the parameter value of the specific vertex exceeds the threshold, the corresponding temporal region is colored to the vertex's region color.

The BEP (**Figure 2:** Left: left atrial main cavity (grey) and regional division of the LAA, with five regions going from the ostium (orange) to the tip (purple) of the LAA. Right: Circle plots show temporal correlations of scalar fields within different LAA regions. right) is designed to be interactive, allowing users to make real-time updates to the coloring by adjusting the threshold. Furthermore, users have the ability to create custom regions by utilizing brushing techniques on both 2D and 3D LAA surfaces. A specific region of interest for the use of brushing is the pulmonary ridge area, which is of utmost interest for the DRT assessment. These custom regions are then rendered in the BEP, providing a more tailored and focused visualization. Additionally, users can select specific segments within the BEP. Once a segment is selected,it is highlighted on the 3D surface, and the animation time is automatically set to the corresponding time step of the selected segment. This interactive functionality enhances the user's ability to explore and analyze the data correlation within the cardiac cycle, enabling a more dynamic and customizable visualization experience.

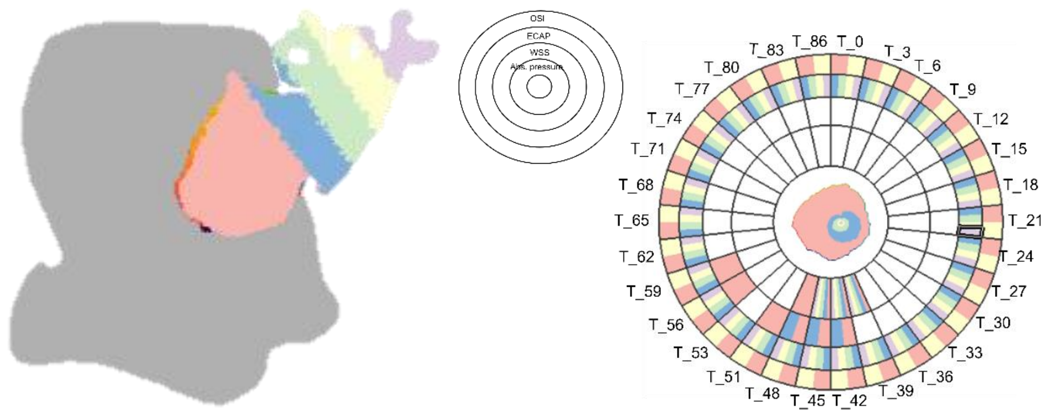


Figure 2: Left: left atrial main cavity (grey) and regional division of the LAA, with five regions going from the ostium (orange) to the tip (purple) of the LAA. Right: Circle plots show temporal correlations of scalar fields within different LAA regions.

2.2 Analysis using statistical plots

The second view comprises the matrix-based visualization designed to display combinations of two parameters in each entry, as shown in **Figure 3:** Analysis of scalar field correlations using density plots and histograms. The upper and lower triangular matrices represent cases with different device configurations.. Feedback from clinicians and fluid modeling researchers was used to determine the most relevant parameters to visualize, which are scalar fields obtained from fluid simulations. The upper and lower triangles of the matrix represent two distinct cases.

In the non-diagonal entries of the matrix, scatter plots are used to provide an overview of the distribution of the data. These scatter plots show the relationship between the two parameters being compared. On the diagonal entries of the matrix, histograms are used to visualize the distribution of each individual parameter. This allows users to examine the frequency and range of values for each parameter combination separately. To provide flexibility for the user, the number of histogram bins can be adjusted. By default, the number of bins is set to five, but users can modify this value to suit their specific needs.

The view involves visualization of the density and distribution of scalar field combinations using a color scale. The color scale ranges from yellow to blue, with blue indicating frequently occurring values and yellow representing uncommon values found in only a few regions. Overall, this matrix-based visualization provides a comprehensive overview of the data distribution for the combinations of parameters being analyzed. The scatter plots and histograms offer insights into the relationships and individual distributions of the parameters, enhancing the user's understanding of the data.

Comparing two cases requires mentally rotating the plots in the lower triangular matrix around 90◦. Moreover, a difference visualization can be activated showing changes between the cases using a gray-to-red color scale. Using this scalar field, the user can directly see if parameter values would be changed by the implantation of a specific occluder configuration. To ensure comparability between the two cases, statistical plots depicting the same scalar field combination are plotted within the same attribute range. The attribute range is determined by the minimum and maximum values of the scalar fields in both cases. Users have the flexibility to define the attribute range, as extreme values may be uncommon. The plots are updated for each time step, creating an animation that showcases the distribution of data over the cardiac cycle.

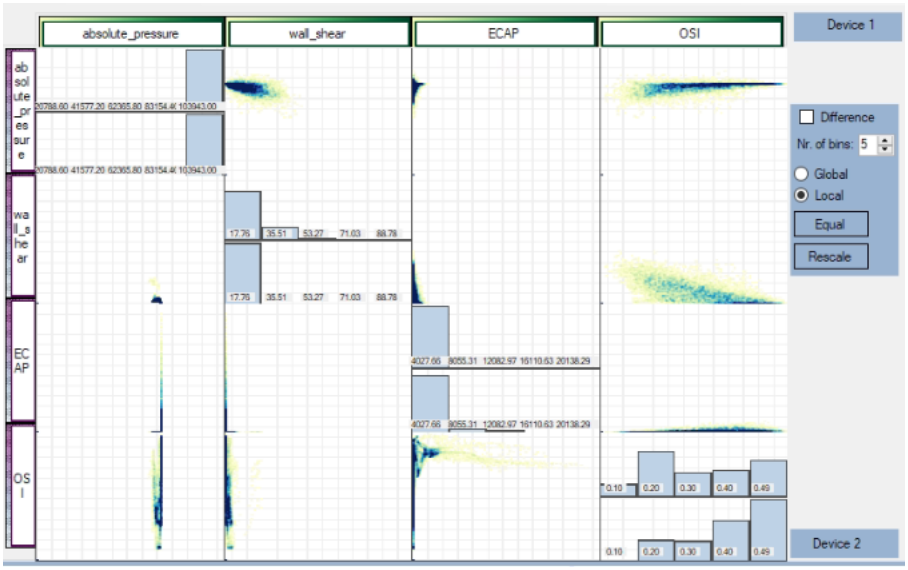


Figure 3: Analysis of scalar field correlations using density plots and histograms. The upper and lower triangular matrices represent cases with different device configurations.

2.3 Analysis of the left atrial appendage surface

The third and fourth views display 2D and 3D visualizations of the left atrial appendage, with the aim of providing a detailed exploration of high-risk regions throughout the cardiac cycle. Each view is divided into two sections, showcasing two cases with different device configurations. To establish spatial connectivity between the views, the ostium area is highlighted as a reference point.

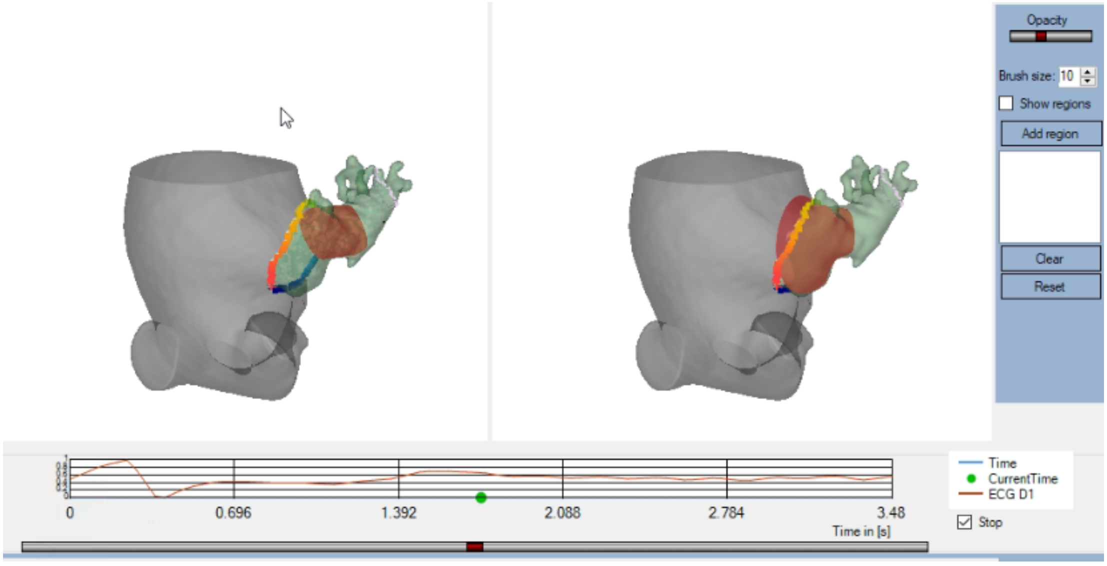


Figure 4: 3D reconstruction of the left atria (grey) and its appendage (green) with an implanted occluder device (red). The left and right panels illustrate two distinct left atrial appendage occluder device configurations, uncovering and covering the pulmonary ridge, respectively, due to the different device sizes and positioning. At the bottom of the figure, an electrocardiogram is depicted to identify the cardiac phase corresponding to the visualized scalar fields.

In the 3D visualization, as shown in **Figure 4:** 3D reconstruction of the left atria (grey) and its appendage (green) with an implanted occluder device (red). The left and right panels illustrate two distinct left atrial appendage occluder device configurations, uncovering and covering the pulmonary ridge, respectively, due to the different device sizes and positioning. At the bottom of the figure, an electrocardiogram is depicted to identify the cardiac phase corresponding to the visualized scalar fields., the opacity of the mesh can be adjusted to reveal the implanted occluder. This scalar field allows for a clearer visualization of the occlusion device within the LAA. Below 3D meshes, a timeline is visualized together with an electrocardiogram (ECG) signal to provide temporal orientation within the cardiac cycle. The 2D map, depicted in **Figure 5**, provides a quick overview and offers the possibility of simultaneously exploring multiple scalar fields. This allows for a more comprehensive analysis of the data, as users can examine various parameters and their spatial relationships within the 2D representation.

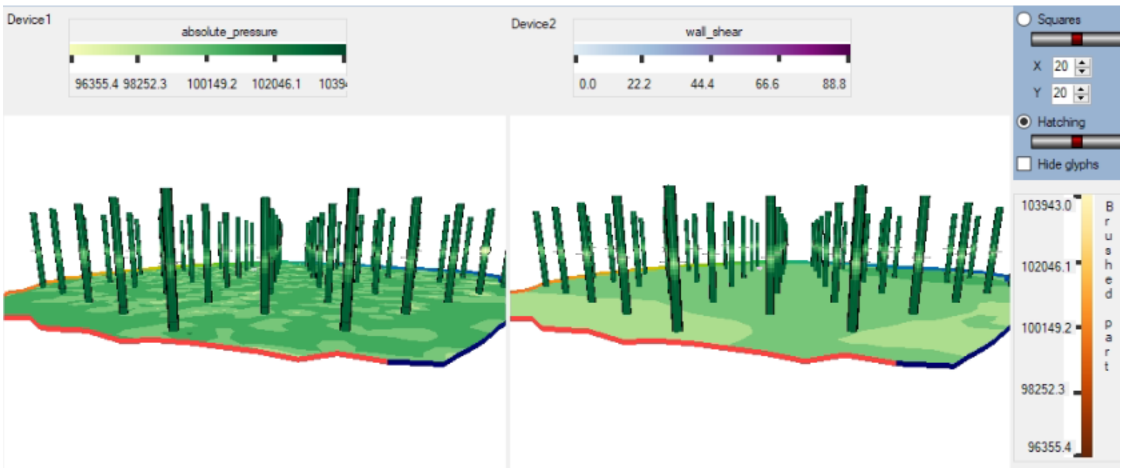


Figure 5: 2D flattening of the left atrial appendage with glyphs to show simultaneous scalar field correlations (in this example, the absolute pressure and the wall shear stress), where left and right represent cases with different device configurations.

To showcase two scalar fields simultaneously on both the 2D and 3D LAA views, the hatching method is used, where one scalar field is color-coded and the other is represented by an image-based hatching scheme. However, hatching discretizes the data range into four patterns, which limits quantitative analysis. The second method, called checkerboard visualization, overcomes this limitation. It divides the surface into a grid, initially set at a default size of 20×20, but adjustable by the user. Both scalar fields are color coded. The user can emphasize one scalar field over the other by changing the distribution between the two parameters using a slider. By default, both fields are equally distributed.

To incorporate the temporal component while showcasing two scalar fields, 3D violin glyphs are utilized. These glyphs are placed on the 2D map at regular grid points, with a sampling rate of 10%. The user can add glyphs at specific regions by clicking on the map. The first scalar field is visualized using a yellow-to-green color scale, while the second scalar field corresponds to the radius of the glyph. The current time is indicated by a disc at the corresponding height of the glyph.

These visualization techniques provide a comprehensive and dynamic exploration of high-risk regions within the LAA over the cardiac cycle and an assessment of distinctions between different device configurations. The combination of 2D and 3D views, along with the incorporation of multiple scalar fields and the temporal component, enhances the user's ability to analyze and interpret the data effectively.

2.4 Brushing and linking

To facilitate the analysis and comparison of different device configurations, the framework incorporates brushing and linking capabilities that allow users to explore the LAA at regions of interest and directly compare them between different cases.

In the scatterplot, if scalar field combination of interest is detected, the user may want to further analyze the same region in the 3D or 2D surface views. To enable this, the user can mark a region using the brushing tool on the scatterplot, which is then linked to the 2D and 3D views, where the region in question is highlighted. This allows for a seamless transition from the scatterplot to the surface views, focusing on the specific region of interest. Similarly, in the 2D and 3D views, the user can brush a region, and the corresponding regions will be highlighted in the other views. This linking functionality ensures that the user can easily compare and analyze the same region across different visualizations.

Furthermore, the 2D and 3D surfaces are linked to each other, meaning that selecting a point in one view will change the camera perspective in the other view. This synchronized interaction enhances the user's ability to explore and understand the LAA from different angles and viewpoints. Additionally, the visualizations of different cases within the same view are also linked in the same way. This allows for a direct comparison between different device configurations, further facilitating the analysis and evaluation of optimal device configurations.

3. Domain expert evaluation

We recruited four domain experts, with two to seven year of experience with LAAO intervention. There were three engineers and one interventional cardiologist. The questionnaire consisted of four questions regarding personal experience, 17 questions regarding effectiveness of particular visualisation window that were to be rated on a 5-point Likert skale, and two open questions regarding possible improvements. Questions were complemented with screenshot of visualization object. We surveyed the experts via Typeform, below is attached the report of the questionnaire with actuall questions and responses.

References

[1] C. C. L. S. E. G. C. L. W. V. M.-A. S. C. C. L. R. M. L. Federico Veronesi, «Quantification of mitral apparatus dynamics in functional and ischemic mitral regurgitation using real-time 3-dimensional echocardiography,» Journal of the American Society of Echocardiography, pp. 347-354, 2008.

[2] M. Meuschke, T. Günther, P. Berg, R. Wickenhöfer, B. Preim i K. Lawonn, «Visual analysis of aneurysm data using statistical graphics,» IEEE transactions on visualization and computer graphics, vol. 25, núm. 1, pp. 997-1007, 2018.

Evaluation survey of LAAO visualization platform

4 responses

Please select your age:

4 out of 4 answered

41-50 years old	2 resp.	50%
20-30 years old	1 resp.	25%
31-40 years old	1 resp.	25%
older than 50	0 resp.	0%
Rather not say	0 resp.	0%
Younger than 20	0 resp.	0%

Please select your gender:

4 out of 4 answered

Male	4 resp.	100%

Female 0 resp. 0%

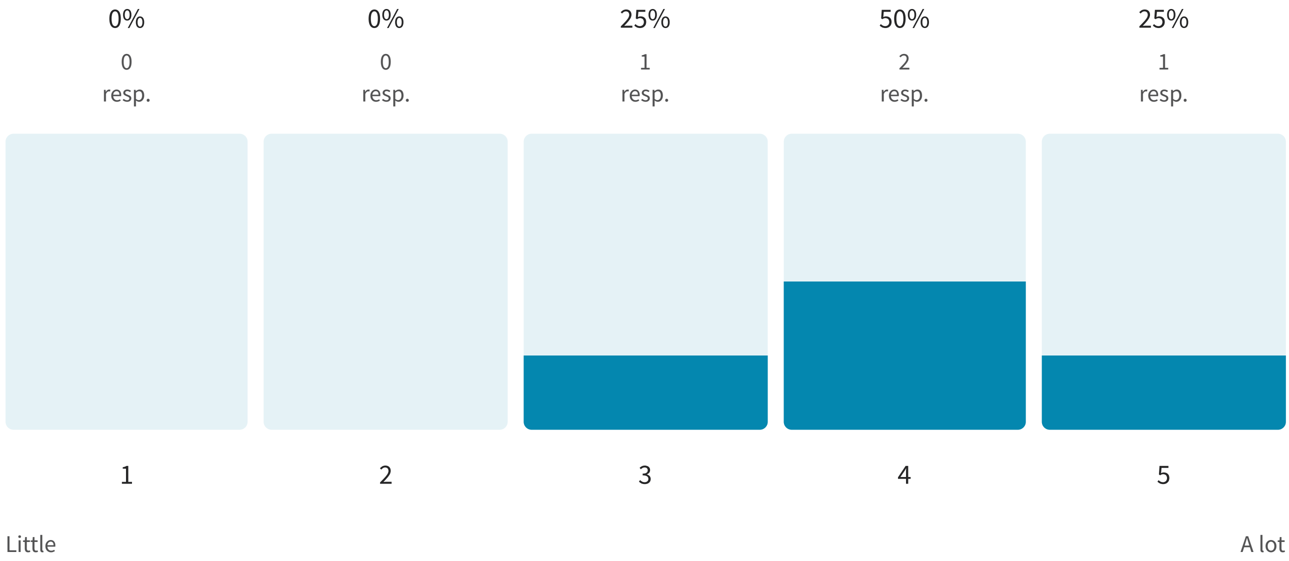
Other 0 resp. 0%

Rather not say 0 resp. 0%

How satisfied are you with the overall user interface of the LAAO visualization platform?

4 out of 4 answered

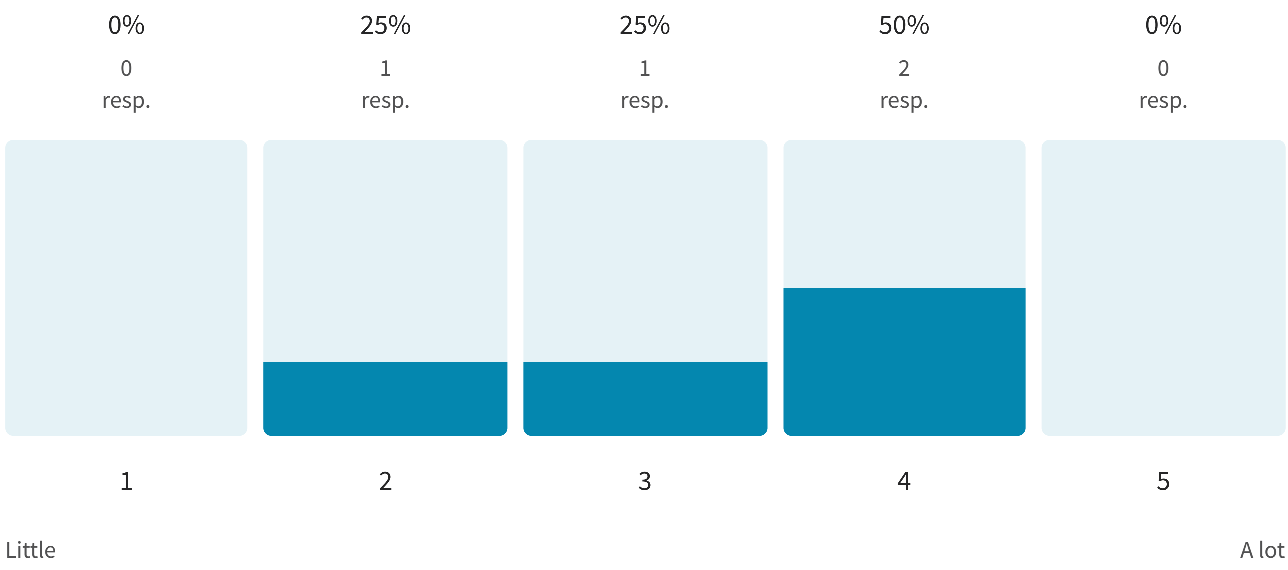
4.0 Average rating



How easy is it to navigate through different views and functionalities of the LAAOVis platform?

4 out of 4 answered

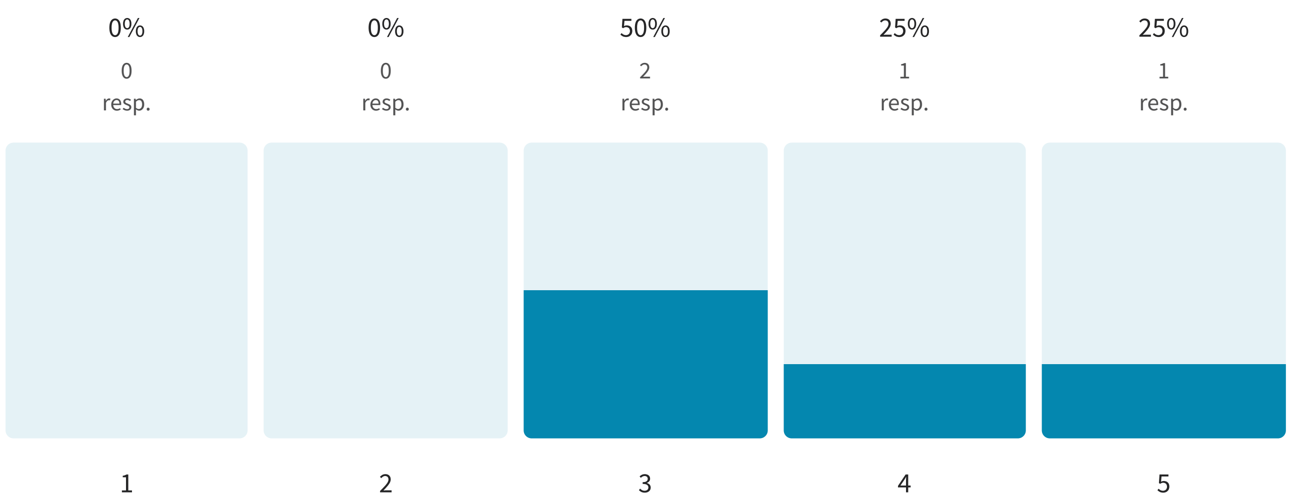
3.2 Average rating



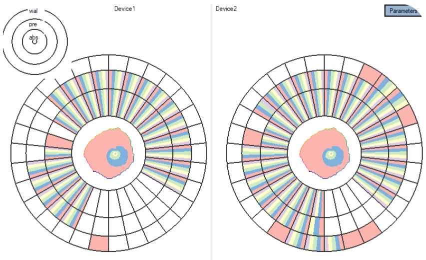
How visually appealing do you find the design of the platform?

4 out of 4 answered

3.8 Average rating



Little A lot



How effective are circle plots in exploring and analyzing changes in hemodynamic parameters over time?

4 out of 4 answered

3.2 Average rating

1	2	3	4	5
0%	0%	75%	25%	0%
0 resp.	0 resp.	3 resp.	1 resp.	0 resp.

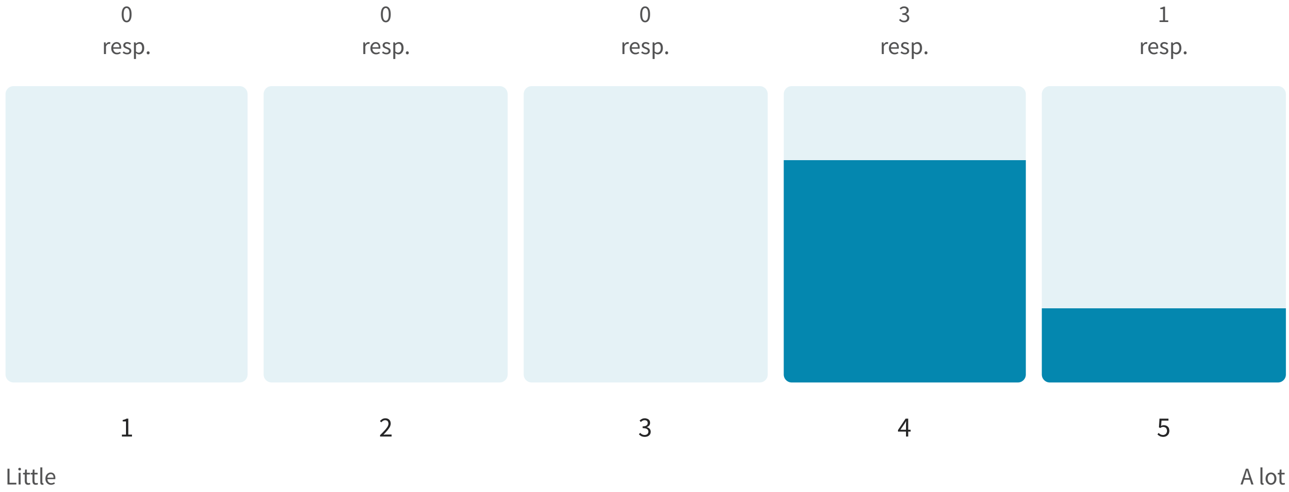
Little A lot

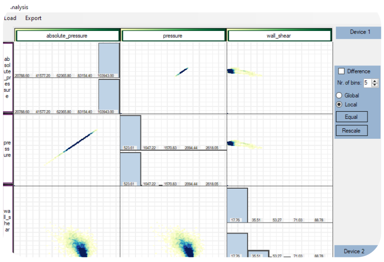
How effective are circle plots in comparing suitability of different device configurations?

4 out of 4 answered

4.2 Average rating

0% 0% 0% 75% 25%

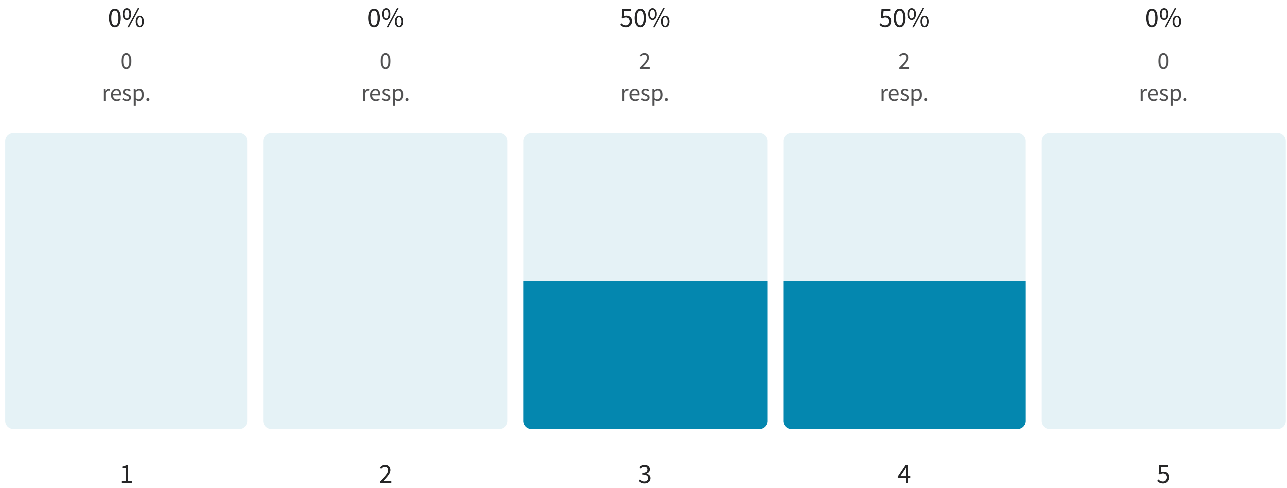




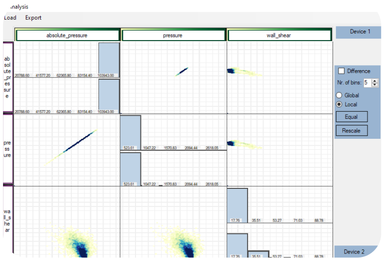
How effective are statistical plots in exploring and detecting correlations between parameters?

4 out of 4 answered

3.5 Average rating



Little A lot



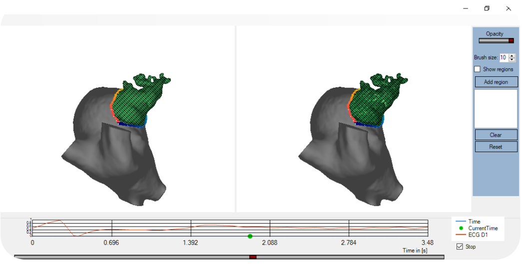
How effective are statistical plots in comparing the suitability of different device configurations?

4 out of 4 answered

3.8 Average rating

1	2	3	4	5
0%	0%	25%	75%	0%
0 resp.	0 resp.	1 resp.	3 resp.	0 resp.

Little A lot



How effective are 3D meshes in exploring and analyzing changes in hemodynamic parameters over time?

4 out of 4 answered

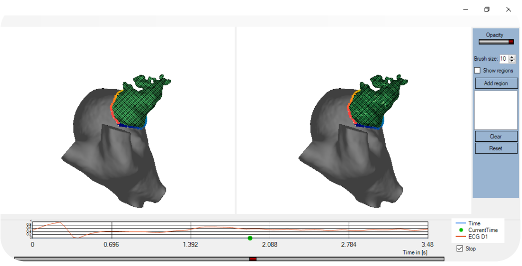
4.5 Average rating

0% 0% 0% 50% 50%

1	2	3	4	5
0 resp.	0 resp.	0 resp.	2 resp.	2 resp.

1 2 3 4 5

Little A lot



IS ECG plot effective for temporal orientation within cardiac cycle in animations?

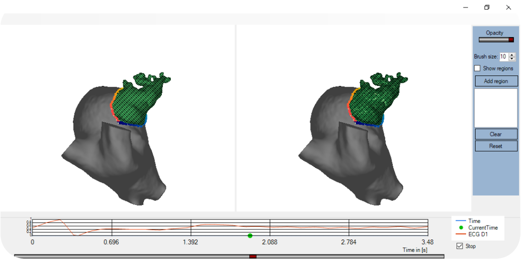
4 out of 4 answered

3.5 Average rating

1	2	3	4	5
0%	25%	25%	25%	25%
0 resp.	1 resp.	1 resp.	1 resp.	1 resp.

1 2 3 4 5

Little A lot



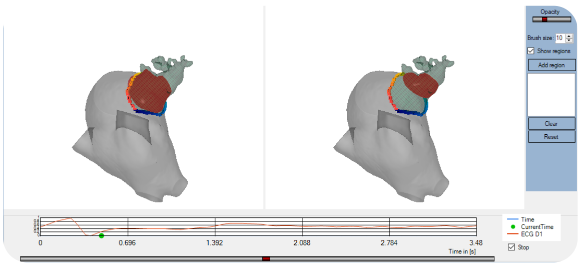
How effective are 3D meshes in comparing different device configurations?

4 out of 4 answered

4.2 Average rating

1	2	3	4	5
0%	0%	25%	25%	50%
0 resp.	0 resp.	1 resp.	1 resp.	2 resp.

Little A lot

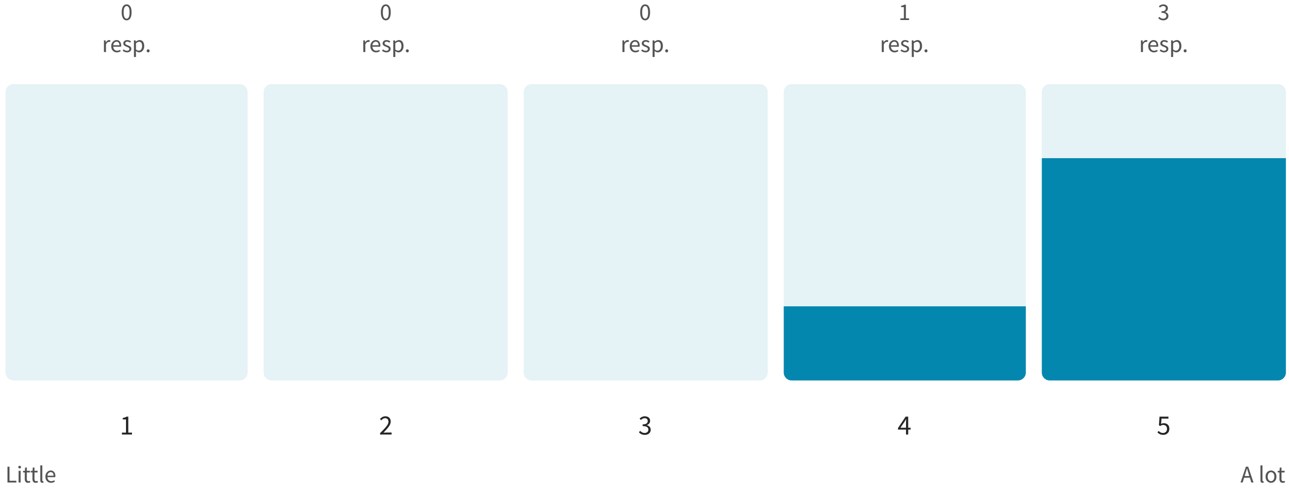


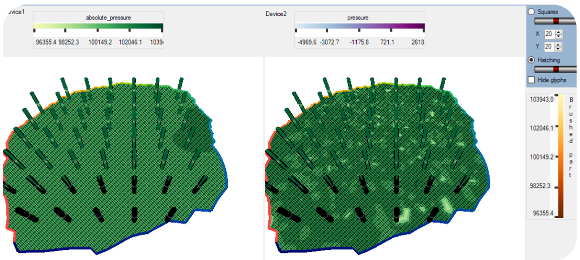
How useful are device visualisations within 3D meshes in comparing different device configurations?

4 out of 4 answered

4.8 Average rating

0% 0% 0% 25% 75%

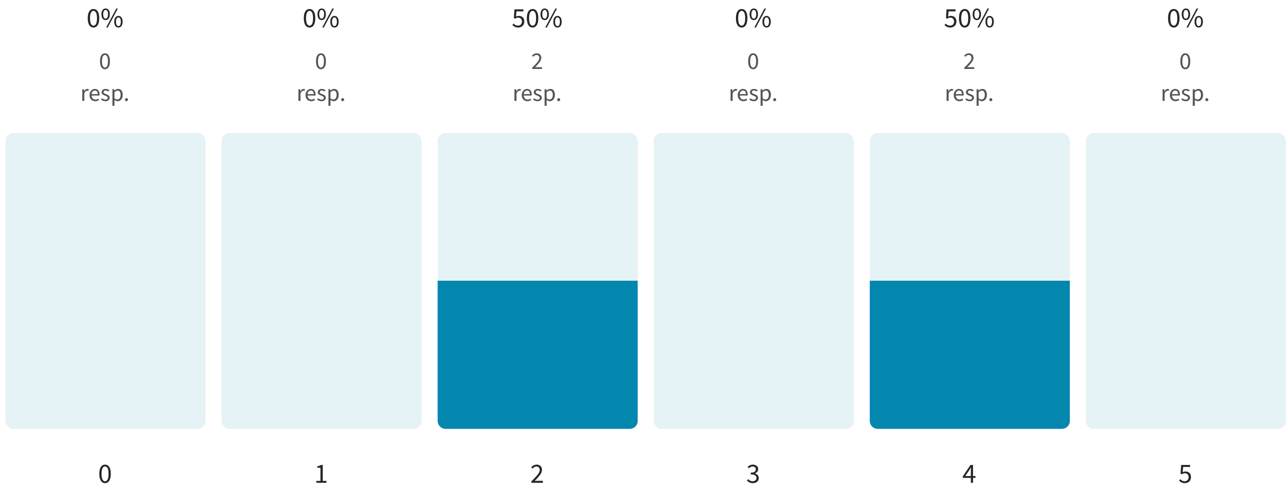




How effective are flat map surfaces of LAA in comparing cases with different device configurations?

4 out of 4 answered

3.0 Average rating



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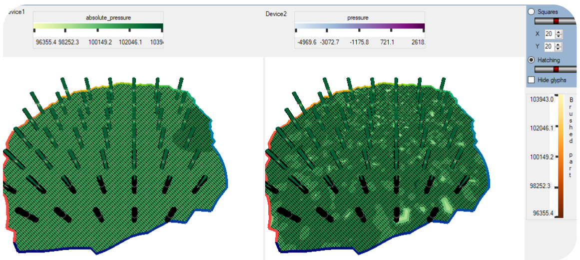


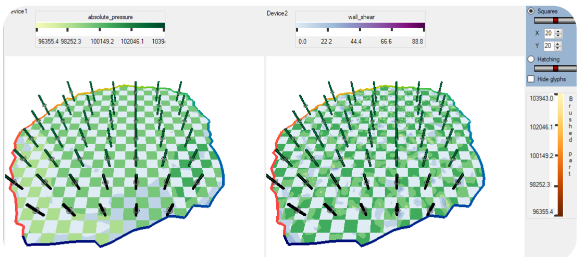
How effective are flat map surfaces of LAA in detecting regions with high DRT risk?

4 out of 4 answered

2.8 Average rating

1	2	3	4	5
0%	50%	25%	25%	0%
0 resp.	2 resp.	1 resp.	1 resp.	0 resp.

Little A lot

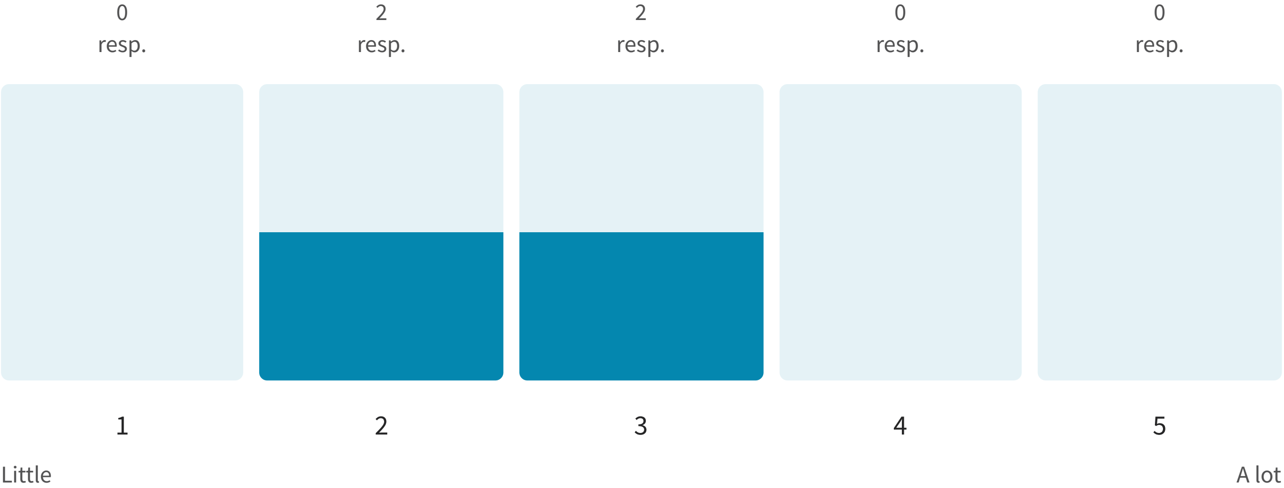


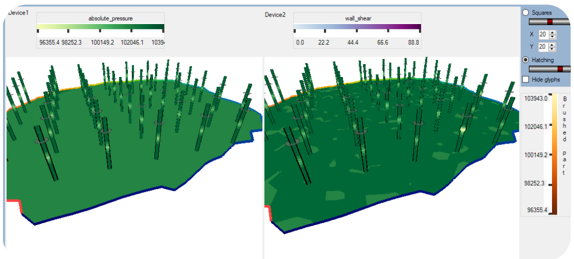
Are checkerboard visualisations effective for detecting high DRT risk regions?

4 out of 4 answered

2.5 Average rating

0% 50% 50% 0% 0%

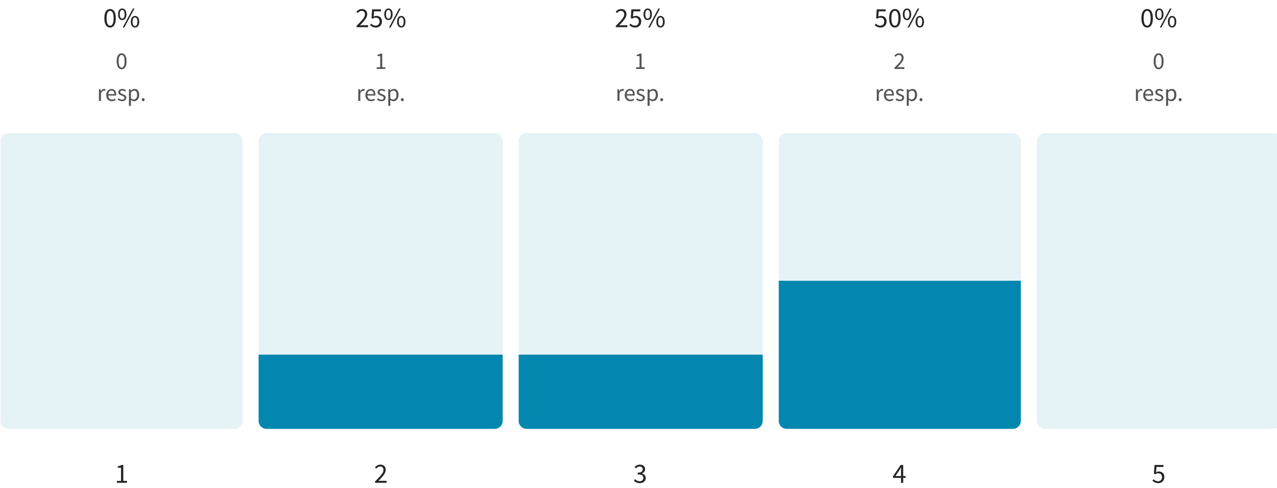




Are glyphs effective for visualising multiple features and the temporal component?

4 out of 4 answered

3.2 Average rating



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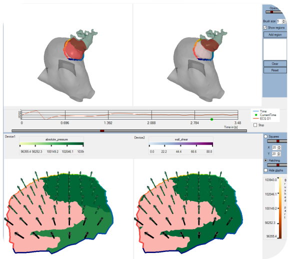
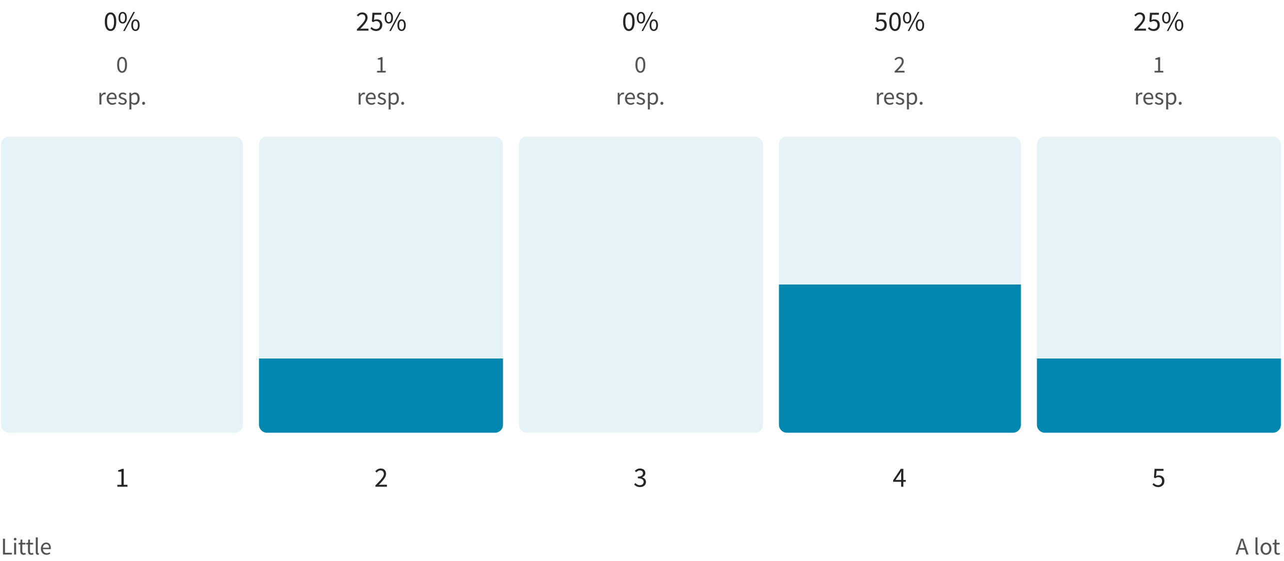


Are brushing and linking features effective for comparing two cases?

4 out of 4 answered

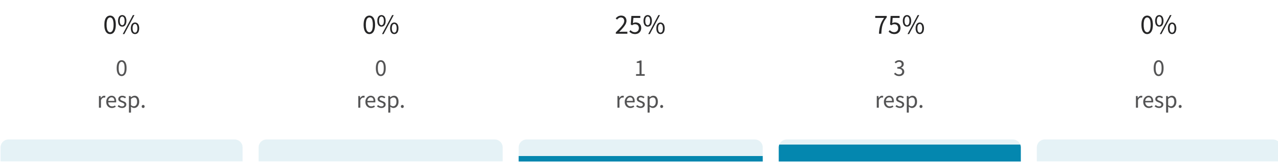
3.8 Average rating

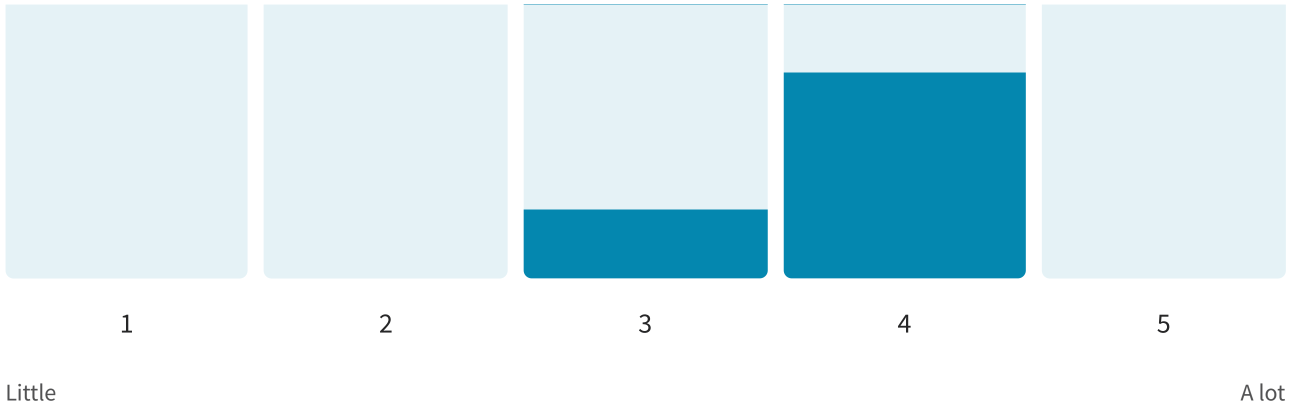


How likely is it that you would use LAAOVis to analyze the differences between different device configurations when choosing an optimal device for LAAO?

4 out of 4 answered

3.8 Average rating





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