To investigate the applicability of streak visualization for blood-flow visualization a user study was conducted. Both streak and path visualization are intended to visualize flow over time, and, therefore, we compare the effectiveness of both methods for identifying time-varying flow features. That is, we evaluate the effectiveness of using streak visualization in comparison with path visualization to identify vortices. To this end, the users were asked to count the number of vortices in synthetically generated data. Note that this evaluation focuses on whether the users perceive the vortices using path and streak visualization, not whether they are able to extract all of them. For the automatic extraction and highlighting of vortices in uncertain flow data automated methods exist and could be used instead.

Vortex recognition is a non-trivial task, especially in medical flow analysis, e.g., the number of vortices and their temporal behaviour can be used to classify aneurysms and assess the risk of rupture. The counting of vortices requires users to see when vortices form and when they breakdown (disappear), thus the users have to determine whether a vortex is a newly formed vortex or a pre-existing one.

In order to obtain temporally changing flow data with a known number of vortices, a mathematically defined flow is used. We generated a base laminar flow in a tube with a parabolic velocity profile, i.e., the speed increases parabolically depending on the distance to the wall of the tube. A fixed number of vortices where superimposed onto this flow throughout the spatial and temporal domain. For each vortex, the location of its core and the phase in which it forms were randomized within a range that ensured the vortex is visualized.

Since the temporal component is crucial here, only path and streak visualization were used. The streak visualization was animated over time, while the path visualization consisted of 10 stills spread out through the temporal domain. The users were presented with 6 flow visualizations in total and had to answer how many vortices they have counted (1 to 10) and how certain they were of their answer using a Likert scale from 1 to 7. To avoid the learning effect, the order, number of vortices and type of visualizations were randomized. At the end of the study the users where asked which visualization type they liked best for this task, again using a 1-to-7 Likert scale.

The user study was conducted with 24 participants with various backgrounds: 18 visualization/computer graphics researchers, 4 medical students/doctors and 2 cardiovascular PC-MRI researchers. Note that, all medical students were in the last phase of their studies.

The figure below shows the outcome of the user study, showing both the average and median. The users were asked how uncertain they were of their answers and is mapped to the y-axis (range 0 to 1). The x-axis shows how much the answer of the participant deviated from the actual number of vortices. When asked which visualization type they like best for this task, all users showed a preference for the streak visualization with a score of six or higher out of seven. Using the streak visualization, the answers deviated less from the actual number of vortices. Furthermore, the users were generally more certain of their answers using the streak visualization. For both visualizations the users seem to rather underestimate the number of vortices.

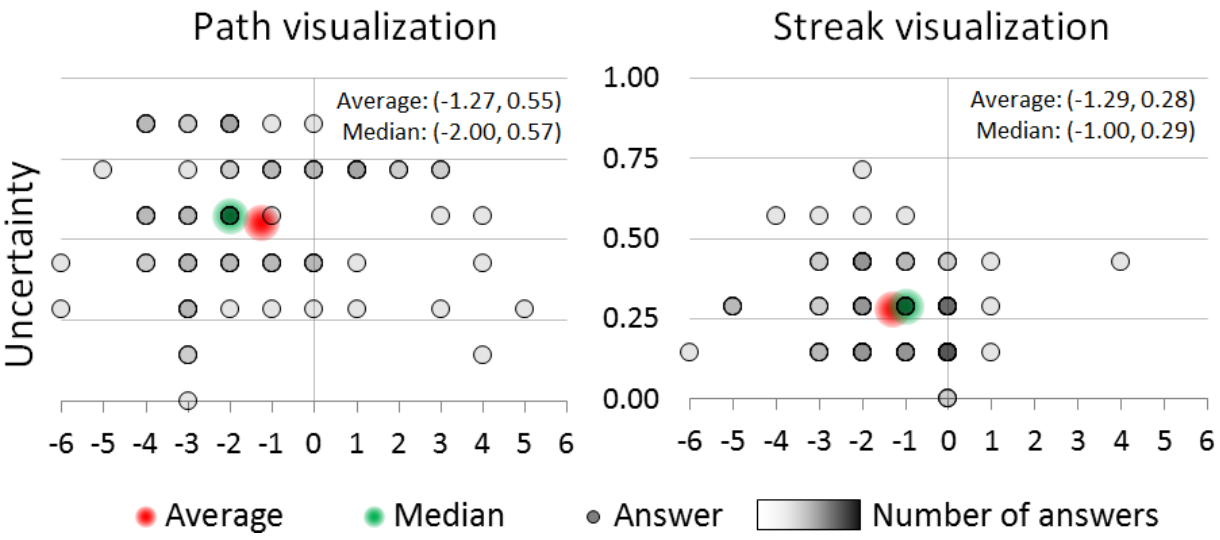

Figure 1 The answers of the user study for both the path and streak visualization. The y-axis represents the users uncertainty of their answer i.e. a lower value means the user is more certain, the x-axis shows the deviation from the true answer. The red and green dot represent, respectively, the average and median deviation and uncertainty. If more answers fall in the same position the point is rendered darker.

The figure below shows a histogram of the actual deviation from the number of vortices per visualization type. It shows that the number of correct answers is higher for the streak visualization.

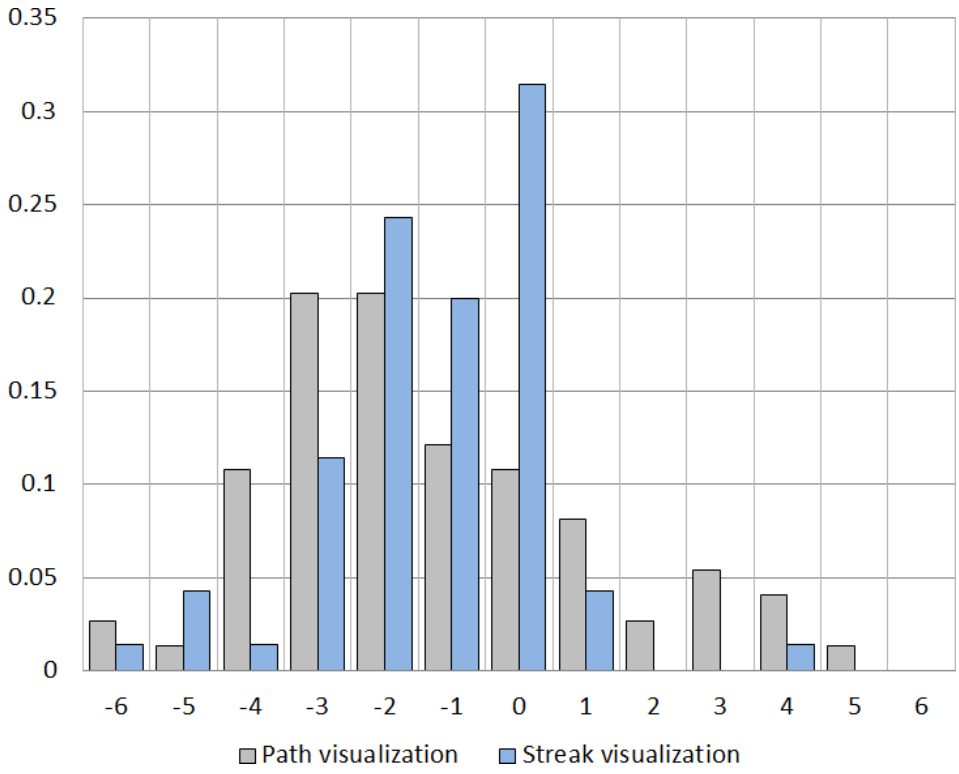

Figure 2 A histogram of the deviation from the actual number of vortices as counted by the users using path (grey) and streak (blue) visualization. Normalized with the total number of answers per visualization type.

While path visualization is often used in flow visualization, recognition of vortices is difficult. The study suggest that the use of streak visualization can be beneficial for this task and to identify similar flow patterns, and thus justifies the use of streak visualization in blood-flow visualization.