Eurographics Conference on Visualization (EuroVis) 2026
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(Guest Editors)

COMPUTER GRAPHICS *forum*
Volume 45 (*2026*), *Number 3*

APPENDIX – Tubes or Ribbons? Comparing Texture-space Visualization for Multivariate Line Data

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In this appendix, we provide additional data from our results that did not fit in the main paper. Namely, we report (1) detailed statistical analysis of subjective and objective measures, (2) more notable quotes from the semi-structured interview regarding participants' preferences and strategies that constitute actionable feedback, and (3) a more detailed description of the rendering pipeline.

Objective measures were task performance metrics: completion *task time* and the cumulative counts of each camera interaction type (*orbiting* in degrees, *panning* as a percentage of the screen width, and *zooming* as a percentage of the distance to the orbital focus). Subjective measures included between-task 7-point Likert ratings for the four statements on task difficulty (*difficult*), visualization complexity (*complex*), *ease* of interpretation of visualization, and satisfaction with visualization (*satisfying*). For the subjective measures, scores for the two negatively worded items (difficult and complex) were inverted (indicated with (i)) so that higher scores consistently indicate better outcomes. For all repeated-measures ANOVAs reported below, we applied Greenhouse–Geisser corrections when Mauchly's test indicated a violation of the sphericity assumption. In the following, while the statistical analyses are presented in tables, we also describe in text the main effects of tasks that were omitted from the main paper, as their discussion lies beyond the primary scope of this work.

In summary, this appendix contains the following contents:

1. Full statistical results

Table 1: *Repeated-measures ANOVA results for all subjective measures using the combination of line primitives and tasks.*

	difficult (i)				complex (i)			
Effect	df_e, df_{err}	F	p	η_p^2	df_e, df_{err}	F	p	η_p^2
Line primitive	1, 9	0.826	.387	0.084	1, 9	0.512	.492	0.054
Task	3, 27	2.988	.049	0.249	1.36, 12.244	0.930	.385	0.094
Line primitive × Task	3, 27	2.918	.052	0.245	3, 27	5.695	.004	0.388
	easy				satisfying			
Line primitive	1, 9	3.716	.086	0.292	1, 9	0.804	.393	0.082
Task	3, 27	2.022	.134	0.183	3, 27	0.375	.772	0.040
Line primitive × Task	3, 27	2.948	.051	0.247	1.575, 14.178	0.725	.470	0.075

A statistically significant main effect of the tasks was found for the statement "The task was difficult to complete," F(3, 27) = 2.988, p = 0.049, η_p^2 = 0.249. Pairwise comparisons using paired-sample t-tests with Bonferroni correction indicated a statistically significant difference only between tasks A and D, t(9) = 4.221, p = 0.013, Cohen's d = 0.756. Task A (M = 5.3, SD = 1.59) was perceived as less difficult than task D (M = 3.9, SD = 1.95).

Table 2: *Repeated-measures ANOVA results for all objective measures using the combination of line primitives and tasks.*

	orbiting				panning			
Effect	df_e, df_{err}	F	p	η_p^2	df_e, df_{err}	F	p	η_p^2
Line primitive	1, 9	0.201	.664	0.022	1, 9	0.814	.391	0.083
Task	1.754, 15.782	7.630	.006	0.459	1.319, 11.873	6.033	.024	0.401
Line primitive × Task	1,761, 15.853	0.582	.549	0.061	1.482, 13.340	0.825	.426	0.084
	zooming				task time			
Line primitive	1, 9	0.125	.732	0.014	1, 9	0.244	.633	0.026
Task	1.639, 14.749	7.012	.010	0.438	3, 27	12.860	$< .001$	0.588
Line primitive × Task	1.699, 15.292	0.030	.954	0.003	1.37, 12.33	0.349	.633	0.037

For the objective measurements, we observed statistically significant main effects of the tasks for all metrics: orbiting, panning, zooming, and time, with F(1.754, 15.782) = 7.63, p = 0.006, η_p^2 = 0.459; F(1.319, 11.873) = 6.033, p = 0.024, η_p^2 = 0.401; F(1.639, 14.749) = 7.012, p = 0.01, η_p^2 = 0.438; and F(3, 27) = 12.86, p < 0.001, η_p^2 = 0.588, respectively. Pairwise comparisons using paired-sample t-tests with Bonferroni correction revealed no statistically significant differences for orbiting and panning (all p > 0.5). However, we found significant differences for zooming between tasks A and D, t(9) = -3.59, p = 0.035, Cohen's d = -0.74, and between B and D, t(9) = -3.441, p = 0.044, Cohen's d = -1.029. For task time, significant differences were observed between A and D, t(9) = -3.448, p = 0.044, Cohen's d = -1.053, and between B and D, t(9) = -5.271, p = 0.003, Cohen's d = -1.629. Task D (M = 1303.95 %, SD = 1376) resulted in more zooming than tasks B (M = 406.5 %, SD = 373.35) and A (M = 659.1 %, SD = 661.3). Similarly, completion time was higher for task D (M = 69.9 s, SD = 53.131) compared to tasks A (M = 37.12 s, SD = 23.9) and B (M = 19.19 s, SD = 9.385).

Table 3: *Repeated-measures ANOVA results for all subjective and objective measures to assess the spatial nature of tasks.*

	difficult (i)			complex (i)		
Effect	$F(1,9)$	p	η_p^2	$F(1,9)$	p	η_p^2
Line primitive	0.826	.387	0.084	0.512	.492	0.054
Task	1.053	.332	0.105	2.359	.159	0.208
Line primitive × Task	5.121	.050	0.363	5.192	.049	0.366
	easy			satisfying		
Line primitive	3.716	.086	0.292	0.804	.393	0.082
Task	4.314	.068	0.324	0.167	.693	0.018
Line primitive × Task	1.058	.331	0.105	1.227	.297	0.120
	orbiting			panning		
Effect	$F(1,9)$	p	η_p^2	$F(1,9)$	p	η_p^2
Line primitive	0.201	.664	0.022	0.814	.391	0.083
Task	10.348	.011	0.535	9.293	.014	0.508
Line primitive × Task	0.724	.417	0.074	1.878	.204	0.173
	zooming			task time		
Line primitive	0.125	.732	0.014	0.244	.633	0.026
Task	5.078	.051	0.361	19.258	.002	0.682
Line primitive × Task	0.041	.845	0.004	1.046	.333	0.104

For objective measures, there was a main effect of task on orbiting (F(1, 9) = 10.35, p = 0.011, η_p^2 = 0.535), panning (F(1, 9) = 9.29, p = 0.014, η_p^2 = 0.508), and task completion time (F(1, 9) = 19.26, p = 0.02, η_p^2 = 0.682). Pairwise comparisons indicated that spatial tasks required more orbiting (M = 344.58°, SD = 437.05) and panning (M = 245.89%, SD = 210.85) than non-spatial tasks (M = 82.71°, SD = 123.20 for orbiting; M = 95.04%, SD = 132.20 for panning). Thus, participants took longer to complete spatial tasks (M = 53.51 s, SD = 29.23) than non-spatial tasks (M = 25.22 s, SD = 9.73).

2. Notable interview quotes

Table 4: *Overview of notable statements from the semi-structured interviews regarding subjective preference for view-aligned ribbons or tubes with with embedded visualization.* ***P***n *refers to the* n*-th participant according to their assigned sequential number.*

	Ribbons	Tubes
User preference	1 (of 10)	6 (of 10)
Reasons given	*Color perception*: **P1** – "I like that for the ribbons, there is just one level of brightness, it looks flatter."	*Color perception*: **P4** – "From far away, I think it's easier to observe the color for the tube." *Structural perception*: **P3** – "I just get a better sense of depth from the tubes." **P8** – "To me, the sense of depth from the shading that the tubes have is just really helpful." **P9** – "The ambient occlusion effect is more visible on them, they convey space better" *Bundle occlusion*: **P2** – "If they're super close, it's much less distracting with tubes, less occlusion" **P8** – "Especially here, where lines are close by, it just looks more clear." *Geometric consistency*: **P9** – "I find it visually easier to digest when the tubes are static and only the visualization moves around the surface." **P10** – "I find it easier if you don't have to mentally undo their orientation, which here has no actual meaning."
Perceived detrimental impact	1 (of 10)	0 (of 10)
Reasons given	**P10** – "I always thought I'm not looking at them from a good direction [...] I felt I had to move 2, 3 more times to see things better with ribbons [...] Tubes were easier."	—

Table 5: *Overview of notable statements from the semi-structured interviews regarding user strategies and actionable feedback for visualization practitioners.* ***P*n** *refers to the* n*-th participant according to their assigned sequential number.*

Reported strategies	*Recognize characteristic color patterns when in overview*: **P4** – "I found color is the most important thing [...] then the grey line, it was easy to find." **P5** – "I mainly went after colors, like blue or red for angular velocity, or high vorticity which is neither blue nor red." **P6** – "I first checked whether something catches my eye, the yellow and red from the boxes and pluses popped out from afar." → highlights how **double-encoding with color** improves usefulness of embedded visualization when viewing from a distance, which in turn requires minimizing overlap of utilized colormaps.
(practical relevance limited)	*Re-assume overview position to identify more promising areas*: **P6** – "I went back out since you said all instances are somewhere in view from here." *Leverage domain knowledge*: **P1** – "Since I knew there is a pressure difference there, I looked there first." → embedded visualizations should not replace data filters
Visualization design feedback	*Filtering*: **4** (of 10) **participants** mentioned they would prefer to change visualization settings frequently to hide variables they deem unimportant at a given moment, rather than trying to maximize readability of as many simultaneous variables as possible everywhere: **P2** – "If I don't care for e.g. pressure, it would be nice if there was a quick toggle for that layer." **P4** – "For example you could mask this [layer] and only show this [other layer], or cycle through to hiding all other things." **P6** – "If I were to personally use this, I would probably configure 2 or 3 combinations to show which I would then switch between as needed." **P7** – "Everything here is occluding the line, and you won't be able to see it until you turn it [the other layers] off temporarily." *Focus+context*: **1** (of 10) **participants** highlighted the need for displaying context as embedded visualizations typically require zooming in: **P7** – "Your visualization now is very good for the focus, but you loose context a little bit [...] with a little 3d window you could still navigate the context and show where you are currently" *View alignment*: **2** (of 10) **participants** would prefer the ribbon orientation to be taken from the data instead: **P7** – "Every time I have to find the [+/-] shape and it takes me some time to think about [...] I would really prefer a more natural connection to the geometry" **P10** – "I would rather like consistent geometry that is completely related to the flow [...] this rotation is not in the data."
Interest in using embedded visualizations	**If available in tools they use** – 5 participants (**P1**, **P2**, **P5**, **P6**, **P7**) **Considering for own custom tools** – 3 participants (**P3**, **P8**, **P9**) (8 of 10) **No interest** – 2 participants (**P4**, **P10**)
Concrete interest in additional variables	**3 variables** – 2 participants (**P2**, **P6**) **4 variables** – 2 participants (**P5**, **P8**) **5 variables** – 1 participant (**P7**) (5 of 10)

3. Rendering – additional details

The overall rendering pipeline replicates the design proposed by Russig et al. [RGDG23] for rasterization hardware. The main design points are a deferred rendering process, with the primitive surfaces first being ray-cast to a *G-Buffer* in a geometry pass, and direct illumination, ambient occlusion and glyph drawing performed on visible fragments in the deferred pass. Rays are cast in the geometry pass by rasterizing conservative proxy quadrilaterals for each curve segment. Our improved ribbon raycaster can be plugged into the geometry pass, replacing the tube raycaster.

The flow through the pipeline is as follows:

- **Preprocessing**:
  1. Construct Hermite splines interpolating the streamline samples:
     – Store sequence of Hermite nodes as entries in a vertex buffer.
     – Construct index buffer linking pairs of Hermite nodes into Hermite curves, forming a "line list" made of index pairs. (line lists, as opposed to line strips, allow easy re-ordering of individual segments, e.g. for visibility sorting)
  2. Voxelize Hermite spline tubes with the selected radius to get a density field for ambient occlusion (our ribbon re-uses the density field obtained from the tubes, which yields convincing results)
  3. Compute arc-length parameterization of each spline such that glyphs can be placed equidistant with minimal distortion.
  4. For each embedded visualization layer:
     – Instantiate glyphs along each spline at equidistantly chosen positions, and store them in a contiguous buffer region per layer.
     – Construct glyph index ranges for each curve segment and layer that link it to the glyph sequence it overlaps with.
- **Rendering**:
  1. Dispatch geometry pass by drawing an indexed line list:
     Vertex shader: Apply modelview transformation to Hermite nodes.
     Geometry shader: Create proxy quadrilateral – surround the tube with a bounding box oriented towards the viewer, emitting only the vertices of the front face.
     Fragment shader: Cast ray and **test for intersection with the primitive**[← our ribbon raycaster hooks into the pipeline here]. Store hit data in G-Buffer: primitive base color, hit point and normal, surface *uv* coordinates, segment index.
  2. Dispatch deferred pass by drawing a full-screen quad:
     – Determine albedo by doing for each embedded visualization layer:
       ○ If glyph:
         ◇ Find glyph overlapping with fragment by binary searching the segment's glyph sequence.
         ◇ Determine glyph color and alpha by sampling the overlapping glyph.
       ○ If plot:
         ◇ Find plot control points bracketing fragment by binary searching the segment's control point sequence.
         ◇ Construct local plot by interpolating control points and determine plot color and alpha by sampling local plot.
       ○ Blend *over* (a) the color from the layer beneath if it exists, or (b) the base surface color from the G-Buffer.
     – Perform voxel cone tracing to determine the ambient lighting term.
     – Perform local lighting.

To ensure high image quality, we also anti-alias the rendered images. Since we are doing deferred rendering, this must be done through frame post-processing. For this, we employed temporal anti-aliasing [Kar14].

References

[Kar14] KARIS B.: High quality temporal anti-aliasing. *Advances in Real-Time Rendering for Games, SIGGRAPH Courses* (2014). 6

[RGDG23] RUSSIG B., GROSS D., DACHSELT R., GUMHOLD S.: On-Tube Attribute Visualization for Multivariate Trajectory Data. *IEEE Transactions on Visualization and Computer Graphics 29*, 1 (Jan. 2023), 1288–1298. doi:10.1109/TVCG.2022.3209400. 6