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Design principles for origin-destination flow maps

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ABSTRACT
Origin-destination flow maps are often difficult to read due to overlapping flows. Cartographers have developed design principles in manual cartography for origin-destination flow maps to reduce overlaps and increase readability. These design principles are identified and documented using a quantitative content analysis of 97 geographic origin-destination flow maps without branching or merging flows. The effectiveness of selected design principles is verified in a user study with 215 participants. Findings show that (a) curved flows are more effective than straight flows, (b) arrows indicate direction more effectively than tapered line widths, and (c) flows between nodes are more effective than flows between areas. These findings, combined with results from user studies in graph drawing, conclude that effective and efficient origin-destination flow maps should be designed according to the following design principles: overlaps between flows are minimized; symmetric flows are preferred to asymmetric flows; longer flows are curved more than shorter or peripheral flows; acute angles between crossing flows are avoided; sharp bends in flow lines are avoided; flows do not pass under unconnected nodes; flows are radially distributed around nodes; flow direction is indicated with arrowheads; and flow width is scaled with represented quantity.

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1. Introduction

Flow maps visualize movement using a static image and demonstrate not only which places have been affected by movement but also the direction and volume of movement. Design principles for flow maps are largely based on expert intuition and aesthetic considerations (Dent, Torguson, & Hodler, 2009; Imhof, 1972; Slocum, McMaster, Kessler, & Howard, 2009).

This article focuses on origin-destination flow maps. An origin-destination flow map shows flows between nodes or areas. The geometry of the flows is either unknown or not important for the visualization. We limit this research to non-branching origin-destination flow maps. Although there are no empirical user studies conducted by cartographers on which to base flow map design decisions, the graph drawing community has identified aesthetic criteria relevant to the creation of node-link diagrams (Gibson, Faith, & Vickers, 2013; Purchase, Pilcher, & Plimmer, 2012). Graph drawing research aims to develop methods for the two-dimensional representation of graphs. The challenge of representing a graph – a set of nodes connected by edges – is related to the problem of mapping origin-destination flows for two reasons. First, origin-destination flows form a graph; the starts and ends of flows are the nodes and the flows are the connecting edges. Second, in both graph drawings and origin-destination flow maps, the geometry of links does not need to be accurately represented, but should be adjusted for optimal readability. User studies in graph drawing have evaluated a multitude of design options, also known as aesthetic criteria, which are relevant for cartographic origin-destination flow maps. However, only some of the aesthetic criteria from graph drawing are applicable to flow maps because unlike node-link diagrams, the position of geographic nodes in flow maps typically cannot be adjusted.

As flow data become more available, there is a pressing need to systematically evaluate the effectiveness of design principles for flow maps. Computational flow mapping methods can then be developed based on scientific evidence rather than intuition.

To identify design principles for origin-destination flow maps, we conducted a quantitative content analysis of 97 maps with non-branching flows. A user study

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evaluated the effectiveness of several of the identified design principles. We compared (a) curved and straight flows, (b) arrows and tapered line widths to indicate direction, and (c) flows between nodes and flows between areas. From the user study, we recommend design principles for flow maps.

2. Related work

2.1. Cartographic design principles for flow maps

In cartography, design principles are applied to increase readability and aesthetics, reduce visual clutter, and minimize the odds of misunderstanding represented information. Design principles for flow maps are rarely discussed at length in cartographic literature. The exception is Dent et al. (2009), who recommend placing small flows over larger flows if they must overlap (implying that crossings and overlaps should be avoided), using arrows to indicate direction, visually balancing the distribution of flows, adapting map projections to direct attention, using width to show quantities, and scaling arrowheads proportionally to line width. Tobler (1987), in his seminal work on automated flow mapping, also prefers varying width to varying color for showing quantity. He reports that students prefer small flows stacked on top of large flows. Imhof (1972) suggests using multiple parallel lines or placing small icons along flow lines to show types, quantities, or velocities of movements. Szegö (1987) shows various seldom-used variations of flow map. Dent et al. (2009), Slocum et al. (2009), and Imhof (1972) mostly show maps with curved flows, but do not explicitly recommend using curved flow lines. We are not aware of any user study evaluating the effectiveness of the flow map design principles identified by these authors.

2.2. Aesthetic criteria for graph drawing

A series of studies empirically evaluate design principles in graph drawing – known as aesthetic criteria – by assessing users' task performance, preference, and behavior (Purchase, 2014). Developers apply aesthetic criteria to design algorithms and evaluate diagram layouts produced by a variety of algorithms (Von Landesberger et al., 2011). Some of the aesthetic criteria for graph drawing are relevant to flow mapping, but there are three reasons why applying them to origin-destination flow maps is difficult. (1) The position of nodes in origin-destination flow maps is fixed or possible movements of nodes are spatially restricted. (2) The sources and destinations of flows in maps are often areas, not nodes (as in node-link diagrams). (3) User studies in graph drawing commonly ask subjects to verify the existence or length of a path between two nodes or identify the shortest path between two nodes. These tasks are relevant for node-link diagrams, but flow maps are created to answer questions such as what is moving, how much is moving and where, or at which locations movements are particularly long, short, large, small, sparse, or dense.

In the literature review, we concentrate on studies in graph drawing that look at aesthetic criteria relevant to the design of origin-destination flow maps (i.e. nodes that are not movable). Other aesthetic criteria for graph drawing such as uniform edge length, even distribution of vertices, or placing important nodes at the top or center of the graph, or in symmetric arrangements, are not applicable for flow maps and are not discussed. We group the aesthetic criteria applied to graph drawing into three categories: edge geometry, arrangement of edges, and direction indication.

2.2.1. Edge geometry for graph drawing

Cartographers commonly use curves instead of straight lines in flow maps. However, there is no evidence from graph drawing that curved edges result in faster or more accurate interpretation than straight edges. Xu, Rooney, Passmore, Ham, and Nguyen (2012) evaluate the effect of curving edges in graphs. They compare reading node-link diagrams with straight edges, slightly curved edges, and heavily curved edges. Xu et al. find that straight edges result in shorter answer times and less reading errors than curved edges. It is important to note that all edges in their study have the same amount of curvature, that is, curvature is not adjusted for each individual edge to reduce overlap as a cartographer would do when creating a flow map. A visual inspection of sample graphs used in Xu et al.'s study reveals that graphs with increased curvature contain more visual clutter than corresponding graphs with straight edges, which may influence the participants' ability to interpret the graph in an accurate and timely manner. Lombardi graphs – graphs with circular arcs and perfect or near-perfect angular resolution – are evaluated in two user studies. Xu et al. (2012) find that Lombardi graphs are faster to read than graphs with random curvature, but not more accurate. Lombardi and straight lines are equal in error rate and response time. Helen C. Purchase, Hamer, Nöllenburg, and Kobourov (2013) find that study participants perform better with straight edges than with Lombardi graphs.

Findings regarding user preference for curved or straight edges are contradicting. Xu et al. (2012) find that study participants prefer straight edges to curved edges, but their study maps contain considerable visual clutter. This differs from Purchase et al. (2013) who find that circular Lombardi arcs are preferred to straight edges.

Some evidences show that reducing the number of sharp edge bends in graph drawing has a positive effect on readability (Purchase, Cohen, & James, 1995). This finding aligns with common cartographic practice, where lines are smoothly curved and the number of bends is minimized to improve legibility and clarity.

2.2.2. Arrangement of edges for graph drawing

Several studies find that reducing the number of edge crossings significantly decreases error rates and reading time in graph drawings (Huang, Hong, & Eades, 2006; Purchase et al., 1995; Ware, Purchase, Colpoys, & McGill, 2002). This is relevant for the design of cartographic flow maps because flow lines frequently overlap in information-dense flow maps.

Another finding from graph drawing relevant to flow map design is that edges crossing at acute angles have a negative impact on response time (Huang, Eades, & Hong, 2014; Huang, Hong, & Eades, 2008). However, minimizing the number of edge crossings is more important than maximizing crossing angles in node-link diagrams (Huang & Huang, 2010).

Increasing the angles between edges incident at one node is a commonly accepted aesthetic criteria in graph drawing, although there are contradicting studies evaluating its effectiveness. W. Huang (2007) finds a significant positive effect for increasing the angular resolution, while Purchase (1997) and Purchase et al. (1995) find no significant effect.

2.2.3. Direction indication for graph drawing

Although direction on flow maps is mainly indicated by arrowheads (see next section), studies evaluating different methods for indicating direction in node-link diagrams draw contradicting conclusions. Holten and van Wijk (2009) find that with edges of similar length, a common trait in graph drawings, tapered flow widths perform better than arrows to indicate direction. They recommend avoiding arrowheads whenever possible. Tapered width also outperforms hue and brightness gradients and is better at indicating direction than oriented curved edges. In a user study done with eye tracking, Netzel, Burch, and Weiskopf (2014) confirm that tapered width performs better than arrowheads. Repeated arrowheads and comet symbols did not perform as well in the study, but differences between the four visualization techniques are small.

Netzel et al. (2014) argue that tapered width is not effective for long paths, which are common in flow maps, because of the small gradient in width along long paths. They also find that participants prefer tapered width to arrows, comets, and equidistant arrows, respectively. It is important to note that in all studies, line widths do not vary to show different quantities. In geographic flow maps, however, line width is commonly varied to indicate quantity.

3. Identification and evaluation of design principles for origin-destination flow maps

3.1. Quantitative content analysis of existing flow maps

We conducted a quantitative content analysis of origin-destination flow maps to identify common characteristics and design principles. Quantitative content analysis, a common method in map analysis (Edsall, 2007; Kessler & Slocum, 2011; Muehlenhaus, 2011) allows for the comparative analysis of large samples of visual media using statistical methods (Riff, Lacy, & Fico, 2014, pp. 20–29).

The research question was: *Do the exemplar flow maps possess specific design traits?* We defined 35 variables (i.e. codes). Two researchers analyzed (coded) each variable in the 97 sample maps. All the maps in our analysis were static origin-destination flow maps without branching or merging flows.

The 35 variables encoded general map characteristics, such as year of publication, language, geographic area, type of data represented (transportation, economy, etc.), inclusion of a legend, level of data measurement (nominal, ordinal, ratio, or interval), content of the base map, etc. The following codes were specific to flow maps: type of flow origins and destinations (points, areas or other) and their cartographic representation (pictographic point symbol, proportional symbol, point, polygon), symmetry and curvature of flow lines, indication of flow direction (unidirectional, bidirectional, no direction), arrowhead style (wide, slim, decorative, internal on line), number of arrowheads, flow text labels, visual variable, geometric versus mimetic/pictorial lines, use of transparency, changes of line width, number of flow intersections, and angles between intersecting lines.

Once a preliminary set of codes was defined, Marston and Muehlenhaus separately coded the same 15 maps to verify the codes were unambiguous and to test consistency between the two coders. Differences between the two coders were discussed and some code definitions were improved. Marston then coded all 97 maps.

3.1.1. Sample set

Professional cartographers across the United States and Europe were invited through e-mail to provide flow maps that they considered well designed. Of the seven cartographers who provided maps, three worked in academia and two worked for major media outlets. We also collected flow maps from online and print media outlets, atlases, and an overview study by Parks (1987), who collected more than 700 flow maps from geography textbooks published between 1891 and 1984. As a matter of convenience we included 27 maps from Parks' survey that showed non-branching origin-destination flows in an attempt to counterbalance any possible trends in current cartographic design.

The following maps were not included in the content analysis:

- Maps with merging or branching flows
- Maps with flow lines following paths along geographic features, such as rivers or roads (called *traffic flow maps* by Dent et al. (2009)) or maps with flow lines restricted to certain areas (e.g. ocean shipping routes circumnavigating landmasses)
- Maps with symbols indicating orientation in flow fields (called *continuous flow maps* by Slocum et al. (2009))
- Maps with flows appearing as three-dimensional lines above a map or globe
- Maps with animated flows
- Maps produced with algorithmic methods to automate flow layout (e.g. maps produced with software described by Tobler (1987)). Note: Maps with flows arranged with interactive digital vector graphics editors were included.

The oldest map is from 1929. Of the 97 sample maps, 22 maps were created between 1929 and 1950, 16 maps between 1951 and 1975, 24 maps between 1976 and 2000, and 35 maps since 2001. Forty-nine maps were created before 1990 and 48 were created after 1990, when mapmaking with digital tools became common. All 21 maps created between 1962 and 1987 are from Parks (1987).

The majority of maps are in English (73%), while the remaining maps are in French (20%), German (5%), or other various languages (2%). Notable map sources and authors include Philippe Rekacewicz (Le Monde Diplomatique, 13 maps), Richard E. Harrison (4 maps), volume 11 of the Atlas de France (2000, 4 maps), and the New York Times (9 maps, all from 1947). Twenty-five maps were related to air traffic, of which nine were air route maps collected from recent inflight magazines.

Nearly half of the maps (40%) show quantitative flow data. In 93% of the maps, flows represent one variable (e.g. line width representing volume of material movement); in the remaining 7% of maps, flows represent two variables (e.g. line width representing volume and color representing type of material movement).

We aimed at collecting maps from different epochs, but did not aim at collecting a predefined percentage of quantitative and qualitative maps, or English and non-English maps. The results presented below are specific for our collection of maps, which was influenced by the selection of contacted cartographers and other arbitrary factors.

3.1.2. Quantitative content analysis results

For **visual variables**, we find that size (i.e. line width) is the predominant visual variable used to show different moving volumes: 90% of all quantitative maps vary line width, 7.5% place multiple parallel lines per flow, and 2.5% vary color to show quantities. Flow line width is constant per flow in every quantitative map and in 89% of all maps. The line width starts narrow and widens in 9% of all maps, and starts wide and narrows in 2% of all maps. Of the quantitative flow maps, 30% vary a second visual variable (7.5% vary texture and 22.5% vary color). For maps not showing quantitative flows, 66.7% do not vary any visual variables, 19% vary hue, 11% vary width, and 4% vary texture. Flow lines appear completely opaque in 89% of all maps, and have a transparency effect in 11% of all maps. Almost one-quarter (23%) of maps have labels (representing the flow value) on all flows or a selection of flows.

3.1.2.1. Line geometry. Flows are curved in 48% of all maps, straight in 27%, a mixture of curved and straight in 22%, and have straight lines with corners in 3% of all maps. Of the maps with curved flows, 77% show all flows with symmetric curves , 21% use a mixture of symmetric and asymmetric , and 2% use asymmetric curves exclusively.

3.1.2.2. Line arrangement. In 40% of all maps, flows do not intersect. Flows intersect at angles greater than 30° in 52% of all maps, and have intersection angles both larger and smaller than 30° in 8%. (We chose a threshold of 30° because Weidong Huang et al. (2014) found that response time in graph drawings exponentially increases for crossing angles smaller than 30°.) Three-quarters of maps (74.2%) show enumeration areas behind the flows. Of all maps, 74% show flows that start or end at point symbols , 38% show flow lines that do not start or end at point symbols, but inside an area, and 26% show flow lines that start or end outside an area or along the border of an area. Some maps use a combination of these techniques.

3.1.2.3. Direction indication.

Fifty percent of all maps indicate flow direction and arrowheads are used exclusively (100%) to indicate direction. Very few maps (3%) have two or three arrowheads per flow, and only 2% of all maps have arrowheads placed within the line, not at the end of the flow line.

3.1.3. Identified design principles for flow maps

From the quantitative content analysis, we identify the following design principles for the 97 flow maps in our sample set:

- Almost every quantitative flow map varies line width to show different quantities.
- Flows are often curved, but sharp bends in flow lines are avoided and symmetric curves are preferred.
- The number of intersections of flows is minimized.
- Larger intersection angles are favored to acute angles.
- All maps where flow direction is indicated use arrowheads.
- Tapered flow width to indicate direction, which was recently recommended for graph drawing, is not used.
- Arrowheads are rarely placed within lines because this method is difficult to apply to thin lines, which are common on quantitative flow maps.
- Unlike edges in graph diagrams, flows in maps can start and end at areas instead of nodes. Cartographers use this opportunity to declutter dense areas.

3.2. User study to evaluate flow map design principles

We conducted an online user study to evaluate some of the cartographic design principles for origin-destination flow maps identified in the content analysis. We also evaluated user preferences for design techniques. The purpose of this study is to guide authors of flow maps in their design decisions and direct the development of an automated method for creating flow maps (Stephen & Jenny, submitted).

3.2.1. User study goals

The user study had four goals. (1) Evaluate whether curved flows are more effective than straight flows. Although flows are commonly curved in cartography, this question has never been evaluated for flow maps. Results from graph drawing studies are inconclusive on the effectiveness of curved edges. (2) Evaluate whether direction is better communicated with arrowheads (used exclusively in the maps in the quantitative content analysis) or with tapered line widths (recommended for graph drawing). (3) Evaluate whether flows starting and ending in areas are more effective than flows starting and ending at nodes. (4) Evaluate user preference for these three design principles. We did not evaluate other flow map design principles identified in the content analysis because they had been confirmed by studies in graph drawing.

3.2.2. User study design

The online user study consisted of a 3-part survey. Part 1 tested user error rates and response times between different map designs. Part 2 tested user preferences between map designs. Part 3 collected participant demographics.

Part 1 had 18 questions. Each question contained a flow map. Participants were asked to report the number of flows (selecting a number from 0 to 12) of a specified class and/or direction that were connected to a specific location. An example of a typical question is, "How many flows of size 100–200 are flowing from place B?" The questions required participants to identify nodes and flows, and count flows. Identifying and counting are two simple yet fundamental tasks for answering more complex questions such as which locations have movements that are particularly long, short, large, small, sparse, or dense. We asked simpler questions because assessing more complex questions would have increased the complexity of the analysis considerably.

Maps were viewable for 30 s and then hidden; responses could be submitted after time expired. Each question had two versions; half of the participants answered the first version and the other half answered the second version. Each version showed the same map and question, but used a different design technique. Three questions tested curved flows against straight flows with a different map for each question. Three questions tested arrowheads against tapered flows for indicating direction with a different map for each question. Twelve questions (three different maps, four questions per map) tested flows starting and ending at nodes against starting and ending in areas.

The nine maps shown in the survey were modeled after existing flow maps to ensure they accurately simulated real-world examples. All flows were grouped into three or four classes and legends for flow classes were included. We used classed flows with a small number of classes to reduce the likelihood for participants to misinterpret the legend when interpolating flow widths. The maps varied in location, scale, and flow density. To reduce learning effect and ensure participants were exposed to every design technique, participants were randomly assigned one version of each question and answered one or two questions for each design technique.

Part 2 contained nine randomly ordered questions. Participants were shown two maps containing the same information, but with different design techniques, and were prompted to select the map they preferred. Three questions compared straight flows to curved flows, three compared arrowheads to tapered flows, and three compared flows moving to and from nodes to flows moving to and from areas. The maps in this section were the same maps from Part 1.

Participants were recruited through Amazon Mechanical Turk, a web-based crowdsourcing tool that allows participants to complete tasks for small payments. Participants were paid $1 USD for completing the survey and an additional $1 USD for quick and accurate responses. To address concerns that participants might submit responses without reading the questions, two questions were added to Part 1 asking participants to select a specified answer. Responses were rejected if they failed to answer both of these questions correctly. Responses were also rejected if a participant's answer to six or more questions was three or more away from the correct answer. This filters out responses where participants read the question, but did not look at the map. A minimum browser window width of 1000 pixels was enforced to ensure participants could see the full map images. Participants were only allowed to complete the survey once.

A total of 215 valid survey responses were collected, resulting in 99–109 responses to each version of each question in Part 1, and 215 responses to each preference question in Part 2. Of the 215 participants, 202 were from the United States, 10 are from India, 1 is from Sri Lanka, and 2 did not specify. There were 120 male and 95 female participants. All participants were 18 years or older and the average age was 37 years. Of the 215 participants, 111 participants had a bachelor's degree or higher and 106 participants did not have a bachelor's degree.

3.2.3. User study results

Questions are numbered 1–18. Results are presented below in tables for groups of related questions. We report effect sizes with confidence intervals rather than p-value statistics in response to increasing concerns about the use of null hypothesis significance testing (Cumming, 2014; Dragicevic, Chevalier, & Huot, 2014). Figure 1 shows differences in percent correct between two map styles. For example, the difference for question 1 is computed as follows: 79.3% correct answers for curved flows – 67.0% correct answers for straight flows = 12.3%. Figure 1 also show 95% confidence intervals for the bootstrapped differences.

3.2.3.1. Curved vs. straight lines.

The following questions were asked:

- Question 1 (for the maps Figure 2, top): "How many flows of size 0–100 are connected to place A?"
- Question 2 (for the maps in Figure 2, middle): "How many flows of any size are connected to place A?"
- Question 3 (for the maps in Figure 2, bottom): "How many flows of any size are connected to the point labeled Marseille (near the bottom of the map)?"

All three maps with curved flows had lower error rates than the maps with straight flows (Table 1, Figure 1). Results for question 1 showed an uncertain difference between curved flows with 79.3% correct and straight flows with 67.0% correct. Results for question 2 showed a likely difference between 89.9% correct for curved flows and 69.8% for straight flows. The difference

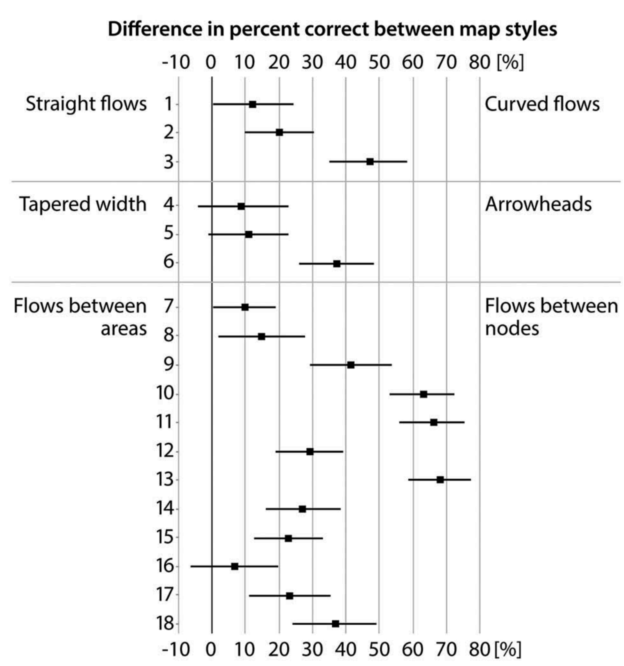

Figure 1. Differences in percent of answers correct and 95% bootstrap confidence intervals. Positive differences indicate more correct answers; this is the case for curved flows, arrowheads and flows between nodes.

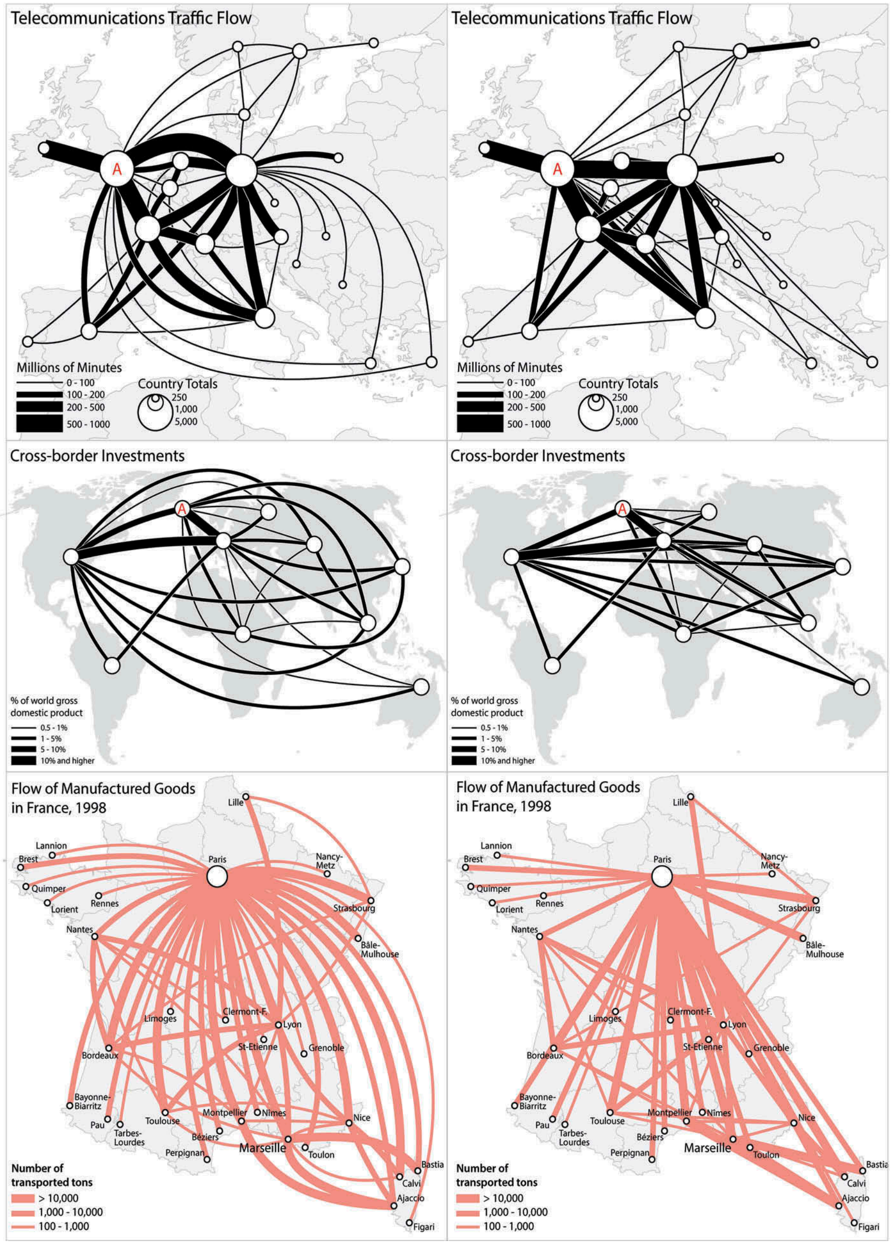

Figure 2. Maps with curved and straight flow lines for questions 1 (top) (modeled after Telegeography Inc. (2000)), 2 (middle), and 3 (bottom) (modeled after Atlas de France (2000)).

Table 1. Percent correct and median time for questions comparing straight and curved flows.

Question	Maps Figure 2	Curved: % correct	Straight: % correct	Curved: median time (s)	Straight: median time (s)
1	Top	79.3	67.0	14.9	15.6
2	Middle	89.9	69.8	12.5	13.7
3	Bottom	77.4	30.3	18.7	21.5

was large for question 3 with only 30.3% correct for straight flows and 77.4% correct for curved flows.

For all three questions curved flows had shorter median completion times than maps with straight flows (Table 1).

Questions 1 and 2 always labeled the same node with “A,” and question 3 always asked about the same node (Marseille) to simplify our study. Alternative studies could replace place A and Marseille with a selection of locations with more varied characteristics.

The percent correct for questions 2 and 3 concerning straight flows was adjusted for participant error. The straight-flows maps in these questions contained flow overlap that completely obscured two flows in question 2 (Figure 2, middle) and one flow in question 3 (Figure 2, bottom). Because the obscured flows were relevant for answering the questions, it was impossible to accurately count the flows. Responses with the correct number of flows were considered correct. Responses that undercounted up to two flows in question 2 and one flow in question 3 were also considered correct. Without this adjustment, the percent correct for the straight flows maps in questions 2 and 3 were 0% and 14.7%, respectively. These issues illustrate that it is often impossible to create unambiguous flow maps with straight lines.

The percent correct for the curved-flows map in question 3 was also adjusted to allow for undercounting one flow. This map contains a thin flow from Nantes to Marseilles that merges with a thick flow and is difficult to see. This particular flow line is poorly arranged because it is impossible to detect when focusing on a narrow area around the node of Marseille. Without the adjustment, the percent correct for curved flows in question 3 was 18.9%.

3.2.3.2. Arrows vs. tapered flows. The following questions were asked:

- Question 4 (for the maps in Figure 3, top): "How many flows of size 100–200 are flowing from place B?"
- Question 5 (for the maps in Figure 3, middle): "How many flows of size 10,000–50,000 are flowing from place A?"
- Question 6 (for the maps in Figure 3, bottom): "How many flows of size 2,000–4,000 are flowing to place A?"

Flows with arrowheads had modestly to clearly lower error rates than flows with tapered widths for all three questions (Table 2, Figure 1). Results for question 4 (51.4% correct for arrowheads and 42.5% correct for tapered widths) and question 5 (51.4% correct for arrowheads and 42.5% correct for tapered widths) did only show a modest difference. Results for question 6 (Figure 3, bottom) showed a clear difference with 51.4% correct for arrowheads and 14.2% correct for tapered widths.

Question 6 asked participants to identify the number of flows of a specific size flowing *to* a location, while questions 4 (Figure 3, top) and 5 (Figure 3, middle) asked about flows flowing *from* a location. The measured median time for answering question 6 with tapered lines was 29.9 s, which means that most participants reached the maximum viewing time of 30 s for this map. The considerably lower percent correct and long view time for question 6 with tapered flows suggests it is easier to read outgoing flows than incoming flows when using tapered line width. Question 6 used longer and thinner flow lines with only three classes, whereas questions 4 and 5 used four classes and thicker flow lines for all classes. It is unclear whether this difference influenced results.

Flows with arrowheads were faster to interpret for all three questions (Table 2).

3.2.3.3. Flows between areas vs. flows between nodes. We used three different maps and asked four questions per map (12 questions total) comparing flows between areas and flows between nodes. All questions (except for question 16) were: "How many flows of any size are flowing to/from place X?" X is replaced with A, B, C, or D (see the forth row in Figure 4). On each map, four nodes or four areas were labeled with A, B, C, and D (Figures 5–7).

All maps with flows starting and ending at nodes resulted in lower error rates and response times were shorter than maps with flows starting and ending in areas (Figure 4). The differences in percent correct indicate that participants tended to be better at counting flows with flows starting and ending at nodes than with flows starting and ending in areas (Figure 1).

Questions 7, 8, and 16 had relatively smaller differences in accuracy rate between design techniques (Figure 1). The maps in these questions had noticeably less visual clutter (fewer flows passing through the area and fewer intersecting flows nearby) around the area referenced in the question as well as a more compact polygon shape for the area in question. By visually inspecting the survey maps, we noticed that areas with one or more flows passing through the area (but not starting or ending in the area) increased error rates for flows between areas. This is the case for questions 9, 10, 11, 13, and 18, which had error ratios greater than two (error ratio = % correct for areas/% correct for nodes). For map pairs with a higher error ratio, the median response time ratios were higher (correlation coefficient $\rho = 0.81$) (Figure 4).

All questions asked for the number of flows to or from a given node, except question 16, which asked for the number of flows of a *certain class* starting at node or area A. Participants had considerable difficulty answering this question for both maps and the results did not show a clear difference between the two conditions. We speculate that participants answering incorrectly did not accurately read the question.

3.2.3.4. User preference. In Part 2 of the survey, we showed participants three map pairs with straight and curved flows, three map pairs with arrows and tapered lines, and three map pairs with flows moving between

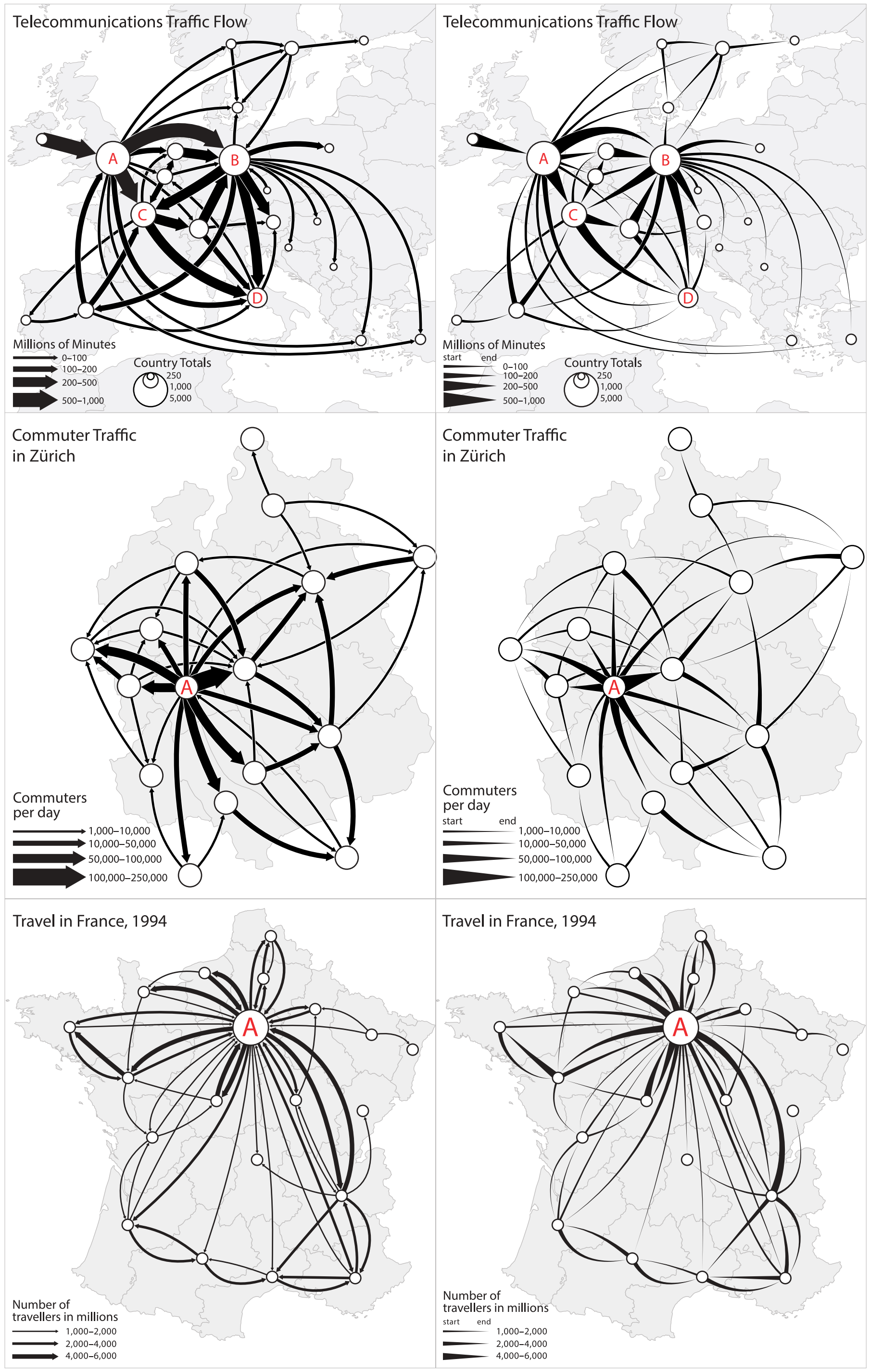

Figure 3. Maps with arrowheads and tapered lines for questions 4 (top), 5 (middle), and 6 (bottom).

Table 2. Percent correct and median time for questions comparing arrowheads and tapered lines.

Question	Maps Figure 3	Arrows: % correct	Tapered: % correct	Arrows: median time (s)	Tapered: median time (s)
4	Top	51.4	42.5	19.7	23.0
5	Middle	31.1	20.2	20.3	22.2
6	Bottom	51.4	14.2	22.7	29.9

nodes and areas. Participants selected the map they preferred. Participants clearly preferred curved to straight flows (with 73%, 77%, and 83% preference for each of the three questions, respectively), arrows to tapered flows (88%, 88%, and 92%), and flows moving between nodes instead of areas (80%, 80%, and 78%).

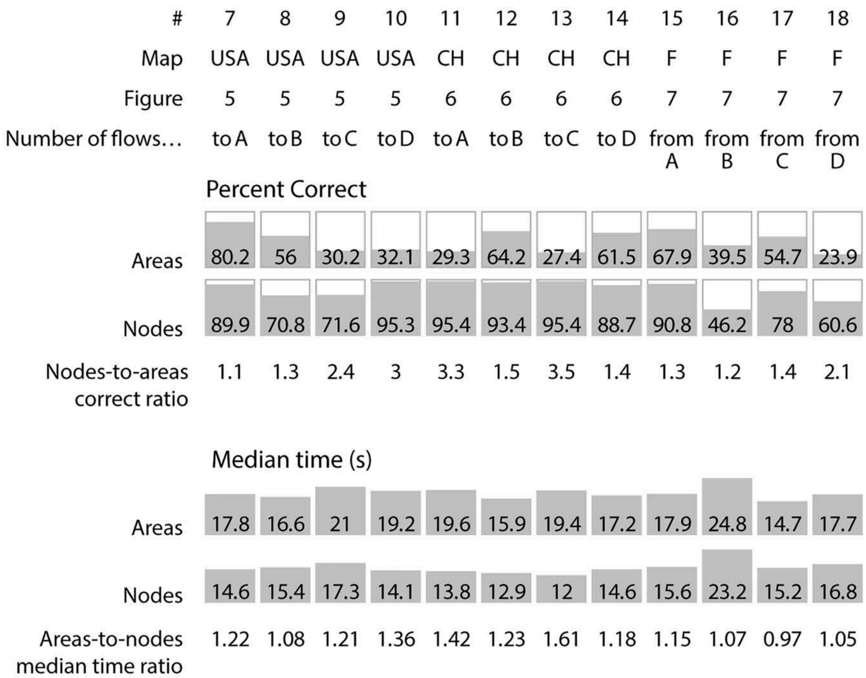

Figure 4. Percent correct and median time for questions comparing flows between areas and flows between nodes.

3.2.4. User study conclusions

Results of the user study were consistent with results of the quantitative content analysis. The design techniques evaluated in the user study that are most often employed by cartographers in the survey maps – curved flows, arrowheads to indicate direction, and flows moving between nodes – were preferred by survey participants and resulted in more accurate and faster interpretation when compared to straight flows, tapered flows, and flows between areas.

3.2.4.1. Curved vs. straight lines. The maps for our study (Figure 2) illustrate that it is often impossible to create unambiguous flow maps with straight lines. We found that curved flows performed better than straight flows and that participants preferred curved flows. Our results align with findings that people prefer curved contours (Bar & Neta, 2006; Silvia & Barona, 2008) and that people prefer circular arcs in graph drawing (Purchase et al., 2013). Results from our study differ from results for graph drawings by Xu et al. (2012), who found that straight edges outperform curved edges and straight lines are preferred. We speculate that the difference in our findings can be explained by the manual layout of our maps. We arranged flows so that overlaps between flows were minimized, flows did not intersect at acute angles, and flows used less curvature than flows in the study by Xu et al.

3.2.4.2. Arrows vs. tapered flows. Our results differ from those by Holten and van Wijk (2009) and Holten, Isenberg, Van Wijk, and Fekete (2011), who found that tapered line width performs better than arrows to indicate direction in graphs. In their studies, edges were all approximately the same length and width did not vary with quantity. In our geographic flow maps (Figure 3), where flow lengths could vary considerably and quantity was expressed by varying line width, tapered line widths were less effective. There are three reasons we believe this to be the case: (1) long flows have a considerably smaller gradient than short flows (as noted by Netzel et al. (2014)), resulting in different, potentially confusing gradients; (2) flows in quantitative maps and graphs can be relatively thin to show small quantities, resulting in a very weak gradient; and (3) the direction of incoming flows is difficult to determine with tapered line width. We also find that study participants preferred arrowheads to tapered flows. We advise against using tapered flow width for indicating direction on geographic flow maps with thin or long flows.

3.2.4.3. Flows between areas vs. flows between nodes. We found that flows between nodes instead of areas result in lower error rates. Study participants preferred flows between nodes. The quantitative content analysis revealed that almost two-thirds of all maps use flow lines that flow between areas or were not closely connected to a node. A closer inspection of the survey maps (Figures 5–7) indicated that error rates for flows between areas decreased when the shape of the area were compact (close to a circle) and flows were

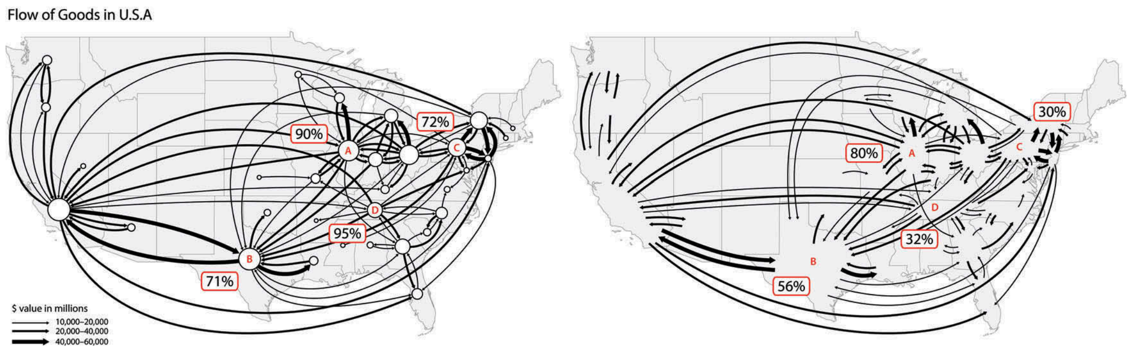

Figure 5. Map for questions 7–10 comparing flows between nodes (left) and areas (right). Percentages correct were added to the maps post-study.

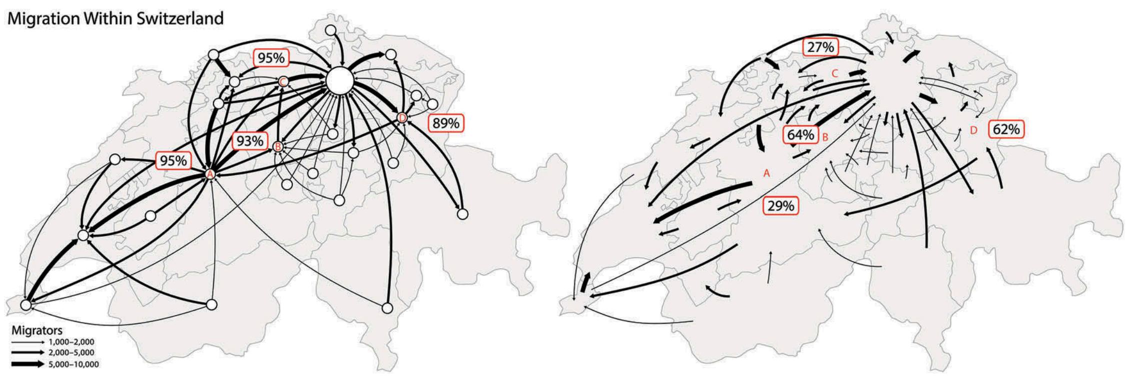

Figure 6. Map for questions 11–14 comparing flows between nodes (left) and areas (right). Percentages correct were added to the maps post-study. Map modeled after Atlas of Switzerland (1981).

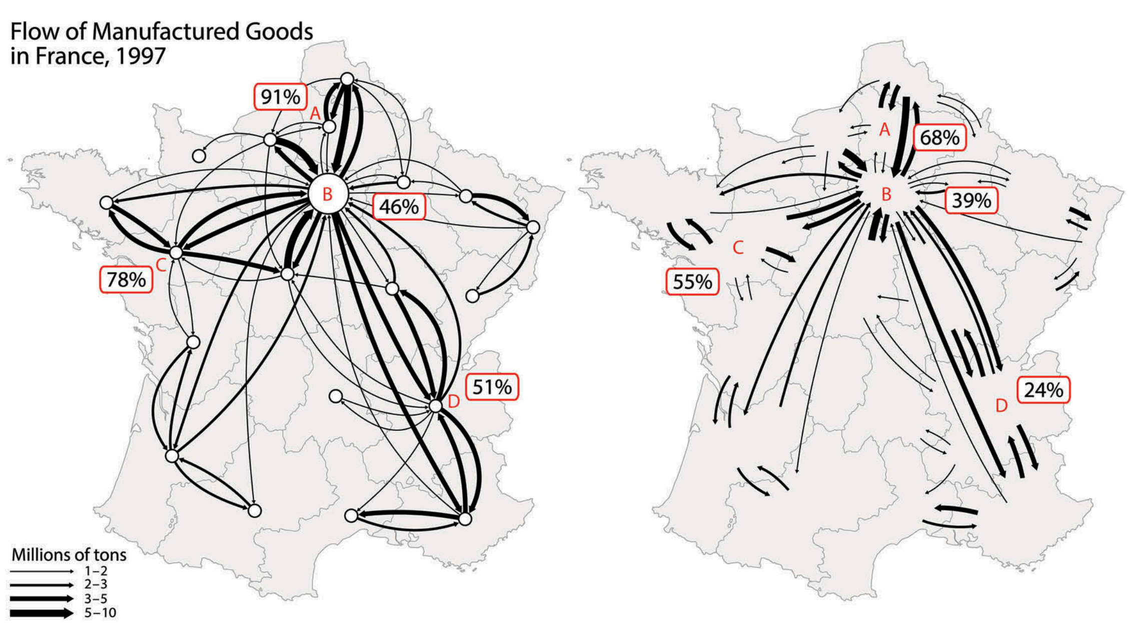

Figure 7. Map for questions 15–18 comparing flows between nodes (left) and areas (right). Percentages correct were added to the maps post-study. Map modeled after Atlas de France (2000).

radially arranged around the compact shape. Error rates for flows between areas increased when other flows passed through the origin or destination areas.

Despite these results, we do not suggest always arranging flows between nodes because it can be misleading in certain instances. For example, when flows between areas are represented as lines between nodes, readers could misinterpret the lines to indicate flows between cities instead of larger surrounding areas (e.g. multiple provinces). It is unclear under what circumstances this type of misinterpretation occurs. Based on visual inspection of complex flow maps in our content analysis, we assume that flows between areas can outperform flows between nodes when maps are information dense (i.e. a large number of flows or dense non-flow information) because flows between areas reduce visual clutter, such as flow-on-flow intersection and overlaps with other map features. Further research is needed to test these assumptions.

4. Design principles for origin-destination flow maps

The design principles discussed here are derived from various sources; several were identified in the quantitative content analysis and verified in the user study, others originate from user studies evaluating aesthetic criteria for graph drawing. These design principles aim to make flow maps unambiguous and efficient to read. We identify the following design principles for origin-destination flow maps without branching or merging flows.

4.1. Design principles for the geometry and arrangement of flow lines

The number of flow-on-flow and flow-on-node intersections and overlaps must be minimized (Huang et al., 2008; Purchase et al., 1995; Ware et al., 2002). Curving and geometrically arranging flow curves reduce overlaps and intersections (Figure 8(a)). Longer flows can be curved more than shorter or peripheral flows.[1]

Cartographers should avoid sharp bends in flow lines (Purchase et al., 1995), and prefer symmetric flows to asymmetric flows (Figure 8(b)). Asymmetric flows are permissible to avoid overlaps with other flows or nodes.

Acute angles between crossing flows must be avoided (Figure 8(c)) (Huang et al., 2008, 2014). Flows must not pass under unconnected nodes (Figure 8(d)) (Wong, Carpendale, & Greenberg, 2003).

A radial distribution avoiding narrow angles at nodes is preferable (Figure 8(e)) (Huang, 2007). Small flows are best placed on top of large flows, as suggested by Dent et al. (2009).

4.2. Design principles for the representation of flow quantity and direction

Quantity is best represented by scaled flow width (Dent et al., 2009). Varying color brightness can also show quantity, applying dark colors to larger values, and bright colors to smaller values (Figure 9). Varying brightness shows differing quantities, but we hypothesize that it could make flows easier to identify in dense areas when they are ordered by quantity (largest in the background and smallest in the foreground). A slight gradient in hue or saturation might also increase readability. A user study is required to evaluate this hypothesis.

Direction is best indicated with arrowheads. The size of arrowheads is adjusted to flow widths. The size of smaller arrows is increased to improve readability (Figure 10). Overlaps between arrowheads and flows should be avoided.

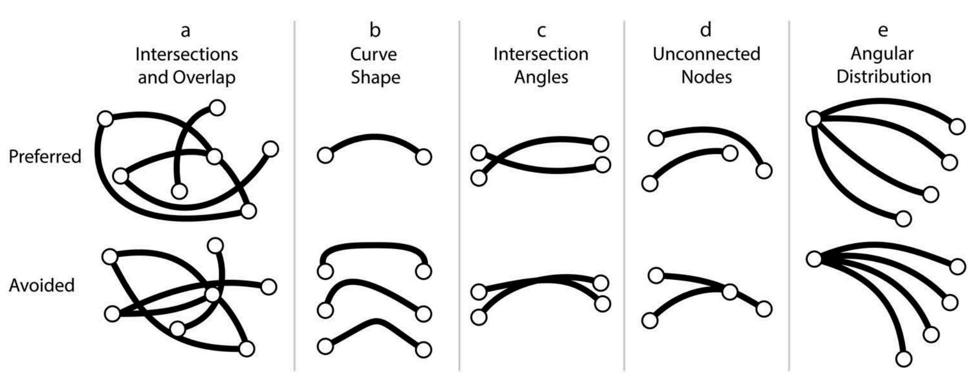

Figure 8. Design principles for flow maps: Preferred (top) and avoided (bottom) arrangements.

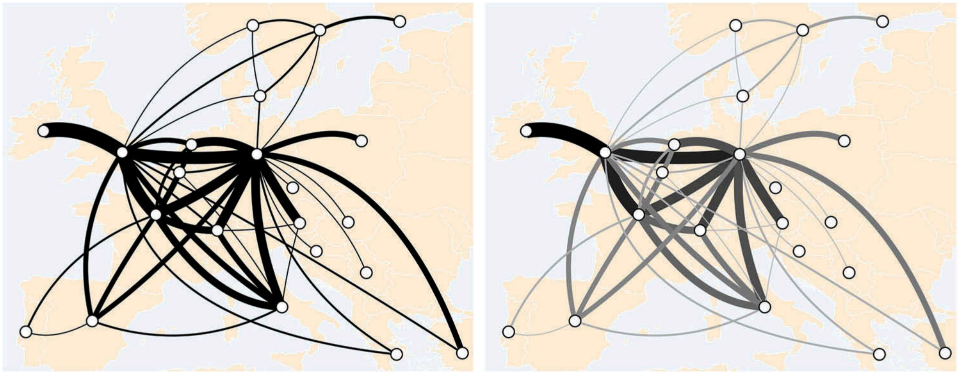

Figure 9. Quantities represented by width only (left) and width and brightness (right). Map after Telegeography Inc. (2000).

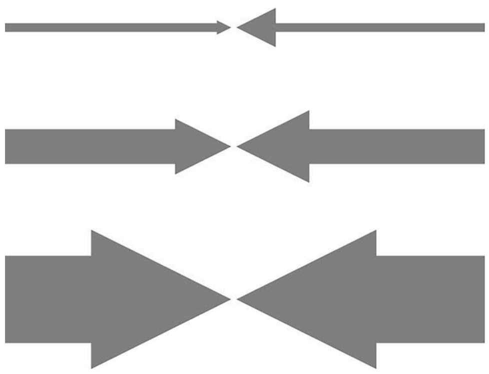

Figure 10. Size of arrowheads proportional to line width (left) and enlarged for thin flows to increase readability (right).

5. Conclusion

Information in flow maps is often dense and visual clutter is difficult to resolve because nodes can only be moved within small geographical limits. To create unambiguous and legible maps, flows often need to be curved. The quantitative content analysis, user study with geographic origin-destination flow maps, and previous studies in graph drawing resulted in a set of verified design principles for non-branching origin-destination flow maps. The design principles help cartographers increase the readability of maps. We identify the following design principles: number of flow overlaps should be minimized; sharp bends and excessively asymmetric flows should be avoided; acute intersection angles should be avoided; flows must not pass under unconnected nodes; flows should be radially arranged around nodes; quantity is best represented by scaled flow width; flow direction is best indicated with arrowheads; arrowheads should be scaled with flow width, but arrowheads for thin flows should be enlarged; and overlaps between arrowheads and flows should be avoided.

The user study showed that flows between nodes instead of areas result in lower error rates. However, we do not suggest always arranging flows between nodes because for some maps, it may not be clear whether the lines represent flows between nodes (e.g. cities) or areas (e.g. countries).

The presented design principles are applicable to static origin-destination flow maps with moderate amounts of flows. Additional research is required for improving the visualization of large and dense flow data sets.

Note

1. We observe that longer flows are curved more than shorter flows or peripheral flows on maps used for the quantitative content analysis, but have not analyzed the effectiveness with a user study.

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