3D Network Spatialization: Does It Add Depth to 2D Representations of Semantic Proximity?

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Abstract. Spatialized views use visuo-spatial metaphors to facilitate sense-making from complex non-spatial databases. Spatialization typically includes the projection of a high-dimensional (non-spatial) data space onto a lower dimensional display space for visual data exploration. In comparison to 2D spatialized displays, 3D displays could potentially convey more information, as they employ all three available spatial display dimensions. In this study, we evaluate if this advantage exists and whether it outweighs the added cognitive, perceptual, and technological costs of 3D displays. In a controlled human-subjects experiment, we investigated how viewers identify document similarity in 3D network spatializations that depict news articles as points connected by links. Our quantitative findings suggest that similarity ratings for 3D network displays are similar to those obtained in a prior 2D study we conducted. With both types of displays, viewers mostly judged document similarity on the basis of metric distances along network links, as opposed to node counts or distance across the network links. However, node counts do affect similarity assessments with 3D displays more than with 2D displays. We also find no significant differences in similarity judgments whether 3D displays are presented monoscopically or stereoscopically. We conclude that any advantage of 3D displays in conveying more information than 2D displays does not necessarily outweigh their additional demands on cognitive, perceptual, and technological resources.

1 Introduction

The exponential growth and availability of online relational text data (e.g., the Web 2.0, online journals, Facebook, Wikipedia, etc.) requires new methods to help people more efficiently select information and construct new knowledge from big text data sources [10]. Ongoing research in GIScience and information visualization has focused on how to effectively depict multivariate, typically non-numeric and non-spatial, data stored in very large databases by means of computational techniques that transform high-dimensional datasets into low-dimensional spatialized data displays [12]. The spatial arrangement of depicted information items in such displays is typically based on the distance-similarity metaphor [8], which states that closer items will be seen as more similar, and more similar items should therefore be placed closer to one another in the spatialized display. The resulting "information spaces" can be visualized in various ways, e.g., as two-dimensional (2D) or three-dimensional (3D) simple point maps, network maps, or continuous terrains [12].

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Along with the public's increased exposure to low-cost, immersive, stereoscopic 3D display technology (i.e., 3D gaming engines, TVs, and cinemas), there has been growing interest in the information visualization community in designing and using 3D spatializations that depict a corpus of documents in all three available spatial display dimensions [11]. However, it is still unclear how the distance-similarity metaphor will operate in 3D [6]. Few empirical evaluations have examined design guidelines for cognitively inspired and perceptually salient 3D information spatializations [16]. Researchers in information visualization claim that users should be able to extract more information from 3D displays than from 2D displays, as we live in a 3D world [21]. They also argue that less data is lost when high dimensional databases are reduced only to 3D rather than 2D. The 3D displays can supposedly reveal more information, as they contain an additional degree of freedom for display and interactive exploration [6]. For example, as Sedlmair et al. [11] suggest, a common argument for the use of 3D scatterplots is that the intrinsic dimensionality of a dataset is likely to be greater than two dimensions; so 3D displays are able to convey more information. However, researchers have also recognized that this additional supply of information may come with various costs, including perceptual issues (occlusion problems and size-estimation difficulties in perspective views) (e.g., [13]), cognitive demands (the need for direct interactivity and motion parallax to avoid the perceptual issues), and additional technological complexity (the requirement for fast 3D graphics cards and advanced 3D display technology) [6, 11, 14].

In our study, we investigate how users interpret monoscopic and stereoscopic 3D spatialized views and compare what we find to previous work with 2D displays [4]. We are interested in exploring whether the addition of a third display dimension outweighs the potential increased costs of constructing, displaying, interacting with, and interpreting 3D views. We systematically evaluate how different notions of distance might influence the operation of the distance-similarity metaphor in interactive 3D network spatializations.

2 Related Work

2.1 Prospects and Challenges of 3D Visualization

The need to develop 3D design guidelines has gained recognition within the visualization community [11], but we still lack a good understanding of how people perceive and interpret 3D displays [17, p. 259]. We include as 3D displays any graphic or image that appears to extend over three spatial dimensions, even though it is actually a 2D object (e.g., computer screen or piece of paper). We distinguish monocular from stereoscopic (binocular) displays. Monocular displays create the appearance of depth via monocular cues, i.e., features of the display that create depth even when viewed with a single eye [17, pp. 259–260]. These can be further distinguished as static monocular displays (using occlusion, size changes, linear perspective, etc.) or dynamic monocular displays (using movement, including motion parallax, as part of animated displays). Dynamic monocular displays can be further distinguished as interactive or not. In contrast, stereoscopic displays create the appearance of depth via so-called "true 3D," the experience of visual depth that results when the brain combines the offset images from the two eyes during binocular viewing of actual 3D objects or of specially created 2D images (i.e., created to present two offset images separately to each eye).

Of course, 2D information displays have been used for a long time, and respective design guidelines have evolved alongside by long-standing practice, for example, as employed for cartographic maps [1]. The question arises then whether common 2D cartographic design principles can be applied to 3D spatialized data displays, and if so, how? As Bertin [1] writes, a 2D network map is efficiently depicted when the nodes are connected to each other in a manner that minimizes the number of links that intersect or cross each other. Likewise, 3D networks can be depicted in similar fashion, but additional perceptual cues (i.e., graphic variables) are necessary to account for the visually more complex representational structures. Bertin [1] contends that the addition of a third dimension to monoscopic graphs can create a sense of volume, and he also suggested that network links should not cross each other. To depict monoscopic 3D network displays, Bertin suggests changing the thickness of the links according to viewing distance, producing the impression of depth via linear perspective. We are skeptical that this would work unless the network was fairly small and simple in structure. But as is true for Bertin's other design guidelines, those concerning 3D networks have mostly not been examined empirically to this day.

Herman et al. [7] contend that adding an extra dimension to displays can facilitate the depiction of large data structures but might make it difficult for users to find the most appropriate perspective and insightful view on the data space. A good example of this is shown in Figure 1. This monoscopic, static 3D display was created with specialized, state-of-the art 3D network software [20] by Dunne et al. [3] and was voted one of the best scientific visualizations of 2013 in Wired Science[1]. The 3D graph depicts the food web of Estero de Punta Banda trophic species, including its parasites and concomitant links. Green indicates basal taxa, red indicates free-living taxa, and blue indicates parasites. The vertical axis corresponds to short-weighted trophic levels [3]. Unfortunately, relationships between the red, blue, and green balls cannot be identified in this 3D network, due to massive over plotting and extensive crossing of the links. Partial and complete occlusion of the colored balls makes connection properties and distance estimation along the links impossible, due also to depth-perception issues.

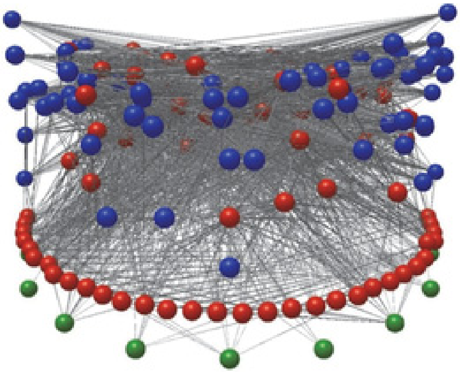

Fig. 1. The food web of Estero de Punta Banda trophic species (extract from Dunne et al., 2013)

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[1] On the Web at: `http://www.wired.com/wiredscience/2013/12/best-scientific-figures-2013/` (accessed Feb. 2014).

This graph might be improved by providing stereoscopic or interactive viewing capabilities. However, Ware [17] points to a list of possible problems with stereoscopic 3D displays, including stereo-blindness (even some people with two functional eyes do not experience stereopsis), diplopia (double vision), the frame cancellation problem, the vergence-focus problem, and stereopsis loss for distant objects; in fact, stereo vision only suggests depth for relatively close distances within about 10 meters. Furthermore, various optical illusions (e.g., the filled-space or Oppel-Kundt illusion, the vertical or vertical-horizontal illusion) have been identified that will modify perceived distances, even in monocular displays [2, 8, 9, 23].

A potential advantage of interactive dynamic 3D graphs is that viewers can find optimal views without intersecting links or occluding features [16]. Indeed, users can manipulate interactive dynamic displays until they find the best view with the least number of occlusions among the depicted features. Ware and Mitchell [19] found that adding 3D depth cues like those available in interactive dynamic displays increased the efficiency and accuracy with which viewers were able to explore very large 3D network displays as compared to non-interactive displays, including static 2D displays. Supplying such interactive 3D would involve additional development time for designers, and might place additional perceptual and cognitive demands on viewers, including those involved in display interaction. Thus, a major 3D spatialization challenge is employing appropriate 3D layout techniques to uncover the essence of buried data relationships, at the same time implementing additional visual cues and human-display interaction mechanisms to support the most effective and efficient human visuo-spatial exploration of the 3D data space.

2.2 Our Prior Spatialization Research

A variety of forms of distance or proximity might work best to convey item similarity in spatialized network displays, including the number of nodes or links between items, metric distance between items along links, or metric distance between items directly across the space within which the network is embedded. We have previously reported on various empirical studies investigating which type of proximity would most likely be intuitively understood by viewers to show the relatedness or semantic similarity between documents in very large databases displayed in 2D and 3D point spatializations, and in 2D network spatializations [4, 6, 8]. These studies also investigated how visual variables besides distance might influence the perception and understanding of the distance-similarity metaphor in spatializations. For example, links that connect nodes in network displays can vary in width, color hue, or color value [4], similar to the visual variables employed for networks such as highways shown on cartographic maps [1]. Another study highlighted how test instructions can influence the use of proximity to judge similarities between items in spatialized displays [5].

In a study on 3D point-display spatializations, we replicated our finding with 2D displays that viewers map judgments of document similarity onto distances between document points, as long as no apparent features such as clusters or lines emerge from sets of points [6]. We also found that variation among participants in their similarity judgments is noticeably larger with 3D than with 2D displays. With 3D displays, we specifically hypothesized that variation in the degree to which participants rotate the displays into the fronto-parallel plane might lead to variation in the apparent distances between assessed points, and thus variation in assessed similarities. "Fronto-parallel" orientation occurs when document points being compared all lie within the same display plane fronto-parallel (normal) to the line of sight. In this orientation, proximal distances (on the retina as well as on the monitor screen) between pairs of points are maximized.

3 Experiment

While many researchers and designers have great enthusiasm for 3D displays, no research we know of has clearly demonstrated their superiority. Based on our previous study with 3D point displays [6], we believe that adding the third dimension will actually detract somewhat from people's ability to see similarity relationships in spatialized displays. This is because people map document similarity onto inter-point distance, as we have shown in earlier work on 2D displays. In order to see distance most clearly, we hypothesize that participants will rotate the 3D displays until all three comparison points are brought into the fronto-parallel plane. This process takes extra time and may not be carried out optimally by all participants or even carried out at all. We thus designed a mixed-factorial experiment to assess the effectiveness of 3D network-spatializations representing documents collected in a very large text document database. Our study design is based on our previous study of 2D network spatializations [4], allowing direct comparison to the results of that study. We investigate how users interpret the distance-similarity metaphor in 3D node-link displays depicting conflicting notions of distance, specifically network metric distance vs. topological proximity (see Fig. 2 for an example stimulus).

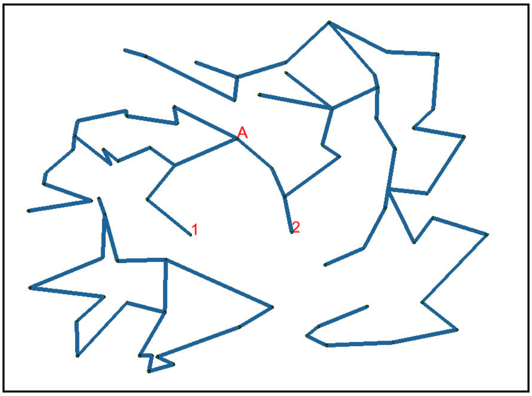


Fig. 2. Example 3D stimulus varying the visual variables of network metric distance and topological node proximity (node count) between assessed entities 1 and 2, with respect to reference entity A.. A is closer to 2 than to 1 in metric distance along the network but equally close in terms of node proximity.

3.1 Methods

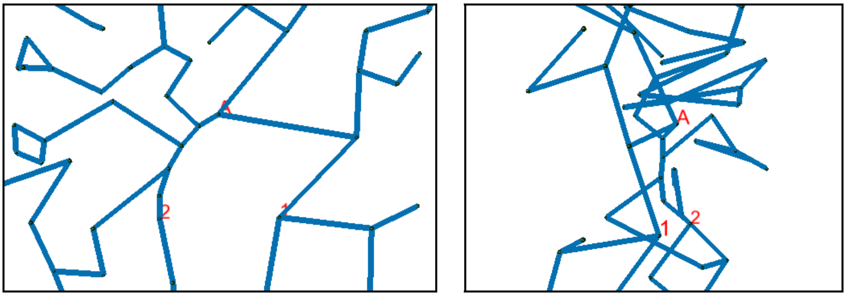
Participants. Twenty-eight participants (14 females and 14 males) took part in the experiment, with an average age of 29 yrs. One participant indicated a lack of depth perception, but none claimed to have a color deficiency. Fourteen participants were undergraduate students with geography and other majors, and the other fourteen were not affiliated with a university. We tried to recruit mostly participants with little previous professional experience, training, or college degrees in GIS, cartography, computer graphics or graphic design, to minimize a potential bias due to user background and training. The majority of the recruited participants (19) had less than one year of training in the above-mentioned academic fields, but 7 had between one and five years, and two had more than five years of training in these fields.

Set-up and Materials. The 3D network spatializations were visualized using a Cyviz Geowall, consisting of a Windows PC with a dual-output graphics card, two aligned digital overhead projectors, a back-lit projection screen (2.23 m x 1.80 m), and a pair of polarized glasses for stereoscopic viewing. Participants sat facing the screen at a distance of 2.20 m.

Sixty-five 3D network-displays were created using Vizard 3.0, a Python-based software designed to produce interactive 3D graphics and virtual worlds. The displays consisted of nodes (points) that supposedly represented documents, connected by straight links. Three nodes were distinctly labeled as ‘A,’ ‘1,’ and ‘2.’ In order to empirically evaluate the way network displays are viewed and interpreted under various conditions, we had participants specifically compare the apparent semantic similarity between documents ‘A’ and ‘1’ to that between documents ‘A’ and ‘2.’ The network stimuli were modeled after our earlier study of static 2D spatialized network displays [4]. We thus replicated the 2D configurations and x- and y-coordinates of the nodes from this 2D study but added random z-coordinates to nodes. Compared to the prior 2D study, participants in this 3D study could actively control the rotation of the displays. We randomized the initial orientation of each 3D network upon first being viewed by participants so that it was not in the fronto-parallel (FP) orientation (Figure 3). Participants thus had to rotate the displays if they wanted to get them into FP orientation. When the displays were rotated to FP orientation, the comparison points were maximally distant from each other on the 2D image and at the same viewing distance from the participant. The resulting 2D views matched the displays from our earlier 2D study.

We divided the stimuli into a sequence of four blocks, where the links connecting the nodes were depicted varying a combination of network distance and node proximity, as well as link hue, value, and width; in the present report, we focus only on network distance and node proximity, as we expect those variables to be most sensitive to displaying in 2D vs. 3D. Unlike our previous 2D study, we kept the direct distances between points across the network (i.e., not along network links) constant in this 3D study. In 15 of the trials, we systematically varied metric distance along the network links so that A:2 was equal in length to A:1, twice as far apart, or three times as far apart (in two additional trials we omit below, we varied network distance so that A:2 was either 1.5 or 2.5 times as far apart as A:1, but only for displays that equated node proximity). At the same time, these 15 trials varied node proximity so that A:1 and A:2 were equally far apart (two nodes each), A:1 was three nodes apart while A:2 was two nodes, A:1 was two nodes apart while A:2 was one node, A:1 was three nodes apart while A:2 was one node, or A:1 was four nodes apart while A:2 was one node.

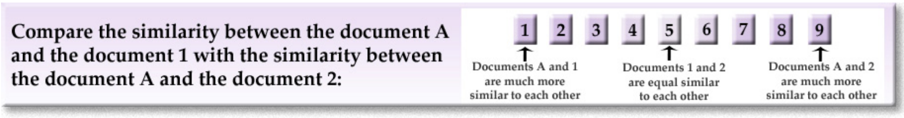
In order to control for a biasing effect due to the horizontal-vertical and filled-interval illusions, we systematically controlled the arrangement of the comparison points A, 1, and 2 along the x and y-axes, but used equal z-coordinates. As the main dependent variable, we recorded participants' similarity ratings of the two pairs of comparison nodes, the viewing angles every 0.016s, as well as the viewing time between each display rotation. We also recorded background questionnaire responses and participants' display preferences for a qualitative analysis.



(a) fronto parallel plane view (b) random starting configuration

Fig. 3. Example 3D stimulus with two different 3D views

Procedure. Participants were randomly divided into two viewing groups: monoscopic mode (only one projector was switched on, without polarized glasses) and stereoscopic mode (two projectors were switched on, with polarized glasses). Participants were individually tested in a session that lasted approximately 45 minutes. After welcoming participants, the Geowall environment was explained and participants signed a consent form. They were then seated in front of the screen and asked to fill out a background questionnaire. They were told that 3D images would appear on the screen and that they would have to interact with the images before answering a test question, using a mouse to input their answer. Subsequent instructions were delivered from slides appearing on the screen. Participants read that they would view 3D-network displays representing information from a database containing documents such as, books, new stories, or journal articles, depicted as black dots. For each display, participants were to judge the similarity of a reference document labeled 'A' with that of two other documents, labeled '1' and '2.' They compared the similarity of these two pairs of documents with the response scale shown in Figure 4, but they were not given any instructions or advice as to how to judge similarity between the documents. Ratings were collected on a 9-point interval scale, with a value of '1' representing "A and 1 much more similar", a value of '9' representing "A and 2 much more similar", and a value of '5' in the middle representing "1 and 2 equally similar to A". Hence, a mean rating less than 5 indicates that participants saw A:1 as more similar, while a mean rating greater than 5 indicates they saw A:2 as more similar.



Compare the similarity between the document A and the document 1 with the similarity between the document A and the document 2:

Documents A and 1 are much more similar to each other

Documents 1 and 2 are equal similar to each other

Documents A and 2 are much more similar to each other

Fig. 4. Response scale used for each test stimulus

Participants viewed thirteen practice trials, where they had the possibility to get acquainted with the test environment, how to respond, and how to rotate the 3D dynamic displays. This was followed by sixty-five trials divided into four blocks for which we recorded participants' similarity judgments and display interactions. Within a block, displays were shown in randomized sequences to avoid potential learning effects. After completing the 3D display portion of the experiment, participants were asked to fill in a post-test questionnaire in order to better understand how they believed they had assessed the similarities of the documents for each kind of display. After completing the test, they were given a meal voucher for the university cafeteria to thank them for participation.

4 Results

4.1 Similarity Ratings

The mean similarity ratings for the 15 trials that contrasted network distance and node proximity are presented in Table 1. The pattern of means suggests that when documents are equal in node proximity and equal in network metric distance, participants rate them equally similar to each other (i.e., average similarity rating does not significantly differ from 5.0), replicating the results from Fabrikant et al.'s [4] 2D study. Also consistent with results from the 2D study, we find that in 3D participants rate documents to be more similar when they are relatively closer in network metric distance. However, unlike our prior 2D study, adding relatively more nodes between documents seems to make them appear less similar, over and above any effects of network distance. When node proximity and network distance conflict, similarity tends to cancel out and earn ratings near 5, similarly to the 2D study results.

Table 1. Mean similarity ratings of the 15 displays varying network metric and node proximity between A:2 and A:1. A mean rating less than 5 indicates that participants saw A:1 as more similar, while a mean rating greater than 5 indicates they saw A:2 as more similar.

		Network metric distance		
		A:1 = A:2 (1:1)	A:1 < A:2 (1:2)	A:1 < A:2 (1:3)
Node Proximity	A:1 = A:2 (2:2)	5.3	4.3*	3.6**
	A:1 > A:2 (3:2)	4.5	5.4	4.2
	A:1 > A:2 (2:1)	5.3	4.5	5.0
	A:1 > A:2 (3:1)	6.8**	5.4	4.9
	A:1 > A:2 (4:1)	6.1*	6.0*	4.8

* p<.05 (significantly different than 5.0), ** p<.001 (significantly different than 5.0)

In order to more systematically assess the variables in the study, and to examine possible statistical interactions between them, we carried out a mixed ANOVA (multivariate approach) that examined network distance (three levels) and node proximity (five levels) as repeated-measures factors (i.e., that varied across trials within participants), and viewing mode (two levels) as a between-case factor (monoscopic vs. stereoscopic mode). Network distance was significant as a main effect (F[2, 25] = 9.70, p<.001), as was node proximity (F[4, 23] = 4.19, p<.01). These two effects show that participants found documents less similar if they were further apart in either metric distance or in node count. In contrast, viewing mode had virtually no effect on similarity ratings (F[1, 26] = 0.03, ns); whether displays were viewed monoscopically or stereoscopically did not influence ratings. None of the tests for 2-way or 3-way interactions among the factors were statistically significant either (all p's >.15). Finally, another set of analyses found no significant effects of participants' background and training (i.e., gender, study major, profession, age, map reading abilities, frequency of map use) on similarity ratings.

We further examined the effects of network distance and node proximity by calculating Pearson's correlation coefficients separately for each participant, averaging them after Fisher's r-to-z transform, and then converting them back to r. We correlated the network distance of trials (1, 2, or 3) against the similarity ratings for those trials, arriving at an average correlation of r = -.31, suggesting a modest tendency for participants to rate A:1 as increasingly more similar on trials with greater relative distance between A:2 than A:1. Likewise, we correlated the node proximity of trials (0,1, 2, 3, or 4) against the similarity ratings for those trials, arriving at an average correlation of r = .37, again suggesting a modest tendency for participants to rate A:1 as increasingly more similar on trials with greater relative node count between A:2 than A:1. This latter finding differs from our 2D study in finding that node proximity had an influence on the operation of the distance-similarity metaphor in 3D.

4.2 Rotation Times

We also recorded the times that participants rotated the display along the x and y axes[2] (i.e., pitch and yaw) in the 3D display space during the time they viewed each display, to the nearest 0.016s. The mean rotation times in seconds for the 15 trials that contrasted network distance and node proximity are presented in Table 2. No consistent pattern stands out.

In order to more systematically assess any effects on rotation time, we again carried out a mixed ANOVA (multivariate approach) that looked at network distance and node proximity as repeated-measures factors, and viewing mode as a between-case factor. Confirming the lack of an obvious simple pattern in Table 2, network distance was not significant as a main effect (F[2, 25] = 1.03, ns). Node proximity, however, was significant as a main effect (F[4, 23] = 7.97, p<.001). Viewing mode, whether

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[2] Although the display could also be rotated along the z axis (roll), we did not record this, as this rotation did not change the apparent distances or nodes between the comparison document points.

displays were viewed monoscopically or stereoscopically, was again nonsignificant as a main effect (F[1, 26] = 3.07, ns). However, viewing mode did interact significantly with network distance (F[2, 25] = 3.23, p<.05). Under monoscopic viewing, distance was significantly related to rotation times, while under stereoscopic viewing, it was not. An examination of the mean rotation times across trials varying in relative network distance between A:1 and A:2 revealed that participants viewing monoscopically rotated the displays 1.5–2 s more when the relative distances were two or three times different than when they were equal. In contrast, when viewed stereoscopically, participants rotated the displays with .6 s no mater the relative distance differences. Neither of the other 2-way interactions nor the 3-way interaction among the factors were statistically significant either (all p's >.4). Finally, another set of analyses found no significant effects of participants' background and training (i.e., gender, study major, profession, age, map reading abilities, frequency of map use) on similarity ratings.

Table 2. Mean time in seconds spent rotating the 15 displays varying network metric and node proximity between A:2 and A:1

		Network metric distance		
		A:1 < A:2 (1:1)	A:1 < A:2 (1:2)	A:1 < A:2 (1:3)
Node Proximity	A:1 = A:2 (2:2)	12.4	11.6	11.6
	A:1 > A:2 (3:2)	11.3	13.4	12.3
	A:1 > A:2 (2:1)	8.9	7.8	7.0
	A:1 > A:2 (3:1)	7.1	11.0	8.1
	A:1 > A:2 (4:1)	9.1	10.6	11.8

We calculated Pearson's correlation coefficients of rotation time with network distance and node proximity separately for each participant, again averaging them after Fisher's r-to-z transform, and then converting them back to r. Consistent with our ANOVA finding of no simple linear relationships between these variables, neither network distances of trials (r = .03) nor node proximity (r = -.19) had substantial linear correlations with rotation time.

5 Discussion

In this 3D network spatialization display study we were able to replicate findings from our prior work on 2D displays [4], with one significant exception. In contrast to the 2D spatialized network displays, where the number of intervening nodes did not have an effect on people's similarity judgments, we do find that node proximity has a significant effect for the employed 3D displays, as suggested by the newly found main effect of node count on similarity ratings and the correlation of node proximity with participants similarity ratings. Participants judged documents connected with fewer intervening nodes as more similar, compared to documents with more nodes in between, irrespective of increasing network metric distance. This is somewhat surprising, but could be explained as follows: Assigning a random z-coordinate to node positions in the 3rd dimension might have added an additional visual cue for document similarity assessment which is not available in 2D. In Figure 3a, the 3D configuration is shown in FP orientation, essentially identical to the view in the prior 2D study. The nodes in this FP/2D view do not seem particularly salient, as not all links change direction at node intersections. This is in contrast to the non-FP views, which are only available in 3D, as shown in Figure 3b. In the z-dimension of the 3D space, document nodes appear much more salient than they do in 2D, as all the links change direction at node intersections, due to randomly assigned z-values. The “ups and downs” of the links might involve increasing attentional costs to assess the distance-similarity metaphor. In fact, this might explain the additional time participants needed for all displays compared to in the 2D study. Perhaps it is easier and faster just to count the nodes for similarity assessment than to visually estimate metric distance along the links in 3D space; estimating distance seems to be much harder in 3D than 2D space. In fact, participants spend significantly more time rotating monoscopic displays to assess network metric distance in the displays, compared to stereoscopic 3D displays, where distance estimation is facilitated by visual depth perception.

Our results provide unique evidence that irrespective of the display mode employed (i.e., mono or stereo viewing), participants rated document similarity in 3D much as they did in 2D. As about 20% of the population cannot see stereoscopically, and considering the extra technological expense to add either motion parallax (3D mono) or distance parallax information for 3D stereo viewing, we argue that these additional costs do not outweigh the potential benefit of facilitating more accurate distance measurements with 3D stereo. In fact, one might argue that the motion parallax provided with interactive 3D displays (i.e., rotation of the 3D network structure) is equally useful or even sufficient for distance judgments (i.e., similar to rotating one’s head when trying to judge objects at farther distances in a real world scene), if not more effective and efficient. It is more cost effective when considering hardware needs, display development time, ease of deployment, etc. Motion is also considered one of the strongest visual cues to attract attention [17, 22], irrespective of viewing distance. As Ware and Franck [18] suggest, adding motion to 3D network displays is more important than adding stereo for comprehension of the structure. As participants took significantly less time to rotate the 3D displays in stereo mode on those trials where metric distances differed, one might argue that stereo could be useful if response time (i.e., response efficiency) were an issue, for example, in a decision context of time pressure. However, overall, the difference in the response times suggesting increased cognitive costs with 3D over 2D displays is a compelling reason why 3D spatialized network displays should not be used at all, as similarity ratings are quite similar for 2D and 3D (except, of course, for node proximity).

6 Conclusions

We set out to answer the research question of whether 3D network spatialization would add depth to 2D representations of semantic proximity. Our findings suggest that the interactive 3D viewing mode (i.e., mono vs. stereoscopic displays) did not influence participants' similarity ratings, as compared to static 2D displays evaluated in a prior study [4]. Moreover, similarity ratings for the 3D network displays are very similar to the ones obtained in the 2D network study. That is, viewers mostly map judgments of document similarity onto distances along the network, in 3D as well as 2D space. In contrast to our earlier 2D study, node proximity did have an effect in the present 3D experiment; we believe the nodes became more salient due to direction changes of the links in the 3rd dimension. In other words, viewers find it visually easier to simply count nodes, which is also time efficient, than trying to estimate network metric distance, which is more error prone [13]. Moreover, as in our prior studies on spatialized displays, user-related factors (i.e., group differences), such as gender, age, and previous training, did not significantly affect the similarity ratings.

Similarity ratings of the 3D displays are almost identical to those collected with 2D displays, but it takes participants longer to make decisions in 3D. The potential benefit of adding the third dimension, which allows one to interactively change perspective on the data space and add more information to the representations of abstract data, seems not to benefit participants' decision efficiency. Participants seem not to better understand the distance-similarity metaphor or make faster decisions in 3D, compared to 2D. It might be that an increase in response times in the 3D study corresponds to an increase in users' cognitive load when judging the displays. In fact, response time is further influenced by the viewing mode of the 3D display. If stereo is available, participate take significantly less time to rotate the displays before responding, compared to monoscopic 3D displays, especially when comparing metric network differences in the displays. We have not yet analyzed the qualitative data collected from the post-test questionnaires (e.g., display preferences, how they rated similarities between documents, and which measure they used for each display type), which we aim to do in future work.

These quantitative results thus lead us to conclude that although 3D displays might have the benefit of conveying more information than 2D spatialized views, this advantage is not necessarily enough to overcome the additional demands on cognitive, perceptual and technological resources engendered by interacting with 3D displays.

We recognize that our study had participants judge similarities absent a specific decision-making context, such as document topic or a specific application for the task. We did this to be as general as possible, without limiting our conclusions to a specific context. However, we recognize that real decision-making situations do generally come with a context. Future research should examine how and to what degree context influences the use of 2D and 3D network spatializations.

With this study, we hope to help information visualization designers to create expressive spatialized views that depict document similarity in intuitive ways for effective and efficient decision-making based on increasingly massive (text) databases. Our results to date lead us to conclude that a potential information increase afforded by adding an additional (third) display dimension does not outweigh the increased perceptual and cognitive costs caused by more resource-demanding 3D displays.

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