Gaze-Driven Links for Magazine Style Narrative Visualizations

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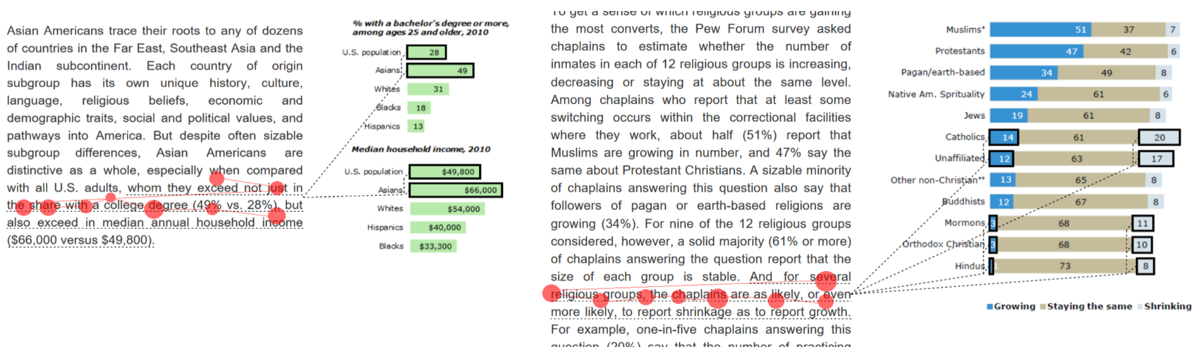

Figure 1: Sample gaze-driven interventions for magazine style narrative visualizations in the form of visual links meant to support mapping of the datapoints in the visualization that are referred to in the specific sentence the user is reading.

Abstract

Magazine Style Narrative Visualizations (MSNV) can be challenging due to the need to integrate textual and visual information. This problem has prompted researchers to design dynamic guidance meant to ease the mapping of the information provided in the two modalities. We contribute to this line of work by evaluating gaze-driven adaptive guidance that dynamically links relevant sentences in the text to the corresponding datapoints in the visualizations (see Fig. 1). We conducted a user study that involved participants reading a series of MSNVs extracted from real-world sources. Results show that the adaptive links significantly improve the comprehension of the MSNVs as compared to receiving no guidance. This improvement comes at no expense of user reading time, and is consistent regardless of the MSNV complexity.

Index Terms: Human-centered computing—Visualization—Visualization application domains—Information visualization; Human-centered computing—Visualization—Empirical studies in visualization

1 Introduction

Visualizations embedded into narrative text, known as *Magazine Style Narrative Visualization* (*MSNV* for short) are commonly used in real-world sources (newspaper, blog, textbook, science articles…) to tell stories with data [25]. However, as it is often the case for multimodal documents, processing MSNVs can be challenging due to the need to split attention between two information sources, which can increase reading time and cognitive load, and hinder learning and comprehension [3, 12, 16, 28], especially in users with lower levels of cognitive abilities [10]. In particular, a major difficulty is the need to map the specific information provided in the text to the corresponding datapoints in the visualizations [10, 16, 18, 26, 28]. To alleviate this difficulty, researchers have designed guidance meant to increase the user comprehension and experience by mapping the textual information to the corresponding datapoints in the visualizations as they read through the text, which is also our main research goal. Specifically, Steinberger et al. [26] examined how to guide user attention in MSNVs by displaying upfront a set of lines linking words in the text to the corresponding information in the visualization, leading to reduced visual search time. However, providing all the links upfront does not scale to MSNVs that contain many links between the text and the visualization, as it may overly clutter the visualization and overwhelm the user [2, 15]. Zhi et al. [29] and Metoyer et al. [22] proposed an approach that allow the users to willingly trigger highlighting guidance as they read through the MSNV. While this approach increased user engagement, it however did not result in improved comprehension, possibly because not all users used the self-triggered guidance in an effective manner.

Instead of relying on explicit user activation, other work proposed to leverage eye-tracking as an implicit source of information [20, 27]. Namely, Tateosian et al. [27] used eye-tracking to highlight places on a map mentioned in the MSNV text. They found that users liked this guidance, however, no evaluation was conducted to evaluate whether it improves user comprehension of the narration nor their reading time. In [20] we proposed gaze-driven interventions that dynamically highlight the relevant parts of the visualization when the user spontaneously reads the corresponding part in the text, as captured via eye-tracking (*highlighting interventions* from now on). These interventions led to improved comprehension of the MSNVs, but only for users with low levels of visualization literacy (vis literacy from now on, a cognitive skill). Users with higher vis literacy were, however, outperformed by low vis literacy users when receiving the interventions. This indicates that high vis literacy users might benefit from support in processing the MSNV, but the highlighting intervention is not providing it. Feedback from high vis literacy users indicate that the highlights were not always clearly noticeable (especially in MSNVs with many data points); or that it was difficult to retrieve a sentence when resuming reading the text after a switch from the sentence to the visualization.

In this paper, we propose an extension of the highlighting interventions of Lallé et al. [20], by augmenting them with visual links that connect a sentence in the text to the referred datapoints in the visualization (*link interventions*, showcased in Fig. 1). These links are inspired by those from Steinberger et al. [26], but address the key limitation that the links in [26] were all displayed upfront, making it

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difficult to scale up to more complex documents with many possible links. We do so by using eye-tracking to dynamically deliver links that correspond to the sentence that the user is currently reading. To further avoid drawing too many lines over the MSNV, our link interventions use branching trees to merge nearby links.

We evaluate the effectiveness of the link interventions proposed in this paper with a formal user study involving participants to read a set of MSNV snippets. We compare the participants' outcomes with those of users who underwent the same task with the highlighting intervention of [20], and with no intervention [10], while controlling for the levels of vis literacy and complexity of the MSNV.

We contribute to existing research by providing a novel gaze-driven mechanism to dynamically display visual links in MSNVs, thus addressing the scaling issues that arise with the static links originally proposed in [26]. Visual links have also been used as visual guidance in stand-alone visualizations and multimodal documents other than MSNV, e.g., [1, 9, 23, 24], however not in a dynamic way based on eye-tracking patterns as we do. We show that our proposed link interventions significantly improve the user's comprehension, and this improvement is consistent across MSNVs of varying complexity. These results show for the first time the value of adaptive guidance in MSNV over no guidance, as related work has found no improvement in user performance [29], or an improvement only in a subset of the users [20].

2 Design of the Link Interventions

The highlighting interventions of Lallé et al. [20] were visually displayed by thickening the border of the bars that are described by a sentence in the text, when eye-tracking indicates that the user is reading that sentence. The link interventions (see Fig. 1) augment this bar highlighting mechanism with two components: the sentence that references the currently highlighted bars is highlighted as well (*sentence highlighting* from now on); and the set of lines that is drawn over the MSNV to connect that reference to all highlighted bars (*links* from now on).

A well-known pitfall of such links is that drawing too many links over the documents generally overwhelm the user [2, 7, 14, 15, 24]. This makes it difficult to deliver these links in a way that scales to long or complicated MSNVs that can typically include multiple references (up to 7 in our study, up to 30+ in some of the Pew Research MSNVs on public policy [18]). Previous work has addressed this issue by using color to distinguish links [17, 23], and by inferring link pathways that avoid interception [28], but these approaches still have pitfalls, such as limited number of colors, and the fact that seeing too many links generally overwhelms the user anyway as stated above. Our proposed mechanism addresses this issue by dynamically displaying one link intervention at the time, when the user reads the related sentence. As the user reads through the text and encounters a new textual reference to the chart, the previously displayed links and sentence highlighting are removed, so that only the most recent intervention is shown. Another scaling issue is due to the fact that that a single sentence can already refer to many datapoints in the visualization (up to 13 in our dataset), meaning that linking a single sentence could already clutter the MSNV. We address this scaling issue by plotting the links as branching trees, with the text reference as the root, the relevant bars in the visualization as leaves, and the number of lines drawn over the documents minimized by merging branches when suitable.

To generate the branching tree for a given sentence, our algorithm identifies subsets (clusters) of the referenced bars that are close together, so that the connection from the sentence to these bars can be drawn as one outgoing line with a branching point where the line splits into branches that connect to the relevant bars, as shown in Fig. 1. This approach takes advantage of the fact that bars in bar charts tend to be aligned, so the length of the branches can be kept minimal. Bars are identified as being "close together" (i.e., belonging to the same cluster) if they are adjacent or if there is only one non-relevant bar in between. The position of the branching point for each cluster, namely the point where the link is split to connect to all the bars within the cluster, is computed to be as close as possible to the relevant bars to minimize clutter in the visualization, and depends on the relative position between the reference sentence and the relevant bars so as to scale to MSNVs with different layouts. Namely, for vertical bar charts, the branching point is located either just below the lowest bar, or above the tallest one, depending on whether the reference sentence is above or below the bars, respectively. The same approach applies for horizontal bar charts, depending on whether the text is on the left side or the right side of the bar chart. To trigger the links, we use the eye-tracking mechanism that has been thoroughly evaluated in [20]. In particular, to avoid unwarranted interventions the mechanism waits for a sufficient amount of fixations accumulated in a reference before triggering the intervention (see [19] for more details). The source code of this mechanism and the link interventions, along with demo videos, is fully available at: *github.com/ATUAV/ATUAV_Experimenter_Platform/tree/link_intervention_study*.

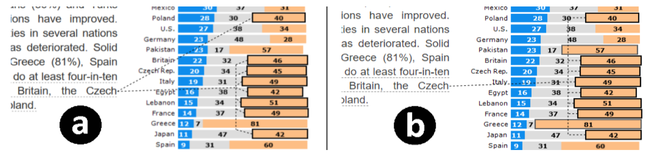

Figure 2: Multiple clusters (a) vs one cluster (b)

We pilot tested the link interventions with 6 participants in order to identify a suitable way to visually display the links and the sentence highlights over the MSNVs. The pilot tests aimed to fine-tune the clustering strategy for the branching trees, and the visual rendering of the links, as follows:

(i) Clustering. We experimented with two approaches for clustering the relevant bars, by either using the algorithm described in the previous section to cluster nearby bars and merge the corresponding links (see Fig. 2a); or by clustering all bars into one cluster, to ascertain whether it is sufficient to merge all links together (see Fig. 2b). Overall, the pilot participants reported that merging all bars into one cluster is not suitable for highlighted bars that are too far from each other, which happens in at least 5 of our 14 MSNVs. We thus opted for using the approach based on multiple clusters.

(ii) Visual rendering. Based on the feedback from the pilot participants, we opted to display links with black dashed lines, because black was preferred as it is a neutral color, and dashed lines were found to be better distinguishable from the elements of the charts such as the axes and the bars borders. Dashed underlines are also used for the sentence highlighting, as these underlines were found to be less intrusive than background highlighting, and more useful than no highlights at all.

3 User Study

To evaluate the link interventions, we conducted a user study with 30 participants (57% female, 59% students, ranging in age from 18 to 57), and compared the performance and experience of this group of users (*link group* from now on) to those of the 50 users who received the highlighting intervention in [20] (*bar group*) and of the 56 users who received no intervention in [10] (*control group*). The participants of the three groups were recruited in a similar way via advertisement on Craigslist and at our campus, with no repetition allowed. The procedure and task, fully detailed in Lallé et al. [20], were kept consistent across all groups, thus conforming to a between-subject design. Namely, after calibration of the Tobii T120 eye-tracker, participants read in a randomized order 14 MSNV snippets extracted from real-world sources, each consisted of a text

Table 1: Summary statistics of dependent measures per group.

Measure	Control group	Bar group	Link group
Comprehension (%)	71.9 (±3)	74.4 (±4)	77.3 (±2)
Time-on-task (secs)	56.3 (±32)	60.1 (±33)	58.1 (±29)
Interest	3.37 (±1)	3.31 (±1)	3.56 (±1)
Ease-of-understanding	4.00 (±1.2)	4.05 (±1.2)	4.19 (±1.1)

paragraph and one accompanying bar chart. The 14 snippets range in complexity from a few lines of text and a simple bar chart, to up to 30 lines of text and a dense grouped/stacked bar chart. After reading each MSNV, participants answered a set of questions designed to gauge their comprehension of the MSNVs, and self-reported their interest in the MSNV and perceived ease-of-understanding. Time-on-task was also collected. The VisLit 101 - Bar chart test [6] was used to measure the participant's levels of vis literacy. A questionnaire was administered at the end, along with an interview to gauge the perception on the interventions. There was no significant difference ($p > .1$) among the 3 groups (link, bar, control) in terms of demographics (age, gender, prop. of students) and vis literacy score.

4 Analysis and Results

4.1 Effectiveness of the Link Interventions

In this section, we evaluate the effect of our proposed gaze-driven link interventions on MNSV processing, in terms of both user performance (*accuracy* on the comprehension questions and *time-on-task*) and experience (perceived *ease-of-understanding* and *interest*). Summary statistics for these dependent measures are shown in Table 1.

We compare the performance and experience of the participants in the three study groups while accounting for the possible influence of the participant's levels of vis literacy and complexity of the MSNV. To account for MSNV complexity in the analysis, we aggregate the different complexity metrics (e.g., length of the text, number of datapoints) identified in [10] using a Principal Component Analysis (PCA) with one component. We use PCA because in our dataset, all complexity metrics are moderately to highly correlated (r from .4 to .8), so PCA is suitable to aggregate them without losing much information [11]. The PCA yields a Kaiser's sampling adequacy and communalities above the acceptable limit of 0.5 [11], and the eigenvalue over Kaiser's criterion indicates that one component is suitable for our data [11]. As expected, the resulting PCA component is correlated with each complexity metric ($r > .6$), and thus captures the overal levels of complexity of the MSNVs.

We run four mixed models, one per dependent measure, with group (control, bar, link), vis literacy and MSNV complexity as the independent variables. Participant ID and MSNV ID are added as random effects in the mixed models, to account for variability across the participants and the documents, respectively. We adjust all p-values using the Benjamin–Hochberg method [5] to control for the false discovery rate, based on the total number of generated p-values. When needed, we run post-hoc pairwise comparisons with the Benjamin–Hochberg adjustment. For the pairwise comparisons involving vis literacy, we use a 3-way median split to divide the participants into three bins (*Low*, *Medium*, *High*) based on their vis literacy scores, as done in [20]. Mann–Whitney U tests ensure that there are significant differences ($p < .001$, $r > .3$ in all cases) among the bins. As a result, the mixed models reveal three main sets of significant effects:

(i) A main effect of group on comprehension ($p < .01$, $r = .22$). The pairwise comparisons indicate that the link group is significantly more accurate on the comprehension questions than the control group ($p < .01$, $r = .39$), with an increase in accuracy of about 5% (see Table 1). There are no significant differences ($p > .1$) between the link group and the bar group, and between the bar group and the control group. These results indicate that the link

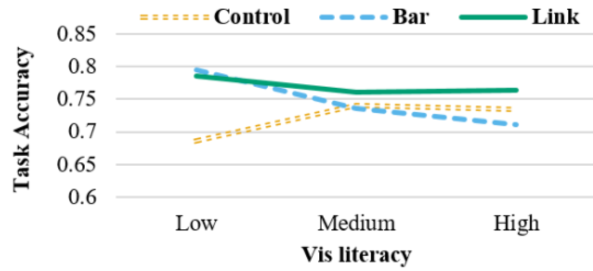

Figure 3: Interaction effect of group with vis literacy on accuracy.

interventions successfully improve user comprehension as compared to no intervention. This is noteworthy as both the bar highlighting interventions, and the previous forms of guidance provided in MSNV [20, 26, 27, 29] yielded no such significant improvement in comprehension, meaning there was so far no evidence for the value of adaptive interventions in MSNV, compared to no intervention. It is also noteworthy that the mixed models reveal no significant effects of groups on time-on-task, with small effect sizes ($p > .1$, $r = .09$), suggesting that the effects found on comprehension come at no expense of longer time-on-task.

(ii) An interaction effect between group and vis literacy on comprehension ($p = .006$, $r = .36$), shown in Fig. 3. The interaction effect is generated by the fact that both bar and link interventions have their greatest impact on low vis literacy users, for which the difference with the control group is statistically significant with a substantial boost in accuracy on the comprehension questions of nearly 11% on average. It is noteworthy that we are able to closely replicate the results in [20] for these low vis literacy users.

However, as already reported in [20], the bar highlighting interventions fail to help high vis literacy users, who are significantly less accurate than low vis literacy users ($p < .001$, $r = .28$), with a drop in accuracy of nearly 7.5% (see Fig. 3, dashed blue line). In contrast, the difference between low and high vis literacy users in the link group is no longer significant ($p = .2$, $r = .09$), suggesting that the link interventions address some of the drawbacks of the bar interventions for high vis literacy users identified in [20]. This is valuable since the link interventions are meant in part to address the negative feedback provided by these high vis literacy users.

(iii) Main effects of MSNV complexity on comprehension ($r = .25$), **time-on-task** ($r = .45$), and **ease of understanding** ($r = .35$). Pairwise comparisons show, as expected, that each of these measures get worse as complexity increases. However, the lack of a statistically significant interaction effect ($p > .1$) between group and MSNV complexity on all our dependent measures ($r = .16$ for accuracy, $r = .28$ for time, $r = .04$ for ease, $r = .09$ for interest) indicates that the effectiveness of the link interventions is not influenced by the complexity of the MSNV in our study. As a matter of fact, the improvement in comprehension of the link group over the

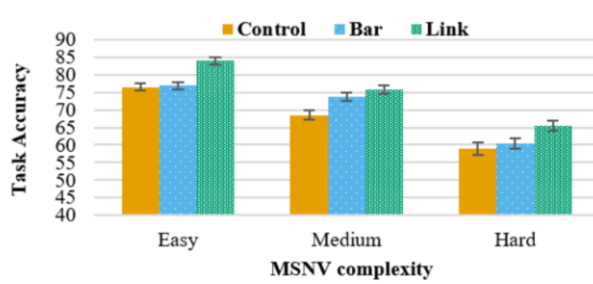

Figure 4: Interaction effect of group with complexity on accuracy.

control group is consistent across all MSNVs, as shown in Fig. 4 for easy, medium and hard MSNVs. Similarly, our data show that time-on-task is essentially unaffected by interventions regardless of the MSNV complexity. This suggests that the link interventions did not slow down the users even in harder MSNVs, which provides additional evidence for the fact that the link interventions scaled to our more complicated MSNVs. This is a promising result because scaling with complexity was a key limitation of previous work on providing visual links in MSNVs [26], and we specifically designed the link interventions to address this challenge.

4.2 Perception of the Link Interventions

We examine the ratings provided by the participants in the link group on the questionnaire about their perception of the links, along with the feedback they provided in the post-interview to elicit their ratings. Overall, participants found the links to be "somewhat useful" to process and comprehend the MSNV (mode of 5 out of 7 in the questionnaire). In particular 23 participants (77%) provided positive feedback about the usefulness item: *"I liked how the interventions drew my eyes to the information;" "The interventions helped in tying the graphs to the snippets and understanding the statistics;" "It made it easier to focus on the data;" "They came up at the right time when reading the text and it assisted me in understanding the text better."* Notably, the usability issues reported by some of the high vis literacy users on the lack of noticeability of the bar highlights, and the difficulty in retrieving the reference sentence [20], did not come up anymore.

Participants reported that the links were not confusing (mode of 2 out of 7) and well-integrated in the MSNV (mode of 6). Only 5 users (16%) complained about the way the visual links were drawn (e.g., *"I felt like sometimes the lines crowded the words"*). This finding further indicates that the mechanism we propose to display the link interventions was intuitive enough to most users, which is notable because we provided no training to the participants prior to being exposed to the link interventions.

A possible concern is that 15 participants (50%) found the interventions to be "somewhat distracting" (mode of 5 out of 7), mostly because the interventions are displayed dynamically, thus pulling their attention away from the text, e.g.: *"sometimes [the intervention] distracted me whenever I didn't understand and had to read a little slower"; "The interventions distracted me from the text, I lost focus several times causing me to go back and re-read"; "Sometimes I wanted to complete reading the paragraph before looking at the visual."* While this was expected given that the links are provided dynamically during reading, this distraction remained moderate on average (a mode of 5 is labeled as "somewhat distracting" in the questionnaire), and participants still generally perceived the links as useful and not confusing as mentioned above, and did benefit from them in terms of comprehension of the MSNV (cf. Sect. 4.1). Furthermore, the levels of distraction remained similar to the ones reported in the bar group [20], meaning that the links themselves did not generate additional distraction.

5 Discussion and Conclusion

Providing dynamic guidance to processing MSNVs has attracted recent interest from the VIS community, albeit with mixed results in terms of increasing user performance [20, 27, 29]. Contributing to this previous work, we found that our proposed gaze-driven link interventions improved the users' accuracy on comprehension questions, as compared to no intervention, for similar reading time, thus showing for the first time that adaptive guidance can improve MSNV comprehension. We also extend previous work on providing static visual links in MSNVs [26], by leveraging eye-tracking to deliver the links in a way that scales to longer or more complicated MSNVs. Recent visualization research has also examined the value of eye-tracking to drive adaptive guidance in processing maps, with mixed results, as the interventions improved user engagement but not their accuracy [4, 13]. Thus our findings provide the strongest evidence to date for the value of gaze-driven adaptive guidance to visualization processing. Our research also uncovered additional relevant findings for the design of adaptive guidance in MSNVs, and has some limitations to be addressed in future work, as follows.

Role of vis literacy. Our work provides further evidence that it is important to consider specific user needs when designing adaptive guidance. The design of our link interventions was inspired by limitations of the adaptive bar interventions that in [20] were related to the user's levels of vis literacy. Our findings show that the link interventions addressed at least some of the drawbacks of the bar interventions that were identified for high vis literacy users. This finding is noteworthy because the role of user characteristics during visualization processing has been extensively studied (see [8, 21] for an overview), but there is still limited understanding about their influence on the value of adaptive visualizations. Thus our findings provide further evidence for the importance of leveraging relevant characteristics to examine how different user groups benefit from adaptive guidance, and future work could be focused on further examining how and why vis literacy interacts with the effectiveness of the bar highlighting and link interventions.

Distraction due to dynamicity. Although issues with the link interventions being distracting did surface in our study, participants mostly perceived these interventions as useful, well integrated in the MSNV and not confusing. This indicates that our gaze-driven mechanism and our algorithm for the link interventions were overall well-received by the users, in addition to being effective in terms of user comprehension. Still, moving forward, it is important to study ways to reduce distraction. As a possible low-hanging fruit, it might be sufficient to signal ahead with an icon or an indicator the reference sentences that can trigger an intervention, so that the user is less surprised by its appearance. Alternatively, mixed-initiative approaches to mitigate this distraction could be helpful, while still retaining the current mechanism as it has been shown to improve comprehension. Such mixed-initiative strategies could include displaying partially-transparent links that the user can decide to explore by hovering the mouse over them, or allowing the user to toggle the interventions on and off altogether. Overall, research on eye-tracking-based dynamic support to visualization processing is still preliminary, and identifying best practices to deliver such support to enhance user performance while keeping low levels of perceived distraction and intrusiveness is an important research question.

Avoiding occlusion. We proposed to use branching trees as visual cues to merge as many links as possible as a way to reduce visual clutter, which was found appropriate by most users who found the links to be easy-to-use, and only 3 of them (10%) complained about occlusion. Still, with our current approach the links can still occlude some elements of the bar charts, and future work could be focused on inferring pathways for the branching trees that minimize occlusion.

Scaling to longer MSNVs and other layouts. While we used MSNVs of various complexity to test the link interventions, these MSNVs were excerpts from real-world documents, and usually substantially shorter than the original documents. We believe that the type of gaze-driven guidance we investigate should be even more helpful in longer, more challenging documents, but we will test this hypothesis by running a new study focusing on testing the proposed interventions with full-length MSNVs featuring several visualizations. Moreover, while our proposed method takes into account the relative position of the bar charts to the text, we focus only on MSNV snippets whereby the text and the chart are side by side. There is thus a need to further evaluate the link interventions across different document layouts. We also plan to investigate how to leverage the gaze-driven links in MSNVs with different visualizations than bar charts, which may require the links to be displayed differently.

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