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Larger crossing angles make graphs easier to read

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ABSTRACT

Objective: Aesthetics are important in algorithm design and graph evaluation. This paper presents two user studies that were conducted to investigate the impact of crossing angles on human graph comprehension.

Method and results: These two studies together demonstrate our newly proposed two-step approach for testing graph aesthetics. The first study is a controlled experiment with purposely-generated graphs. Twenty-two subjects participated in the study and were asked to determine the length of a path which was crossed by a set of parallel edges at different angles. The result of an analysis of variance showed that larger crossing angles induced better task performance. The second study was a non-controlled experiment with general real world graphs. Thirty-seven subjects participated in the study and were asked to find the shortest path of two pre-selected nodes in a set of graph drawings. The results of simple regression tests confirmed the negative effect of small crossing angles. This study also showed that among our four proposed candidates, the minimum crossing angle on the path was the best measure for the aesthetic when path finding is important.

Conclusion: Larger crossing angles make graphs easier to read.

Implications: In situations where crossings cannot be completely removed (for example, graphs are non-planar, or a drawing convention is applied), or where effort needed to remove all crossings cannot be justified, the crossing angle should be maximized to reduce the negative impact of crossings to the minimum.

1. Introduction

Graphs are often drawn into node-link diagrams when they are difficult to understand in their original non-visual format. One issue with node-link diagrams, however, is that the same graph can be drawn in many different ways by changing layout; research has shown that layout affects people's ability of understanding graphs. Researchers in the graph drawing community have proposed a number of criteria that jointly define a good layout [11]. The minimum number of edge crossings and the maximum number of symmetries are two examples. These criteria are often called *aesthetic criteria*, or simply *aesthetics*.

Despite the growing interest in finding aesthetics based on how people draw and read graphs (e.g., [19,24,26,29,40]), most aesthetics that are currently in use were originally proposed to produce visually pleasing layouts based on personal intuition and expert judgment. It is also believed that graph drawings can be effective in conveying the embedded information to the viewer if their layout satisfies these aesthetic criteria. Empirical investigations led by Purchase have shown that most of them are indeed important for human graph comprehension (e.g., [39,41]). In a further study that compared a set of aesthetics for their effects on human graph comprehension, Purchase [42] found

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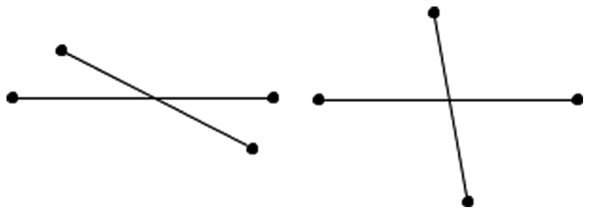

Fig. 1. According to Ware et al. [46], the crossing on the right is less confusing than that on the left.

that the aesthetic of edge crossings was the most important one having the greatest negative impact.

These findings are significant and have led to the aesthetic of edge crossings becoming one of the most widely discussed topics in graph drawing research. For more than two decades, much effort has been devoted to minimizing the number of crossings in graph drawings (see [6] for a survey). However, crossing minimization is NP-hard [22]. Further, algorithms that are designed for crossing minimization usually do not scale well with the size and complexity of graphs and are often difficult to understand and implement, limiting practical use. Given the fact that real world graphs are often large and complex and that crossings are often unavoidable in any drawing (real graphs are rarely planar), the benefit of minimizing crossings may not justify its cost. Further, it is known that a good layout is often the result of a balance between aesthetics, rather than a combination of extremes of one or two aesthetics [28]. Therefore, the next question that is natural to ask is whether it is possible to achieve a better or the same level of layout quality if we do not minimize the number of crossings.

Prior research has suggested that adjusting how edges cross with each other may help in achieving this. First of all, it may not be always necessary to remove crossings. Huang et al. [25] conducted a user study on sociogram perception and found that crossings were important only for tasks that required tracing edges or paths. This finding was confirmed by eye tracking studies of Huang [23] and of Körner [34,35]. In these studies, both eye movement and task performance data revealed that node locating and node degree counting tasks appeared not to be affected by crossings. Second, findings from neurophysiology research [4,44] indicate that objects of the human visual field are processed at the same time with a set of neurons that are coarsely tuned to "respond preferentially to bars with particular orientations". Based on this, Ware et al. [46] suggested that acute-angle crossings could be more confusing to human eyes than close-to-90-degree crossings when rapid information processing is needed (see Fig. 1). Third, Huang and Eades [24] reported that subjects performed equally well with crossing and no-crossing drawings in an eye tracking study and suspected that the impact of large-angle crossings could be insignificant. In a follow-up study, Huang [23] observed that close-to-90-degree crossings appeared to be ignored by subjects, while small-angle crossings caused very slow eye movements with extra back-and-forths around crossing points, leading to performance degradation.

The above-mentioned studies suggest that increasing the size of crossing angle could help to reduce or even offset the negative effect of crossings. In response to these studies, investigations of layout methods that aim to increase crossing angles have begun [14]. These investigations include a number of studies of the so-called "RAC (Right Angle Crossing) drawing problem", that is, the problem of drawing graphs so that every crossing angle is 90 degrees. The requirement that all crossing angles be 90 degrees is very restrictive, and in general, the RAC drawing problem is NP-hard [2]. Many methods have been recently developed to solve the RAC drawing problem for restricted classes of graphs (see, for example, [3,9,12]). The more practical investigation of the problem of drawing graphs with crossing angles that are large but not necessarily 90 degrees has not received as much attention as the RAC drawing problem. Currently, it is unknown whether the problem of drawing a graph with all crossing angles more than α degrees is NP-hard for $\alpha \neq 90$. Despite this, some heuristic methods and mathematical properties have been investigated (see, for example, [8,15–18]).

However, the possible effect of crossing angle on graph reading performance has not been systematically tested with rigorously-designed controlled experiments. In an attempt to fill this gap, we designed and conducted two user studies that are presented in this paper. It should be noted that the first study has been briefly reported in a conference [27] while the second study is newly conducted research.

The main contributions of this work are as follows:

1. We empirically validated the effect of crossing angles on human graph comprehension.
2. A new two-step approach was introduced and demonstrated for testing graph aesthetics.
3. A new type of statistic hypothesis testing, equivalence testing, was introduced and demonstrated for graph evaluation.
4. Four different measurements of crossing angle are validated and their relative importance for human graph comprehension was compared.
5. The minimum crossing angle on the path was found being the most important for path finding tasks.

The remainder of this paper is organized as follows. In Section 2, our two-step approach to validation of graph aesthetics is introduced. This approach is demonstrated in two studies which are presented in the next two sections. Section 3 presents the first study, which is followed by the second study described in Section 4. Section 5 presents a general discussion. Finally, the paper concludes in Section 6.

2. The two-step approach

To validate an aesthetic of graph drawings, a straightforward approach would be to vary the score of the aesthetic in a set of drawings of the same graph, while ideally, values of all other variables (aesthetics) are kept constant. Then we test whether there is a significant difference between these drawings. However, a drawback of this approach lies in the complexity of graph structures: it is almost impossible to keep other variables constant,