The Effect of Internal Patterns on Perception Accuracy in Bar Charts

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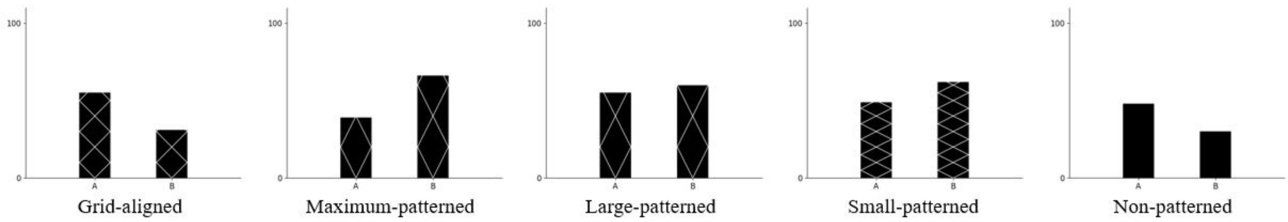

Figure 1: *Five bar charts designs in this study. The last chart is the experiment's control condition.*

Abstract
Bar charts are widely used for comparing categorical data due to their simplicity and effectiveness, while pictographs enhance engagement and memory retention. This study aims to combine the strengths of both visualization techniques through redundant encoding, integrating internal patterns to improve perception accuracy. By testing various pattern designs, the study evaluates their impact on value estimation. Results indicate that some patterns enhance accuracy, while others increase complexity that can hinder readability. These findings contribute to optimizing bar chart design for clearer and more intuitive data interpretation.
Keywords : *Bar Charts, Pictographs, Redundant Encoding, Quantitative Evaluation.*

1. Introduction

The human visual system is a complex network that processes and interprets visual information efficiently. Visualization leverages this capability by transforming complex datasets into images that enhance pattern recognition and comprehension. As data-driven decision-making becomes increasingly vital, the ability to interpret vast amounts of information quickly is crucial. Effective data visualization methods allow users to identify patterns, compare values, and extract insights, making large datasets more accessible and actionable.

Bar charts, widely used for categorical comparisons, present quantitative information in a clear and structured manner. They are particularly useful for summarizing discrete data points, such as product sales or population distributions. Over time, enhancements like internal patterns and shading have been introduced to improve visual appeal and highlight specific data categories. While these enhancements may contribute to aesthetics, their impact on the accuracy of data interpretation remains uncertain. This study aims to explore whether such visual features facilitate or hinder the user's ability to interpret bar chart data effectively.

Internal patterns in bar charts may serve as visual aids by dividing bars into countable segments, potentially improving value estimation by providing reference points. However, they could also introduce visual noise, making interpretation more challenging. Research suggests that the human brain can instantly recognize small quantities without counting (subitizing), but as numbers increase, reliance on estimation or counting grows [CF14]. Consequently, simpler patterns may support accurate estimation, whereas complex designs might be disregarded as visual noise. This study examines whether different pattern sizes enhance or obstruct accurate data perception, seeking an optimal balance between visual appeal and readability.

The study evaluates how internal patterns in bar charts impact perception accuracy, specifically in value estimation. It investigates whether patterns provide helpful visual cues or introduce unnecessary complexity by testing different pattern sizes. The finding of this study highlights the importance of intentional design choices in bar charts, demonstrating that patterns can enhance or hinder perception accuracy. Future research could investigate additional pattern variations, shapes, or icons to identify an optimal design that maximizes both aesthetic appeal and functional clarity.

2. Related Works

Since the study focuses on the effects of internal patterns in bar charts, the reviewed studies will be centered around similar or relevant visualization (and encoding techniques) namely bar charts and pictographs.

2.1. Bar Charts and Perceptual Theory in Data Visualization

Bar charts are fundamental tools in data visualization, particularly valued for their simplicity and effectiveness in representing data. Their design allows for easy comparisons of quantities by utilizing length as the primary encoding variable. Cleveland & McGill [CM84] established the theoretical foundation for understanding bar chart perception, finding that position and length are among the most reliable encoding channels for quantitative accuracy, surpassing other channels such as area or volume in other chart types. This research highlights the strengths of bar charts for accurate data interpretation and provides a basis for examining how additional visual elements might affect user comprehension.

Studies have since expanded on Cleveland & McGill's [CM84] framework, exploring how variations in bar design impact perception accuracy [TSA14]. Other studies have emerge to improve bar chart visualization such as the concept of scale-stack bar charts [HSBW13], width-scale bar charts [HWBvL20], and Du Bois wrapped bar charts [KWCD20] to address challenges in visualizing large value ranges, allowing for easier interpretation of data across multiple scales. These variation preserves the ability to make quantitative comparisons while managing extreme data ranges, demonstrating that thoughtful modifications can enhance a bar chart's utility. The evolution of bar charts in visualization research emphasizes both the stability of basic designs and the potential for enhanced configurations, setting the stage for investigating other embellishments, like internal patterns.

2.2. Impact of Visual Encodings in Bar Charts

Visual encodings, such as texture, shading, and internal contrast, influence how users perceive and interpret bar charts. These enhancements can provide useful reference points that improve accuracy but may also introduce distractions that hinder readability if not carefully implemented. Studies indicate that decorative elements, such as rounded edges and caps, may attract attention but can slightly reduce accuracy compared to simpler designs [SHK15]. This highlights the need for careful selection of visual embellishments that maintain data clarity.

Research by Díaz et al. [DMPV18] examined the impact of internal contrast enhancements, such as quantized gradients and Tufte's encoding [Tuf86], on user accuracy. Their findings suggest that these enhancements can significantly improve perception by providing subtle visual breaks that aid in value estimation. Similarly, He et al. [HZII24] found that some black-and-white textures effectively differentiate categorical data in bar charts without reducing readability, particularly in monochromatic settings.

While certain enhancements improve perception accuracy, others that focus on aesthetics may introduce unnecessary complexity. This study aims to explore design options that enhance accuracy while supporting visually engaging and accessible bar chart representations.

2.3. Pictograph in Visualization

Pictographs are widely used in data visualization to bridge the gap between numerical data and abstract visual representation, making information more accessible and memorable. The ISOTYPE system exemplifies this approach by using simple pictographic elements to facilitate quick recognition and recall, potentially enhancing user engagement. However, their effectiveness in improving comprehension remains debated.

Haroz et al. [HKF15] found that pictographs, particularly when divided into discrete symbols, enhanced memory recall for small quantities. This aligns with cognitive theories suggesting that the human visual system efficiently processes small sets of items [CF14]. However, their study did not explore whether pictographs improved value estimation accuracy over extended exposure.

Burns et al. [BXF*22] compared traditional area charts with count-based pictographs, revealing no significant differences in comprehension. However, pictographs required more cognitive effort as users had to count discrete symbols, which some found less intuitive. While pictographs encouraged personal engagement with the data, area charts were perceived as simpler and more straightforward for quantitative interpretation.

These findings suggest that while pictographs enhance engagement and memory retention, their impact on comprehension varies depending on context. This study explores whether integrating countable visual elements within bar charts can potentially have the same benefits as pictograph and help users interpret data more accurately.

3. Methodology

The methodology of this study comprises three main components: chart design, survey design, and the experimental procedure. These are to address the research objectives and ensure a rigorous evaluation of the impact of internal patterns in bar charts on perception accuracy. Three key research questions are as follows.

- Does internal patterns in bar charts affect perception accuracy?
- Does internal pattern size influence perception accuracy?
- Does bar positioning (left or right) impact perception accuracy?

This study utilizes a limited set of patterns, and its methodology and tools employed impose certain constraints. Despite these limitations, the study aims to enhance bar chart design for improved readability and effectiveness in data communication.

3.1. Chart design

This study focuses on bar charts to examine the effects of internal patterns on value estimation. To isolate this factor, other elements such as grid lines and labels are simplified. Based on previous research by Cleveland & McGill [CM84] and Díaz et al. [DMPV18], the charts feature two bars of equal width, labeled "A" and "B," with a black-and-white color scheme to eliminate color-related biases. Bar values range randomly from 30 to 70, aligning with previous findings that tends to show negative bias within this range.

Internal patterns are assigned to bars to assess whether they influence estimation accuracy. Each pattern is a variation of a simple tessellation of rhombuses whose horizontal diagonal is the width of a bar. The study includes five variations as illustrated in Figure 1:

- Grid-aligned: its unit rhombus is also a square.
- Maximum-patterned: the height or the vertical diagonal of its unit rhombus matches with the smallest bar height.
- Large-patterned: the height or the vertical diagonal of its unit rhombus is twice the width of the bar.
- Small-patterned: the height or the vertical diagonal of its unit rhombus is half the width of the bar.
- Non-patterned: a standard solid-colored bar chart as the experiment's control condition.

Participants are required to input estimated values for each bar. Responses must be integer values between 0-100, and two inputs are required per chart. The non-patterned bar serves as a baseline for comparison, helping to determine the effects of internal patterns.

3.2. Survey Design

The study was conducted using a customized version of Google Forms due to its low cost, extensive feature, and simplicity. The survey was designed with three distinct sections:

- Introduction & demographic data: participants provided information on age, gender, educational background, eyesight, and display device. A sample question was included to familiarize participants with the interface.
- Primary task: participants were required to estimate and answer numerical values for 15 bar charts or 30 numbers.
- Post-survey: participants assessed task comprehension, rated difficulty on a Likert scale, and provided qualitative feedback. All were optional.

To mitigate order bias, the Latin square method was utilized. A total of 75 unique bar charts were generated across five encoding styles, distributed across five separate surveys. Each survey contained 15 charts to ensure survey could be complete in 15 minutes [SB17]. Participants were randomly assigned to one of the five surveys.

3.3. The Experiment

Using Cochran's Formula [Coc77], the survey aimed for 385 individual bar estimations per encoding type, requiring 65 participants. Recruitment was conducted through personal and professional networks in January 2025. To ensure data integrity, quality control measures included validating whether the higher estimated value corresponded to the correct bar, identifying and removing extreme outliers via the interquartile range (IQR) method, and excluding participants who self-reported poor eyesight or failed the task comprehension check.

Of the 120 participants who initially began the experiment, 91 completed the survey, which was expected to be sufficient. However, after applying quality control measures, 49 valid responses remained, yielding 294 bar estimations per encoding type. The final sample consisted of 26 female participants, 22 male participants, and one who preferred not to disclose their gender. Most respondents were aged 26–35, and over half held a bachelor's degree. Regarding device usage, 38 participants used phones, five used tablets, and three each used laptops and desktop computers.

This methodological approach ensured that the collected data were both reliable and representative, supporting a comprehensive analysis of the impact of internal patterns in bar charts on perception accuracy.

4. Results

This section presents the findings of the study, focusing on the impact of internal patterns on bar chart perception accuracy. The analysis was conducted using statistical methods with a significance level of 0.05. A one-way analysis of variance (ANOVA) was employed to determine whether there were statistically significant differences in perception accuracy across the different encoding groups. If significant differences were found, Tukey's honestly significant difference (HSD) test was used as a post-hoc analysis to identify specific group differences. Additionally, a one-sample t-test and other test methods were used where applicable.

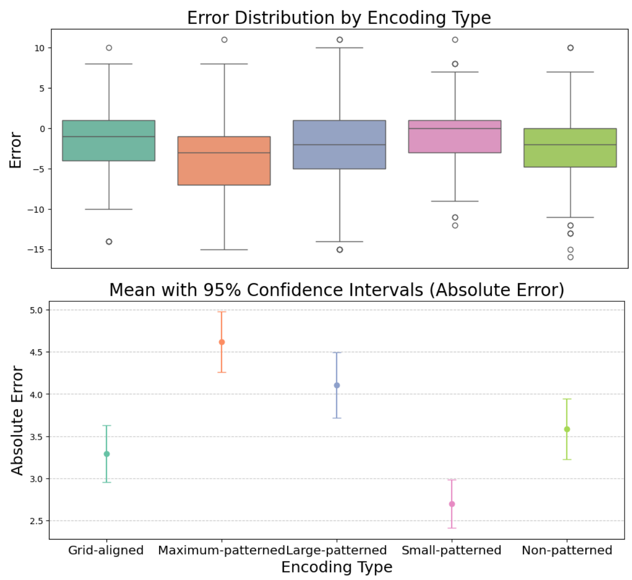

Figure 2: *Box plot of the probability distribution of the estimation error by encoding groups (above). Error bar plot of mean absolute error for different encoding groups (below).*

4.1. Presence of Negative Bias

Figure 2 presents the initial analysis of the empirical probability distribution of estimation errors. The results showed a consistent negative bias across all encoding types, indicating a general tendency for participants to underestimate bar values. The maximum-patterned bars exhibited the largest underestimation (−3.10), followed by large-patterned (−2.08), non-patterned (−2.00), and grid-aligned (−1.78). The Small-patterned bars demonstrated the least negative bias, with a mean error of −0.71. A one-sample t-test confirmed that all encoding groups had significant negative bias ($p < 0.0005$), with the maximum-patterned encoding having the strongest effect.

Further analysis of variance distribution using Levene's test for equality of variance and Bartlett's test for homogeneity of variances indicated statistically significant differences between groups ($p < 0.0001$). A pairwise Levene's test revealed that the small-patterned encoding exhibited significantly different variance compared to the non-patterned encoding ($p = 0.0051$), with similar trends observed when comparing small-patterned to other encoding groups. These results suggest that while most encoding types had comparable variance distributions, the small-patterned bars introduced distinct variability in participant estimations, potentially influencing the interpretation of bar chart values.

4.2. Internal Patterns on Bar Chart

To assess the effect of internal patterns on perception accuracy, absolute error was used as the primary metric. A one-way ANOVA revealed significant differences between encoding groups ($p < 0.0001$), indicating that encoding type influences accuracy. Given the violation of homogeneity of variances (via Levene's test whose $p < 0.0001$), Welch's ANOVA was also conducted, confirming significant differences between groups.

Post-hoc comparisons using Tukey's HSD test identified that small-patterned encoding exhibited the lowest absolute error, significantly lower than the non-patterned encoding ($p = 0.0007$). Conversely, maximum-patterned encoding had the highest absolute error, significantly greater than non-patterned encoding ($p = 0.0041$). The ascending ranking of absolute errors across encoding types followed this order: small-patterned, grid-aligned, non-patterned, large-patterned, and maximum-patterned. This could be observed in the plot of means with 95% confidence interval in Figure 2.

These findings suggest that internal patterns can either enhance or hinder perception accuracy, depending on their size and design. Small, structured patterns appear to aid value estimation, whereas excessive pattern density introduces cognitive load, increasing error rates. The results highlight both the benefits and potential drawbacks of pattern inclusion in bar chart designs, emphasizing the need for careful consideration in visualization strategies.

The final research question examined whether bar positioning (left or right) influences perception accuracy and value estimation. A one-way ANOVA comparing absolute errors between bars on the left and right showed a higher error for right-positioned bars (labeled as "B" or positioned further from the y-axis), but the difference was not statistically significant.

5. Conclusion and Discussion

This study examined the impact of internal patterns on bar chart perception accuracy, emphasizing how different pattern designs influence value estimation. The findings indicate that small-patterned bars improved estimation accuracy, likely due to their discrete, countable structure within the *subitizing* range. Additionally, their alignment with the base-10 numerical system, where each pattern unit represents a value of 10, may have further supported accurate estimation. In contrast, maximum-patterned bars produced the highest error rates, likely due to visual overload and the inability to count individual patterns effectively. These results suggest that redundant encoding, when thoughtfully designed, can enhance data interpretation, but excessive complexity may impair accuracy.

Previous research [DMPV18] has shown that internal lines within bars improve value estimation accuracy by providing consistent reference lines. This study explored whether point-based visual cues within patterns could serve a similar function. Each pattern in this study contained four reference points, hypothesized to aid estimation by providing implicit visual anchors. However, this study results did not conclusively support point-based referencing as an effective alternative to line-based references. Further research is needed to determine whether optimized spatial arrangements or hybrid approaches, such as dotted reference lines, could improve the interpretability and flexibility of pattern-based bar charts.

This study explores the integration of pictographic elements into bar charts to enhance both aesthetic appeal and functional effectiveness. Prior research suggests that ISOTYPE-based pictographs improve memory retention and engagement [HKF15], potentially benefiting bar charts while preserving their quantitative representation. However, the impact of pattern shapes, referencing techniques, and pictographic symbols on accuracy and estimation remains uncertain. Beside this there may be opportunities to enhance understanding of other type of bar chart such as mean bar chart [KW21] using findings from this study. Future research should investigate whether these elements enhance comprehension or introduce visual distractions. Understanding these factors will help refine pictograph-inspired bar charts for improved usability and interpretability.

This study highlights the importance of intentional design choices in bar charts, demonstrating that patterns can enhance or hinder perception accuracy depending on their structure and complexity. To optimize readability, patterns should be countable, structured, and aligned with familiar numerical values. While pictographic and alternative referencing techniques show potential, further research is needed to refine their impact on data visualization. Ultimately, well-designed internal patterns can enhance both functional accuracy and aesthetic appeal, improving the effectiveness of bar charts in communicating complex information.

Acknowledgments

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References

[BXF*22] BURNS A., XIONG C., FRANCONERI S., CAIRO A., MAHYAR N.: Designing with pictographs: Envision topics without sacrificing understanding. *IEEE Transactions on Visualization and Computer Graphics 28*, 12 (Dec. 2022), 4515–4530. doi:10.1109/TVCG.2021.3092680. 2

[CF14] CHOO J., FRANCONERI S. L.: Enumeration of small collections violates weber's law. *Psychonomic Bulletin Review 21*, 1 (2014), 93–99. doi:10.3758/s13423-013-0474-4. 1, 2

[CM84] CLEVELAND W. S., MCGILL R.: Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American Statistical Association 79*, 387 (Sept. 1984), 531–554. 2, 3

[Coc77] COCHRAN W. G.: *Sampling techniques (3rd ed.)*. John Wiley Sons, New York, 1977. 3

[DMPV18] D´IAZ J., MERUVIA-PASTOR O., V´AZQUEZ P.-P.: Improving perception accuracy in bar charts with internal contrast and framing enhancements. *22nd International Conference Information Visualisation.* (2018), 159–168. doi:10.1109/iV.2018.00037. 2, 3, 4

[HKF15] HAROZ S., KOSARA R., FRANCONERI S. L.: Isotype visualization: Working memory, performance, and engagement with pictographs. *CHI '15: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (2015), 1191–1200. doi:10.1145/2702123.2702275. 2, 4

[HSBW13] HLAWATSCH M., SADLO F., BURCH M., WEISKOPF D.: Scale-stack bar charts. *Computer Graphics Forum 32*, 3 (2013), 181–190. doi:10.1111/cgf.12105. 2

[HWBvL20] HÖHN M., WUNDERLICH M., BALLWEG K., VON LANDESBERGER T.: Width-scale bar charts for data with large value range. *EuroVis 2020 - Short Papers* (2020), 103–107. doi:10.2312/evs.20201056. 2

[HZII24] HE T., ZHONG Y., ISENBERG P., ISENBERG T.: Design characterization for black-and-white textures in visualization. *IEEE Transactions on Visualization and Computer Graphics 30*, 1 (Jan. 2024), 1019–1029. doi:10.1109/TVCG.2023.3326941. 2

[KW21] KERNS S. H., WILMER J. B.: Two graphs walk into a bar: Readout-based measurement reveals the bar-tip limit error, a common, categorical misinterpretation of mean bar graphs. *Journal of vision 21*, 12 (2021), 17–17. 4

[KWCD20] KARDUNI A., WESSLEN R., CHO I., DOU W.: Du bois wrapped bar chart: Visualizing categorical data with disproportionate values. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), pp. 1–12. 2

[SB17] SALEH A., BISTA K.: Examining factors impacting online survey response rates in educational research: Perceptions of graduate students. *Journal of MultiDisciplinary Evaluation of the Eurographics Conference on Visualization 13*, 29 (2017), 63–74. 3

[SHK15] SKAU D., HARRISON L., KOSARA R.: An evaluation of the impact of visual embellishments in bar charts. *Computer Graphics Forum 34*, 3 (2015), 221–230. doi:10.1111/cgf.12634. 2

[TSA14] TALBOT J., SETLUR V., ANAND A.: Four experiments on the perception of bar charts. *IEEE Transactions on Visualization and Computer Graphics 20*, 12 (Dec. 2014), 2152–2160. doi:10.1109/TVCG.2014.2346320. 2

[Tuf86] TUFTE E. R.: *The visual display of quantitative information.* Graphics Press, 1986. 2

Proceedings published by Eurographics - The European Association for Computer Graphics.