1.1 Overview

The idea behind the experiment is to find the effects of redundant encoding on people's ability to comprehend the visualization quickly and accurately. Two parameters are taken into consideration i.e. Speed and Accuracy of a participant on both sets of Redundant and Non-Redundant experimental conditions i.e. two sets of 11 pairs of graphs (Pie Chart, Bar Chart, Scatter Plot, Line Chart, Maps,) with multiple variations of each chart with different data sets in order to average out the results for each type of chart. As two conditions need to be tested i.e. Redundant and Non-Redundant, we decided to conduct a within group approach experiment because of the following reasons: -

- Within group method requires fewer participants and every participant is exposed to all possible conditions.
- There are several factors like, mood of a participant that determines the level of participation which can affect the results. Hence, in order to avoid such differences and to get statistically correct results for each condition to evaluate results fairly.
- Higher chances to identify the true differences between Redundant and Non-Redundant visualizations.

In order to handle the learning effect and to counteract the possible order effect of within-group approach the order in which the questions asked in the experiment for both conditions is randomized.

An entity to be measured is called as a variable. Following are the two key variables in the experiment: -

1. **Independent variable(cause) -** Shape, Colour, Ordering, Label, Colour Hue, Size used as redundant encodings.
2. **Dependent variable(effect) -** Speed and Accuracy measured to evaluate redundant and non-redundant encodings.
3. **Confounding variables-** In order to obtain precise results, we must consider the factors that affect both dependent and independent variables. These variables can hamper validity of an experiment, cause us to incorrectly analyze the results and therefore, should be properly handled.

Following are the confounding variables along with approaches to overcome them:

Confounding Variables	Approach to overcome
Previous experience – experienced people can read visualizations quickly and accurately as the approach and methods to read various encodings are known to them, compared with the people who are not aware about the purpose of different encodings can take time or may interpret the encodings wrongly.	Participants familiar with basic visualizations to be considered.
Ability to perceive hue (Between 2 hue colour level), Size: where difference between data values is not significant.	Select colors having significant amount of difference in shades. Add a layer of dark color hue on Shapes to differentiate the size.
Noise - Environment around participants	Request participants to maintain silence.

Fatigue – Exhausted mind cannot give accurate results.	Give a short break after every 2 questions. Ask participants to come for the experiment with fresh mind.
Eye sight of the participants.	Select participants with no vision disability.
Ambient light of the room.	Should have same amount of ambient light throughout the room.
Resolution and Brightness of the devices	Laptops having same resolution and brightness.

1.2 Data collection

To evaluate the participants' performance, we will collect the following data:

- To measure accuracy, we will collect the answers given by the participants for each question.
- To measure speed, we will record the time required by the participants to answer each question.

Objective measurements are independent of observer i.e. unbiased measurement. Example: timing measures such as stop-watches, electronic timing devices and distance measure such as measuring tapes. **Subjective measurements** are dependent of observer. This measurement is based on observer's opinion and feelings while performing experiment.

In the experiment both Objective and Subjective measurements are considered. Objective measurements tell us about participants' performance (How correct the answers were - accuracy, how fast they were able to answer the given question - Speed) in carrying out the particular task without taking their opinion into consideration. We are also taking participants' opinion (Subjective measurement) into account as to which visualization (Redundant or Non-Redundant) is easy to interpret and answer the questions in an effective and faster way.

Collected data will be used to find how the addition of different redundant visual encoding (color, size, shape, order, labels) affects the user's ability to perceive the visualization in term of Speed and Accuracy. We can see how easy and accurate it is to get insights from the visualization based on the answers given by the participants and the time required to answer them. For ex: in pie-chart, how the redundant encoding of color hue can help readers to make more accurate judgements speedily.

1.3 Selected subjects

The main goal of this experiment is to check if redundant encodings has any effect on the way the visualizations are perceived in terms of accuracy and speed. For our experiment we will be targeting people from UCD i.e. students across different courses who have at least basic knowledge of reading charts. Students from the University have basic education background who can read charts and can also learn and comprehend different types of redundant encodings used in the charts to answer questions quickly and accurately. The group will have students of different age groups, gender.

We can request students to be a part of our experiment by sending them an email or put posters to tell them to be present for this survey event. In order to source larger audience we may consider using Mechanical Turk for the experiment to source larger audience based on HIT rate and educational level.

1.4 Data analysis

As it is a within group experiment each participant is exposed to both redundant and non-redundant set of visualizations to measure Speed and Accuracy.

- Speed measured in seconds.
- Accuracy is measured in terms of (correct answers/incorrect answers) to the questions.

For a particular visualization type, the speed of answering questions across all the different versions were averaged for redundant and non-redundant set respectively. For instance, in case of bar graph, speed of answering each question in 3 different bar graphs (Number of Houses Sold, Top 10 non-Irish Nationalities, Data Science jobs in US) were added up for the redundant and non-redundant set separately. This figure was then averaged by the total number of observations (total number of questions across 3 different versions of bar graph * number of participants) for each redundant and non-redundant set.

Similarly, in order to check the accuracy of judgement, number of errors were counted for each chart type across all the different versions for redundant and non-redundant set. This measure if divided by the total number of questions asked in all versions for a particular chart type gives the error rate. Since, the number of questions in redundant and non-redundant set for a particular chart type are same we can ignore the denominator and focus on raw error counts.

By comparing speed and accuracy with chart type and its redundant pair. All these comparisons will be considered to reflect on the idea of whether adding a redundant encoding improves speed and accuracy of cognition.

1.5 Practical setup

Initially, we will conduct a pilot experiment to ensure everything goes well in the actual experiment. Pilot experiment will help us to find the problems in the experiment design and the issues which can be fixed before the actual experiment. Each participant would be requested to answer two sets of questions online i.e. redundant and non-redundant questionnaire and time taken for each question along with their response will be stored in database for further analysis.

The actual experiment will be performed offline within a controlled environment i.e. in a computer lab to ensure there's no disturbance around the participants to help them focus on the task given in order to get more accurate readings without any noise in the data recorded. The ambient light of the room will be maintained same throughout the room and will make sure that resolution and brightness of all the desktops are same.

Following are the instructions to be given to the participants: -

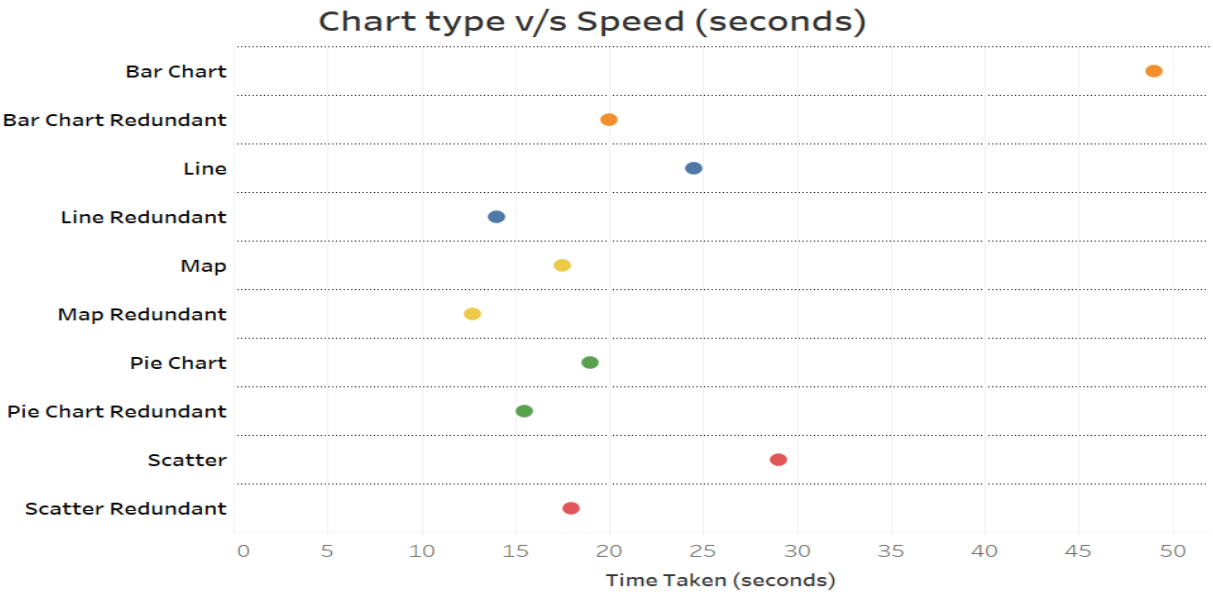
- Not to use any external gadgets like mobile while completing the tasks or do anything which can consume time unnecessarily.
- Not to access to any material online or external sources while answering the questions.
- Encouraged to answer all the questions properly.

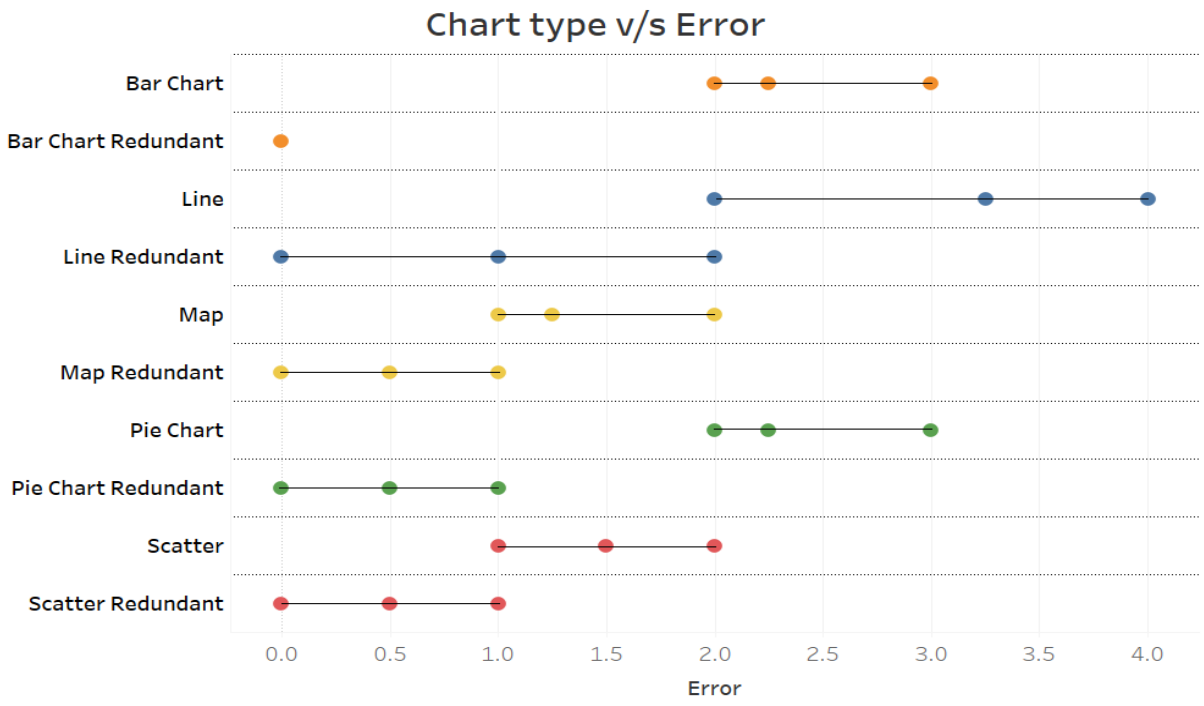
We can use Mechanical Turk to source larger audience for our experiment. Here we can create a HIT containing our sample visualizations along with questions providing detailed instructions to carry out the survey. The participants can be selected based on their HIT rate (90% & above) and educational level. Dummy questions can be included to filter out responses and check if the survey was attempted properly.

2 Pilot Experiment

2.1 Data Analysis

Below are the visualizations containing results of the pilot experiment:





*Speed measured in seconds *C- Correct, NC- Incorrect, NC CS- Incorrect & Can't Say			Rohit				Rafeh				Manjunath				Tejaswi			
			Redundant		Non-Redundant		Redundant		Non-Redundant		Redundant		Non-Redundant		Redundant		Non-Redundant	
Chart Type	Visualization Name	Question No	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed	Accuracy	Speed
Pie Chart	Top 10 countries-Pop	1	C	15	C	35	C	10	C	27	C	11	C	42	C	18	C	29
		2	C	17	C	19	C	9	C	18	C	10	C	18	C	14	C	18
	Top 10 popular cars	1	C	17	NC	20	C	17	C	25	C	15	C	19	C	13	NC	27
		2	C	23	C	15	C	19	C	24	C	17	NC	13	C	15	C	23
	Top 10 retailers - 3	1	C	18	C	22	C	12	NC	14	C	13	NC	23	C	12	C	13
		2	C	13	NC	20	C	11	NC	13	C	10	NC	20	C	13	NC	11
	Top 10 retailers - 3.1	1	C	10	C	18	C	10	C	22	C	8	C	24	C	12	C	22
		2	NC	12	C	21	C	14	C	19	NC	12	C	19	C	11	C	21
Bar Chart	Number of Houses Sold	1	C	10	C	21	C	15	C	20	C	13	C	23	C	14	C	18
		2	C	11	NC	19	C	8	C	16	C	10	C	21	C	12	NC	15
		3	C	70	NC	198	C	55	NC	190	C	60	NC	217	C	75	C	185
	Top 10 non-Irish Nationalities	1	C	8	C	13	C	15	C	19	C	14	C	15	C	9	C	17
		2	C	7	C	21	C	7	NC	14	C	9	NC	25	C	11	C	15
	Data Science jobs in US	1	C	19	C	45	C	17	C	42	C	15	C	36	C	21	C	46
		2	C	15	NC	27	C	13	C	31	C	13	C	29	C	17	NC	31
Map	Statewise Crime in US	1	NC	15	NC	22	C	21	C	27	C	17	C	21	NC	15	NC	31
		2	C	13	C	16	C	8	NC	12	C	8	NC	14	C	12	C	10
		3	C	11	NC	15	C	12	C	18	C	11	C	14	C	9	C	11
Line	Tickets sold at different zoo's	1	NC	13	NC	17	C	15	C	18	NC	15	C	17	C	12	C	15
		2	C	14	C	24	C	25	NC	27	C	21	C	26	C	17	C	27
		3	C	15	C	18	C	17	C	20	C	15	NC	18	C	14	C	20
		4	C	12	NC	27	C	13	C	24	C	11	NC-CS	45	C	13	NC	19
		5	C	13	NC	33	C	10	C	31	C	10	NC-CS	45	NC	15	NC	36
	Average house price across county's	1	C	14	C	23	C	13	C	20	C	13	C	31	C	12	C	11
		2	NC	11	NC	27	C	12	C	21	C	12	C	25	C	10	NC	13
		3	C	16	C	24	C	18	NC	25	C	19	C	27	C	15	NC	28
Scatter	Bills paid vs tip on Family Size	1	C	31	C	39	C	34	C	38	C	31	C	44	C	28	C	41
		2	C	10	NC	17	C	7	C	12	C	9	NC	16	C	10	C	11
		3	NC	11	C	21	C	18	NC	29	C	16	C	23	NC	12	NC	39
	Bills paid vs tip on Dinner/Lunch	1	C	18	NC	37	C	20	C	25	C	19	NC	45	C	17	C	25

We found that when the chart was too complex to comprehend (e.g. "zoo" line chart where it had multiple lines crossing/overlapping each other, bar chart to find groups of counties in "Number of houses sold" chart), it was quite time consuming for the participants to keep track of each line/ segregate unordered bars based on length and answer the questions effectively. Introducing redundancy by adding color in line chart and ordering, hue and labels in bar chart, the error rate reduced significantly for bar chart from 2.25 to 0 and halved in case of line chart. For pie charts, adding ordering and hue as redundant encoding greatly improved accuracy (reducing error rate by nearly 4 times) as it became easy to interpret the difference in similar slices. Participants rated redundant pie chart easier to interpret than non-redundant one. Adding shape and size as redundant encodings in maps and scatter plot made it easier to interpret the nuances between two states (crime rate Map chart)/groups (Bills vs Tip scatter plot) which improved accuracy. The speed of answering improved significantly (approximately twice) in case of bar, line and scatter chart. Different colors for each line, different shapes and size for different groups in scatter plot and ordering in bar charts made the visualizations more interpretable and reduced the time taken by participants to answer the questions. Also, there were few questions where the time taken to answer non-redundant set was less or almost same to that of redundant set. Furthermore, the mean time for interpreting map and pie chart did not vary significantly but there was a significant decrease in error rate.

To summarize, by comparing speed and accuracy of each chart type with its redundant pair, we conclude that adding a redundant encoding improves speed and accuracy of cognition.

2.2 Reflections

Our results with adding redundant visual encoding closely relate with our hypothesis which validates our point that addition of redundant encoding improves speed and accuracy of perception.

Following are the learnings of our experiment:

- While designing and carrying out our experiment we understood the significance and importance of handling the confounding variables properly to achieve expected results. For instance, while designing our experiment low brightness of the screen hampered readability of visualization. Therefore, while carrying out the experiment, we ensured that all laptops have same screen resolution and brightness.
- We understood the differences in design approaches for between and within group and their uses based on the application. For instance, we used within group approach as we wanted to discover true difference in speed and accuracy between redundant and non-redundant set of visualizations and reduce noise.
- Questions could be framed in a better way making them more detailed and extend them to cover wide range of conditions.
- We learned various visual properties used in encoding, such as position, length, angle, area, or color known as visual variables.
- We found that choice of redundant visual encoding depends on the type of data. E.g. For categorical data shape and color is more effective and for quantitative data size and color is more effective. This indicates that using a combination/ pair of visual encodings may lead to redundancy gain in terms of perceptual accuracy and response times than either encoding has alone.
- We learned ways to interpret data collected to draw meaningful inferences from the experiment by using statistical measures like mean, error rate, accuracy.
- Although our experiment validates our hypothesis, we observed that we cannot extend the claim to all possible encoding combinations and might need to run the experiment across a wide range of audience, cover more conditions for different chart types to find effective redundant encoding pairs.

When the charts were too complex to comprehend, adding redundant encodings helped to get a faster and accurate response. However, we found that sometimes the mean processing time for a chart type did not vary significantly which meant that addition of redundancy did not aid or hamper visual cognition. Therefore, the role of redundant encoding in such cases is purely for aesthetic purpose and this notion can help designers to weigh aesthetics over concerns that such redundancy might confuse or hinder interpretation.

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