Technology Project: The Cognitive Ergonomics of Interactive Decision-making in Personal- and Action-Space within 3D Virtual Reality Environments

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Index Terms: Immersive analytics and visualization—Perception and cognition

1 Abstract

An experiment was conducted to quantify the decision-making performance as a function of two kinds of spatial depth ranges: personal space and action space. The participants were presented with a prediction-centered decision-making task. They were provided with some relevant information (i.e. highly correlated to the prediction) and irrelevant information (i.e. uncorrelated to the prediction). This information was presented at variable spatial depth. The decision-making effectiveness was measured by in terms of their interaction with the virtual environment and decision-making performance. It was compared across four environment configurations to correlate decision-making effectiveness and spatial depth of information presentation. The overall decision-making accuracy for this task (27.6%) was very low to concretely conclude anything. Moreover, the repeated ANOVA test showed the results to be statistically insignificant.

2 Background

Virtual reality environments (VEs) have immense potential to be a platform for visualizing and analyzing information for complex and collaborative decision making, making them ideal candidates for the future of operation centers dedicated to situation awareness and management of complex networks. Owing to their interactive [1] and immersive nature, the users can become active participants in their process of comprehension of information. The development of a VE requires many design considerations as per its purpose. However, how best to design environments to support specific workflows remains an open question. Effective data visualization is the bridge between the quantitative content of the data and human intuition, and thus an essential component of the scientific path from data into knowledge and understanding.

The space around the user can be segmented into personal space (the zone surrounding the user within arm's reach; typically, within 2 meters) and action space (the circular region just beyond personal space; typically, within 30 meters). Prior work [4] has demonstrated that people attend to the personal space, differently from the action space. For designing an effective VE, it is crucial to answer the question how people attend to problem-solving information in different depth configurations of a VE. The correlation between spatial depth of information presentation and decision-making effectiveness can then be utilized to present the task-relevant information at optimal spatial depth in order to improve the decision-making effectiveness.

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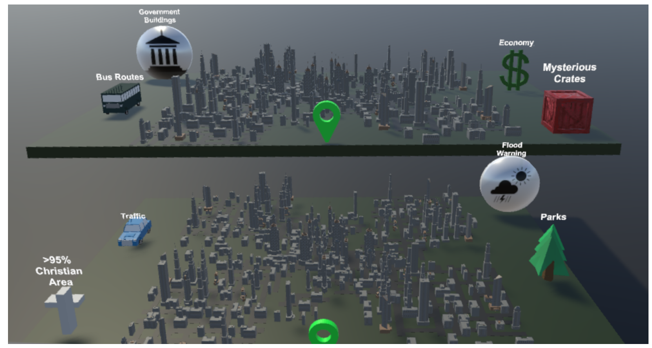

Figure 1: Snap from the experiment task showing that the information is presented in personal space (within arm's reach) and action space (outside arm's reach).

The external visualizations in VEs have the potential to augment cognition and to allow effortful cognitive processes to be off-loaded onto less effortful visual system processes. The results of previous controlled studies of the effects of interactivity in visual-spatial tasks are mixed. A study [6] on spatial reasoning with external visualizations concluded that providing participants with active control of a computer visualization does not necessarily enhance task performance. The participants who saw the most task-relevant information , and this is true regardless of whether the task-relevant information is obtained actively or passively. Thus, the VE design should be utilized to accurately convey relevant information to the user which is important for decision-making. If we purport interactive VEs to effectively extend analytic workspaces, we must guarantee that this effectivity is invariant with respect to interactivity.

Prior work [7] presents a set of ten low-level analysis tasks that largely capture people's activities while employing information visualization tools for understanding data. These primitive tasks are to retrieve, filter, derive, find extrema of, sort, determine the range of, characterize the distribution of, detect anomalies within, cluster, and correlate data. These tasks are recommended to incorporat in information visualization systems to facilitate the user's analytic activities.

3 VR Techniques

In this project, I have evaluated cognition and perception processes using data visualization in virtual reality. The key components of a decision-making task are to understand the provided data and analyse it to discover meaningful hidden patterns in it and then interpret the knowledge of these patterns to arrive at a logical decision. Visualization is the main bridge between the quantitative content of the data and human intuition, and it can be argued that we cannot really understand or intuitively comprehend anything (including mathematical constructs) that we cannot visualize in some way [1]. Humans have a remarkable pattern recognition system in our heads, and the ability for knowledge discovery in data-driven science depends critically on our ability to perform effective and flexible visual exploration.

With this project, I tried to answer the question: ”What is the effect of perceived spatial depth on decision-making within interactive VEs?” Here, I focus on part of that question by looking at decision-making as a function of two kinds of spatial depth ranges: personal space and action space.

4 METHOD

A prior study [2] investigated insight generation and decision making with visualizations in 2D and 3D Virtual Environments. Here the participants were presented with a task to predict the location of a possible future threat in a fictional city on the basis of a 3D visualization of the city. I have expanded this experimental task as per the requirements of this project.

4.1 Prior Task Details

In this task, a terrorist has been leaving bombs in crates around a fictional city. Officials believe the terrorists were following a pattern in choosing their targets. The participants were expected to determine the most likely location for the next crate to be placed in so that security can be increased within the area. The time limit was 10 minutes.

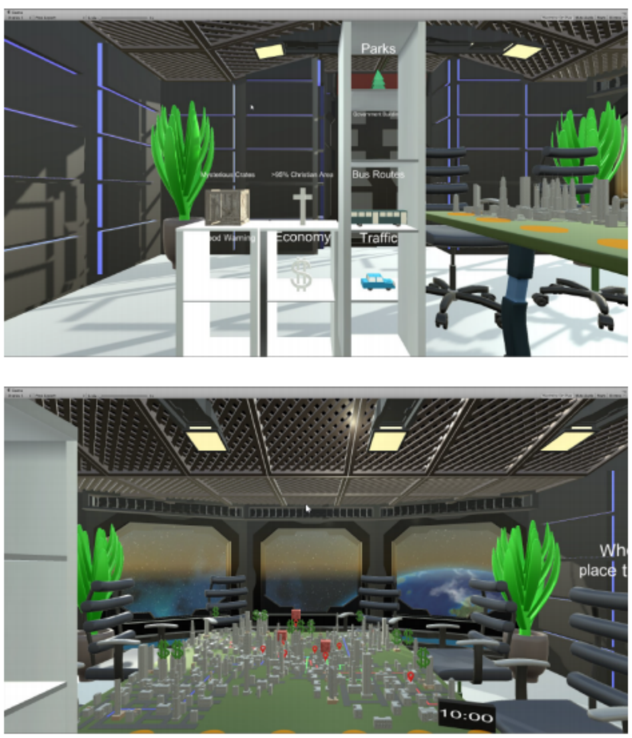

Figure 2: (a) The shelf containing the icons for the map overlays. (b) Information visualization on the city model in the prior task.

To assist with this, the user had access to a 3D visualization of this fictional city containing information about the city and the previous attacks. The information consists of relevant information (mysterious crates location, government building locations, income for areas and bus routes) and irrelevant information (traffic, flood zones, park locations, and religious centers). The correct answer was achieved by realizing the correlation between important variables and precisely indicating the next attack location on the map. In this study, all information was presented within personal space.

A map of a fictional city was created using Unity version 5.6.3, VRTK version 3.1. Geo-spatial and socio-cultural information was displayed with user controlled overlays. The participants interacted with the application using HTC Vive controllers. The map-overlays were on a shelf located to the side of the map in reach of the participant as shown in 2. Participants activated overlays by grabbing them with controllers and placing them on the circles at the front of the table. The timer was located at the front left of the table. Participants were free to move within the virtual environment and could view the map from both an egocentric and allocentric perspective (by looking directly down on the map).

4.2 Modified Virtual Environment

A new virtual environment was developed from scratch using the prior virtual environment as a reference to accommodate the presentation of relevant and irrelevant information at varying spatial depth. I have used Unity 2019.2.1, VRTK 3.3 and Steam 1.2.3 for the development of this project.

4.2.1 Personal space and Action space

In the prior design, the fictional city information was presented on a table in personal space. Since two spatial depth configurations for information presentation was required, a replica of the table is created. The first representation of the fictional city is placed in the personal space with respect to the participant’s initial position such that the model is within arm’s reach of the participant. The second representation of the fictional city is placed in the action space as shown in 1. This model is twice the size of the personal space model and farther away from the participant. The participant is free to move in the environment. The participant can view the map from both an egocentric and allocentric perspective (by looking directly down on the map).

4.2.2 Geo-spatial and socio-cultural information

The participant has access to the geo-spatial and socio-cultural information of the fictional city. The participant is provided with the three types of information:

- Position information: This includes the location of three mysterious crates, nine government buildings and three parks.

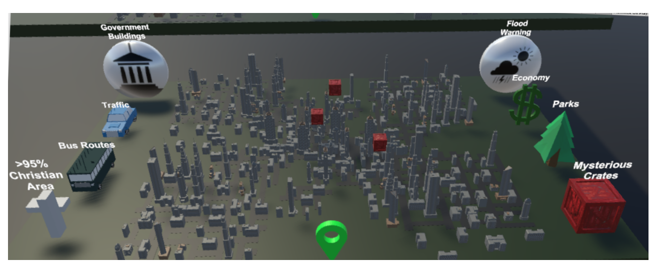

Figure 3: A red crate object is placed over the locations of the three mysterious crates in the city.

- Regional information: This includes the regions of economy (high income, medium income, low income), region with more than 95% christian population and two regions with flood warning.

- Map information: This includes the map of the color coded traffic (green: no traffic, yellow: moderate traffic, red: traffic delays) and bus routes (red, blue and green line bus).

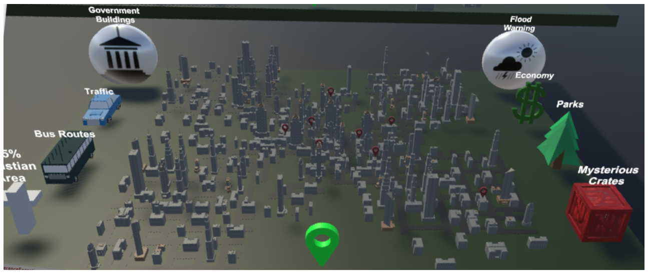

Figure 4: A red marker is placed over all the nine locations of the government buildings in the city.

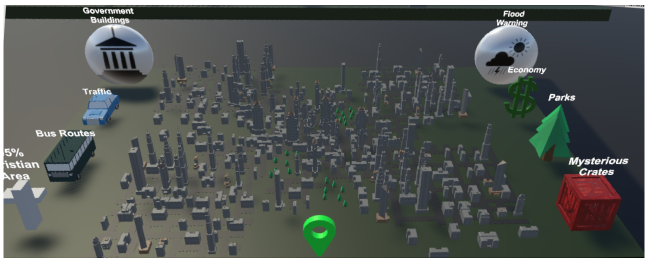

Figure 5: A bunch of tree objects are placed over the park locations in the city.

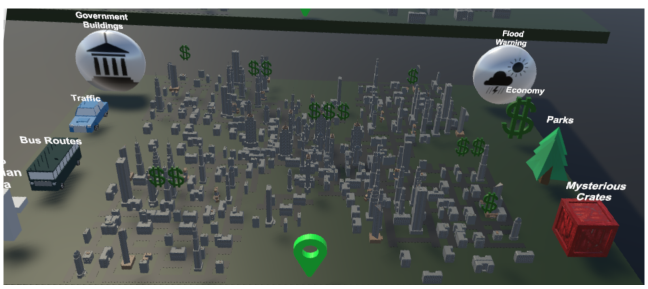

Figure 6: The income areas are denoted by placing a few dollar symbol objects over each area in the city.

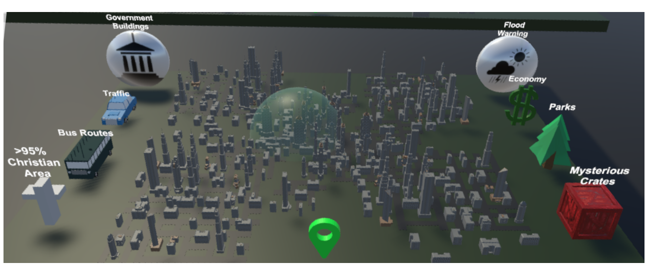

Figure 7: The region with more than 95% christian population is highlighted with the translucent dome in the city.

The information that highly correlated with the prior threats is government buildings (position information), high income zones (regional information) and the bus routes (map information). In this project, I have used the exact same geo-spatial and socio-cultural information as the prior task. All this information is fictional and was carefully created while avoiding any conflicting information to fulfill research purposes of the prior task.

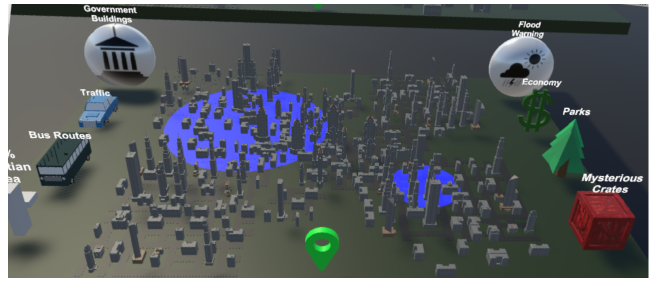

Figure 8: Two regions with flood warnings are highlighted in the city.

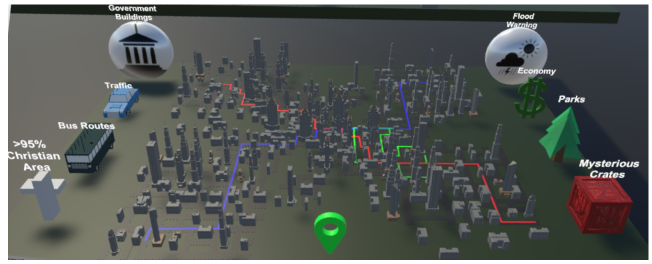

Figure 9: Bus routes are highlighted in the city.

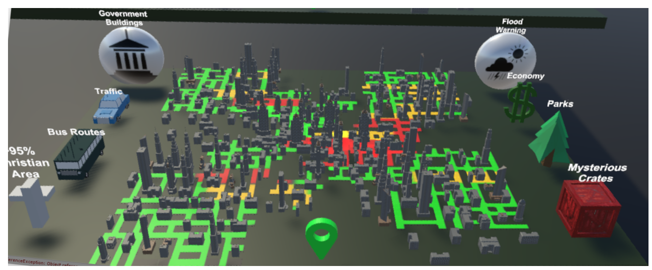

Figure 10: Traffic zones are highlighted in the city.

4.2.3 Map Overlays

In the prior task, the icons for each category of the information were displayed on a shelf. The participant then activated the overlays by grabbing them with controllers and placing them on the circles at front of the table. Here, the participant had to walk to the shelf to activate an overlay everytime. This design imposed certain barriers on the participant's movement within the VE and thus decreased the time efficiency. I improved this design in the new VE to overcome this barrier. In the new VE, the 3D icons are present on the sides of each table. The participant can activate an overlay for a variable by pointing at its icon and clicking the touchpad press on the Oculus Touch controllers. Similarly, another point and click action deactivates the map overlay. Alternatively, the participate can toggle an overlay with a controller by pressing the trigger button on the controller. This design is more convenient and less restrictive as compared to the previous design. The participant can grab the final marker with a point and grab action or by just grabbing the final marker with a controller. The participant can use either the left or right controller for performing these actions.

The map overlay structure varies according to category of the information. For the position variables, an icon is placed on the city model to mark the corresponding locations. For the regional information, the region of the city is marked using an icon or highlighted by projection of an image. For the map information, an image is projected on the city model. For solving the decision-making task, the participant has to place a marker on the most likely location of the next crate.

4.2.4 Analysis Tasks

I attempted to incorporate analysis tasks to facilitate the participant to make an informed decision within this interactive VE. Prior work [7] suggests a set of ten low-level analysis tasks. Those are to retrieve, filter, derive, find extrema of, sort, determine the range of, characterize the distribution of, detect anomalies within, cluster, and correlate data. However, all the information related to this task is nominal (no meaningful order exists). Also, all this information is fictional and was carefully created while avoiding any conflicting information to fulfill research purposes of the prior task. Hence, modifying the information to incorporate analysis tasks was beyond the scope of this project.

In order to improve the analytic capabilities of this application, the data for this task should be augmented to introduce scalar and ordinal variables to the existing categories. Some of the possible ways of augmenting each category of information suitable to this particular dataset and task are discussed below:

- Crate Locations: The time of the day when the crate was placed, the day of the week the attack happened, number of people affected by the attack.
- Government Buildings: The buildings with high ranking officials, buildings dealing with money/currency, building rankings according to importance.
- Parks: The average number of people visiting the park, the age group of people visiting the park.
- Flood zones: The flood warning zones doesn't seem like an important variable for predicting the next crate location.
- Economy: Quantify the income of each region in the city, the regions with the most tourists
- Religion: The percentage of christian population in every region in the city, the location of the churches in the city, the time of prayers/festival celebration.
- Traffic: The peak hours during the day, the average number of vehicles on a road, the average number of accidents on a road.
- Bus Routes: The average number of travellers, frequency of each bus line, the timings for the first and last bus and the peak hours during the day.

Since this task deals with the crate locations placed by the terrorists, the most important variables are those which indicate population, money and high impact areas.

4.3 VE Configurations

In this study, the depth range (personal, action) and information relevance (relevant, irrelevant) are independent factors. This study is a 2x2 within-subjects design. Every participant was exposed to four VE configurations one after the other:

- The irrelevant information was presented in the personal space and the relevant information was presented in the action space. The participants were free to make the decision in any one of the spaces.
- The relevant and irrelevant information was presented in the action space. The participants had to make their decision in the action space.

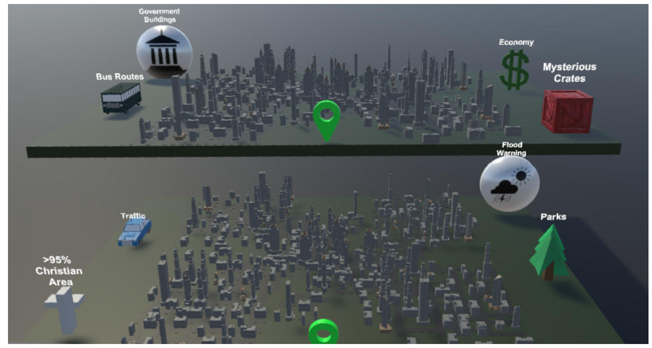

Figure 11: The irrelevant information is presented in the personal space and the relevant information is presented in the action space.

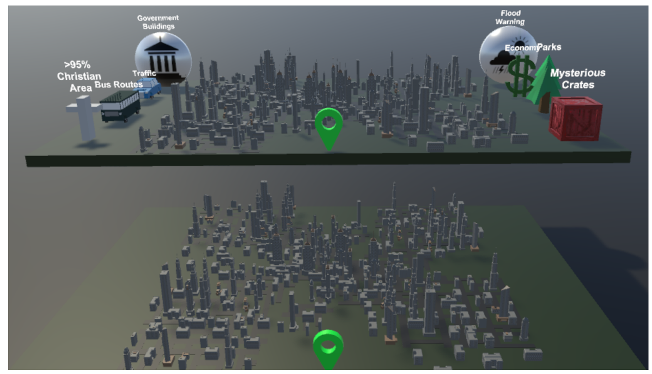

Figure 12: The relevant and irrelevant information is presented in the action space.

- The relevant information was presented in the personal space and the irrelevant information was presented in the action space. The participants were free to make their decision in any one of the spaces.

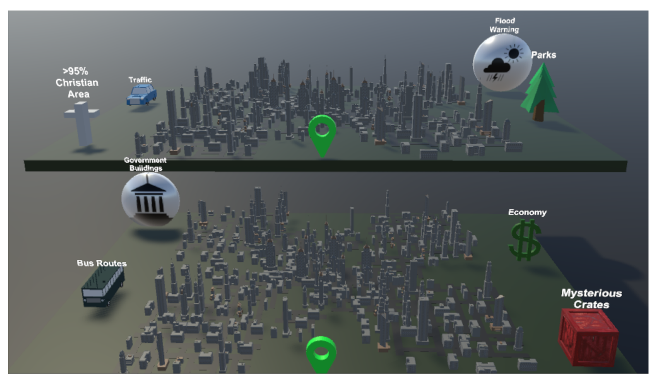

Figure 13: The relevant information is presented in the personal space and the irrelevant information is presented in the action space.

- The relevant and irrelevant information was presented in the personal space. The participants had to make their decision in the personal space.

In this experiment, the participants's problem solving performance was tested. Obviously, some subjects might have performed better than others regardless of the condition they were in due to

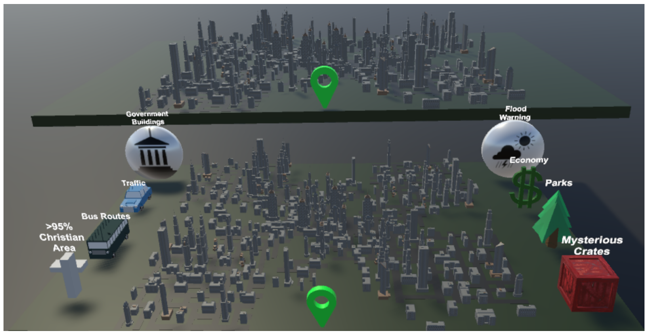

Figure 14: The relevant and irrelevant information is presented in the personal space.

differences in their skills. To address this concern, a within-subjects design was used for this study. Within-subjects designs control these individual differences by comparing the scores of a subject in one condition to the scores of the same subject in other conditions. However, if all the subjects attempt the task in the same order of VE configurations the results may be biased. This was addressed by counterbalancing the order of VE configurations. The order in which the participant was exposed to the above four configurations was uniformly varied to ensure unbiased results.

4.4 Dependent Variables

The dependent variables indicating the decision-making performance and VE activity were logged by the application. Specifically, they are:

- Accuracy of prediction: A prediction for the decision-making task is a location on the city model. A prediction is considered accurate if it lies in certain radius to the correct location.
- Time to each prediction: The total time spent by the participant in each VE configuration. Also, the time duration between the marker was first grabbed and the final prediction was also recorded.
- Information usage count: The number of times a category of information was activated by clicking its icon.
- Information usage duration: The total time for which a category of information was active on the city model.
- Displacement: The physical displacement of the participant from their starting location in the VE.

This study has 2 nominal independent variables i.e. spatial depth and information relevance and scalar dependent variables. Also, it has repeated measures due to the within-subjects design. Thus, for testing the hypothesis, repeated measures ANOVA test was used.

4.5 Power Analysis

The parameter values used for power analysis for repeated measures ANOVA test are as shown in the table below:

Effect size	0.1	0.25	0.4
Significance level	0.05	0.05	0.05
Power	0.80	0.80	0.80
Sample Size	273.5429	44.59927	18.04262

The sample size was evaluated for 3 values of effect sizes 0.1, 0.25, and 0.4 represent small, medium, and large effect sizes respectively. For large effect size, atleast 18 participants are required to reject the null hypothesis. The 'pwr' package in R was used for these calculations.

4.6 Hypothesis

The null hypothesis is that variation in the depth of presentation of information does not affect decision-making. In this case, the participants are expected to exhibit similar decision-making performance and VE activity i.e. they will have similar number of incorrect predictions, time to each prediction, information usage count and locomotion displacement from starting location in all four configurations.

Our alternative hypothesis is that variation in the depth of presentation of information affects decision-making. In this case, the participants will have significantly better decision-making performance and VE activity in one of the four configurations. They are expected to have a lesser number of incorrect predictions, lesser time for each prediction, and lesser information usage count. It is hard to comment about locomotion displacement from starting location. It depends on whether personal or action space space is the perceived depth for effective decision making.

4.7 Procedure

18 college-aged students participated in the experiment. They had access to the 3D visualization of the fictional city in the personal and action space. They were able to activate the geo-spatial and socio-cultural information via the map overlays. They were asked to predict the location of the next crate by placing a green marker. Once they confirmed their decision they automatically moved to the next configuration. Every participant attempted the decision-making task in four configurations and made one decision every time. The order of these four configurations was uniformly varied to overcome any bias. The visualisation was displayed using Oculus Rift S HMD and the map overlays were controlled using Oculus Touch controllers. There was no time limit for solving this task. All the dependent variables were logged during the experiment.

5 Results

The participants attempted the decision-making task in four configurations:

- C0: The irrelevant information was presented in the personal space and the relevant information was presented in the action space.
- C1: The relevant and irrelevant information was presented in the action space.
- C2: The relevant information was presented in the personal space and the irrelevant information was presented in the action space.
- C3: The relevant and irrelevant information was presented in the personal space.

	C0	C1	C2	C3
Number of correct decisions	7	3	5	4

Out of the 18 participants, 9 participants predicted the correct location atleast in one configuration out of all the four configurations. The overall decision making accuracy percentage was 27.6% across all the decisions. This is a poor overall accuracy to concretely conclude anything. The best accuracy was observed in C0 followed by C2, C3 and C1. In both C0 and C1, the relevant information was presented in the action space. Hence, the spatial depth is not the influencing the decision accuracy. Moreover, in C0 and C2 the relevant and irrelevant information was presented at different spatial depths and the accuracy was the highest. It is more likely for the participant to see the relevant information when relevant and irrelevant information is presented at different spatial depth.

The average amount of time for which each information was active and total time spent in a configuration as shown below:

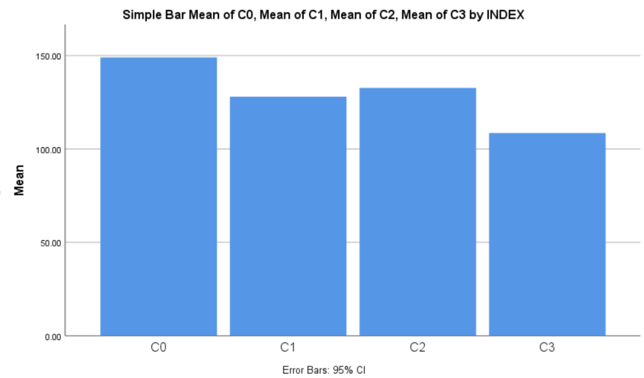

Figure 15: Mean of the total time spent in each configuration

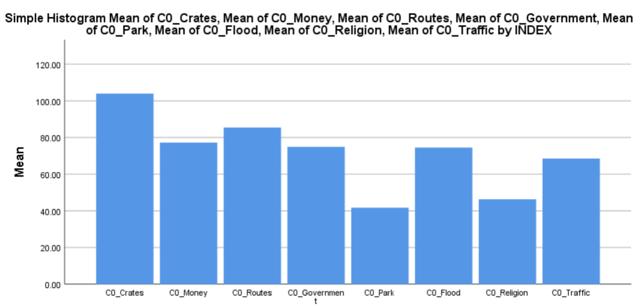

Figure 16: Mean of the time for which each information was active in C0

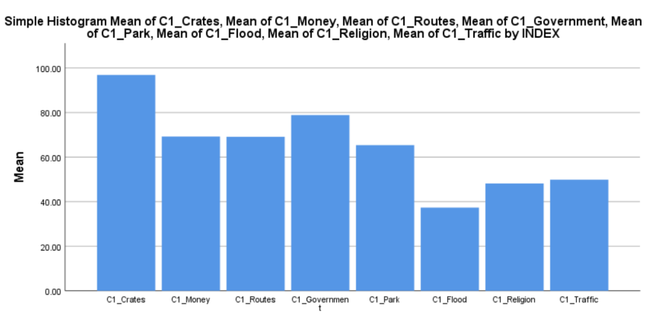

Figure 17: Mean of the time for which each information was active in C1

On an average the participants spent 149, 128, 133 and 109 seconds in C0, C1, C2 and C3 configurations respectively and 8 min 39 sec in total for four predictions. In all the configurations, most of the relevant information was active significantly for more time than

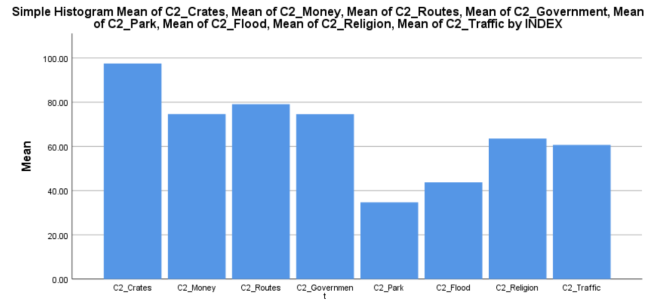

Figure 18: Mean of the time for which each information was active in C2

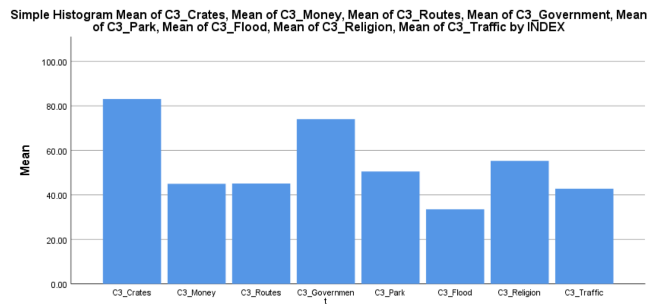

Figure 19: Mean of the time for which each information was active in C3

the irrelevant information. Most of the people figured 3 out of the 4 relevant factors correctly during the experiment.

The information usage count data for the relevant and irrelevant information has little variation in the median values across the configurations. Most of the participants activated a category of information once in each environment configuration. No meaningful pattern is observed in the information usage count data.

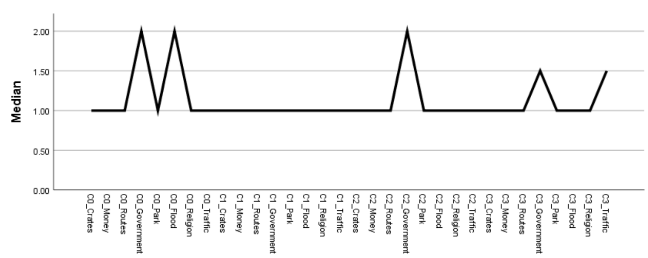

Figure 20: Median of the information usage count of relevant and irrelevant data across all the configurations

The displacement data shows lot of variation across the participants. No meaningful pattern is observed in the displacement data too.

The participants were free to place the final marker on the model either in personal space or in the action space in each configuration. 91.6% of the participants placed the final marker on the model with the relevant information. This indicates that participants were more sensitive towards the task relevant information as compared to the irrelevant information.

Repeated measures ANOVA was performed on the accuracy of prediction, the time to each prediction, information usage count and information usage duration. The significance values for each of these dependent variables are greater than 0.1. Hence, the results are statistically insignificant.

6 Reflection

In this project, I have built a VE for a prediction-centered decision-making task which incorporates the configurations of varying spatial depth for presentation of information. This has enabled us to correlate decision-making performance with spatial depth.

The overall decision-making accuracy (27.6%) is very low to concretely conclude anything. The trends observed in the data were that for both C0 (the highest accuracy) and C1 (the lowest accuracy), the spatial depth (action space) of the relevant information presentation was same. Hence, the spatial depth was not the influencing the decision accuracy. Moreover, in C0 (the highest accuracy) and C2 (the next highest accuracy) the relevant and irrelevant information was presented at action space and personal space, personal space and action space respectively. It is more likely for the participant to see the relevant information when relevant and irrelevant information is presented at different spatial depth. This experiment hints that presenting information at varying spatial depth does not necessarily improve the decision-making accuracy, whereas seeing the most prediction relevant information does, and this is true regardless of whether the relevant information was presented in personal space or action space.

In all the configurations, most of the relevant information was active for significantly more time than the irrelevant information. Most of the people figured 3 out of the 4 relevant factors correctly during the experiment. Also, 91.6% of the participants placed the final marker on the visualization with the relevant information. This indicates that participants were more sensitive towards the task relevant information as compared to the irrelevant information.

7 Conclusion

The overall decision-making accuracy for this task (27.6%) was very low to concretely conclude anything. Moreover, the repeated ANOVA test showed the results to be statistically insignificant.

7.1 Ethical Impact

7.1.1 Privacy

Most of the Virtual Reality(VR) technologies have access to user's personal information like patterns of eye movement, motor responses, and reflexes, which together constitute a person's distinct 'kinematic fingerprint.' Yet more information about the habits, interests, and tendencies of VR users may be captured as well, which could be stored and deployed in ways that threaten personal privacy [8].

Since this is a data visualization tool, its software will have access to the data visualized by the user as well. This raises major concerns about the privacy of this data. In certain cases, this tool can have access to sensitive data which may be dangerous if shared/sold to other agencies. Data related to national security, health records, financial records are examples of sensitive data.

7.1.2 Manipulation

This tool is useful to assist people in making complex decisions effectively with the help of visualizations and the low-level data analysis features. According to our hypothesis, the way of information presentation affects the decision making process. Additionally, problematic representations or misrepresentation of information can affect the decision itself. The risk of personal manipulation is even more grave than privacy violation.

Since VEs can be readily modified according to specific aims of influencing beliefs, emotions, and behavior, such manipulative potential could be easily exploited for a variety of purposes, ranging from commercial to political ends [8]. Any misrepresentations can alter users' views of actual individuals, people groups, objects and perspectives on real life issues. VR programs could be used to manipulate users in other ways as well in order to influence their offline behaviors [3].

7.2 Societal Impact

Virtual reality (VR) is a powerful technology with a potential to alter human society. VR has the ability to change perceptions and interactions and hence it can lead to massive psychological consequences. Most of the social risks are associated with the way VR blurs the distinction between the real world and the illusion. The immersive and addictive nature of certain VR technologies are the root causes of most mental health issues. In some cases, the VEs welcome aggressive, sexual, age inappropriate, unacceptable behaviour which is unacceptable in the real world and this may result in concerning offline behaviour [5]. However, this particular project is very different from these kind of VR technologies. In my opinion, there are minimal negative societal implications.

The application of effective data visualization for improved decision-making in interactive VE can be found in almost every field. Practically, any complex decision-making task with an associated dataset will be benefited with this project. It is self-evident that improved decision-making will benefit the society as a whole. Some important possible applications are as follows:

- In academia research with the advances in science, we are dealing with tons of data. The knowledge of effectiveness of data visualization as a function of perceived depth can help to create better VE designs for analytical task in interactive VEs.

- In the field of health and medicine, a doctor can use a more effective data visualization tool for better insight in complicated cases. It will be helpful for accurate analysis of patient's disease based on his health records.

- In field of teaching and learning, better visualization tools will help the students to grasp the subject better. With the advantage of interactivity, the learning process can become more practical and hence more effective.

7.3 Future Directions

The overall accuracy of the decisions was quite low. This task can be experimented with an easier problem to see if the spatial depth of presentation has a greater effect when participants are better able to arrive at an accurate response.

The fictional information for this task can be augmented to include more numerical information. This will enable us to incorporate the primitive data analysis tasks within this VE and understand its role in improving the decision-making performance. The inclusion of low-level analysis tasks in the VE will also improve the overall analytic capability of this application. However, this data augmentation process requires meticulous work to ensure that all the information is coherent. Also, special care should be taken to avoid introduction of any ambiguities.

Currently, this project is designed for a single user task. However, application-wise it will be more useful to study this problem for multi-user case. That way we can actually study the effectiveness for collaborative decision-making scenario. However, multi-user system adds certain complexity to the design. Every user will have a different personal space depending on the user's position. The design challenge is to present the information at certain depth for every user.

8 Acknowledgements

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