Interactive 3D Data Visualisation in AR:

How can we educate people about their spending habits through the use of 3D data visualisation in AR?

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Abstract

Graphical representations of data have been used for hundreds of years for the pupose of communicating ideas, educating and solving problems. Their use and form have evolved over time as new presentation techniques and technologies were developed. In recent years, the field of big data has been expanding signififcatly, which has led to an increase in demand for interactive data visualisations. This demand is driven by the need to understand large amounts of data that are becoming increasingly difficult to be processed by the human brain. Along with the growing need for data visualisations, new immersive technologies have been developed which offer new possibilities in presenting information, allowing users to be 'immersed in data'.

Behavioural data is an area of big data that is continuously growing. This data is collected and processed with the goal of improving physical, mental, and emotional wellbeing. The idea of learning about our own activities can also be extended to the field of personal finance. Currently the financial data visualisations that are being developed are mostly designed to be used by specialists in the finance industry, and there is a lack of research on providing visualisation tools for individuals who wish to learn about their own personal financial situation. This gap in the research, paired with recent developments in the area of immersive technologies showed to me that this is still a relatively unexplored area. This research paper aims to address this by answering the following question: *How can we educate people about their spending habits through the use of 3D data visualisation in AR?*

This paper answers this question in three parts. Firstly, through the creation of a design framework for effective visualisations in AR. This involves the creation of a set of design guidelines based on the findings of the literature review. The resulting guidelines focus on perception and HCI in AR. They are intended to serve as a framework for the creation of a prototype interactive data visualisation that is capable of displaying spending habits in AR.

The prototype data visualisation that is created is intended to be used with Microsoft HoloLens 2. The data used in this project consisted of a sample dataset based on the outgoing transactions obtained from bank statements.

The effectiveness of the prototype and the underlying guidelines was then evaluated by conducting expert reviews with two design specialists and two finance specialists. The feedback was then analysed based on the common themes identified within the qualitative data. The results were used to revise and update the guidelines and, in some cases, to create additional guidelines, such as the need to consider varying levels of visual literacy for users. The final output of the paper is thus a set of design guidelines that is intended to be used as recommendations for creating effective visualisations in AR.

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1. Introduction

1.1 Background and context

Throughout history, visualisations have been used to communicate, educate and to solve problems. One of the oldest examples of visualisation goes back as far as 30,000 years ago when early man used paintings to graphically present information (Ward et al., 2015). In recent years there has been an increase in demand for interactive data visualisations driven by the expansion of big data. One of the types of data that is continuously growing is behavioural data. The concept of quantified self describes the acquisition and collection of data on different aspects of people's everyday lives, from healthcare to fitness (Marcengo & Rapp, 2014). The idea of self-knowledge through data can also extend into personal finance. The recent developments in financial visualisations focus on developing tools for business specialists and there is a lack of visualisation for individuals who wish to learn more about their financial situation (Olshannikova et al., 2015).

Along with growing demand for data visualisations new immersive technologies have been developed which offer new possibilities in presenting information and designing interactive solutions. The combination of these two gives rise to a new concept of immersive analytics which aims to encourage intuitive interaction techniques available in AR and VR by taking advantage of a broader range of senses (Bushel et al., 2018).

1.2 Research Question

This body of work addresses the following research question:

"How can we educate people about their spending habits through the use of 3D data visualisation in AR?"

The outcome of this paper will be in the form of a series of guidelines for creating effective visualisations in AR. The guidelines are expected to form a list of recommendations for designers that wish to create effective data visualisations in AR. The set of design guidelines that are formed are based on the findings from the literature review which explores the meaning of the visualisation, the current methods of presenting finance data, and most importantly, the visual and interactive components by examining the current theories of perception and HCI in AR.

There are two primary questions underlying the research : "what is data visualisation?" and "how do we perceive and interact in AR?". The first question aids to gain a better understanding of the topic and its importance. The field of data visualisation is broad and derives its meaning from many fields such as science, statistics, or computer graphics. Therefore, I will aim to find the most appropriate and comprehensive definition of the visualisation, which will form the basis of this research paper. The second question is central in defining the design principles; it informs the “how?” and “why?” of the steps necessary to create robust data visualisation.

In order to demonstrate the effectiveness of the design guidelines, a prototype interactive data visualisation was produced that is designed to be used in AR. The purpose of this visualisation is to facilitate educating users about their spending habits and serves an example of the design guidelines in action.

1.3 Methodology

As outlined above, the main objective of this research paper is to formulate design guidelines which will serve as a basis for the creation of effective data visualisations in AR. In this case, the guidelines are used to visualise personal finance data obtained from bank statements.

Firstly, in order to address the research question, a set of design principles was developed based on the literature review. The current definitions, evolution of visualisation techniques and their use, as well as current methods of representing financial data were first examined to clarify the meaning and importance of data visualisations. Secondly, perception theories and interactive techniques for immersive technologies were studied to identify the characteristics of successful data visualisation in AR.

The resulting guidelines were put into practice in the creation of a 3D data visualisation of spending habits in AR. For this purpose, the low fidelity prototype method was chosen as the most suitable given its low development cost, flexibility, and ability to effectively communicate the design ideas. This technique is commonly used in the early stages of the development process (Nissinen, 2015). As a result, a series of static images presenting two scenarios from the visualisation was created using Rhino 3D application; diagrams generated from the model were then placed into real-world context with the use of Photoshop. Additionally, a paper model was created that represented the real size view of one of the charts. The design decisions follow the proposed guidelines and take into consideration the chosen AR display; the choice of technology and its technical features have an impact on the overall design of the visualisation. The developed prototype is intended to be used with Microsoft HoloLens 2 which is a type of holographic head mounted display (HMD). The device provides fully immersive experience with a wide range of multimodal interaction models including gestures and voice control.

The next step in the research process is the assessment of the robustness of the visualisation and the underlying design guidelines. Given the nature of the prototype, the evaluation methods are limited to qualitative forms of assessment. The expert reviews were chosen as the most appropriate testing method as they can provide quick and valuable insights into usability and accessibility issues (Tory & Moller, 2005). The visualisation was reviewed by four experts: two experts in the area of design consisting of academics lecturing at Trinity College Dublin with experience in graphic design, HCI, and 3D information visualisations and two experts in the area of finance with professional experience working in the banking industry as quantitative analysts. The advantage of having the experts from both fields is the ability to collect diverse research data. The evaluation study received ethical approval of the Ethics Committee of the School of Computer Science and Statistics, Trinity College Dublin, on 25 February 2020. An email confirmation of the ethical approval can be found in Appendix C. The interview questions were designed to allow the experts to fully express their opinions on the visualisation and to test the usability of the prototype by asking specific task-oriented questions such as identifying average values or trends within the data. The feedback was then analysed using thematic analysis method for working with qualitative data (Guest et al., 2012). The emerging themes are discussed under the following headings: data representation, charts annotations and typography, colour, interactivity, and other comments. Based on the outcomes of the analysis, the initially proposed guidelines were revised. As a result, one additional recommendation on the importance of visual literacy was included and the points on accessible interactions, depth perception and colour consideration were updated, while the remaining guidelines remained unchanged.

1.4 Chapter Outline

The research paper is divided into three main sections:

Chapter 2 outlines the literature review concluding with the initial set of guidelines. This section discusses the meaning of data visualisation, its history, and the current methods of visualising financial information. It also explores current research in the area of perception and interactivity in order to determine the design features of successful visualisation in AR. The focus of this section of the paper is on researching way to create immersive and accessible solution enhancing user experience.

Chapter 3 presents the prototype 3D data visualisation that was created and gives an overview of the design decisions that were implemented in line with the set of guidelines created in the previous section. This section discusses the design implications of choosing the Microsoft HoloLens 2 as the chosen AR display and outlines the steps involved in data preparation.

Chapter 4 discusses the rationale, setup, and findings of the expert reviews. Based on the thematic analysis of qualitative data, the results were organised into five main categories and discussed under the following headings: data representation, charts annotations and typography, colour, interactivity, and other comments. The guidelines were revised in accordance with the outcomes of analysis. Subsequently, one additional guideline on visual literacy was created and the initial guidelines on accessible interaction, depth perception and colour consideration were updated. This section concludes with the final set of recommendations.

2. Literature Review

2.1 Introduction

The aim of the literature review is to specify what guidelines are appropriate for designing visualisations of personal spending data using AR technologies. It should be noted that the literature used in this review was mainly found through Google Scholar database. The searched keywords included data visualisation, information visualisation, financial data visualisation, immersive analytics, and visualisation in AR and MR. The literature found consisted mainly of academic journal articles and books. In order to get the thorough understanding of the topic the research covered the following areas: what is data visualisation, visualisation of financial data, perception in visualisations, and interaction techniques.

The first section of this chapter answers the question of what data visualisation is. It gives an overview of the existing definitions and compares them in order to identify the most accurate definition of visualisation. This section also contains a brief summary of the history of data visualisations showing their evolution.

The second section of this chapter outlines current research and developments in the area of financial data visualisation. The aim is to examine the main trends in the financial industry and to identify the users. The focus is on the 3D visualisations in MR.

The third section explores perception in visualisations. The goal is to identify what 3D visualisation should look like in AR. In order to answer this question, the common challenges and issues such as the issue of depth perception and the problem of cluttered displays are identified. The applications of features such as colour and composition are also discussed.

The fourth section explores the interaction aspect of data visualisation. It introduces a wide range of interaction techniques and examines their applications. The focus is on the users and their experiences. The concept of fluidity is discussed in the context of immersive technologies.

The final section is the conclusion. Based on the information gathered in the previous sections general guidelines are formulated that form the basis of the final visualisation of the spending habits.

2.2 What is data visualisation?

2.2.1 Definition of data visualisation

Data visualisation is a field that draws from many other disciplines such as statistics, science, psychology, and computer graphics. Many definitions exist that attempt to clarify the meaning and purpose of data visualisation.

Ward et al. (2015, p. 1) provide a basic definition of visualisation. They describe it as “the communication of information using graphical representations”. Their explanation focuses on the communication of information through pictures. However, there are three key words in this definition which can be considered equally important: communication, information, and graphical representation.

Kirk (2016, p. 31) presents his definition of data visualisation as “the representation and presentation of data to facilitate learning”. In this definition, the word ‘information’ is replaced by the word ‘data’ and ‘graphical representation’ is equivalent to ‘representation and presentation’. Kirk goes beyond the definition specified by Ward et al. (2015) by including the purpose of data visualisation. He believes the goal of visualisation is the facilitation of understanding. He stresses the significance of this cognitive process and breaks it down into three parts: perception, interpretation, and comprehension. Each stage is dependent on the previous one.

The importance of understanding is apparent in other definitions of data visualisations. Gatto (2015, p. 5) points out: “the main goal of data visualisation is to elucidate patterns, gaps, schemes, regularities, and connections that may not be easily identified by rapidly reading raw data or long texts”. He further identifies data visualisation as an important tool that improves the understanding of data and helps to reduce quantitative skills gaps. Similarly, Ware (2013, p. 2) recognises visualisation as an important part of cognitive systems and defines it as “an external artefact supporting decision making”. For Ware, interactive visualisation is the interface between a human and a computer.

In the context of this project, facilitating learning plays an important role since the main aim of the final data visualisation is to educate people about their spending habits. The user of the end product is the wider audience and will have mixed abilities and needs. Therefore, it is necessary to ensure the visualisation addresses a wide range of everyday users.

The key element of the visualisation is the data itself. Kirk (2016) considers it to be crucial raw material that plays a fundamental role in the visualisation. The quality of data will have an impact on the trustworthiness of the design. This view is supported by Tufte (2001). According to him, graphical excellence of data visualisation is based on telling the truth about the data.

The type of data should also be considered in the process of the visualisation. According to Carr (1999), there is a difference between information visualisation and scientific visualisation. The latter is linked to nature or to the physical world and suggests ways to present and organise the information. Whereas, information visualisation typically requires “the designer to invent a way to transform the data into graphical representation” (Carr, 1999, p. 1). He specifies information visualisation as “the presentation of abstract data in a graphical form so that the user may use his visual perception to evaluate and analyse the data” (Carr , 1999, p. 1). In his definition he defines the type of data as abstract. In line with his definition the data used in this project is considered to be abstract.

The most cited definition of visualisation by Card et al. (1999, p. 7) combines all the elements discussed above: visualisation is “the use of computer supported, interactive, visual representations of abstract data to amplify cognition”. This appears to be the most comprehensive definition outlining the process and the purpose of data visualisation. Hence, it will form the foundation of this project and will be considered in the creation of the guidelines.

2.2.2 History of data visualisations

Despite data visualisation being a relatively modern area of study, it has deep historical roots that go back as far as prehistoric times. Paintings in the Chauvet Cave dated as far back as 30,000 years ago can be considered to be one of the first known information visualisations. According to Ward et al. (2015, p. 9) “early visualisations came about out of necessity: for travel, commerce, religion, and communication”.

Tufte (2001) and Friendly (2006) studied the cartography of early data visualisations. One of the examples is John Snow’s dot map that plotted the location of deaths from cholera in central London in September 1854. The map was used to identify the cause of the deaths and to prevent further spread of disease. Tufte (2001) argues that this graphical representation was far more efficient than any computational analysis lacking the visual representation of data. According to Friendly (2006), this was an important graphical discovery that marks a high point of thematic cartography.

Figure 1 - John Snow's dot map of the deaths from cholera in central London in September 1854 (Tufte, 2001, p. 24).

John Snow’s dot map presented in Figure 2 (Tufte, 2001, p. 24) is a valuable example that shows how important and efficient visualisations can be. Throughout history, many other examples can be found that show the significance of data visualisations in a variety of disciplines.

The field of data visualisation progressed further over time and with advancements in technology. Friendly (2006) describes the last quarter of the 20th century as the evolution of data visualisations into mature, vibrant, and multi-disciplinary research area. The advancements in technology and computer graphics allowed for developments of high-d, interactive and dynamic data visualisations.

New technologies such as AR and VR are becoming increasingly important in the field of visualisation. Bushel et al. (2018) vision is to expand human cognition when working with data by using immersive technologies and achieving the “ultimate display” technologies beyond WIMP (“windows”, “icons”, “menus”, “pointers”). They present Microsoft HoloLens and MIT Media Lab’s inForm system as examples of exciting new immersive technologies that can be used to display data. The HoloLens is an AR headset which is a fully self-contained wearable computing device and the inForm is a fully dynamic and interactive physical display consisting of a table mounted array of vertically moving pins. The applications of this technology range from geospatial data displays to architectural models. The examples presented by Bushel at al. show the potential of the new technologies in the field of data visualisation. Mixed Reality platforms open new possibilities in creating engaging and interactive visualisations.

Figure 2 - Microsoft HoloLens is a consumer-level AR device that features instinctual interaction through gestures and voice recognition (Bushel et al., 2018, p.104).

Figure 3 - MIT Media Lab InForm is a Dynamic Shape Display that can model 3D content physically, so users can interact with digital information in a tangible way (Bushel et al., 2018, p.105).

2.3 Visualisations of financial data

Financial data is complex due to its size, multidimensionality, and diversity; it is usually discussed in the context of big data. The research on visualising financial data focuses primarily on market data. This type of data is aimed at financial experts who need to make informed and fast trading decisions. Typical visualisations include pricing data and charts and are restricted to 2D visualisation. According to Marghescu et al. (2007), there is a commercial demand for business users to create straightforward visualisations that will aid efficient and timely decision making.

The most recent developments in the area of financial visualisations include 3D visualisations. Lugmayr et al. (2019) prepared an overview of such projects. The list mostly covers financial trading or banking data. Most of the 3D features of these visualisations are displayed on 2D screens.

However, one of the examples from the list is Citi Holographic Workstation, which is a combination of AR and 2D screens.

Lugmayar et al. (2019) spotted an opportunity to use the immersive technologies for financial markets and developed a prototype of 3D data visualisation of financial data of Australia's energy sector in VR. They concluded their project with the benefits of such 3D visualisation. The main points included representing inherently complex data in a simplified way, easier knowledge and information discovery, and presentation of large amounts of data in a limited space.

While there is an interest in developing 2D and 3D visualisations for financial markets, a gap still exists in the research concerning the field of personal finance and more specifically, personal banking. The existing visualisations are mostly designed for experts and they do not take into consideration everyday users with varied levels of needs and abilities. The aim of this project is to close this gap and create easy to understand and accessible visualisation.

2.4 Perception in Visualisation

AR systems extend the user's perception of the real world by superimposing visual imagery and creating a computer-graphics-enhanced view of the world. As a result, the relationship between the real and virtual objects is a primarily focus. The goal is either to provide additional virtual context to a real object or for the user to focus on the virtual object in the real world (Kalkofen et al., 2009). In this case the latter is true, and the final data visualisation will become a virtual object placed in the real-world context.

It is important for the seamless integration of virtual and real images to use photorealistic rendering. Gervautz & Schmalstieg (2012, p. 29) outline the importance of creating realistic-looking AR scenes. According to them "factors such as registration, occlusion, and shadows contribute to successful visual integration". The photorealism of data visualisation is not of the highest concern since the data points are most often represented in an abstract way. In the context of this project the photorealism rendering is interpreted as a blending of a virtual image with the physical world.

Endsley et al. state the importance of alignment of real and virtual worlds. According to them "placement of virtual elements should make sense in the physical environment. If virtual elements are aligned with physical objects, this alignment should be continuous over time and viewing perspectives" (2017, p.2107). This will ensure smooth integration of both the physical and the augmented worlds.

When creating 3D visualisations in AR, Kalkofen et al. (2009, p. 193) identify "the problem of correct depth perception" as the main issue caused by overlaying parts of the real-world imagery with synthetic images. Ware (2013, p. 46) states that the focal distance of the computer imagery depends on the power of the lenses used. He further explains: “the optics are typically fixed, in AR systems there is only one depth at which both the computer-generated imagery and the real-world imagery are in focus”. He proposes two solutions based on the relationship between an augmenting image to an external object:

If an augmented image is linked to an external object, then these two objects should be at the same focal point.

If an augmented image is not linked to an external object, then the augmented imagery should be closer to reduce visual interference.

Ware (2013, p. 240) further examines the space perception and the depth cue theory in 3D spaces. He divides the depth cues into three categories:

Monocular Static (pictorial): linear perspective, texture gradient, size gradient, occlusion, depth of focus, shape-from-shading, vertical position, relative size to familiar objects, cast shadows, depth-from-eye accommodation

Monocular Dynamic (moving image): structure-from-motion (kinetic depth, motion parallax)

Binocular (requires two eyes): eye convergence, stereoscopic depth

These are particularly useful in creating 3D visualisations. Ware (2013, p. 271) proposes that designers choose which depth cues to include and which to leave out. They should “understand and use the depth cues that are most important for the critical tasks in an application. Implement other cues on which the critical cues depend”.

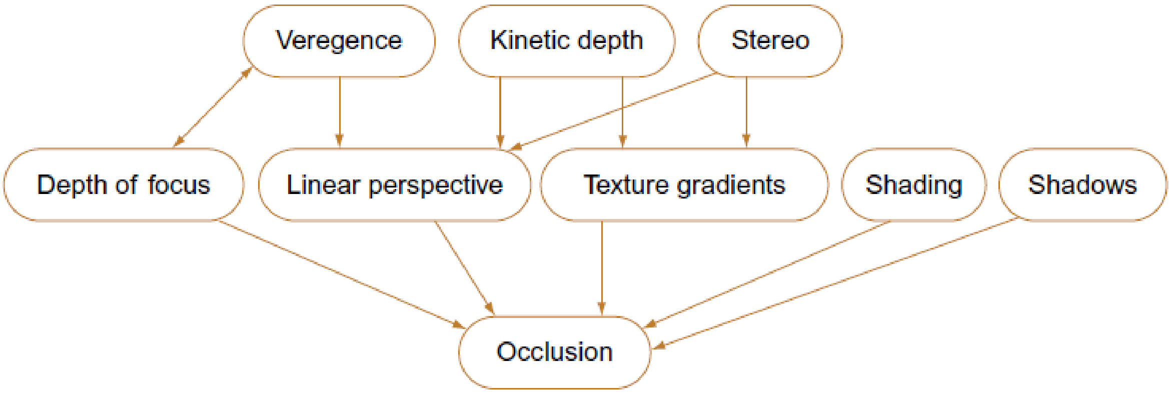


Figure 4 - A dependency graph for depth cues (Ware, 2013, p. 271).

Additional deciding factor in choosing the depth cues is the technology used. For example, head-mounted display (HMD) create specific optical and perceptual problems, i.e. with HMD the image moves with the head and it does not allow for redirection of eyes. This may cause issues with reading. Ware (2013, p. 47) suggests: “when using a head-mounted display to read text, make the width of the text area no more than 18 degrees of visual angle”.

Another class of problems identified by Kalkofen et al. (2009) is caused by the overflow of information added to reality. If too much information is added to the unimportant areas in the original image, the display may become cluttered. If important information from both the virtual and real world is identified in the same area, it may cause the virtual object to occlude the real one. Therefore, it is suggested that an optimal combination of all features is present, rather than giving preference to the virtual features over the real ones.

The size of the chosen AR display will have an impact on legibility of a visualisation. This problem is apparent in compact visualisations on limited-source hardware such as mobile phones. Tatzgern et al. (2013) present filter techniques to reduce data to a manageable amount before a layout is displayed. They focus their approach on the compact explosion diagrams. They avoid clutter and reduce interferences by filtering explosions and annotations, and by adjusting the scene layout by moving the text boxes. This approach can be applied in the creation of data visualisation, when considering the design of data labels and annotations. Alternative layouts or scene modifications should be considered to avoid interference with scene elements.

Cluttered displays can also be caused by inappropriate use of colour in visualisations. Kirk (2016, p. 353) suggests that the choice of colour should be meaningful and “colour should not be used to decorate data”. The use of colour to represent data will depend on the type of data: qualitative (nominal and ordinal) or quantitative (interval and ratio). Colour is a highly influential feature of design and is one of the most powerful sensory cues. Endsley et al. (2017, p. 2107) suggest that “designers should consider size, colour, motion, distance, and resolution when designing for AR”. The features such as colour and composition are particularly important for data visualisations to ensure the information is presented in a clear and efficient manner.

Kirk (2016) and Ware (2013) examine the theory of colour and show limitations of its use in data visualisations. Creating contrast is the main purpose of representing nominal data. In this case, the colour is used to differentiate categories and make them easily accessible. As a result, variations in hue rather than lightness should be considered. Kirk (2016) outlines that no more than twelve data categories should be present. Otherwise it gets increasingly harder to find unique and easily distinguishable colours. In addition to that, the demand for learning and recognition is increased for the viewer. To avoid this issue, it is advisable to offer interactive filters for the users. Ware (2013) proposes colour saturation as the method for showing different numerical quantities. The greater saturation should represent larger quantities and a saturation sequence should be used to encode no more than three values.

Careful choosing of colour is also important in achieving functional harmony and accessible design. Consistent use of colour helps to avoid visual chaos and confusion and minimises cognitive effort (Kirk, 2016).

Tufte (2001, p. 177) emphasises the importance of simplicity in design and states that "good design has two key elements: graphical excellence is often found in simplicity of design and complexity of data". According to him, data visualisation should display an accessible complexity of detail.

In addition to colour, composition of the data visualisation will have an impact on readability of the final data visualisation. Composition involves making decisions about physical attributes of every visual property to ensure cohesive outcome. It defines the layout, size, positioning and hierarchy of the entire visualisation (Kirk, 2016).

2.5 Interactive Visualisation

Interaction is an important part of data visualisations. However, it can very often be overshadowed by the visual component. Elmqvist et al. (2011) describe it as the catalyst for the user's dialogue with the data and the user's understanding and insight into the data. One of the reasons that this is often overlooked is that interaction is difficult to design, quantify and evaluate.

Ward & Yang (2003, p. 1) define interaction in the context of visualisations as "a mechanism for modifying what the users see and how they see it". They propose a complex framework of interaction controls based on the type of interaction operator (navigation, selection, distortion), the space of interaction within different levels of the visualisation (screen, data value, data structure, attribute, object or visualisation structure), along with the parameters of the interaction operator (focus, extents, transformation, magnitude and blender). Although the list is comprehensive, it does not provide guidance on what combination of tools are useful and in what situations.

Yi et al. (2007, p. 1226), on the other hand, propose taxonomy of the interaction techniques based on the notion of user intent as follows:

- *Select*: mark something as interesting
- *Explore*: show me something else
- *Reconfigure*: show me a different arrangement
- *Encode*: show me a different representation
- *Abstract/Elaborate*: show me more less
- *Filter*: show me something conditionally
- *Connect*: show me related items

The interactions listed above are intuitive and encourage thinking about what the users need from the visualisation. Identifying the user's intent is vital for supporting the user's understanding of information.

Pike et al. (2009) support this approach and discuss the importance of capturing user intentionality that is necessary to the enhancement of information displays; in particular the need to recognise what the user is trying to achieve through the interaction. Knowing why a user is following a certain path is critical in developing tools that modify its presentation, suggest alternatives, or identify additional information for the user. They further argue the need for the knowledge-based interfaces which account for the role, context, prior knowledge and aims of the users. They view interaction at a higher level as a reasoning process that occurs within one's mind that is enabled by computational tools. The reasoning strategies, however, vary among the users and it is necessary that a wide range of interaction tools is included in the visualisation to account for these differences.

The notion of inclusive design corresponds to the idea of accessibility. Kirk (2016) advocates the general principle of accessible design when it comes to interactivity. The purpose of interactivity is to add value to the experience and to ensure the features that are deployed are useful. It is important that the interaction features do not obstruct the user's ability to understand data.

Endsley et al. (2017, p. 2107) are concerned with the physical accessibility of interactions in AR. They state that "interaction with AR experiences should not require the user to perform actions that are physically challenging, dangerous, or that require excess amounts of coordination. All physical motion should be easy". While the interactions involved in the data visualisation often do not involve excessive coordination, care should be taken when designing such interactions to ensure that they fit with the user's physical abilities.

The accessibility of interactions can also be identified at a cognitive level and will determine how easy it is to comprehend the information. Ware (2013, p. 352) indicates that "it will be easier to execute tasks in computer interfaces if the interfaces are designed in such a way that they take advantage of previously learned ways of doing things". He suggests that when designing interfaces to move objects on the screen, the eye-hand coordination is important. The object movement should be in the same general direction as the hand movement. This is particularly important for navigation tasks. The eye-hand coordination in combination with well-chosen cognitive models for interaction and providing rapid and consistent feedback will create a transparent design that is so easy to use and disappears from consciousness (Ware, 2013).

Ware's idea of interaction is linked to the concept of fluid interaction, which is a key element in the field of immersive analytics. Elmqvist et al. (2011, p. 327) describe the concept of fluidity as "smooth, seamless, and powerful interaction; responsive, interactive and rapidly updated graphics; and careful, conscientious, and comprehensive user experiences." Fluid design helps the user to stay in the flow of the process. They define flow as a mental state of total immersion in an activity, where the challenges and the skills are balanced resulting in high focus, participation and rewarding outcomes; based on the seven factors of flow: balanced challenge, concentration, loss of self-consciousness, transformation of time, prompt feedback, sense of control and intrinsically rewarding (Elmqvist et al., 2011).

Similarly, to the previously discussed knowledge-based model, the concept of fluidity focuses around the users' experience and matching the visualisation to different levels of the user's cognitive abilities in order to maximise the understanding.

Elmqvist et al. (2011, p. 336) propose the following design guidelines for fluidity:

1. Use smooth animated transitions between states. The key is to avoid abrupt mode switches that can be disorienting and may interrupt the user's flow.
2. Provide immediate visual feedback on interaction. This means the visualisation should be responding in real-time.
3. Minimise indirection in the interface. The interaction operations should be integrated in the visual representation.
4. Integrate user interface in the visual representation. If direct manipulation is not possible the interface should be designed so that it is nearly invisible.
5. Reward interaction. The purpose of rewards is to provide positive user experience. Examples include animations, sounds, and visually pleasing graphics.

6. Ensure that interaction never ends. The visualisation should provide endless possibilities of exploration.
7. Reinforce a clear conceptual model. The operations should be reversible and the multiple views well-coordinated.
8. Avoid explicit mode changes. Integrate all operations in the same mode.

Some of the guidelines proposed by Elmqvist et al. (2011) relate to the points made in the previous section 2.4 on perception. For example, they refer to interface as direct and recommend that the interaction operations are incorporated in the visual display. They suggest that if the direct manipulation is not possible then the interface should be designed so that it is nearly invisible. This corresponds to the arguments made on clutter-free displays. The goal is to minimise the distractions and cognitive burden. Guidelines on the avoidance of explicit and abrupt mode changes that can add to the disorientation and might interrupt the state of flow fall into this category. Thus, can be seen that a strong link emerges between interaction and perception. Defining possible interactive functions that may be required will determine the visible components of the visualisation. The next step of the design process is to determine how these will appear.

In their guidelines Elmqvist et al. (2011) outline that fluid visualisation should follow the model-world metaphor meaning that the interface itself becomes the world which the user can directly 'touch' and control. The concept is in line with the theories of embodied cognition and interaction suggesting that our cognition abilities are explicitly designed to reason, act and move in our physical and social world.

2.6 Conclusions

The purpose of the literature review was to formulate the guidelines for 3D data visualisation of spending habits in AR. This was achieved by reviewing what data visualisation is, current research and developments in the area of visualization of financial data as well as studying perception theories and interactive techniques for immersive technologies. As a result, a set of guidelines was established as presented in Table 1.

Table 1 - initial set of design guidelines for 3D data visualisations in AR

#	Design Guideline	Reference
1.	Work with data: Data is a foundation of creating an accurate information visualisation that will create a trustworthy design.	The key element of the visualisation is the data itself. Kirk (2016) considers it as the crucial raw material that plays a fundamental role in the visualisation. The quality of data will have an impact on the trustworthiness of the design.

		This view is supported by Tufte (2001) . According to him graphical excellence of data visualisation is based on telling the truth about the data. "…it needs to be made clear the core role that data has in the design process. Without data there is no visualisation…" (Kirk, 2016, p. 32)
2.	Design the interaction to maximise the user experience: consider what the user needs.	Yi et al. (2007) created a taxonomy of interactions based on the user intents to encourage thinking about what the user needs when designing interaction techniques. Pike et al. (2009) support this approach and discuss the importance of capturing user intentionality that is necessary to the enhancement of information displays; in particular the need to recognise what the user is trying to achieve through the interaction.
3.	Identify the interaction features before designing the display: There is a link between interaction features and display design. The interactive functions will determine the visible components of visualisation and should be incorporated in the visual representations.	Based on the review of the role of perception and interactivity within visualisation it can be seen that a strong link emerges between the two elements. Defining interactive functions that may be required will determine the visible components of the visualisation. The next step of the design process is to determine how these will appear.
4.	Accessible interaction design: Interaction features should be designed so that they fit with the user's physical abilities and are accessible to everyone.	Kirk (2016) advocates the general principle of accessible design when it comes to interactivity. The purpose of interactivity is to add value to the experience and to ensure the deployed features are useful. It is important that the interaction features do not obstruct ability to understand. "… interaction with AR experiences should not require the user to perform actions that are physically challenging, dangerous, or that require excess amounts of coordination. All physical motion should be easy" (Endsley et al., 2017, p. 2107).
5.	Provide fluid interactive features: maximise the immersion and engagement by smoothly integrating the interactive features.	Fluid design helps the user to stay in the flow of the process. Elmqvist et al. (2011, p. 327) describe the concept of fluidity as "smooth, seamless, and powerful interaction; responsive, interactive and rapidly updated graphics; and careful, conscientious, and comprehensive user experiences".
6.	Identify appropriate depth cues to correct the issue of depth perception in AR: consider the link between the augmented objects and the real world.	When creating 3D visualisations in AR Kalkofen et al. (2009, p. 193) identify "the problem of correct depth perception" as the main issue

		caused by overriding parts of the real-world imagery with synthetic images. Ware (2013, p. 271) proposes that designers choose which depth cues to include and which to leave out. They should “understand and use the depth cues that are most important for the critical tasks in an application. Implement other cues on which the critical cues depend.”
7.	Consider the use of colour when designing the visual display: the colour has an impact on many visual applications of design, e.g. it can act as a depth cue or can be used to represent data. The choice of colour should be meaningful.	Careful choosing of colour is also important in achieving functional harmony and accessible design. Consistent use of colour helps to avoid visual chaos and confusion and minimises cognitive effort (Kirk, 2016).
8.	Cohesive design: ensure there is continuity in the design of the interface and the visualisation itself. The views should be well-coordinated. This will minimise the cognitive burden on the users.	Based on the concept of fluidity of interaction introduced by Elmqvist et al. (2011) the design of the interface should be well-coordinated. The goal is to minimise the distractions and cognitive burden.

3. Data Visualisation Design and Prototype

This chapter gives an overview of the design process. First, the choice of the AR technology is discussed and its impact on of the 3D data visualisation. Next, the sample dataset used in this project is presented and explained. Design decisions are then reviewed with respect to the guidelines developed in section 2.6 of this paper. The final section of this chapter presents the protype of the 3D visualisation.

3.1 AR Technology

The AR technology chosen for this project is the Microsoft HoloLens 2. As previously mentioned in section 2.2 Microsoft HoloLens 2 is a head-mounted holographic device which allows the user to see the physical environment while wearing it. Its benefits include wireless connection and lightweight design (Vijay Pola, 2019). This type of device is used as a holographic display in many industries including medical, manufacturer and science by companies such as *Scopis medical*, *Volvo* and *NASA* (Occhipinti, 2017).

Figure 5 - Microsoft HoloLens 2 (What Is Mixed Reality? - Mixed Reality, 2018)

The choice of the technology has an impact on the design decisions and the presentation of the data visualisation. Therefore, a research has been conducted into the features offered by the device to gain a better understanding of the device’s technical abilities, and its influence on the design.

One of the main features is the HoloLens’ ability to make holographic objects feel real with the use of various real-world coordinate systems depending on the scale of the mixed reality experience. This is relevant in relation to identifying appropriate depth cues and depth perception in AR, which are outlined in the design guidelines in section 2.6 of this paper. For the purpose of this project, the main focus is on the world-scale experience, where the users can place the holograms within the real world. For example, this solution allows users to position the data visualisation on a table or desk. Hence, the hologram should feel like a natural part of the user’s world. The device constantly tracks objects in the coordinate system and maps the environment by considering the user's position in the space, the position of the hologram in the space, and the user's position relative to the hologram (Coordinate systems - Mixed Reality, 2019).

Liu et al. (2018) performed a technical evaluation of HoloLens for multimedia. The process involved identifying the main functional components and designing a series of experiments for each of these components. They point out some limitations to the performance of the sensors which are influenced by lighting conditions, surface textures and the distances between the HoloLens and the real-world objects. Microsoft also warns about some potential handling errors of HoloLens 2, which could affect the user experience. The following is the list of conditions in which a headset might not be able to correctly locate itself in the real world:

- Insufficient sensory data caused by dark spaces, covered sensors or lack of textures in the room
- Dynamic changes in the environment caused by too many people walking in the space
- Significant changes to the environment such as movement of furniture or wall hangings
- Identical spaces in an environment for example two identical conference rooms

Under those scenarios the holograms might not appear, or get dislocated. This shows some of the constraints of the headset which can have negative impact on the fluidity of the experience (Coordinate systems - Mixed Reality, 2019).

The choice of colour when designing for AR devices also requires careful consideration. HoloLens is an additive display meaning that it adds light to the light from the real world. Therefore, the colour impact varies with the user's environment under various lighting conditions. It is advised to use appropriate levels of contrast to avail of clarity (Colour, light and materials - Mixed Reality, 2018).

The nature of the additive display also means that HoloLens renders dark colours as transparent causing the content to be occluded by the real-world objects (Silvennoinen, 2017). It is suggested that a very dark grey is used instead of black. The white colour on the other hand appears bright and should be used sporadically to avoid user discomfort (Colour, light and materials - Mixed Reality, 2018).

Another aspect of the AR design is a selection of suitable interaction methods. HoloLens offers a range of multimodal interactions including hand and motion controllers, hands-free (speech recognition and eye tracking), and gaze and commit. The headset allows the user to interact with the content using hand gestures in combination with voice commands and eye gaze, providing intuitive interactions suitable for all users regardless of the experience (Instinctual interactions - Mixed Reality, 2019). Gestures are specific hand positions that are recognised by the software if the user's hands are visible for the device (Silvennoinen, 2017). One of the interaction models allows for direct manipulation with hands that involves touching the hologram with hands (Direct manipulation with hands - Mixed Reality, 2019).

Table 2 - Summary of the design guidelines and relevant HoloLens features

#	Design Guideline	HoloLens 2 Features
4.	Accessible interaction design.	HoloLens provides a range of interactions designed to keep the user comfortable. Multimodal interaction models are available and include the following: hand and motion controllers, hands-free (including voice control and eye tracking) and gaze and commit. Hands and motion controllers suitable for intuitive content manipulation with low learning curve. Should be suitable for users with all experience levels.
5.	Provide fluid interactive features.	The limitations to the performance of the sensors due to lighting conditions, surface textures and distance between the HoloLens and real objects can have negative impact on the user experience and immersion.
6.	Identify appropriate depth cues to correct the issue of depth perception in AR.	The holographic objects feel real with the use of spatial mapping which allows to keep the holograms in place. A world-locked content option is available allowing the object to become a natural part of the user's world. Some handling errors may occur depending on the environmental conditions, e.g. lack of environmental light.
7.	Consider the use of colour when designing the visual display.	HoloLens is an additive display meaning it adds light to the light from the real world. Hence, white appears bright and black appears transparent. The colour impact will vary with the user's environment; to compensate for various lighting conditions appropriate levels of contrast should be applied to help with clarity.

Despite some constrains described above HoloLens is considered to provide good user experience in mixed reality. The effectiveness of device was evaluated in minimally invasive surgery simulation and scored highly among participants with regards to comfort, image quality, spatial awareness, and practicality (Al Janabi et al., 2019). Another study evaluating the user experience of the headset concluded that interacting with HoloLens has better user experience than interacting with mobile device in AR (Vijay Pola, 2019).

3.2 Data

Working with data is an essential part of the process that sets the foundation for trustworthy data-driven design. The adopted approach to working with data follows the subsequent steps (Kirk, 2016):

1. Gathering of raw data.
2. Examining data.
3. Data enhancement through modification and consolidation.
4. Explanatory analysis: learning about data.

3.2.1 Raw Data Gather and Examination

The purpose of the visualisation is to help users assess their spending habits. Therefore, the main source of data for this project is an extract of current account bank statement. The conventional way of displaying the bank statements is presented in a tabular form as illustrated by the table below.

Table 3 - Extract of Current Account Statement

Transaction	Amount
CNC DAKOI ORIENT 09/01 1	-10.95
CNC TESCO STORES 29/01 1	-12.15
CNC DUNNES 30/01 1	-12.11
Debit Card Charge	-0.46
DD EIR	-55.01
CNC DUBRAY BOOKS 01/02 1	-3

The information provided includes transaction description, date and full transaction amount which is sorted by date.

It should be noted that the extract of the original bank statement for the month of January 2019 served as a foundation for creating a sample dataset on which the final data visualisation is based, and which contains approximately 764 outgoing transactions for the full year 2019. This was a preferred method due to the privacy issues relating to the use of sensitive information such as personal bank statements.

Based on the review of the bank statement the sample dataset was created by dividing the transactions into the following four categories:

1. Bills: direct debits for monthly charges such as utility bills, rent, monthly insurance fees, etc.
2. Groceries: all grocery shopping
3. Entertainment: going out including eating out in restaurants, tickets, etc.

4. Others: all the other transaction including ATM withdrawals, unidentified transactions (e.g. payments to other accounts), etc.

3.2.2 Data Enhancement

The categories introduced in the sample dataset were distinguished based on the frequency of payments and the total amount. They are useful for providing an overall picture and to identify areas of high expenditure. The categories may vary depending on personal spending patterns; however, these four main groups are considered to be relevant to the wider audience.

Table 4 - One day extract of the sample dataset

Category	Date	Month	Amount
Groceries	01/05/2019	May	-14.64
Bills	01/05/2019	May	-890
Entertainment	01/05/2019	May	-12
Other	01/05/2019	May	-100

3.2.3 Explanatory Analysis of Sample Data

In order to gain a better understanding of the dataset some explanatory analysis was performed by calculating the average monthly values for each category. It was found that on average the spending over time was stable for each group.

Table 5 - Average Monthly Spending

Average Monthly Spending				
Month	Bills	Entertainment	Groceries	Other
Jan-19	-34.21	-10.91	-21.20	-28.92
Feb-19	-32.65	-35.85	-19.91	-17.13
Mar-19	-34.86	-23.32	-23.34	-14.78
Apr-19	-30.47	-6.90	-19.88	-22.69
May-19	-29.48	-8.84	-12.51	-23.62
Jun-19	-36.19	-7.00	-18.58	-24.51
Jul-19	-29.37	-17.23	-15.50	-28.31
Aug-19	-34.46	-5.90	-13.80	-25.77
Sep-19	-30.44	-8.13	-15.94	-36.50
Oct-19	-35.23	-9.48	-14.20	-24.52
Nov-19	-30.44	-9.13	-11.90	-20.61
Dec-19	-35.17	-12.39	-17.53	-27.32

Additionally, the spending between the categories was compared by calculating the percentage expenditure values out of total spending for each month. This was useful in identifying the largest areas of expenditure. It was found that each month Bills appeared to have the highest level of spending.

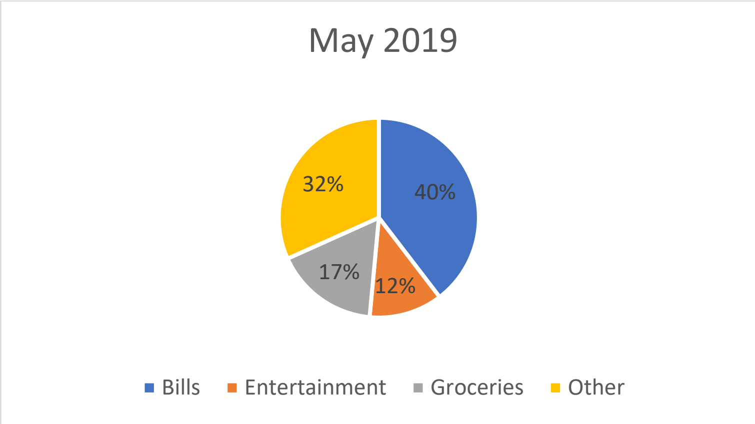


Figure 6 - Pie Chart illustrating relative spending in each category

3.3 Design Decisions

The design of the final visualisation is based on the guidelines formed in section 2.6 of this paper. During the design process each guideline was reviewed and implemented.

The first step in the creation process involved working with data. This exercise is largely discussed in section 3.2 of this paper. Data is a central part of the visualisation's design, and it is important that the type, size and meaning of the data inform the visualisation's outcome (Kirk, 2016). The sample dataset for this project is a 2D table with time being the first dimension and transaction amount as the second dimension classified by transaction type. The purpose of the data visualisation of spending habits is defined as educational with the intention of being explanatory.

The challenge is to implement the 2D data into 3D space. Tufte argues that "the number of information-carrying (variable) dimensions depicted should not exceed the number of dimensions in the data" (Tufte, 2001, p. 68). However, there are other arguments in the field of data visualisation suggesting the value of 3D visualisation since it has the ability to engage the user with their data in less constrained manner than the 2D screen is; the 3D visualisation can indeed be beneficial (Pangilinan et al., 2019).

Therefore, taking the data type into consideration, along with the purpose and the interactive abilities of 3D display, it was decided that the visualisation will have two views in 3D: a pie chart comparing the relative spending in each category and a line graph showing the spending patterns.

The next steps involved identifying the interactive features with an intention to maximise the user experience. Finding appropriate set of interactions involved focusing on the purpose of the visualisation and the potential user intents. As a result, based on the Yi et al. (2007) notion of taxonomy of interactions; the following tasks categories were identified:

1. Explore: the user can explore the data by selecting different timeframes (annually, monthly, daily) and different transaction categories (Bills, Groceries, Entertainment, Other)
2. Reconfigure: the user can move between pie chart and line graph depending on the combination of selected time frequencies and categories.
3. Filter: the user can filter data by selecting different categories and timeframes
4. Select: the user can select individual points of data to find out the details such as average and total values.

Based on the tasks listed above the menu was created. The menu options and views configurations are summarised in Figure 8.

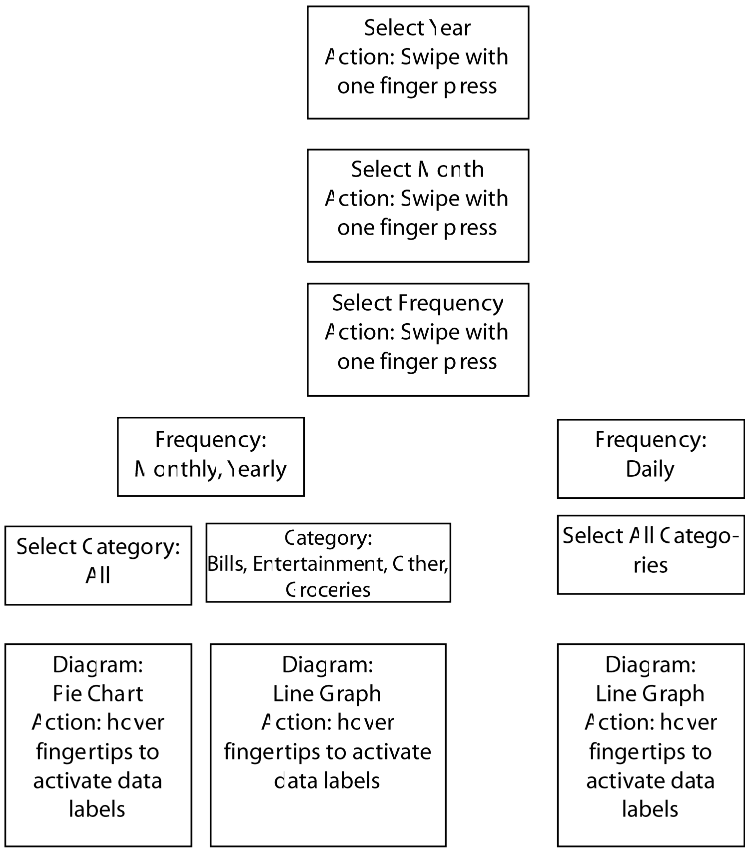


Figure 7 - Menu Options and Scenarios for the visualisation

The proposed interactions involve direct manipulation with hands. The users are able to touch the visualisation and use their hands to control the menu, to obtain the details about the data and to change the position or rotate the charts. The direct manipulation in combination with the voice control provides a multisensory experience which is vital for intuitive design (Pangilinan et al., 2019).

In order to keep the display minimal and well-integrated within the visualisation the menu was incorporated by wrapping it around the pie chart and the line graph. The shape of the menu was determined by the circular base for both views. The wheel shape of the menu encourages the swipe motion (left and right). The width of each wheel is approximately 3 cm to ensure it is comfortable to use. Fitting the wheel menu as the base of the visualisation ensures the cohesive design.

Colour is an important visual component that affects the appearance of the visualisation and its readability. The main purpose of colour used in this visualisation is to differentiate between the categories. Each transaction class was assigned distinct colour as presented in Figure 10. It should be noted that this method works well for small number of classes (Kirk, 2016). In total, there are four categories specified in this visualisation and it is not expected that the number of categories would exceed twelve for this type of data.

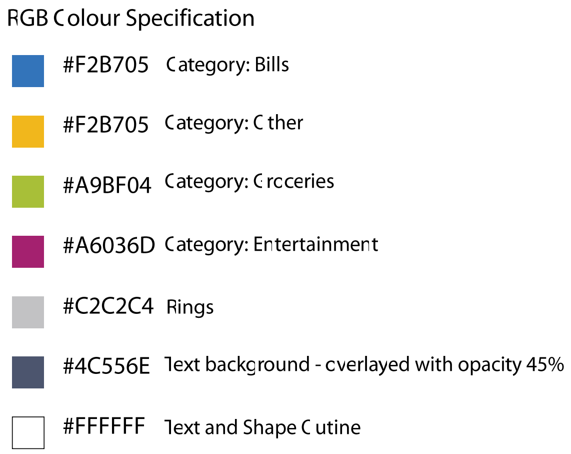


Figure 8 - RGB Colour Specifications

The technical specifications of the HoloLens display were also considered when choosing the colours. As discussed in section 3.1 of this paper the headset is an additive display meaning the bright colours are more visible and black colours should be avoided as it renders transparent. The choice of colour for typography in the menu is white on a dark grey background (Typography - Mixed Reality, 2019).

Table 6 - Summary of design decisions for each design guideline

#	Design Guideline	Design Decision
1.	Work with data.	Data was processed in the following stages: raw data gather, data examination, data enhancement and transformation, as well as data exploration. Sample dataset was assessed and defined as 2D data. In line with the data type, the purpose of the visualisation and the nature of 3D display two data views were chosen: pie chart and line graph.
2.	Design the interaction to maximise the user experience.	The following user task categories were identified: 1. Explore: the user can explore the data by selecting different timeframes and different transaction categories.

		2. Reconfigure: the user can move between pie chart and line graph. 3. Filter: the user can filter data by selecting different categories and timeframes. 4. Select: the user can select individual points of data to find out the details such as average and total values.
3.	Identify the interaction features before designing the display.	Based on the interaction tasks identified, the menu and data labels were created. The menu options include selection of year, month, frequency, and category. Data labels include the details such as total and average values for each data point.
4.	Accessible interaction design.	The users can touch the visualisation and use their hands to control the menu, to obtain the details about the data and to change the position or rotate the charts. The direct manipulation in combination with the voice control provides a multisensory experience.
5.	Provide fluid interactive features.	All user tasks are integrated in the same mode. The direct manipulation with hands in HoloLens is integrated smoothly.
6.	Identify appropriate depth cues to correct the issue of depth perception in AR.	HoloLens uses the spatial mapping to make the visualisations feel real and fit in with the environment. See section 3.1 of this paper.
7.	Consider the use of colour when designing the visual display.	Colour was used to encode different transaction categories; distinct colours were assigned to each one of the four classes. The HoloLens rendering abilities were also considered when choosing the colour. See section 3.1 of this paper.
8.	Cohesive design.	The visualisation design is minimal with incorporated wheel menu wrapping around the charts. The use of colour is consistent throughout all the views.

3.4 Prototype

In order to communicate the concept and to explore and evaluate the design ideas discussed in previous section, a prototype of the data visualisation was created. Two scenarios were chosen for the prototype stage:

1. Pie chart for the month of May with category: All, and frequency: monthly
2. Line graph for the month of May with category: Groceries, and frequency: daily

The prototype included a series of static images. 3D models were produced using Rhino 6 by McNeel. The colour was applied using Adobe Illustrator. The resulting images are orthogonal views of the charts as seen in Figure 9. Additionally, Photoshopped images were used to illustrate the visualisation in the real environment. The charts were placed on a desk to simulate the AR experience as presented in Figure 10. Furthermore, to test the scale of the visualisation in the real world a paper model of Pie chart was created. It was found that this size is suitable for comfortable viewing and interaction with the visualisation.

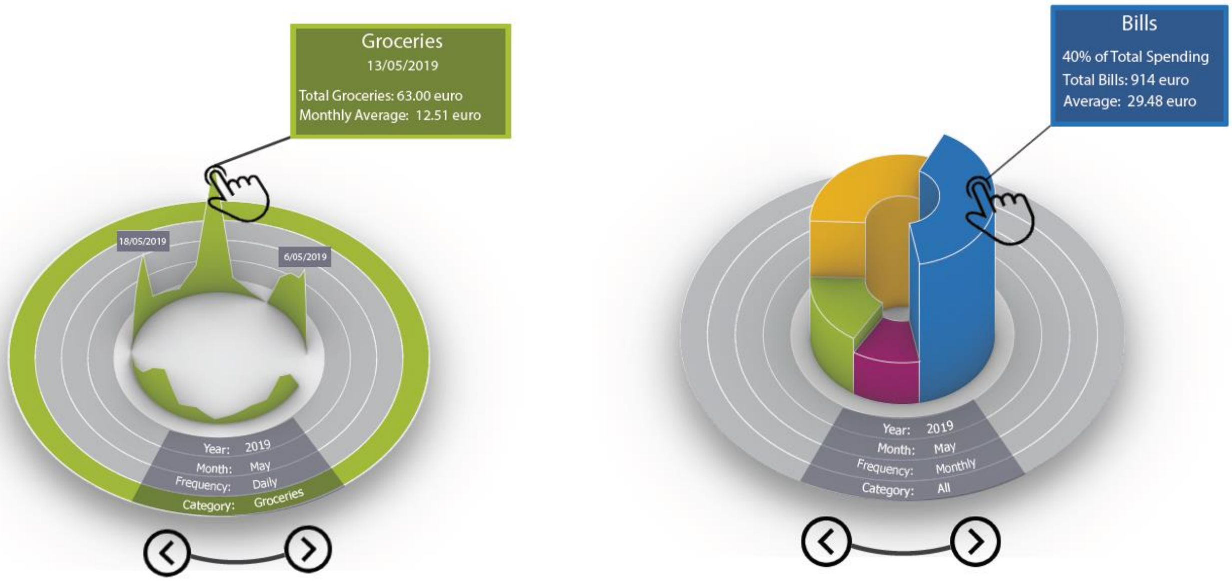


Figure 9 - Data Visualisation 3D models

Figure 10 - data visualisation placed in the real world

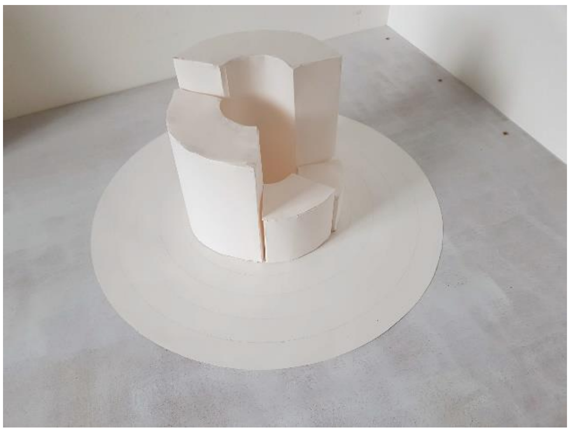


Figure 11 - Paper model of the visualisation

4. Evaluation

Interviews were conducted with experts in the field in order to assess the effectiveness of the data visualisation of spending habits and the underlying design principles. This chapter aims to provide an overview of this process. Firstly, it explains the rationale for choosing the reviews as the most suitable method of evaluation for this project, and the details of the setup for the interviews. Secondly, it presents the analysis of the feedback received from the experts. Lastly, it concludes the results with the final set of revised design guidelines.

4.1 Expert Reviews Rationale and Setup

Many types of evaluation for interactive visualisation systems exist in the field of human-computer interaction. Some of the common techniques include usability tests, focus groups, expert reviews, peer reviews, field tests, case studies and use cases, etc. (Ward et al., 2015).

The choice of low-fidelity prototype for the data visualisation presented in the form of static images imposes some restrictions when choosing the evaluation techniques. The final product is not fully developed to undergo complete usability tests. Therefore, for the purpose of this project, interviews with experts was chosen as the most appropriate form of assessment. Two specialists in the field of design and two specialists in the field of finance were interviewed to assess the effectiveness of the prototype and the underlying design guidelines developed in section 2.6 of this paper.

Mazza & Berre (2007) differentiate between two types of evaluation methods: analytic and empirical. The analytic method involves studies of human cognition and behaviour and is performed during the earlier stages of development, whereas the empirical method is carried out during the implementation phase and it involves the users interacting with the final product. The expert reviews conducted as part of this project fall into the analytic category. Tory & Moller (2005) present this form of evaluation as the appropriate alternative for formal user studies. The reviews require fewer participants and tend to produce quick and reliable insights into accessibility and usability issues.

Furthermore, Mazza & Berre (2007) classify various forms of analytic evaluation techniques as heuristic evaluations or cognitive walk-throughs. The latter method involves the experts walking through a specific task using a prototype and thinking about potential problems. For the purpose of this project, the structure of the interviews is organised into two parts:

1. General questions are asked about the visualisation allowing the experts to fully express their opinion about the prototype and to raise any potential issues.

2. Participants are asked questions oriented towards performing specific tasks such as identifying trends within the data or average values.

It can be seen that the second part of the interview is designed based on the idea of cognitive walk-through to test the usability of the prototype. Full set of questions can be found in Appendix A. It should be noted that the questions are open-ended, and any issues raised were followed up on.

The evaluation study received ethical approval of the Ethics Committee of the School of Computer Science and Statistics, Trinity College Dublin, on 25 February 2020; an email confirmation can be found in Appendix C. All interviews were conducted remotely via Skype. At the beginning of each call, the participants were presented with a short demo of the prototype showcasing various diagrams and explaining the functionality of the visualisation; the full presentation can be found in Appendix B. At the end of the demo the participants were given time to ask questions.

The experts selected for the interviews are independent of the research, ensuring honest and impartial feedback. The two finance specialists were recruited through a professional network of contacts. They have several years of experience working in the banking industry as risk analysts. Their expertise includes analysing large datasets using statistical methods and communicating the results to various stakeholders. Their knowledge of the financial industry provides valuable insights into the usefulness of the visualisation. The two design experts selected are academics teaching Visual Computing and Design at Trinity College Dublin. Their area of expertise covers graphic design, HCI as well as 3D information visualisations. The advantage of having these two groups of participants is the ability to test the visualisation from different perspectives of designing and working with data.

4.2 Analysis of Results

The feedback received from each expert was carefully reviewed and examined using the thematic analysis method, which is commonly used when working with qualitative data. The process involves finding codes and patterns to uncover meaning within complex data (Guest et al., 2012). Some of the techniques involve working with software, journaling, or using affinity diagramming. The journaling method requires researchers to write down detailed notes about common ideas emerging from the interviews; it involves manual annotations and highlighting text. One of the advantages of this process is flexibility and low-cost analysis (Rosala, 2019). Given its benefits, the journaling approach was chosen as a preferred method to examine the data from the expert reviews.

The analysis indicates that in general the interviewees found the visualisation useful in identifying spending habits. However, some issues were uncovered regarding the design and functionality of the visualisation. These were organised into themes and summarised under the following headings:

4.2.1 Data Representation

One of the biggest issues arose in relation to the representation of the data. Two out of four experts (one design and one finance) raised concerns about the presentation of the line graph. As seen in Figure 11, the line graph is wrapped around a circular base. The participants found the layout of the graph unfamiliar and hard to read. They were not able to identify the start and the end of the time series and suggested that the date labels are introduced for all data points in addition to the peak values. On the other hand, only one of the experts found the pie chart more confusing than the line graph, suggesting that the 3D shape of this particular chart type is unfamiliar and therefore hard to read, unlike its 2D representation.

The difficulties in reading the charts experienced by the interviewees can be explained by incongruent formats of the visualisation and the individuals' mental models. Patterson et al. consider the notion of mental model as an important aspect of information visualisation that affects high-level cognitive tasks such as reasoning, analogical reasoning, and implicit learning and in turn it affects the ability to problem solve. A mental model in terms of human reasoning is described as "an organised knowledge structure that involves imagined possibilities and projection which is similar to the idea of sensemaking" (Patterson et al., 2014, p. 49). The line graph and the pie chart are very common data representations which imply standard formatting. Unconventional use of attributes such as the layout and shape caused cognitive discomfort and confusion among the users.

Despite the difficulties in reading the charts, all interviewees indicated that the line graph is useful in identifying the spending patterns, and two interviewees indicated that the pie chart is useful in comparing the total spending amounts between the categories.

4.2.2 Charts Annotations and Typography

Two of the participants expressed the need for additional annotations within the visualisation, which do not need to be accessed via gestures. A legend for the pie chart explaining the colour conventions was suggested to optimise the interpretation of the results. Similarly, the lack of visible value labels for the pie chart was noted and it was suggested that the percentage values are incorporated in the pie chart or the summary of the results is included within the view. The use of annotations is useful to facilitate understanding of the visualisation. Therefore, the goal is to balance the minimal approach to chart annotations with the right amount of easily accessible information (Kirk, 2016).

Most of the annotation features and navigation menu included in the visualisation are based on the text. One of the design experts commented on the inappropriate use of typography in the visualisation's menu. It was suggested that the type is too small and non-linear causing legibility and accessibility issues. It was proposed that the text is removed from the flat surface and comfortably placed at the eye-level to add clarity of depth. Microsoft provides guidelines with regards to the use of typography in mixed-reality; the advised viewing angle for the direct manipulation distance is 0.65°-0.8° with the text height of 5.1mm – 6.3 mm. If the text is placed in the real environment it can be world locked and observed from each angle (Typography - Mixed Reality, 2019).

4.2.3 Colour

The interviewees commented positively on the use of colour. They found it helpful in identifying different categories, with an exception of the lack of the colour annotations previously discussed in section 4.2.2 of this paper. It was suggested that the basic colours used in the visualisation should render well on the holographic display. It was noted, however, that the background colour for the menu appears to be too light and it might be necessary to adjust it depending on the underlying surface colour on which the visualisation is being displayed.

4.2.4 Interactivity

As previously mentioned, due to the nature of the prototype it was not possible to fully assess the interaction features of the visualisation. However, during the interviews it was noted by the experts that the design of the menu is intuitive and fulfils its purpose.

Some concerns were raised around the potential issues with tracing data points on the line graph. The geometry of the line is rather thin and requires high precision tracking. Further empirical methods such as usability tests of more advanced prototypes are necessary to determine the accuracy and responsiveness of the graph. In contrast, the solid geometry of the pie chart was deemed feasible for direct manipulation.

4.2.5 Other Comments

The focus of this project was 3D data-driven visualisation of spending habits in AR. During one of the interviews one of the design experts commented on other possibilities of presenting the data in the context of the actual environment. The 3D data representation of charts was challenged based on Tufte's rule (previously discussed in section 3.3 of this paper) stating that the data representation should not exceed the dataset dimension, in this case 2D. It was suggested that the current data visualisation could be pushed further, fully utilising the available AR technology and improving the immersion of the user experience. It was noted that the existing visualisation consists of only one object and does not take the full advantage of the space available creating less of an interesting experience.

One design expert and one finance expert proposed some additional features which they would find practical as users of the visualisation. The following are the functionalities suggested by the interviewees:

1. An option to set a budget and check the spending against the set targets
2. A function to print a list of daily transactions
3. An option to view pie chart with a daily frequency
4. Inclusion of the current total balance available on the account
5. A summary of the main numbers and statistics
6. A function to visually compare the pie charts results over time and similarly for line graphs

Points 1, 2 and 4 outlined above require an expansion of a sample dataset by including additional variables such as current balance and single transaction. Point 5 relates to the inclusion of additional annotations, whereas the remaining items focus on data reconfigurations.

4.3 Revised Guidelines

The feedback from the expert reviews discussed in the previous section was further analysed in terms of the design guidelines developed in section 2.6 of this paper. As a result, the guidelines number 4, 6 and 7 were updated and one additional rule with respect to visual literacy was formulated. The remaining points are unchanged. Table 5 provides a summary of revised guidelines including comments.

Table 7 - Summary of Updated Design Guidelines

#	Design Guideline	Revised Guideline	Comments
4.	Accessible interaction design: Interaction features should be designed so that they fit with the user's physical abilities and are accessible to everyone.	Accessible design *including interaction features and display*: Interaction features should be designed so that they fit with the user's physical abilities and are accessible to everyone. *The design of annotations and text is equally important to ensure the information is presented in a clear manner.*	It was seen that the lack of annotations and inappropriate use of typography causes potential issues with accessibility and legibility. See comments in section 4.2.2 of this paper. Hence, the guideline on the accessible interaction design was expanded to include the visual design and appearance of display.
6.	Identify appropriate depth cues to correct the issue of depth perception in AR:	Identify appropriate depth cues to correct the issue of depth perception in AR *for all*	A concern regarding the inappropriate use of typography was raised by one of the design experts. One of the issues identified was the lack of clarity of depth

	consider the link between the augmented objects and the real world.	*the augmented objects including text*: consider the link between the augmented objects, the real world, *and the user*.	when the text is placed on a flat surface. See comments in section 4.2.2 of this paper. The guideline on appropriate use of depth cues was updated to specify that it applies for all the objects within the visualisation including text; the relationship between objects and the user should also be considered such as the viewing angle.
7.	Consider the use of colour when designing the visual display: the colour has an impact on many visual applications of design, e.g. it can act as a depth cue or can be used to represent data. The choice of colour should be meaningful.	Consider the use of colour when designing the visual display: the colour has an impact on many visual applications of design, e.g. it can act as a depth cue or can be used to represent data. The choice of colour should be meaningful. *The type of display and rendering capabilities should also be considered.*	Overall, the use of colour in the visualisation was positively received by the interviewees. Potential minor issue was detected with the rendering of the background colour for the menu. Given the experts feedback and the research on the HoloLens display in section 3.1 of this paper, the guideline was updated to highlight the importance of choosing the colours suitable for the device's display.

During the interviews, issues with data representations were identified. The presentation of the line graph and the pie chart did not match the standard formats and caused difficulties in reading the charts. Hence, an additional guideline was created to account for the audience's visual literacy:

Consider the audience's average visual literacy: ensure the chosen data representation fulfils its purpose and effectively communicates results and facilitates learning. Note that novelty visualisations will require additional explanation on how to read the data.

The design rule outlined above is based on the notion of mental models introduced in section 4.2.1 of this paper and the idea of visual literacy, which is defined as "the ability to understand and interpret images" (Nessa, 2013). The line graph and the pie chart are considered as conventional aspects of the visualisation and therefore arbitrary. They "derive their power from how well they are learned" (Ware, 2013, p. 12).

Table 8 - Current Design Guidelines that Remain Unchanged

#	Design Guideline	Comments
1.	Work with data: Data is a foundation of creating an accurate information	During the interviews, the experts indicated additional features which require the expansion

	visualisation that will create a trustworthy design.	of the sample dataset. See comments in section 4.2.5 of this paper. This does not affect the current recommendation on working with data.
2.	Design the interaction to maximise the user experience: consider what the user needs. This project addresses a wider audience of everyday users with mixed abilities and needs. The main aim of this project is to educate people about their spending habits.	The experts proposed additional features to include in the visualisation highlighting the importance of defining potential user intents. See comments in section 4.2.5 of this paper.
3.	Identify the interaction features before designing the display: There is a link between interaction features and display design. The interactive functions will determine the visible components of visualisation and should be incorporated in the visual representations.	No explicit comments were noted with regards to the interaction features in the context of designing display.
5.	Provide fluid interactive features: maximise the immersion and engagement by smoothly integrating the interactive features.	The concern with regards to tracing of the line graph applies to the fluidity of interactions. See comments in section 4.2.4 of this paper. If the user is not able to perform the task accurately and precisely there will be potential loss of engagement. The current guideline stresses the importance of smooth integration of interactive features.
8.	Cohesive design: ensure there is continuity in the design of the interface and the visualisation itself. The views should be well-coordinated. This will minimise the cognitive burden on the users.	No explicit comments were noted with regards to cohesive design.

The experts' comments on the interactivity indicate some potential issues with the integration of the interactive features and user experience. The current guidelines number 2 and 5 referenced in Table 6 regarding the design of interactive features consider the points made by the interviewees and therefore remain valid. No explicit comments or issues were indicated with respect to the remaining principles. However, given their importance in the design process, they were deemed to be valid and remain unchanged.

In conclusion, the following is the final set of guidelines for the design of 3D data visualisation of spending habits in AR:

1. **Work with data**: Data is a foundation of creating an accurate information visualisation that will create a trustworthy design.
2. **Consider the audience's average visual literacy**: ensure the chosen data representation fulfils its purpose and effectively communicates results and facilitates learning. Note that novelty visualisations will require additional explanation on how to read the data.
3. **Design the interaction to maximise the user experience**: consider what the user needs.
4. **Identify the interaction features before designing the display**: There is a link between interaction features and display design. The interactive functions will determine the visible components of visualisation and should be incorporated in the visual representations.
5. **Accessible design including interaction features and display**: Interaction features should be designed so that they fit with the user's physical abilities and are accessible to everyone. The design of annotations and text is equally important to ensure the information is presented in a clear manner.
6. **Provide fluid interactive features**: maximise the immersion and engagement by smoothly integrating the interactive features.
7. **Identify appropriate depth cues to correct the issue of depth perception in AR for all the augmented objects including text**: consider the link between the augmented objects, the real world, and the user.
8. **Consider the use of colour when designing the visual display:** the colour has an impact on many visual applications of design, e.g. it can act as a depth cue or can be used to represent data. The choice of colour should be meaningful. The type of display and rendering capabilities should also be considered.
9. **Cohesive design:** ensure there is continuity in the design of the interface and the visualisation itself. The views should be well-coordinated. This will minimise the cognitive burden on the users.

5. Conclusions

The goal of this research paper was to formulate design guidelines which will serve as a basis for the creation of effective data visualisations in AR. In this case, the guidelines were used to design a prototype interactive data visualisation that is capable of displaying spending habits in AR.

The initial set of guidelines was created based on the findings from the literature review. By studying and comparing various definitions of data visualisation the key elements of effective visualisation emerged. It was found that working with data is an essential part of trustworthy design. A common theme of learning was discovered among different definitions, indicating that visualisation should facilitate the users understanding of data. This concept also appeared in the context of interaction, and building user centred models which further extended to the idea of fluidity in terms of immersive design as well as the importance of accessibility. The review of perception theories centred around AR displays and blending of virtual objects within the real-world. The research highlighted the importance of finding appropriate depth cues when placing the augmented objects within the real-world. Colour was found to be another important characteristic of AR interfaces; it has many functions within visualisation and its appearance has an impact on the usability and legibility of the interface. By combining the research on interaction and perception, it was found that there exists a link between the interaction and the appearance of the display. Hence, the best practice is to first identify the interactive features within the visualisation which will then determine the visual components of the visualisation. Smooth integration of interactive and visual features ensures cohesive design which is important in reducing the cognitive burden on the users.

The proposed guidelines reflecting the findings of the literature review were put into practise by creating a prototype of the visualisation. As a result a series of static images was produced consisting of 3D diagrams created with a help of Rhinoceros 3D application, pictures of Photoshopped 3D models serving as real-world examples and images of real size paper model of one of the views testing its usability. The prototype was useful in communicating the design decisions and in evaluating the effectiveness of the visualisation and the underlying design guidelines.

Expert reviews were chosen as the most suitable evaluation method. The interviews with design and finance experts provided valuable insights into potential accessibility and usability issues. The results were analysed based on the common themes identified. It was found that one of the common issues reappearing in the feedback are difficulties in reading the charts which are laid out in an unconventional way and do not fit the users' mental models. Therefore, one additional guideline was created to highlight the importance of considering the users' levels of visual literacy. Some other issues appeared in relation to accessibility, interactivity and the use of colour have appeared. The relevant guidelines were updated. The resulting framework should be treated as a set of recommendations rather than rigid set of rules. The guidelines are designed to be used in the wider context of creating visualisations in AR.

5.1 Limitations and Future Work

Although the framework created as part of this research paper is aimed to be comprehensive, it is not exhaustive. The guidelines are based on the literature available at this point in time which provides somewhat limited research in the area of data visualisations in MR. As new MR technologies are being developed, more investigation into application of such immersive displays and their impact on human perception and cognition in the context of creating effective data visualisations is required (Olshannikova et al., 2015).

Given the limited time and resources, it was not possible to create and implement a fully functional prototype which could undergo proper user testing. As part of the future work, it would be highly beneficial to design a working version of the prototype that can be implemented and tested by the users in order to obtain some quantitative data in addition to already collected qualitative data.

Some further possible research points were identified during the expert reviews. The 3D form of presenting data was challenged, and it was suggested that the current design of data visualisation could be pushed further, fully utilising the available AR technology and improving the immersion of the user experience. This could be achieved by exploiting the real-world context and introducing the narrative to the data. Some research on storytelling already exists and would be useful to explore its application in AR visualisations.

The comments from the experts also indicate potential future work centred around the user intents relating specifically to the design of data visualisation of spending habits. They suggested some additional features which they would find useful, meaning there is more research required in identifying specific user needs that would add value and maximise the user satisfaction.

Abbreviations

AR – Augmented Reality

HCI – Human-Computer Interaction

MR – Mixed Reality

VR – Virtual Reality

Appendix A – Interview Questions

Interview Questions

Interactive Data Visualisations of Spending Habits in Augmented Reality

In the interviews, open-ended questions will be asked, and issues raised will be followed up on. The following questions are therefore indicative only.

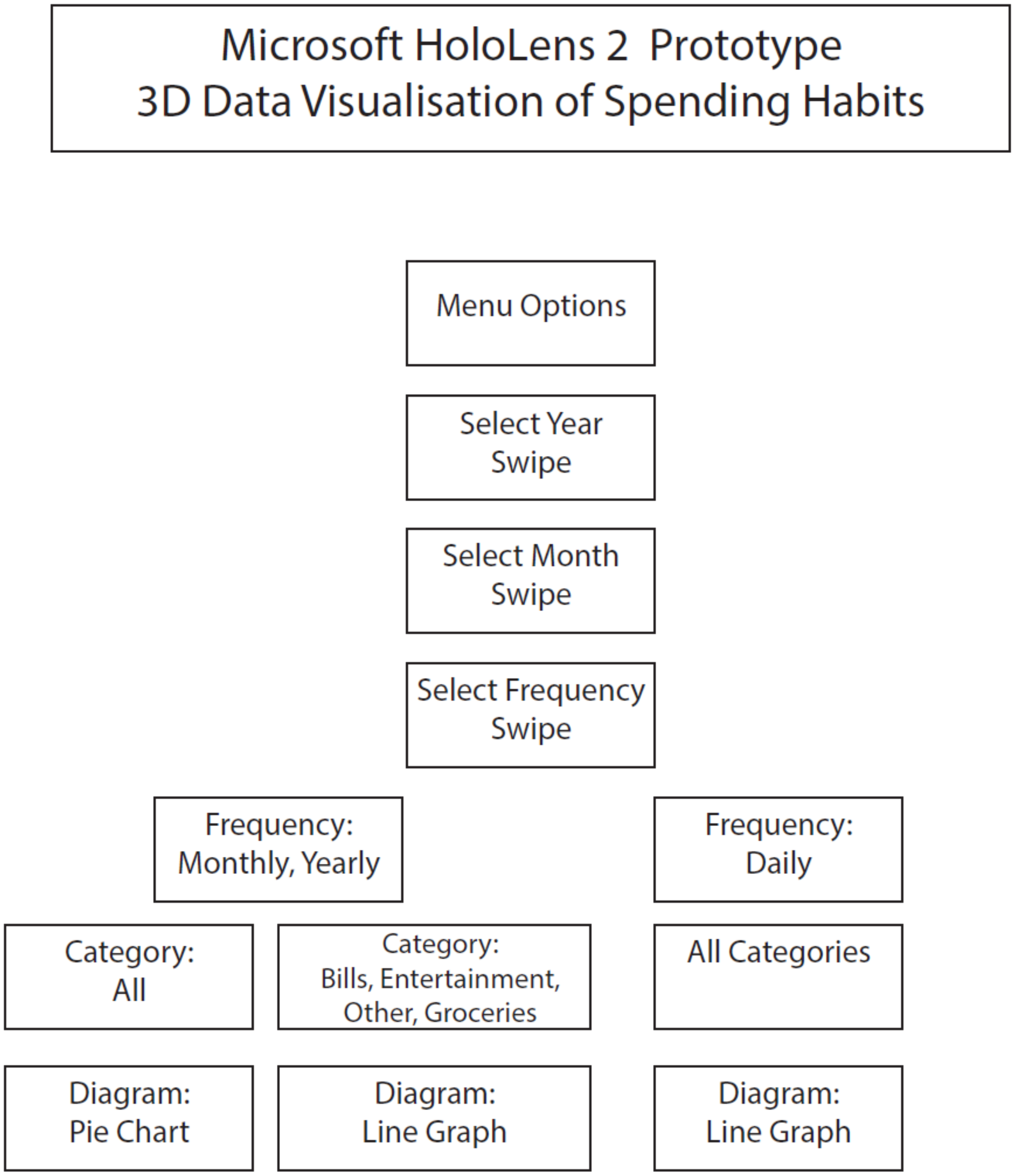
General

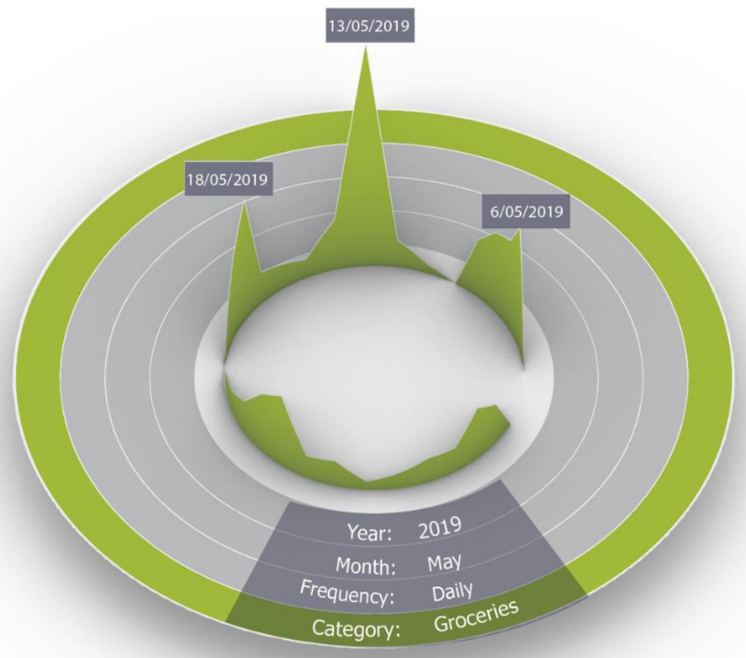
1. In your opinion what kind of purposes this data representation can be used for?
2. In general, what kind of information can you gather from this data visualisation?
3. Do you think this information should be presented differently?
4. Overall how do you find this data visualisation useful in identifying spending habits?
5. What additional features if any do you think should be included in the visualisation?

Task Oriented

6. Can you identify different expenditure classes?
7. Can you identify categories with the highest expenditure points?
8. Can you recognise patterns in spending?
9. Can you determine average monthly expenditures?

Appendix B – Prototype Demonstration

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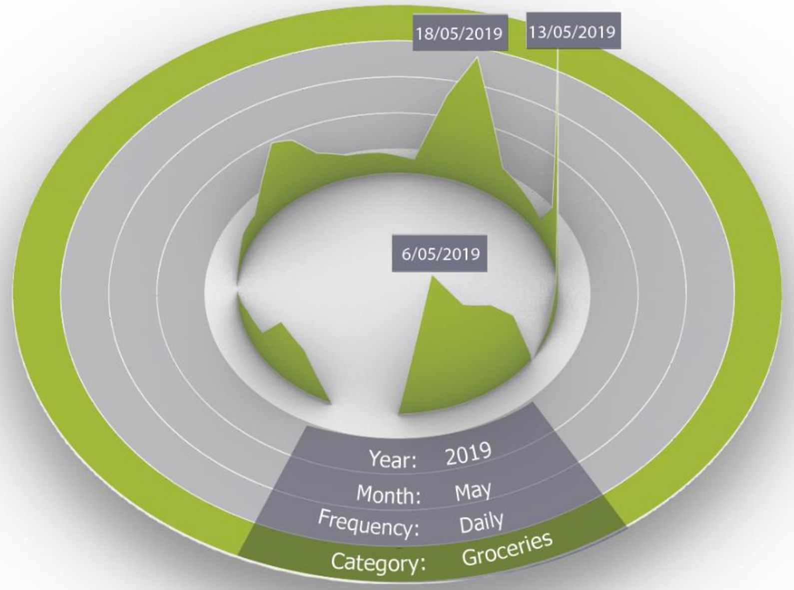
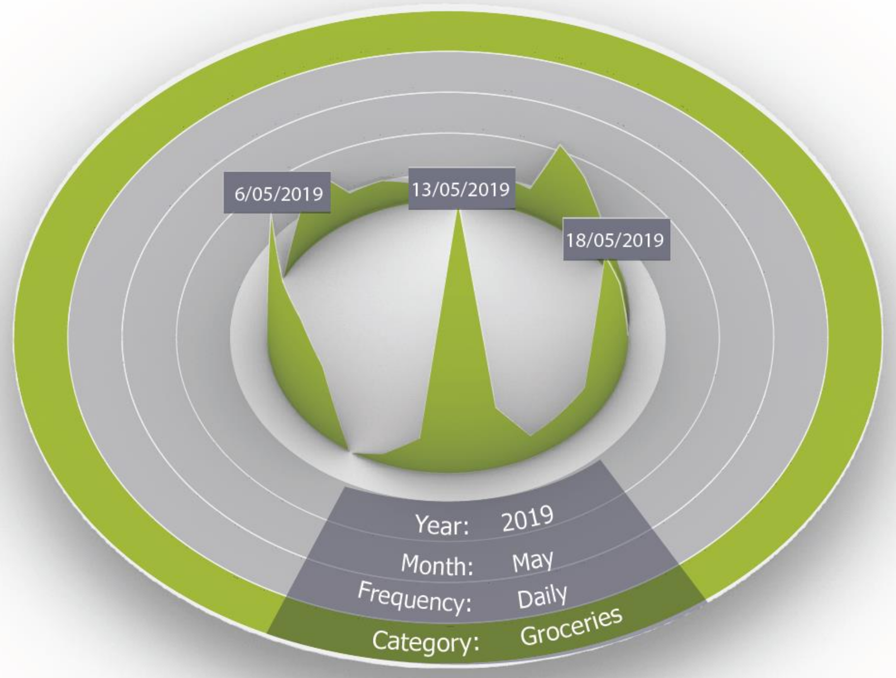
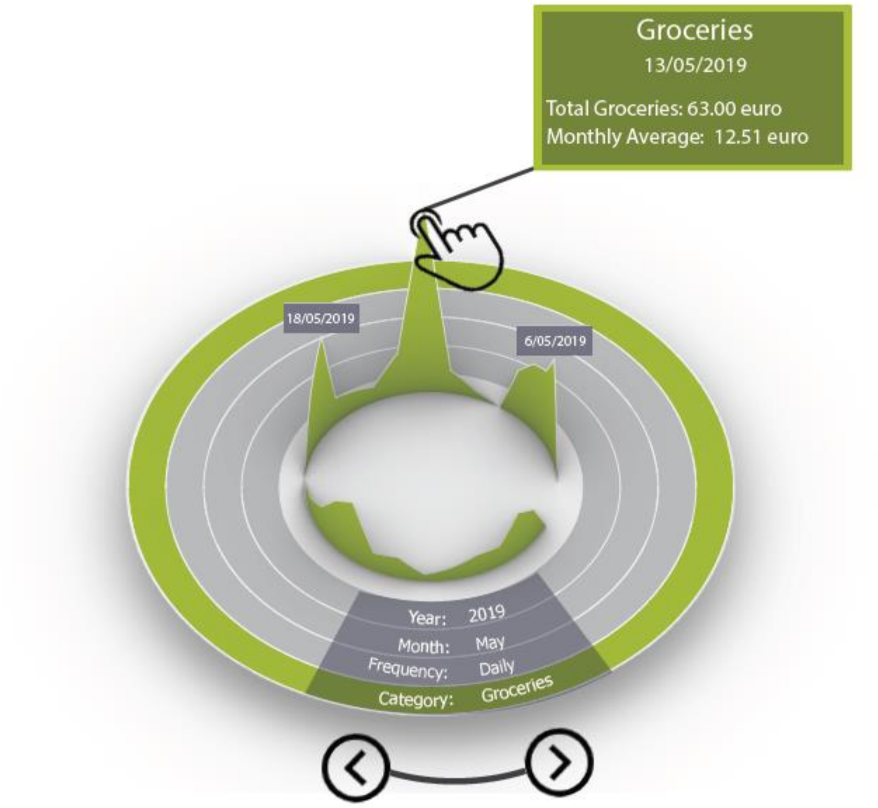
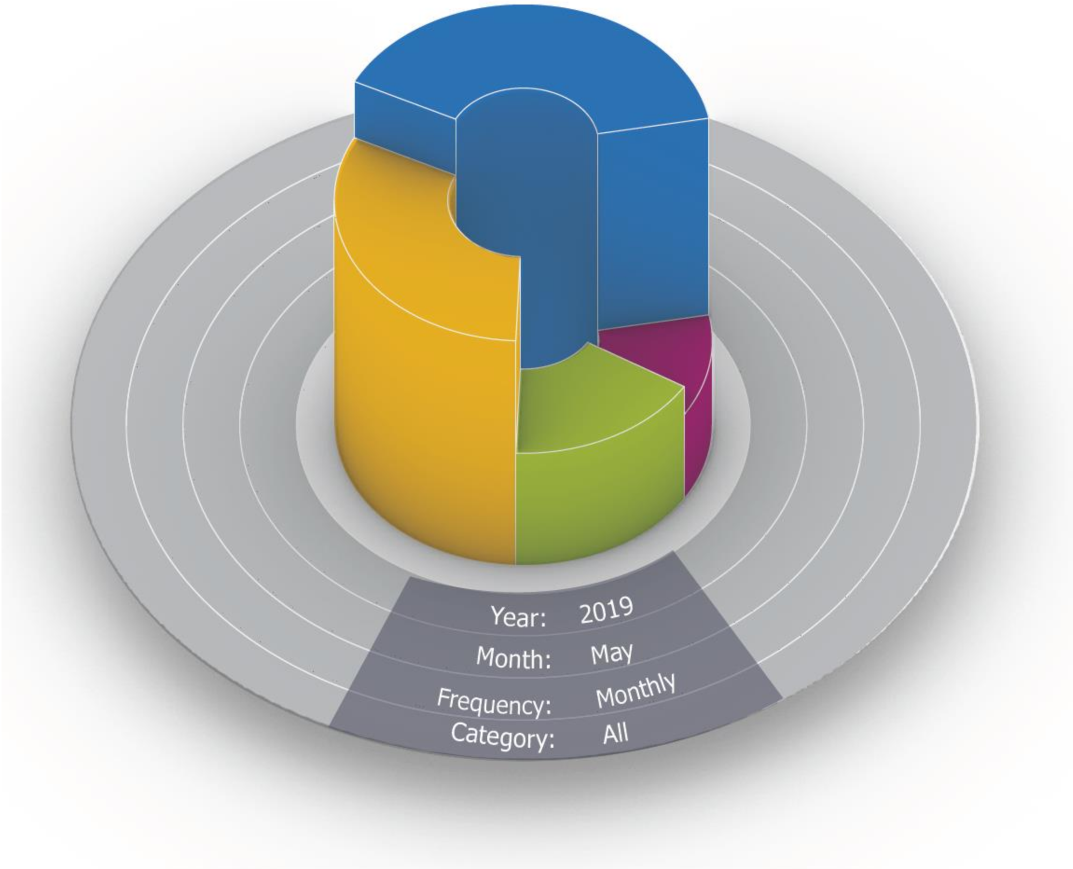
18/05/2019
6/05/2019
Year: 2019
Month: May
Frequency: Daily
Category: Groceries


18/05/2019
13/05/2019
6/05/2019
Year: 2019
Month: May
Frequency: Daily
Category: Groceries


6/05/2019
13/05/2019
18/05/2019
Year: 2019
Month: May
Frequency: Daily
Category: Groceries


Groceries
13/05/2019
Total Groceries: 63.00 euro
Monthly Average: 12.51 euro
18/05/2019
6/05/2019
Year: 2019
Month: May
Frequency: Daily
Category: Groceries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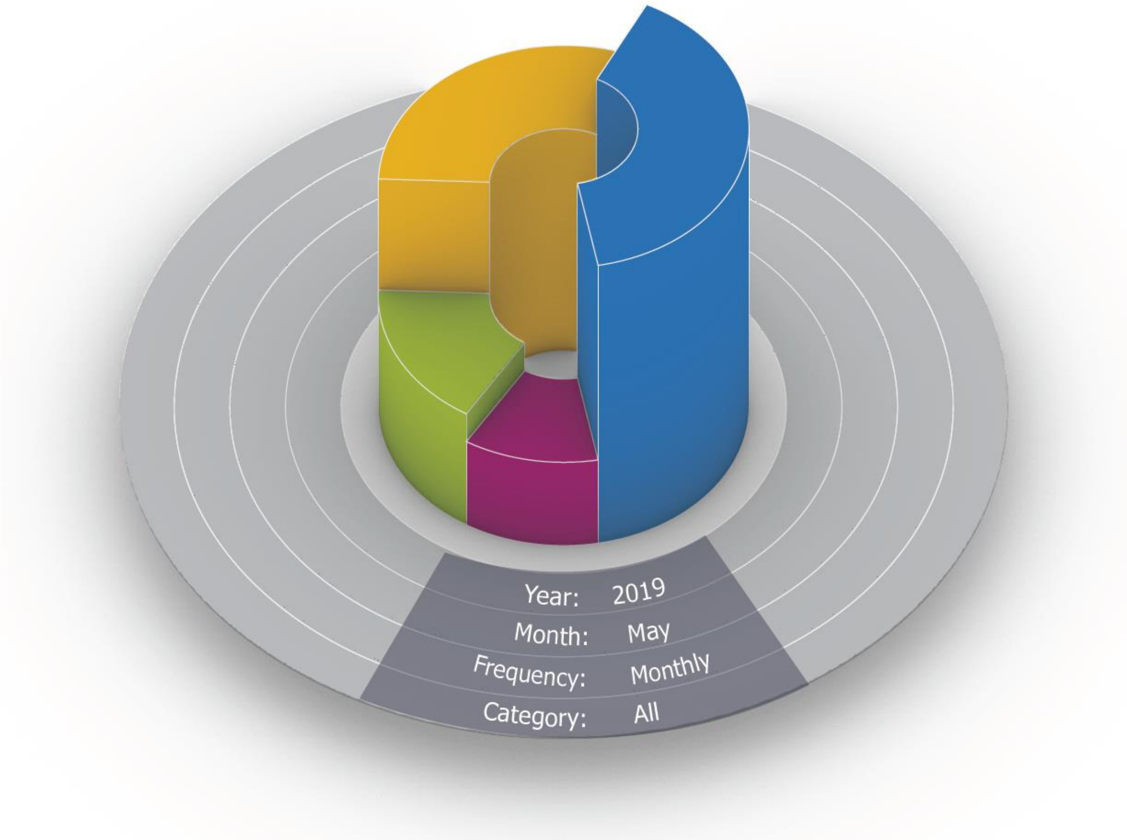
Frequency: Monthly
Category: All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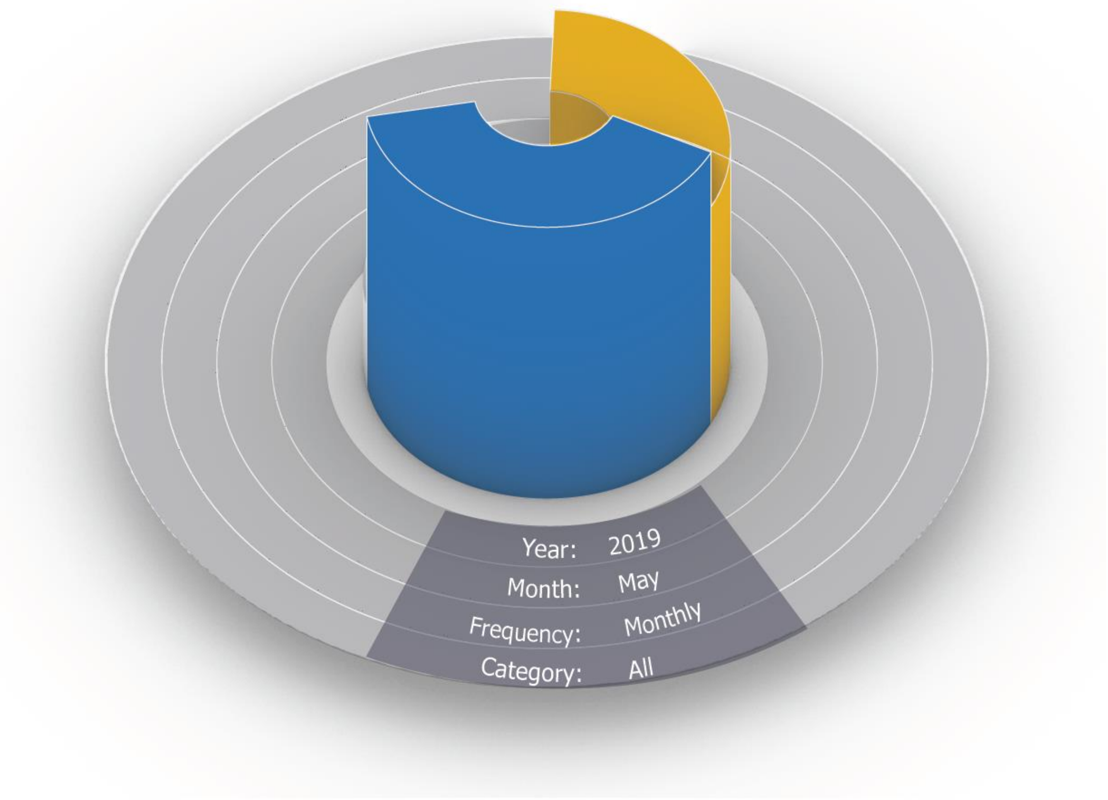
Category: All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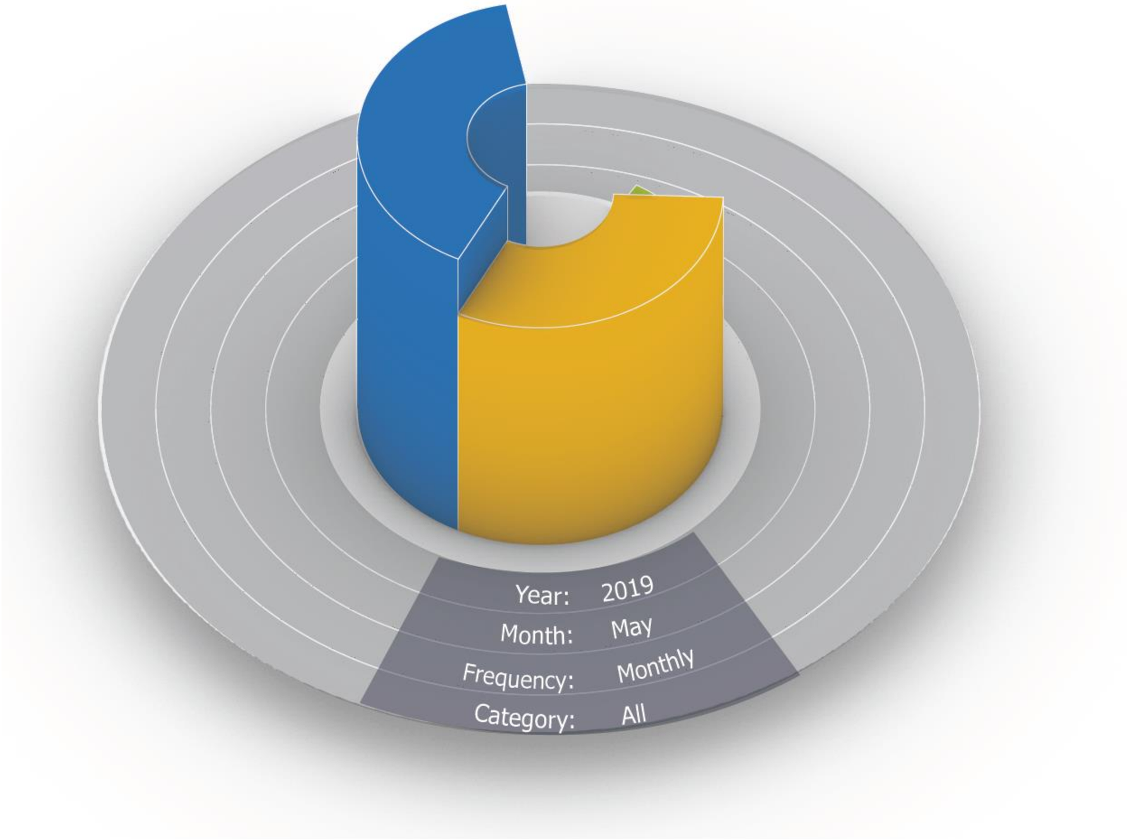
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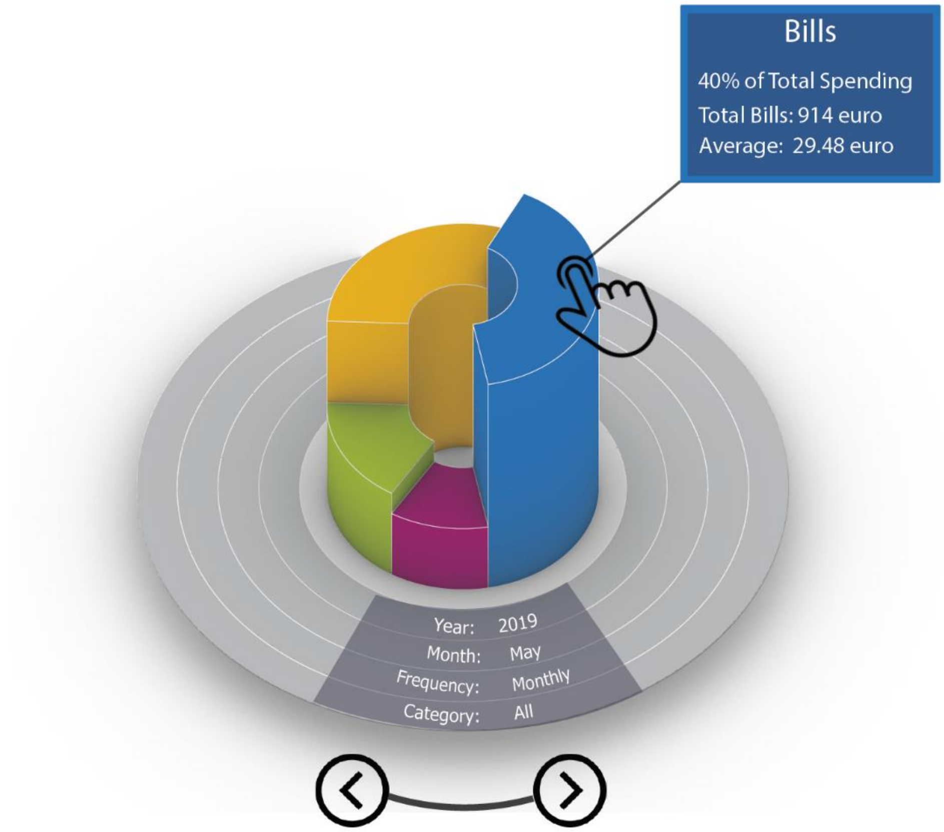
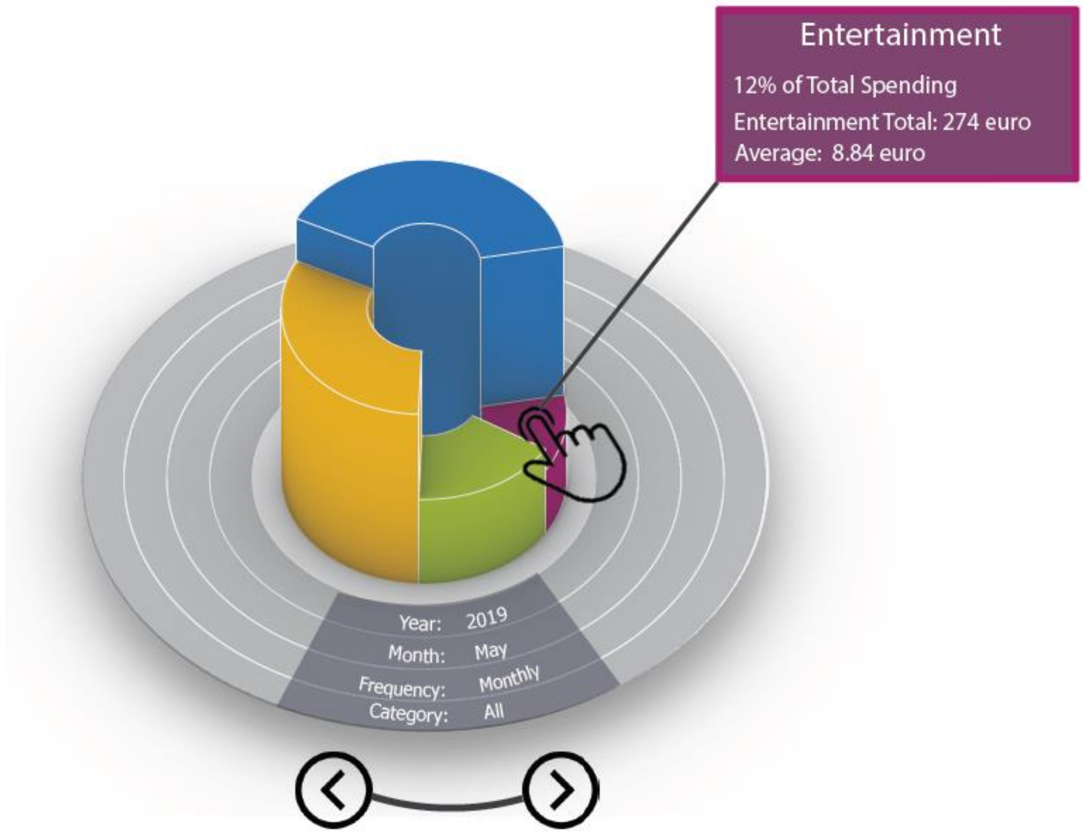
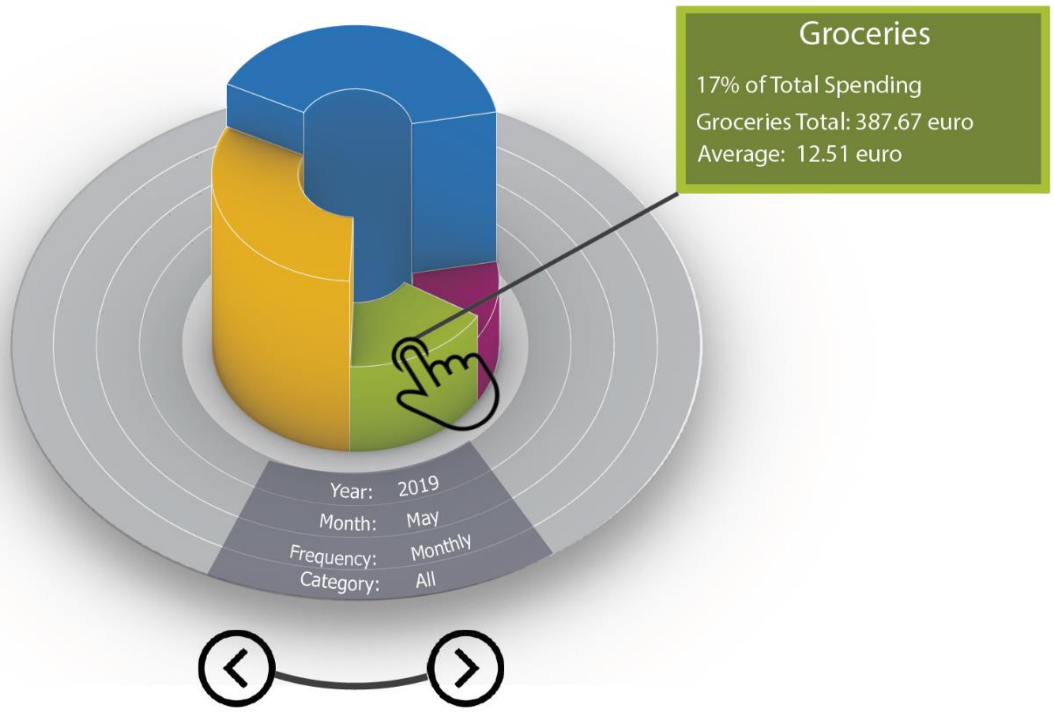
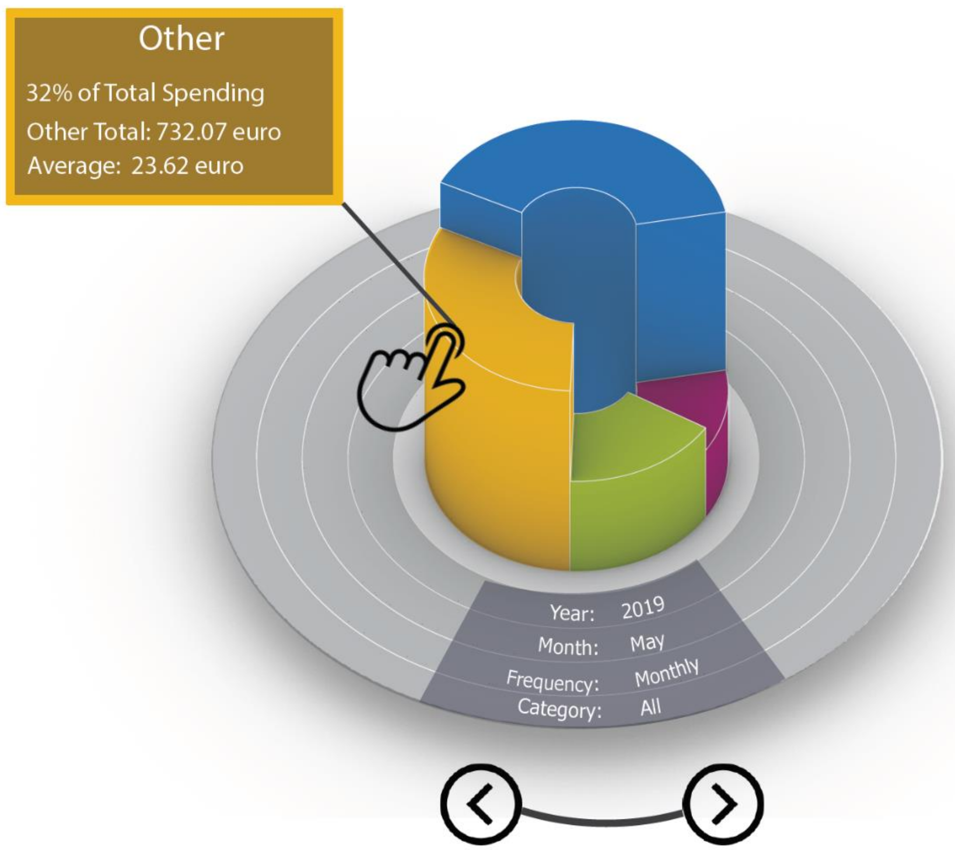
Category: All


Bills
40% of Total Spending
Total Bills: 914 euro
Average: 29.48 euro
Year: 2019
Month: May
Frequency: Monthly
Category: All

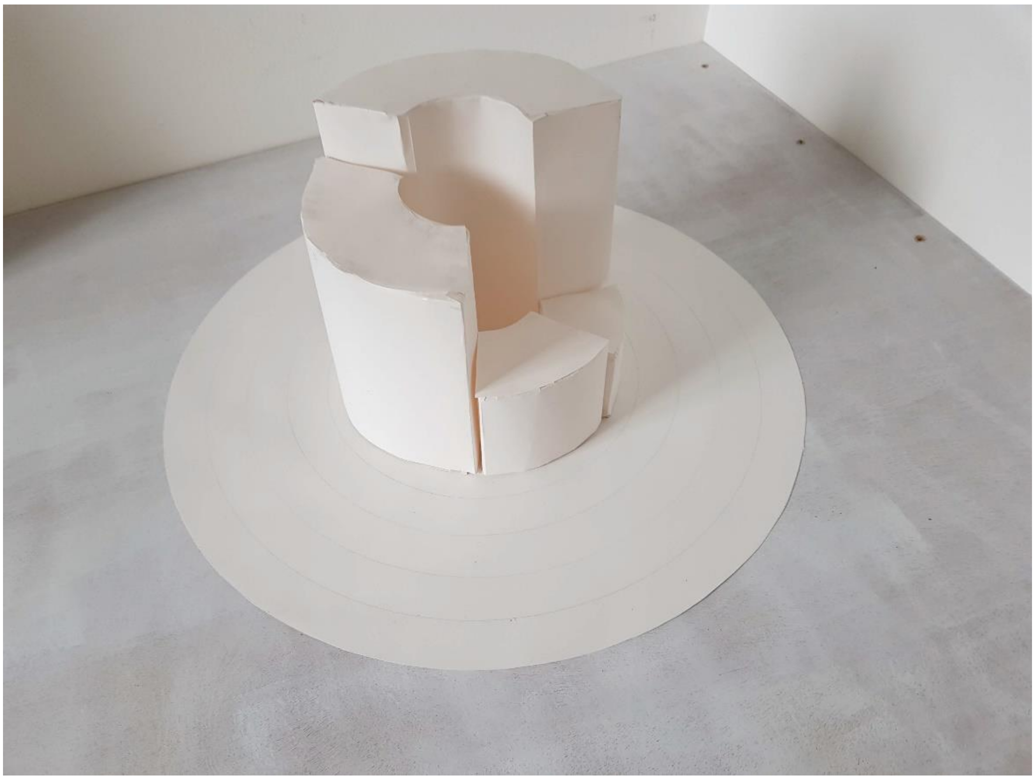

Entertainment
12% of Total Spending
Entertainment Total: 274 euro
Average: 8.84 euro
Year: 2019
Month: May
Frequency: Monthly
Category: All

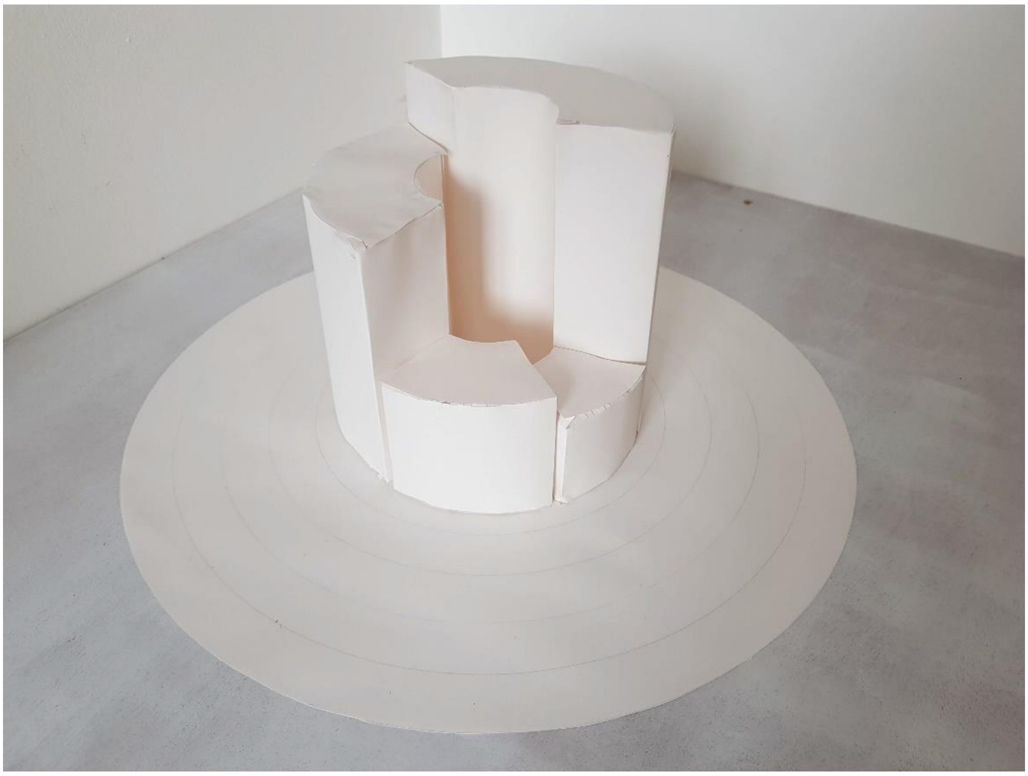

Groceries
17% of Total Spending
Groceries Total: 387.67 euro
Average: 12.51 euro
Year: 2019
Month: May
Frequency: Monthly
Category: All


Other
32% of Total Spending
Other Total: 732.07 euro
Average: 23.62 euro
Year: 2019
Month: May
Frequency: Monthly
Category: All


13/05/2019
18/05/2019
6/05/2019
Year: 2019
Month: May
Frequency: Daily
Category: Groceries


Year: 2019
Month: May
Frequency: Monthly
Category: All





Appendix C – Email Confirmation of Ethical Approval

MYzone

Daria Klaudi Grabowska <grabowsd@tcd.ie>

TCD REC WebApp: The status of 'Interactive Data Visualizations of Spending Habits in Augmented Reality' (726) has been updated by the Committee
1 message

rec-app-help@tchpc.tcd.ie <rec-app-help@tchpc.tcd.ie> 25 February 2020 at 11:42
To: grabowsd@tcd.ie

The status of 'Interactive Data Visualizations of Spending Habits in Augmented Reality' has been updated by the Committee.

Title: 'Interactive Data Visualizations of Spending Habits in Augmented Reality'
Applicant Name: Daria Grabowska
Submitted by: Daria Grabowska
Academic Supervisor: Nina Bresnihan
Application Number: 20191110

Result of the REC Meeting: Approved

The Feedback from the Committee is as follows:
The revised version addresses the issues raised, we wish you success with your study.

The application can be viewed here:

https://webhost.tchpc.tcd.ie/research_ethics/?q=node/726

If amendments are required, please use the following link to edit the application and upload the changes:

https://webhost.tchpc.tcd.ie/research_ethics/?q=node/726/edit

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