Popping the Bubble: Do bubble plots distort interpretation of circle size?

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ABSTRACT

This research tested the hypothesis that an Ebbinghaus illusion can occur in a bubble plot display and thus distort the interpretation of circle size. In order to do this we tested participants' ability to judge circle size in different bubble plot conditions. These conditions varied based on how likely they were to cause an Ebbinghaus illusion to be present in the plot. The research found that conditions that were more similar to the Ebbinghaus illusion showed greater distortion and were distorted in the correctly theorized direction. The implications of these distortions were then assessed based on theoretical guidelines of good visual displays of data.

DECLARATION

Submitted in partial fulfilment of the requirements for the degree of Master of Arts in the Graduate Programme of Research Psychology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

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1. INTRODUCTION

This research study focuses on the intersection between two ideas. Firstly, we look at the way visual displays are used to represent numerical data, specifically in the form of bubble plots. Secondly, we look at the possibility that a particular visual illusion, called the Ebbinghaus illusion (Ebbinghaus, 1913), can occur in bubble plots distorting the interpretation of them. The Ebbinghaus illusion is an illusion of context, where a particular circle's size interpretation is distorted by a set of surrounding circles either to look bigger or smaller than it really is (Ebbinghaus illusion, 2014). Bubble plots are a type of display that are used to show multidimensional data by plotting circles of varying size on an x-y axis, where the change in circle size corresponds to the change in a variable of the data (Bubble chart, 2014). It is in this type of display that an Ebbinghaus type illusion may occur and distort the viewer's interpretation of the display. Much research has been conducted into the making of accurate and easily readable visual displays of data (Cleveland & McGill, 1987; Kosslyn, 1989; Tufte, 1983), and some of this research has focused on visual illusions (Cleveland, Harris, & McGill, 1983). The current research aims to make a contribution to this body of research by examining whether an Ebbinghaus like illusion can occur within bubble plot displays. It will also question whether the distortions of circle size caused by an Ebbinghaus like illusion are enough to make bubble plots inappropriate to use in certain settings.

To answer these questions we will conduct an experiment to see if circle size interpretation is distorted in different bubble plots, where conditions are varied according to how likely they are to provoke an Ebbinghaus type illusion. The magnitude of the distortions in the different plots will be compared and this will be related to the literature on visual perception and causes of the Ebbinghaus illusion. The distortion in circle size will also be related to how they affect the interpretation of the plot and whether they violate proposed guidelines for making quality visual displays of data (Kosslyn, 1989; Tufte, 1983).

The wider implications of this research on the use of bubble plots will involve consideration of appropriate and inappropriate settings for the use of bubble plots. Finally, we will look at the importance of a display being easily interpretable and being an accurate reflection of the data and the relevance of the findings of the current research in this regard.

2. LITERATURE REVIEW

This literature review will focus on literature related to the use of visual displays to represent data and how this relates to the use of bubble plots, and the possibility that a visual illusion, namely the Ebbinghaus illusion (Ebbinghaus, 1913), can be present in bubble plots. The first section of the literature review, section 2.1, focuses on literature related to the use of visual displays to represent data and will explore guidelines that have been proposed to ensure that these displays accurately convey the data they are based on. We will focus on how violations of these guidelines can have effects on multiple levels and stress the need to consider all these levels when assessing the suitability of using particular plots in certain settings. The next part of the literature review, section 2.2, will focus on theories that have been proposed to explain how visual perception works. We add this section because it is important to have some idea of how perception may work when assessing the causes of visual illusions and how likely they are to show up in bubble plots. This section will look at the so called ‘top-down’ and ‘bottom-up’ approaches to perception and more recent approaches that have fruitfully combined the two. This will give us an appreciation of the various sources that provide possible explanations of the Ebbinghaus illusion. We will then go into some detail about the various experiments that scientists have conducted to try and discover the causes of the Ebbinghaus illusion and the role that the Ebbinghaus illusion plays in the debate about dual stream theories of perception. Once we have looked at the possible causes we will assess how likely it is that those causes can operate within bubble plots thereby distorting participants’ interpretation of circle size.

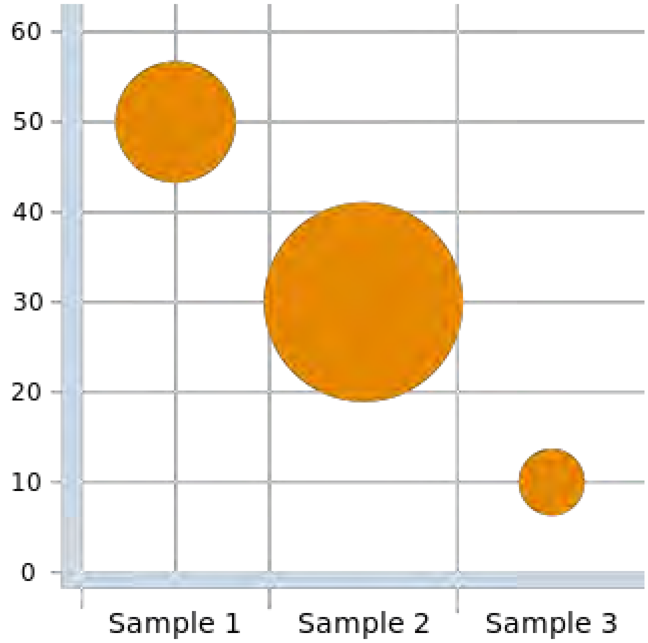

Figure 1: Bubble plot example

(Bubble chart, 2014)

It is necessary for clarity that we first introduce readers to some basic concepts before proceeding with the literature review. The two main concepts used in the current research are bubble plots and the Ebbinghaus illusion. An example of a bubble plot is shown above in Figure 1. It is much like a scatter plot, where data points are plotted on the x and y axis depending on the values of the two variables that the axes represent. A bubble plot extends this by adding another variable and representing this variable by replacing dots with circles. The third variable is represented by the size of the circle, thus enabling three aspects of the data to be displayed in one graphical display.

The Ebbinghaus illusion is an illusion that occurs due to context, the prototypical version of this illusion involves circles surrounded by other circles, as illustrated in Figure 2. The basic configuration of the illusion involves two identical circles surrounded by sets of contextual circles. The sizes of the contextual circles have an effect on the perception of the size of the middle circles. Bigger surrounding circles lead to the middle circle looking smaller, and smaller surrounding circles lead to the middle circle being perceived as bigger. This leads to people making distorted judgements of the size of the two middle circles.

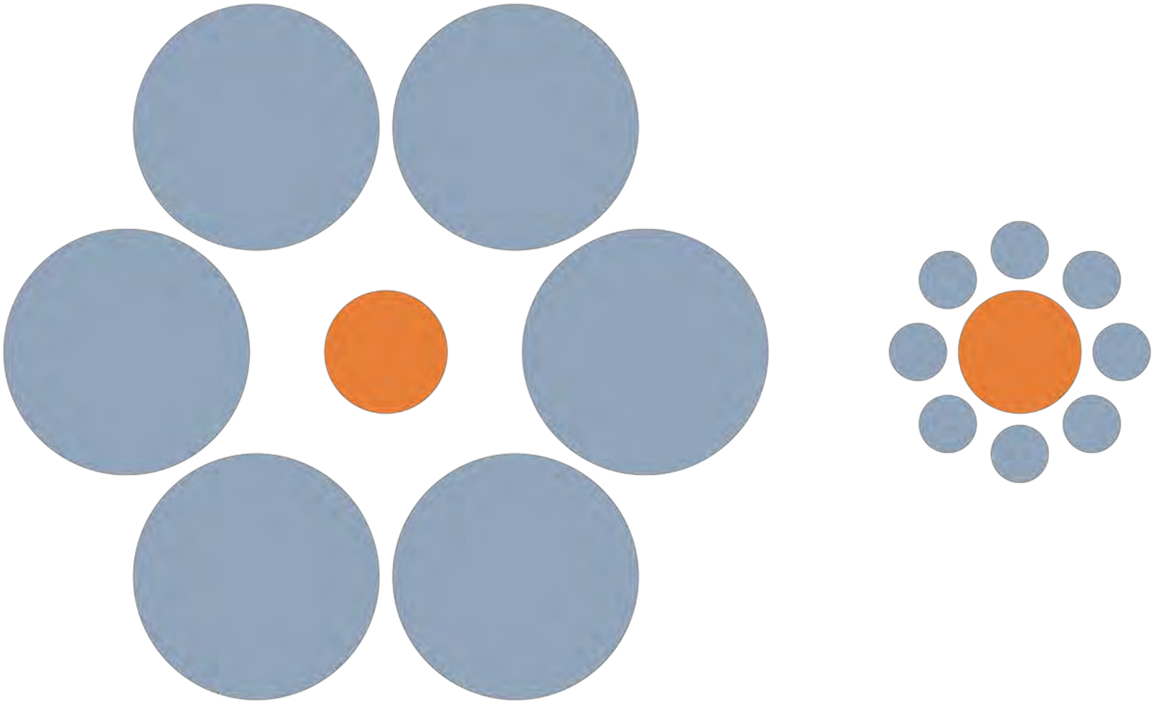

Figure 2: The Ebbinghaus illusion
(Ebbinghaus illusion, 2014)

It is clear when looking at the displays of the two concepts in Figure 1 and 2 above that it could be quite possible that an Ebbinghaus type illusion can occur in a bubble plot if the circles were arranged in the correct locations corresponding to an Ebbinghaus like situation. As we will see in the literature review in section 2.3 when looking at the causes of the Ebbinghaus illusion, these causes are often present in bubble plots.

2.1 Visual displays of data

2.1.1 Brief history of displays of data

The use of visual displays of data has become a ubiquitous feature of the modern world. Their use has become widespread, especially with their ability to be easily disseminated through the Internet. A visual display of data is any display that uses graphical elements to represent data, where changes in data correspond to proportional changes in the graphical elements use to display it (Tufte, 1983). For example this can be accomplished by plotting symbols on an x-y axis or using the area of geometric shapes to proportionately represent numbers. Visual displays of data have an unmatched ability to display and summarise large volumes of data in an easily interpretable form, which can be used to inform people and guide them in their decision making (Tufte, 1983). Thus, it is important that what people take away from the display is in fact an accurate representation of the data. Graphs that fail to do this can mislead people and cause them to make misinformed decisions.

Historically the pioneering use of modern displays of data, as we would recognise them today, is attributed to William Playfair and Johann Heinrich Lambert in the 1700s (Tufte, 1983), but, as Friendly (2008) has shown, the 'roots' of these types of displays are much older. Their development parallels the development of statistics, methods in cartography and advancements in methods that accurately record empirical data. The invention of the printing press also greatly influenced the way graphics were made and used. The idea that demographic information could be useful for purposes of taxes, land ownership and the value of goods drove the collection of large amounts of data, leading to the need for clear and accurate graphical displays for ease of interpretation of this data (Friendly, 2008).

The history of visual displays of data contains many examples of graphical excellence and many examples of where the displays mislead (Tufte, 1983). Two early examples of this – one illustrating what is considered a bad practice and another illustrating what is considered a best practice – will demonstrate the importance of this topic. William Playfair invented many of the most popular displays of data that we use today (Tufte, 1983). He invented the line plot, bar chart, pie chart and circle chart amongst others (Friendly, 2008). It is also fitting that he provides an early example of an unintentional 'bad practice' that leads to a distorted interpretation of a graph. When developing a graphical display in order to argue that the British were overtaxed, he plotted both population and taxes on the vertical scale and then used the slope between the two values as the focus of the display. This is considered a bad practice because one can easily alter the scale of either the population measure or the tax measure changing the slope between them, which can give widely different interpretations dependent on how you have set the axes. It is the flexibility of this practice that is the problem, if by changing the scale of one of the axes you can completely change how people interpret the graph then this practice cannot be trusted. The flexibility of this practice and other related ones has been used by many people either intentionally or unintentionally to mislead others. An early example of an idea that has become a best practice in data displays is in a display done by Christopher Schreiner showing differences in sunspots over the course of a few weeks (Shown below in Figure 3 from Tufte (1983). He used a method now commonly referred to as ‘small multiples’ to display many small graphs on one page which vary on one variable to allow easy comparison between them on that variable. The example he used was visualising the sun’s activity over different time periods, enabling an unprecedented look at how sunspots changed over time (Tufte, 1983).

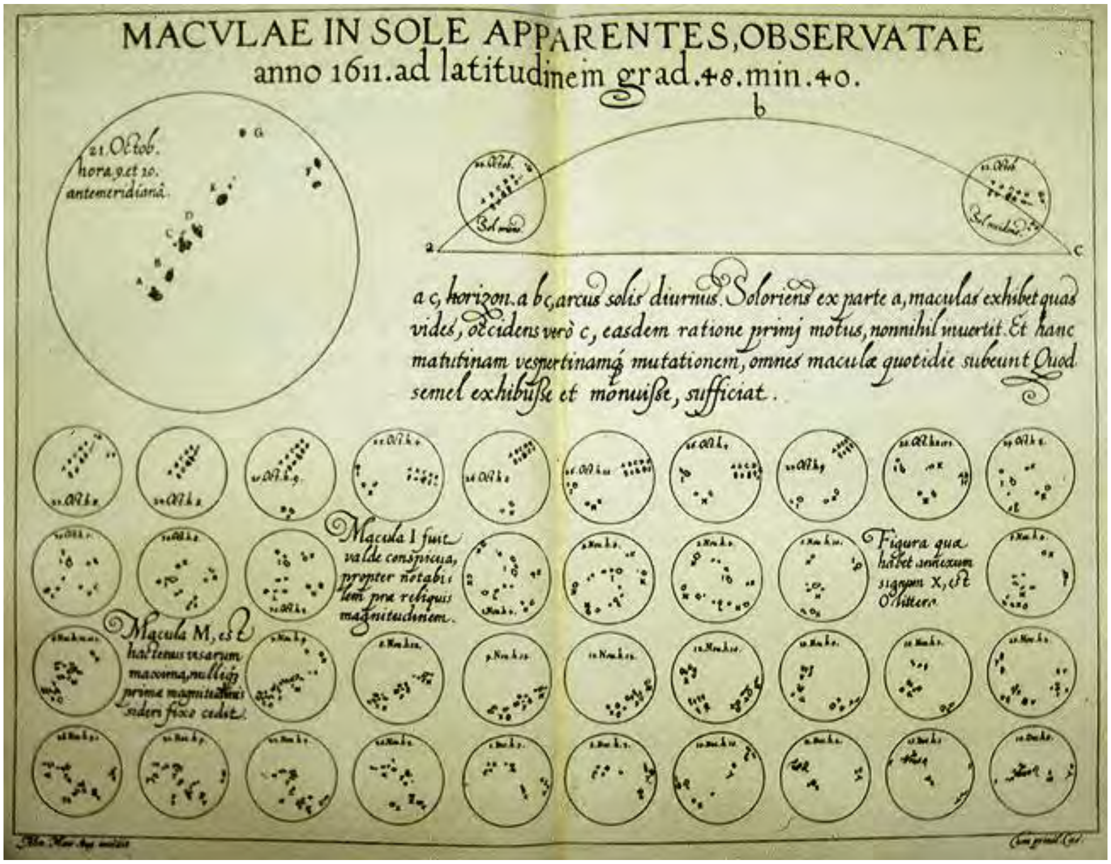

Figure 3: Christopher Schreiner’s Tres Episolae: sunspots

2.1.2 Guidelines for creating good plots

It is from this historical development and extensive experimentation that scientists have learnt so called ‘best practices’ in graph making. This has led to a number of scientists proposing guidelines to ensure that graphs can be accurately interpreted and be useful for decision making (Cleveland & McGill, 1987; Kosslyn, 1989; Tufte, 1983). We will focus in more detail on two schemes, one developed by the statistician Edward Tufte (1983) and the other by psychologist Stephen Kosslyn (1989). They embody very different approaches to creating visual displays of data. Tufte uses historical examples of good and bad practices to develop guidelines for making data displays, and has had some success in designing new displays which has resulted in many of his principles becoming widely known and accepted. Kosslyn on the other hand uses psychological theory to develop his guidelines based on particular aspects of visual perception. It is because of this more theory based approach that Kosslyn's guidelines are more applicable to the current research as will be shown below.

2.1.2.1 Tufte

Tufte has brought significant attention in recent years to the need for good displays of data and has been successful in bringing a great deal of attention to this field of study (Tufte, 1983, 1990, 2006). He has popularised the study of good and bad graphical displays and introduced a number of concepts which are often seen as the *sine qua non* of graphical excellence. One such idea is to maximise the data-ink ratio (Tufte, 1983). The basic idea is that one must remove all nonessential parts of the display leaving only the parts that meaningfully display the actual data. This prevents distractions and makes you focus on the relevant representations of data. Tufte emphasises this point by quoting the statistician John Tukey as saying, "If you're going to make a mark, it may as well be a meaningful one" (Tufte, 1983, p. 140). Tufte has also focussed on the opposite of maximising the data-ink ratio, which is commonly called 'chart junk', where displays are unnecessarily cluttered up with decorative features. This obviously skews the data-ink ratio and needlessly distracts the viewer viewing the display, often to the detriment of interpretation (Tufte, 1983). Although, there has been some debate about the value of chart junk, some research indicates that people more easily remember displays with chart junk than those without (Bateman et al., 2010). Tufte seems to be focusing on interpretability rather than memorability, which could vary widely depending on the how interesting the topic of the graphical display happens to be. Another idea Tufte has popularised is that of small multiples which involves showing multiple small graphs on the same page that vary on a single variable which allows you to make easy comparisons between the different multiples (Tufte, 1983). As shown above in Figure 3 one example of this is the progression of sunspots at different times, but another example could be to show how crime rates have progressed over the years in different cities; here the small multiples are graphs with lines or bars corresponding to crime over an extended period of time and the different multiples (different plots) could be different cities. This allows for easy comparisons between cities of not just current crime rates but also trends, and gives an impressive and intuitive understanding of what is happening over a vast area of space and time.

Perhaps the most relevant of Tufte's ideas for the present purpose is his idea about the **lie factor**, which is related to graphical integrity (Tufte, 1983). The **lie factor** is calculated by dividing the size of the effect shown in the display by the size of the actual effect reported from the data. A **lie factor** above 1 inflates the perceived effect relative to the actual effect, whereas a lie factor below 1 deflates the perceived effect. In the present research there is a possibility that an Ebbinghaus type illusion, or any illusion for that matter, can distort the interpretation of circle size and can lead to an increased **lie factor** in either direction, whereby the graph does not accurately reflect the values of the data.

Tufte's work has led to many advances in displaying data, however he has not focused on theories about vision and perception that are relevant for understanding how people see and interpret visual displays of data. He does not cite much empirical research on these issues and prefers to focus on historical examples. He uses this to develop a system based on what looks intuitively right to him. This has led him to make many contributions to the display of data and Tufte's intuitions have more often than not been right, but this approach is limited in what can be discovered using it, and in terms of the guidelines it offers. If you do not have Tufte's intuitive grasp of good and bad graphics it can be hard to diagnose good and bad practices, let alone understand the reasons they are good or bad. The next set of guidelines are more explicit and for that reason more useful for the current research.

2.1.2.2. Kosslyn

Stephen Kosslyn has done extensive research on the psychology of vision and perception (Kosslyn, 1980, 1996) and has developed a set of guidelines for visual displays of data that take these findings into account (Kosslyn, 1989). The guidelines focus on identifying the various aspects of graphs and what roles they play in the communication of data, specifically focusing on the information conveyed at the syntactic, semantic and pragmatic levels.

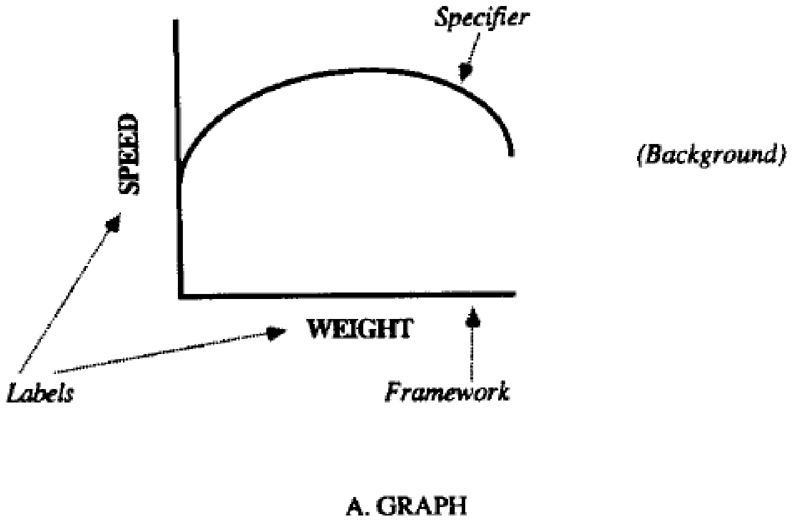

Figure 4: Kosslyn's basic level constituents

Firstly, Kosslyn divides graphs into their basic constituents: the background, framework, specifiers, and labels as seen in in Figure 4 (Kosslyn, 1989). The background is usually left out of the display but can sometimes be added for dramatic effect. For example, if a graph is about poverty the use of a picture in the background showing poverty stricken conditions conveys this message. However, there is a very real threat that having a background may distort or make interpretation of the display difficult, therefore the background is most often left blank or grid lines are used. The next constituent is called the framework, which specifies what is being displayed and the relations that are being displayed. It does not show the data – the actual instances of what is displayed – it shows the meaningful dimensions that are being displayed. For example in Figure 4 the x-axis (**weight**) and y-axis (**speed**) are the framework that gives specific data points their meaning in relation to the whole display.

The next constituent of the display is the specifier, which is the actual data being displayed in relation to the frame work. In Figure 4 it is the curved line and where it is located on the graph, in a circle plot, the location and area of the circle can represent different aspects of the data and various bars and dots can fill this role too. The last aspect of the constituents are the labels;

these are perhaps most important for the semantic and pragmatic levels of analysis. They have the obvious function of conveying to the perceiver just what the data being displayed are about. In Figure 4 both axes are labelled (weight and speed) and this makes the graph meaningfully interpretable. In graphs that use circle size to display aspects of the data, labels must be used to indicate what the change in circle size means or else it does a very poor job of conveying meaning and can confuse the perceiver. These four aspects of Kosslyn's guidelines are interpreted at three hierarchical levels with each of the levels depending on the lower levels, so errors in lower levels can lead to effects at higher levels. These levels are the syntactic, semantic and pragmatic levels (Kosslyn, 1989).

The syntactic level deals with aspects of discriminability, the thresholds whereby humans can make judgements of difference (Kosslyn, 1989). It is no use having differences in the values of data displayed in such a manner that people cannot perceive the difference from the graph. Variation in a graph needs to be adequate enough to be easily perceived and convey two aspects, the first being the presence of a difference, and the second the relative difference. In this the differences between things can be easily seen and compared accurately. Previous research has suggested that differences in circle size may be hard to perceive (Cleveland et al., 1983) and this will be relevant for our current research. Certain features of perception are known to distort the interpretation of certain displays. For example sensory distortions, such as contour integration, can distort aspects of displays leading to distortions in discrimination (Field, Hayes, & Hess, 1993). This effect is relevant to the current research on the Ebbinghaus illusion, as contour integration explanations have been suggested to explain the illusion (Jaeger, 1978). Various aspects of how the constituents of displays are grouped together by perceivers have an effect on how data is interpreted. For example, well known Gestalt laws (Wertheimer, 1938) need to be taken into account because the Ebbinghaus illusion is said to be affected by the circles being grouped together based on similarity, which we will see can affect the semantic interpretation of them as well.

The limitations of working memory also need to be considered when creating displays (Baddeley & Della Sala, 1996). These limitations can make discrimination difficult and give undue attention to prominent, easily noticeable, and groupable features of the display. The visual system is a difference detector and sharp contrasts between aspects of the display can attract greater attention (Kosslyn, 1989). These cognitive limitations create a limit on how much can be displayed and what information can be extracted from the display. Highly cluttered graphs with low data-ink ratios can overwhelm the perceptual system making the graphs hard to compare and interpret.

Kosslyn’s next level of analysis is the semantic level, involving the analysis of the semantic aspects of displays, or how meaning is attached to different marks on the display (Kosslyn, 1989). The intended meaning of aspects of the display should correspond to the usual spontaneous interpretation of those marks. Labels and words should be appropriate for the data they are showing. Greater values of a variable of the data should be shown as located higher in graphs which use a vertical axis to represent information. Time should be represented based on the cultural norm, which in ‘western’ standards means from left to right. These standards aid in the easy and rapid interpretation of what the graph is trying to convey, rather than making people think in a way they are not used to thinking. The linguistic idea of ‘markedness’ is important when choosing labels (Kosslyn, 1989). A marked word is one that is highly specific in use. Use of unmarked and more abstract words are preferred. For example, using ‘how tall/short it is’, which introduces a specific direction, is not advised, whereas the unmarked term ‘height’ is non-specific and generally superior. Familiarity either based on cultural or the universal aspects of cognition is preferred due to it allowing quick and accurate interpretation of the data.

The need to avoid ambiguity is important when making graphs; every detectable difference, in marks on the page or screen, should have only one meaningful semantic interpretation (Kosslyn, 1989; Tufte, 1983). This is a case where problems in the syntactic level lead to violations in the semantic level of interpretation.

The next level of Kosslyn’s system is the pragmatic level. This level deals with whether the flaws in the display lead to real world problems, and whether they are big enough to have meaningful effects in the real world (Kosslyn, 1989). Could a distortion in a display be serious enough to lead to risky behaviour due a person getting misleading information from a flawed graph? Another way in which a display could have real world consequences is if the lie factor is very high, leading to a person having a fundamentally distorted view of reality. This could result from the misrepresentation of a real world effect either by distorting its magnitude or in the worst case scenario a distortion of the direction of the effect. The pragmatic level is analogous to the pragmatics of language, and the various ways that the pragmatic meanings of things can differ from the literal meaning of things based on their context in the real world (Kosslyn, 1989). In language an example of this is indirect speech, where simple sentences can convey more than their literal meaning based on context and cultural norms. We see the pragmatic aspects of the display in the way it relates to the real world and what it conveys based on the link to this context. Focus at this level of analysis is on the aspects of the display that directly links the display to a real world phenomenon.

Kosslyn (1989) proposes three classes of acceptability principles for pragmatic analysis. The first principle is ‘purpose-compatibility’, which states that a display should make the information that a viewer needs to extract explicit. This is explained in terms of three requirements based on Grice’s analysis of language (Grice, 1975). The first requirement is ‘Appropriate amount’, i.e., no more or less information should be provided to the reader. Trying to fit too much information into a display can be detrimental to the message you are trying to convey and vice versa. The second requirement is ‘Appropriate content’, which is related to the purpose of the display. In different settings the goals of the display vary; therefore the graph needs to match the varying requirements regarding aesthetics and interpretation in the different settings. For example a graph in a journal article may require a different configuration compared to a graph displayed in the newspaper. ‘Appropriate format’ is the third and final requirement and is related to finding a match between the data for display and the best type of display/graph to display it. For example, in a regression analysis, the interactions between variables are better displayed using a line graph rather than a bar graph. Graphs that are good at showing finer differences are more appropriate than graphs that only show coarse differences. ‘Purpose-compatibility’ ensures that the graph is displaying relevant information in the best possible way to display it.

The second principle for the pragmatic analysis is the principle of invited inference (Kosslyn, 1989). This is very much related to indirect speech, where although the literal semantic meaning of the graph may be true, the taken away pragmatic message is different. This can happen when people manipulate the framework, distorting aspects of the data giving them greater prominence in the display. One way this is accomplished is when people alter the axes of displays to make small differences seem big. For example, a relatively small increase in taxes can be made to look large by using an axis that does not start at zero and zooms in on the change, magnifying the visual impact of the difference. Another way that this is accomplished is by using an axis without a constant scale where a change in one part of the graph does not correspond to a change in another, emphasising differences in one part of the display while minimising differences in other parts of the display. Many of these tricks on manipulating graphs to give a false impression of the data are detailed in the book *How to Lie with Statistics* (Huff, 1954).

The third principle of pragmatic analysis is related to contextual compatibility (Kosslyn, 1989). The context and the semantic interpretation must be compatible, if not this will make a graph hard to interpret. A graph should be placed in the right context and the aspects of the data it displays should be the ones that are being discussed in the text or the presentation that is being shown. For example when writing a journal article, graphs should be put in the sections that they directly apply to because it would be confusing to a reader to come across a graph that bears no relation to the text they are reading. Likewise during an oral presentation, displays need to be related to what the speaker is saying.

Applying Kosslyn's guidelines can help to improve visual displays of data. The integrity of science depends on using the best tools to make sense of the data and using the best practices with those tools; when this has broken down it has led to many good scientists being deceived (Blakemore, Weston-Smith, & Barlow, 1990).

2.1.3 Application to current research

In applying Kosslyn's guidelines to the current research we need to look at how the different levels of analysis apply to bubble plots and more specifically to how the Ebbinghaus illusion might distort the perception and interpretation of bubble plots. This requires asking questions about the appropriateness of using circle size to convey aspects of the data and which types of analysis violations of Kosslyn's guidelines can occur. Another question has to do with whether visual illusions in the display of data are syntactic violations or semantic violations. This relates to a later part of the literature review where the sensory (syntactic) and semantic causes for the Ebbinghaus illusion are discussed. This question is somewhat artificial as it is likely that the syntactic and semantic levels interact with each other extensively.

The idea of using circle size to display another aspect of the data is a widely used technique, yet it is problematic and in some cases and it has been shown that the interpretation of differences between circle sizes is difficult (Cleveland et al., 1983). Circle size interpretation is likely a syntactic violation where the visual system cannot discriminate between circle sizes in a reliable and accurate manner when their sizes are too similar (Kosslyn, 1989). However, this may not always be a problem if on the pragmatic level they intended message is still intact. In many data displays telling the difference between circle sizes in not the ultimate goal and the information added by the use of circle size to show an extra dimension of the data can benefit the display while not adversely affecting the intended interpretation. Nevertheless there is still a danger that when the technique is used in the wrong setting, and for the wrong purpose, it can lead to misinterpretations occurring.

Semantic and pragmatic aspects of the current research will be somewhat limited due to the fact that the research focuses mainly on the syntactic level, deliberately leaving out labels to limit semantic interpretation of the data. What this aims to achieve is to measure one level of Kosslyn's guidelines namely the syntactic. As effects in the syntactic level influence the semantic and pragmatic levels, the syntactic distortions are likely to affect the semantic and pragmatic levels. However, the current research focuses mainly on getting an idea of the syntactic distortion and its causes.

Visual illusions in graphs have long been of interest in research on visual displays of data (Amer, 2005; Amer & Ravindran, 2010; Cleveland et al., 1983) and they are likely to be classified syntactic violations in terms of Kosslyn's principles (Kosslyn, 1989). They not only make syntactic judgements difficult but can result in false semantic judgements. Visual illusions that have semantic causes can also distort syntactic perception and the avoidance of illusions in displays is important to enable a clear and accurate picture of the data. However, like circle size, the syntactic violations that visual illusions result in are likely to have only limited effects on the pragmatics of the display, making them less important to focus on. In a bubble plot any distortion due to the Ebbinghaus illusion may have a limited effect on the Kosslyn's pragmatic level or it could have a serious effect. It is therefore important to know when and where the violations caused by visual illusions are most serious and have the greatest detrimental effect. In order to understand the causes of the distortions – and when they are most likely to occur in displays – research focusing on these specific questions is needed. To do this we need to have a thorough understanding of illusions and theories of visual perception that attempt to explain how illusions work. These will be the subjects of the next section of the literature review.

2.2. Visual perception

In order to understand some of the causes of visual illusions we need to explore theories of visual perception and how they relate to visual displays of data. The Ebbinghaus illusion is a widely studied illusion and has played a major role in debates about perception (Franz, Fahle, Bülthoff, & Gegenfurtner, 2001; Goodale & Milner, 2005) so is well suited for relating to theories of perception that will be discussed below. An overview of these theories is important when constructing visual displays of data because there are various ways in which perception may be misled by displays, and having greater knowledge about the causes of illusions, such as the Ebbinghaus illusion, can lead to ideas for limiting its effect. Various guidelines can be derived from empirical findings and theories about visual perception. We will first look at a broad overview of theories of perception and then get more specific by looking at how they apply to the Ebbinghaus illusion.

Scientists have categorised theories of perception into two broad approaches, namely the so called 'bottom-up' and 'top-down' theories (Gibson, 2013; Gregory, 1974; Marr, 2010). The way to distinguish these theories is by looking at where the information used in perception originates. The 'bottom-up' theory proposes that the information is in the stimulus (environment) and that perception is direct; the brain's job is solely to detect features already in the stimulus (Gazzaniga, Ivry, & Mangun, 2009). 'Top-down' theories propose that there is not enough information in the stimulus in order for perception to occur, which means that 'previous knowledge' must be used to solve the problem of perceiving the world (Gazzaniga et al., 2009). The ‘previous knowledge’ could be in the form of in built innate assumptions about the world or previously learnt semantic knowledge. Perception in this view is not direct and the brain’s function is to not only detect features of the stimulus but to make inferences from it with added prior knowledge. We will explore these various theories and the implications that they have for the present experiment.

2.2.1 Top-down theories

One of the first modern scholars to argue for the ‘top-down’ theory of perception was Hermann von Helmholtz (Helmholtz, 1962). Helmholtz argued that perception is a series of ‘unconscious inferences’ (Helmholtz, 1962). To him the actual perceived object was a mixture of learnt ‘unconscious’ inferences that symbolised the actual stimuli that they were based on. This echoes the arguments made by Kant in *The Critique of Pure Reason*, where he argued that perception was based on both the information coming from external objects and ‘a priori’ knowledge (Kant, Guyer, & Wood, 1781). For Kant the ‘a priori’ knowledge was innate and not learnt from the environment. This knowledge was in the form of in-built concepts that made sense of the incoming signal; this was part of his broader argument that reasoning about things, such as causality, required that there be innate prior knowledge with which the idea of causality was projected on to the world. This is similar in broad strokes to the modern ‘constructivist’ view of perception, the idea that perception is a constructed thing rather than something direct from the environment.

Perhaps the most well-known recent proponent of the idea that perception is a constructive process was Richard Gregory, who proposed that perception was a hypothesis very much like a scientific hypothesis (Gregory, 1970). The perception as a hypothesis idea meant that perception was a way of making the best guess using a mixture of the external stimuli and prior knowledge. He argued that most of the information that reaches the eye is lost and that perception is a constructive process that involves rebuilding the perceived object from the limited information from the environment.

His main evidence in support of this contention came from errors in perception which were either caused by the perceptual machinery or prior knowledge present in the brain (Gregory, 1970). These errors give away clues as to what is going on behind the scenes in perception, specifically how the perceptual system might work. The most well-known examples of errors in perception are visual illusions. If perception is a hypothesis, then when there are many competing hypotheses, the hypothesis judged to be most probable will win out and be the one experienced. This process is by no means fool proof and can be misleading in various ways, especially in situations where highly unlikely configurations are present in the signal coming from the environment. People have known about this “glitch” for a long time and have exploited it in many ingenious ways, fooling the brain by presenting it a highly unlikely object, which the brain mistakes for a much simpler more probable object. An example is the hollow side of a face mask (Gregory, 1970). Humans tend to be very sensitive to facial recognition and it has been argued that there is a special part of the brain, the fusiform gyrus, which is linked with, amongst other things, facial recognition (McCarthy, Puce, Gore, & Allison, 1997; Scalaidhe, Wilson, & Goldman-Rakic, 1997). The fusiform gyrus has been used to argue that we have an innate capacity to recognise faces (Scalaidhe et al., 1997). Further evidence comes from pathologies where there is selective impairment of facial recognition while other abilities remain intact (Farah, Wilson, Drain, & Tanaka, 1998). In the hollow face illusion we can see our propensity to recognise faces being used to ‘outvote’ an unlikely hypothesis. The result is that when a person sees the hollow side of a mask it is seen as a normal face, extending outwards rather than inwards, a hollow face is an uncommon occurrence in the real world and so the facial recognition machinery comes up with a more likely hypothesis of what it is seeing, namely a convex normal face. The prior knowledge outvotes the actual signal, constructing a more likely perception of what is happening in the field of vision. This is perhaps also the reason for the phenomenon of pareidolia, where faces are seen in inanimate objects that exhibit random patterns which sometimes resemble faces, a highly improbable stimulus (Hadjikhani, Kveraga, Naik, & Ahlfors, 2009).

Another example that provides support for the idea that perception is a hypothesis is the situation where two competing hypotheses are equally likely interpretations of the incoming stimuli (Gregory, 1970). The Necker cube is an example of this as illustrated in **Figure 5.** When looking at a Necker cube you will notice that it flips in between two stable interpretations, one of the cube jutting outwards and down and to the left, and the other jutting outwards and up and to the right. Gregory (1970) argued that the effect was due to there being two equally likely competing hypotheses and this meant that neither could gain dominance in the brain. The incoming stimulus does not cause the alternation between the two interpretations because the incoming stimulus does not change, which suggests a top-down process is a more likely cause.

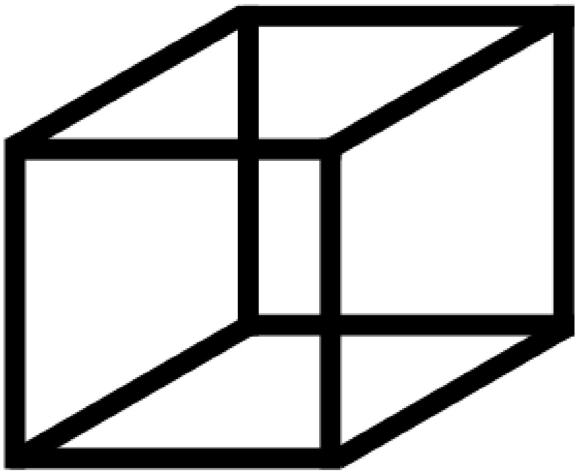

Figure 5: Necker cube

For the current research this view is suggestive. The Ebbinghaus illusion has been shown in previous research to be susceptible to cognitive/top-down differences depending on the type of shape surrounding the inner circle matters − similar shapes yield the biggest distortion while less similar ones yield smaller distortions (Coren & Enns, 1993). Top-down effects seemingly can have an influence on the Ebbinghaus illusion.

2.2.2 Bottom-up theories

The ‘bottom-up’ approach is characterised by perception being driven solely by the information from the incoming signal. There is a one way direction starting from simpler features detected in the retina, which get put together to form larger and more detailed pieces until you have the full perception. The ‘bottom-up’ theory is appealing in that it matches the neuroscientific evidence showing that the areas involved in vision are hierarchically organised, with neurons in V1 (primary visual cortex) responding to simple stimuli such as edges, and parts of the brain that receive inputs from V1 responding to more complex stimuli (Gazzaniga et al., 2009). The ‘bottom-up’ approach however does not mean that perception is only about putting together singular inputs from the retina, these inputs can be correlated in interesting ways to form patterns which can convey information about depth and movement present in the visual scene. These patterns are often called “invariant features” which are said to encode much more about the environment than is traditionally thought. The key idea here is that the information coming in from the outside world conveys more information than the top-down theorists usually gives it credit for.

The most influential of the bottom-up theories is the ecological approach of J. J. Gibson who proposed that perception was direct and that much of the work that top-down theorists thought needed to be done by prior knowledge was already present in the signal in the form of invariant features (Gibson, 2013). The function of the brain was to recognise the information that was already there. Gibson proposed the idea of affordances which were features of the world that invited certain activities due to their composition (Gibson, 1977). A stone affords throwing, the floor affords walking on, certain trees afford climbing based on the strength and position of their branches and an apple affords eating. It is important to stress that affordances are said to exist independent of people, they are dispositional properties of objects in the world, like the solubility of salt (Turvey, 1992). The properties of an apple that make it edible to humans and other animals are there regardless of whether they are taken advantage of by animals. The chemical constituents and the processes that they allow are the affordances. The world is objectively filled with these affordances but there is also a subjective nature to them as well. An affordance taken advantage of by one person or animal might not be used by another. A horizontal flat rigid surface at about knee height has sit on ability, but knee height is different in children than in adults, a certain surface may be too high as an affordance that a child can use. However it still affords sit on ability even though the child cannot take advantage of it at present. If the child were to use another object such as a stool to gain height they would be able to take advantage of said affordance (Gibson, 1977).

The world is full of possible affordances that animals can exploit and this idea is very similar to the niche concept in ecology. It is important to stress that the features of the affordance is objectively in the world, it is not something that the brain can arbitrarily impose on any random thing in the world. Brains have the ability to be able to recognise the affordances that are available to be used by an animal.

Gibson (2013) rejected the idea that the amount of information received by the retina was impoverished, arguing that this does not take into account movement. Movement reveals a lot more information than a static viewpoint. Invariant properties of the scene ‘gift’ the visual system with more information than the constructivist theory proposes (Gibson, 2013). Rather than a 2D retinal image that needs to be reconstructed into a 3D object of perception, the very act of moving can reveal the information in the environment that top-down theorists argue needs to be constructed. Gibson (2013) introduced the idea of the optic array, which is the information in the pattern of light hitting the retina. Unlike the static image traditionally studied in perception, it is the changes in the optic array brought on by movement that are the main source of information about objects in the environment. Flow patterns in the optic array mean that a person is moving, and the direction that they are moving in is indicated by the differences in the speed of the flow in different regions of the retina (Gibson, 2013). When moving forward and facing forward the centre of the visual field stays relatively still while the flow on the boundaries of your vision speeds outwards. This is the case for movement in all directions; each has a specific pattern of flow that indicates which direction it is – the information is present in the signal. Another cue that appears when movement is taken into consideration is that objects further away move slower relative to your movement than objects that are closer. These and many other cues from the environment Gibson (2013) argued were enough to ensure that perception was direct and that information from the environment need not be supplemented by prior information.

An important difference between the two views is the idea that there is a constructed object located in the brain that gets manipulated in certain ways. Gibson (2013) denied this and argued that there was no need for this to happen as the world already has all the information needed. The brain does different things in the two approaches and the ‘representations’ required by these different approaches are very different. The information gathered from affordances and movement according to Gibson was enough for the perception of recognition and action to occur. Unfortunately for the current research Gibson did not focus on visual illusions, dismissing them as artificial situations not relevant to explaining the most important parts of perception, but this is unconvincing as there are many errors in perception that occur in natural settings and even when they arise in an artificial setting an explanation is needed

(Gregory, 1997). For the current research specifically focusing on how visual illusions in a graphical display can distort information interpretation, Gibson's approach does not offer much guidance, unless the distortion of circle size in the Ebbinghaus illusion is due to information afforded by the display, which we will see later on does not seem to be the case. However Gibson's research makes us take the incoming signal seriously and not assume superfluous top-down mechanisms when the information may already be in the signal.

2.2.3 Modern developments

At various stages others have produced theories that are in some ways compromises between the top-down and bottom-up approaches. One such theory is the 'perceptual cycle' suggested by Neisser (1978). He proposed that perception is a constructive process which is a combination of bottom-up and top-down information. "Perception is a cyclic interaction with the world" (Neisser, 1978, p. 106). Neisser suggests that the top-down part of the process is represented by 'schemata' that are anticipations or plans to act. What is constructed in this process is not an image inside the head but either the alteration or creation of schemata. Schemata direct explorations of an object in the world. The schemata are altered based on how well they predict the result of the exploration; greater error in the prediction causes greater alteration in the schemata (Neisser, 1978). This way there is a rich influence on top-down expectations by information from the environment.

A similar theory to this is the sensorimotor account of vision (O'Regan & Noë, 2001). According to this view, perception is an activity that we do, and what we consciously experience has to do with the form in which our perception happens. Expectation or anticipation plays a large role in the theory much like the 'perceptual cycle'. It is the knowledge of how movement will yield sensory change that is important. This incorporates the idea that movement is important in allowing information from the environment but with a top-down expectation of what that movement will achieve. When looking at a line on a piece of paper, we see that line as straight and not varying in width or curving as it moves away from our central focal point. However when looking at how the line appears on the retina, if you move your focal point slightly above the line this causes the image on the retina to look more like a downward curve, when flattened out. This is due to the shape of the eye and the patterns of the cells in the retina.

However we still see it as a straight line, the sensorimotor theory says that our brain learns to anticipate changes like these taking into account the structure of the eye and what changes in the stimulus that moving the eye is expected to produce (O'Regan & Noë, 2001). It is this type of information, the change in the signal based on movement and the peculiarities of the body, that the sensorimotor account says needs to be anticipated by the brain and that our conscious experience depends on these changes (O'Regan & Noë, 2001). One of the implications of this theory is that different types of perception (visual, aural, tactile) are consciously experienced differently not because they are processed in any special part of the brain but because they have very different distinctive information patterns, called sensorimotor contingencies (O'Regan & Noë, 2001). To support this contention O'Regan and Noë give examples where one form of perception is mimicked in another form. In the example of tactile vision substitution (Bach-y-Rita, 1983), blind people are given a medium sized rectangular array consisting of many small vibrating pins arranged in rows, much like the pixels on a screen. This array is then placed on an exposed piece of skin and gets a signal from an attached camera. The signal from the camera is converted into a low resolution (less pixels) 'image' corresponding to the amount of pins on the array and the person experiences the 'picture' through their skin. Blind subjects who have used tactile vision substitution sometimes report that they experience 'visual experiences' from these tactile sensations. The sensorimotor account would explain this by saying that the information patterns or sensorimotor contingencies from the tactile vision substitution are similar enough to those from the visual system and that because conscious experience is determined by those patterns we should expect phenomena like this.

However as Clark (2008) points out this theory is too tied in to the finer details of the sensorimotor changes, because it would mean any changes however subtle in the sensorimotor dependencies yield a corresponding change in conscious experience. Clark suggests that certain insensitivity to such changes would be useful in enabling perception and presents evidence of just such insensitivity (Clark, 2008). He does this by citing the evidence from the dual-stream theory of perception, where perception is said to be processed by two parallel streams in the brain semi-independently of each other. The ventral-stream is dedicated to object recognition and the dorsal-stream is dedicated to perception involved in guided motion through the world (Goodale & Milner, 2005).

The evidence for the dual-stream theory comes largely from patients who have suffered impairments to specific parts of their brains (Goodale & Milner, 2005). One such case is patient DF who suffered lesions to her ventral-stream due to carbon dioxide poisoning and lost the ability to 'consciously' see her surroundings. However, she is still able to navigate through the world surprisingly well and pick up objects from the table without having to grope for them (Goodale & Milner, 2005). This is a case where conscious experience and sensorimotor dependencies do not perfectly line up. Patients that suffer from optic ataxia, stemming from lesions to their dorsal-stream, can see the world and describe it in detail, but they have trouble performing spatial tasks. When reaching for an object they misjudge distances and fail to grasp it correctly (Gazzaniga, 1998). Conscious experience in this situation is not related to the inability to judge and use sensorimotor knowledge. There is also further evidence that suggests that the dorsal stream is somewhat insensitive to many visual illusions, while the ventral stream is affected by them (Aglioti, DeSouza, & Goodale, 1995; Haffenden & Goodale, 2000).

Clark suggest that the 'bottom-up' and 'top-down' approaches can be fruitfully incorporated into the theory of hierarchical 'predictive coding' (Clark, 2013). He cites research within artificial intelligence and machine learning on so called "Bayesian brains" that offer a way to implement something like Neisser's 'perceptual cycle' (Friston, 2003). Top-down information occurs in the form of statistical models for predicting the incoming signals from lower levels in the system. Bottom-up information comes from the stimulus hitting the retina; however, not all the bottom-up information is used, in fact only the parts of the stimulus that are not predicted by the statistical models at higher levels filter up the levels. This is a type of Bayesian process, where the higher levels are priors for the incoming signal. Errors in prediction act as a way to update and correct these priors in order for the model to be more accurate. This theory accords well with the idea that perception is a 'hypothesis', where top-down information can be seen as a causal model to explain bottom-up information. The rich information in the environment is also incorporated into the theory by it shaping and updating the prior information embodied in the brain by these statistical models. This theory allows many different kinds of representations at many different levels of abstraction, with higher up levels being more insensitive to change than lower levels. This theory can explain features that are present in the human visual system, namely, the ability to incorporate the information rich environmental stimulus emphasized by ‘bottom-up’ theorists and to also be somewhat insensitive to this stimulus when prior information embodied in the statistical model outvotes the incoming signal.

This more recent view of perception incorporating ideas from previous theories allows us to think about the causes of visual illusions in various ways. Causes can either be ‘top-down’ or ‘bottom-up’. The hierarchical predictive coding view allows for many different levels of top-down information that can be relatively insensitive to bottom-up information overruling it (Clark, 2013). It also allows ‘bottom-up’ information to richly affect the way perception works through prediction error, much like how science works – it is the differences from what is predicted that are the most important part to take into account. Without them perception would quickly lose any semblance to what is actually in the environment. For the most part this ensures that perception will be close to ‘direct’. However, as revealed by visual illusions, there are rare occasions where perception is fooled and this prediction error does not seem to be capable of being corrected. This is perhaps the result of a trade-off between competing needs where these situations do not occur sufficiently often enough to cause trouble and therefore it would be too costly to ‘fix’ them (Clark, 2013).

2.3 The Ebbinghaus illusion

The illusion used in this research is called the Ebbinghaus illusion (Ebbinghaus, 1913), sometimes known as Tichener circles. In this section we will describe some of the research that has been conducted to explain this illusion and will look at more recent research on whether it is an illusion that only affects the ventral stream perceptual processing or whether it can also affect the dorsal stream.

The Ebbinghaus illusion was discovered by Herman Ebbinghaus and consists of two identical circles each surrounded by other circles (Ebbinghaus, 1913). These other circles are typically either bigger than the central circles or smaller. The usual display surrounds one of the central circles with considerably bigger circles and the other central circle with considerably smaller circles (see Figure 2). When this is done an interesting effect occurs: the circle surrounded by the bigger circles appears smaller and the circle surrounded by the smaller circles appears bigger, making the identical inner circles look different sizes.

Many attempts have been made to explain the Ebbinghaus illusion and the debate in some ways mirrors the debate about top-down and bottom-up perception. We will be reviewing the evidence for whether there is a case for either a cognitive top-down or sensory bottom-up cause of the illusion. We will look first at attempts to classify illusions into various categories based on their appearances and possible causes.

2.3.1 Classifying illusions

Table 1: Types of illusions

Kinds	Illusion appearances
Ambiguities	Necker Cube
Distortions	Ponzo illusion
Paradoxes	Penrose triangle
Fiction	Faces in the fire

Gregory (1997) proposed a tentative classification of illusions based on their appearance and causes. He classified appearance into four categories namely: **ambiguity**, **distortion**, **paradox** and **fiction**. Table 1 provides examples of each of these categories. He classified their causes first into either illusions due to physics or illusions due to knowledge. Physics illusions are due to disturbances of the light before it hits the eye or when it is transmitted from the eye to the brain, which Gregory respectively calls these **'optical'** and '**signal'**. Knowledge based illusions or cognitive illusions are due to misapplied top-down influences. They are divided into two types: '**rules'** and '**objects'**. **'Rules'** are based on knowledge embodied in the general rules used in perception and '**objects'** are more detailed prior knowledge about specific objects that one might be looking at. An example of a **'rule'** based illusion is the ponzo illusion shown in Figure 6. Certain cues of depth and perspective trigger the perceptual machinery's rules to cause the viewer to see an illusory effect, with one line looking shorter than the other. An **'object'** illusion on the other hand relies on a higher level knowledge encoded in the brain, for example the hollow-face illusion where prior knowledge of faces causes the hollow side of the face to look convex.

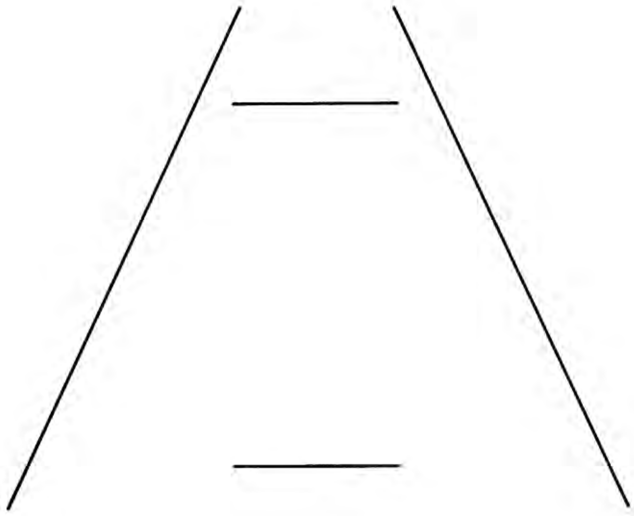

Figure 6: Ponzo illusion

In terms of this classification the Ebbinghaus illusion can be categorized in this way:

- Appearance: The Ebbinghaus illusion distorts circle size therefore it is a type of distortion illusion.
- Causes: Various bits of evidence point to the Ebbinghaus being a top-down illusion. Some evidence indicates that it is may be due to the **'rules'** of the perceptual system rather than conceptual knowledge of **'objects'** but there is also some evidence which suggests that there could be a more high level knowledge of **'objects'** cause, although the extent to which this is true is contentious as we will explore later in section 2.3.2.

Researchers have tried to empirically categorise visual illusions based on the extent to which they affect different people (Coren, Girgus, Erlichman, & Hakstian, 1976). They theorised that since there are likely multiple causes for different visual illusions it is probable that there is variation in the extent to which people are affected by each of those causes. A person highly susceptible to one illusion may be less susceptible to other illusions and using this difference in variation the researchers attempted to empirically categorise different illusions. They did this by presenting different types of illusions to participants and measuring the extent to which they were fooled by them. They then used factor analysis to find the factors that best explained variations in the magnitude of distortion experienced by people when they looked at different illusions. They used an oblique rotation as they suspected that the causes were correlated, and found a model with five factors that best explained the variation in the data, of which the Ebbinghaus Illusion loaded highly on the 2nd factor. Coren et al. (1976) proposed that this second factor is a measure of cognitive contrast, an illusion where higher level cognitive distinctions are made affecting the perception of the constituent properties that make up the illusion. This finding is plausible as there is evidence that top-down cognitive information plays a part in the Ebbinghaus illusion as we will discuss below.

2.3.2 Causes of the Ebbinghaus illusion

A great deal of research has been conducted on the Ebbinghaus illusion in order to find plausible causes for the perceptual distortion of the two identically sized circles making them look different sizes (Coren & Enns, 1993; Coren & Miller, 1974; Jaeger, 1978; Jaeger & Guenzel, 2001). A common tactic used by researchers is to vary the configuration of the illusion in different ways to either break or enhance the illusion. It is hoped that be doing this, that it can give us insight into possible causes of the illusion. Two broad currents in this research can be discerned, mirroring the debate about top-down and bottom-up explanations of perception. The first is that it is explained by a top-down cognitive contrast effect due to prior knowledge encoded in the brain, and the second is that it is due to a form of contour integration, which predicts that contours closer to each are attracted due to the makeup of the visual system (Field et al., 1993). It is likely that both these theories play a role in explaining the illusion.

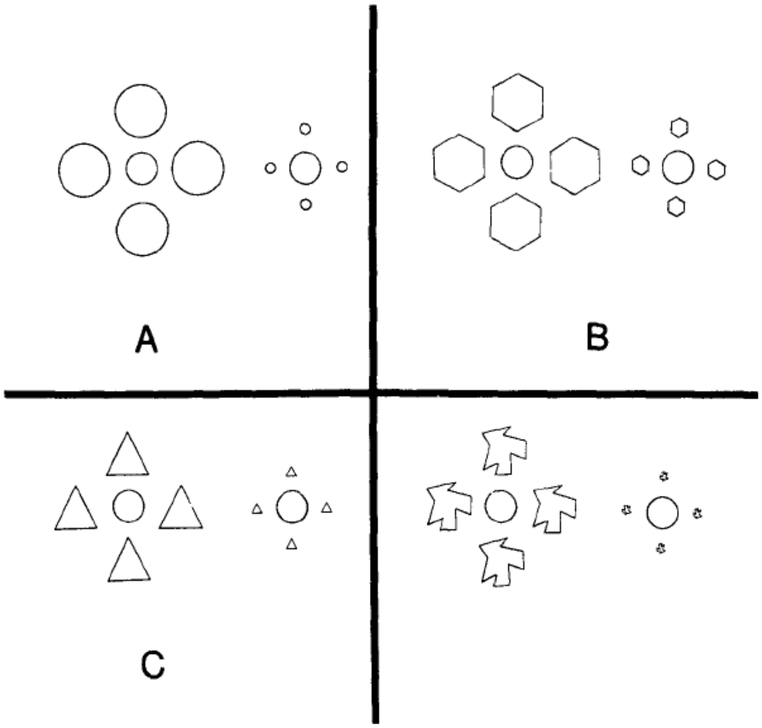

Figure 7: Four variants of the Ebbinghaus illusion

One of the earlier attempts to apply the above method was by Massaro and Anderson (1971) who found that by increasing the number of circles around the central one increased the magnitude of the distortion present in the illusion. They also found that distance had an effect on the illusion and that the further away the surrounding circles were the smaller the effect of the illusion. Coren and Miller (1974) showed that the illusion is influenced by the similarity between the central figure and the surrounding figures, suggesting a top-down influence. They produced four different types of Ebbinghaus illusion, each containing a central test circle but the surrounding shapes were varied (See Figure 7 from Coren and Miller (1974)). The first condition was a standard Ebbinghaus illusion containing only circles (**A**), the remaining three conditions had surrounding shapes that were chosen on how dissimilar they were rated from circles, going from hexagon (**B**), to triangle (**C**), to an asymmetrical jagged shape (**D**). They found that the magnitude of the illusion got weaker as the surrounding figures became more dissimilar from the inner shape.

Another proposed cause of the illusion is offered by Jaeger (1978) who had difficulty replicating many of the previous findings. Increasing the number of circles had an effect on the condition where the circle size is overestimated due to being surrounded by smaller circles, but did not have the corresponding effect on the condition when circle size is traditionally underestimated. He proposed that an explanation based on the theory of contour integration focusing on the interaction between the lines of the inner circle and the lines of the surrounding circles. The greater the extent that the circumferences of these circles are exposed to each other the larger the illusory effect. Smaller surrounding circles expose a greater amount of their circumference to the inner circle than larger circles and therefore the effect is much stronger in this condition.

Weintraub's (1979) findings supported the conclusion that cognitive context is a cause of the Ebbinghaus illusion, while also supporting the theory that contour integration contributes to the illusion as well. The way he did this was by manipulating the amount of circumference in the surrounding circles that was exposed to the inner circle, for example erasing a quarter of the circumference so the surrounding circle was no longer a complete circle. This should affect contour integration effects but not the cognitive contrast effects. This allowed him to separate context and contour dependent effects by showing that the illusion was still present, albeit weaker, when contour integration effects were removed. He also used a sample consisting of a wide range of age groups from 6-21 years old; this allowed him to test if any of the effects were age dependent. He found that contour integration affected all age groups but the context effect was less likely to affect the 6 year old group. The fact that context was less likely to affect the 6 year old group suggests that cognitive contrast effects may only develop at later ages. Weintraub and Schneck (1986) later found that many of the effects of contour integration and cognitive contrast were susceptible to some seemingly arbitrary changes in the usual Ebbinghaus illusion displays. These included an orientation effect, whereby the illusion was susceptible to how the circles were arranged around the inner circle. They also found that the framing extent/ratio, which is the overall size of the display compared to the size of the inner test circle, had an effect on the magnitude of the distortion. This reminds us of the complex nature of the phenomenon and that that there are many influences on the illusion that may not be obvious at first, and that when creating displays it becomes very difficult to account for all possible causes of distortion.

Coren and Enns (1993) proposed that it was not just figural similarity that was causing the effect, but also conceptual similarity. What this means is that it is not only the recognition of similar shapes and contours that drives the illusion but an even higher level of conceptual information, such as the recognition and labelling of an object as a circle. They showed this by presenting to participants versions of the Ebbinghaus illusion that were drawings of everyday things, such as dogs, horses and faces. When the surrounding figures were identical, for example a dog surrounded by identical dogs that were just varied in size, the effect was present and large. When the central dog was surrounded by dogs that were non-identical but recognised as conceptually the same, the effect was still present but smaller, and when the dog was surrounded by faces the effect shrunk. They argued that objects that were more conceptually similar increased the effect while objects conceptually dissimilar decreased the effect, on top of any of the effects of figural similarity already present. However this has been disputed by researchers who argued that the previous research failed to control for the effect of the specific shapes of the drawings and when this was controlled for the effect disappeared (Jaeger & Guenzel, 2001). Choplin and Medin (1999) supported this conclusion and found that it was not conceptual similarity but figural similarity that explained the varying effect of the illusion, specifically the similarity of the closest edges explained the effect better than the conceptual similarity.

Rose and Bressan (2002) argue that neither the cognitive contrast nor the contour integration explanations are sufficient for explaining the phenomenon and have called for a more integrated approach. Their motivation for this is due to their findings that the figural similarity effect, due to cognitive contrast, was not always present in their research when they used angular and hexagonal shapes. Additionally their findings contradicted predictions made by contour integration approaches. They suggest that these findings are more in line with recent developments in the understanding of perception, where the division between ‘top-down’ and ‘bottom-up’ approaches is breaking down and becoming more focused on a dynamic interaction between sensory and cognitive information at multiple levels even down to the retinal level.

Research has also shown that there may be an affective component to the Ebbinghaus illusion (Zadra & Clore, 2011). It has long been thought that affective concerns can distort people's judgement of the size of things. Research by Bruner and Goodman (1947) suggested that poor children judged the size of coins to be bigger than cardboard circles of the same size but this effect was not found amongst rich children. They argued that this was due to the subjective value of the coins being greater for poorer children. A later experiment added support to the idea that size judgement could be influenced by positive and negative emotions. In the experiment it was shown that plastic discs with positive or negative symbols on them led to a distortion in the perception of the size of the discs (Bruner & Postman, 1948). However, there is some dispute as to whether these effects were actually due to affective causes or artifacts of the particular experiments or other methodological flaws (Klein, Schlesinger, & Meister, 1951). More recent research has reignited the debate and suggests that the Ebbinghaus illusion may be affected by affective considerations in line with the older research (Ulzen, Semin, Oudejans, & Beek, 2008). When varying conditions of the Ebbinghaus illusion by putting negatively or positively judged pictures into the test and inducing circles, they found that a significant portion of the variation in judgement of circle size could be explained by the valence of the pictures in those circles. These findings suggest that affective top-down influences may also have an effect. Affective influences on the judgement of circle size may be especially important in displays in highly debated fields such as climate science and mortality due to war, however this is outside the scope of this research.

The picture that is starting to emerge from the evidence is that of multiple causes some of them top-down such as the cognitive contrast and some of them bottom-up as in the case of contour integration. However it seems we are far from being able to account for all the causes of the Ebbinghaus illusion and exactly what configurations amplify or decrease these effects. We will now look at evidence from studies where standard Ebbinghaus illusions were presented but where participants were varied in certain ways and examine how the effect changes when this is done.

2.3.3 Cultural and age variation in the illusion

Researchers using a preferential looking paradigm on toddlers aged 5-8 months suggest that they may be able to perceive the illusion (Yamazaki, Otsuka, Kanazawa, & Yamaguchi, 2010). A possible explanation for this effect could be that contour integration starts at a very young age and this claim is in line with Weintraub's (1979) findings showing that 6 year olds experience contour integration but are less likely to experience size contrast. Other researchers have also tested how age affects the illusion and found that when they controlled for local contour integration, the illusion disappears in children younger than 7 years old and may not have even fully developed in 10 year olds (Doherty, Campbell, Tsuji, & Phillips, 2010). They interpret this to mean that context-sensitivity develops slowly in humans in line with the general trend of development.

In research on a remote culture (The Himba) researchers found that the illusion was less strong compared to English participants (De Fockert, Davidoff, Goldstein, Fagot, & Parron, 2007). They explain this by proposing that the Himba focus more on local analysis than global analysis. This finding accords with Deregowski (1989) who suggested that some cultures when looking at pictorial displays prioritise local rather than global analysis.

These variations in the illusion support two broad conclusions. There are likely two main causes for the illusion: a cognitive contrast effect which is context specific and can vary in different cultures and takes a while to develop in humans, and a contour integration effect that is already present in toddlers and is less likely to vary amongst different people.

2.3.4 Dual stream theory and the Ebbinghaus illusion

Lastly we will look at evidence from the dual stream theory of perception suggesting that the Ebbinghaus illusion largely affects the ventral stream rather than the dorsal stream (Goodale & Milner, 2005). As mentioned above, the ventral and dorsal streams have been broadly associated with two different roles; the ventral stream has been associated with visual object recognition, and the dorsal stream is associated with vision that guides motion through the world (Milner & Goodale, 2006; Westwood & Goodale, 2011). Researchers testing a real life version of the Ebbinghaus illusion where the two inner circles were poker chip sized objects, found that participants reported seeing the circles as different sizes in line with the illusion being present but when reaching to pick up the chips they correctly calibrated their grip size to the true size of the chips. They measured this by using sensors fixed on the thumb and index finger and tracked how grip size changed as people reached for the chips. Their eyes were fooled but their actions were guided accurately (Aglioti et al., 1995; Haffenden & Goodale, 2000). They took this as an indication that the illusion distorts the ventral stream (recognition) while the dorsal stream (action) is more resistant to the illusion. However, other researchers have argued against this interpretation citing methodological difficulties in the research. They argued that the perceptual task and the grasping task were not adequately matched in the study, and when they are the differences between perception and action disappear (Franz et al., 2001). Further evidence that there may be a dissociation between the ventral and dorsal stream processing of the Ebbinghaus illusion comes from patient DF who as we mentioned before, lost her ability to perceive the world due to lesions in her ventral stream, yet when she was given the same test as above she correctly reached for and calibrated her grip to the correct size of the poker chip in the inner circle. This calibration happened before there was any tactile information present that could help her estimate the chip size (Milner & Goodale, 2006). On this basis the preponderance of evidence suggests that the dorsal stream may be somewhat insensitive to the illusion. However in line with the new developments in theories of perception we see that there are multiple dynamic interactions between the two streams and trying to dissociate the two would be very difficult if not impossible.

When taken all together it is likely that the Ebbinghaus illusion has a definite top-down component to it. Multiple studies on size contrast support this conclusion, and there is support from research showing variations at different ages and cultures. Research also indicates the primary role the ventral stream plays in the illusion pointing strongly to top-down processing. However, as we have seen, bottom-up influences such as contour integration also have an effect and there is some evidence that the dorsal stream may be affected by the illusion also.

The implication for the current research is that there will likely be a distortion of circle size in the various bubble plots, which will be due to the figural similarity of the circles leading to cognitive contrast effects. Contour integration effects should also be present due to the influences of the outer edges of the circles on each other. Distances between the circles in bubble plots should also have an effect and the various sizes of the circles can add to the distortion to. This will be due to both top-down and bottom-up processes and in many displays the sum total of their effects will be hard to predict. Any affective influences on the magnitude of the illusion should be limited because the plots used in the experiment were designed to have no meaning attributable to them in order to focus on judgements of circle size in isolation of meaning.

3. AIMS AND RATIONALE

3.1 Aims

The aim of this study is to test whether bubble plots are a suitable way of displaying multidimensional data. More specifically, we will focus on the use of circle size to display an extra dimension of the data and if, when doing this, a type of visual illusion (The Ebbinghaus illusion) can occur in the display and distort interpretation of it. In order to test this hypothesis we will focus on a number of aspects. Firstly, we will look at how suitable circles are at conveying data accurately and whether circle size can be accurately interpreted. As mentioned already, previous research gives us reason to doubt that they can be interpreted reliably. The next thing we will focus on is whether an Ebbinghaus type illusion can show up in bubble plots. This will involve seeing whether bubble plots constructed to recreate Ebbinghaus like conditions can result in circle size being distorted in theoretically predicted ways in accordance with what we would expect if the illusion were present. We will also question whether any distortions are serious enough to worry about when using a bubble plot to display data.

The experiment to test whether circle size interpretation is distorted will be accomplished by comparing the participants' judgements of circle size with the actual circle size displayed in the plot. Significant deviations in judgements from the actual size would indicate that circle size interpretation is inaccurate due to some form of distortion either present in the display or due to the use of circle size. To test whether the distortion is due to the Ebbinghaus Illusion we look to see if circle size interpretation distorts in the theoretically predicted way. Four conditions were created, two that recreate the Ebbinghaus illusion but in opposite directions, where Circle **A** and **B** should be distorted in opposite ways in the two conditions. It is in these two conditions that we expect to see evidence for an Ebbinghaus like distortion of circle size, which should be in the theoretically predicted directions. The distortions should also be large relative to the other two non-Ebbinghaus conditions. The other two conditions are bubble plots meant to minimize the Ebbinghaus illusion, either by the surrounding circles being arranged randomly in the plot or where the surrounding circles were deliberately arranged in order to minimize the chance of the Ebbinghaus illusion occurring.

In the two Ebbinghaus conditions it is hypothesised that the distortions in judgement of circle sizes will follow the theoretically predicted directions, with one circle being judged to be bigger than the actual size and the other circle being judged smaller. In the two other plots, distortions are still predicted but the distorted direction should be less predictable and the magnitude of the distortion should be less than the Ebbinghaus illusion conditions.

Next, we will move on from looking at how judgements of single circle size are interpreted to focussing on comparisons between circles **A** and **B**, and to see if there are any significantly different judgements in **differences** between circles in each condition. It is expected that there should be large differences between the two Ebbinghaus illusion bubble plot conditions, because they are theoretically predicted to distort things in the opposite direction to each other. In the other conditions differences between judgements of circles **A** and **B** are expected but they are not predicted to distort differences as much as the Ebbinghaus illusion conditions and the direction that they distort in are not as predictable:

3.2 Hypotheses

1) Comparing circle size is difficult and leads to distortions in the perceived size of a single circle relative to actual circle size
2) An Ebbinghaus illusion can be present in a bubble plot.
3) Differences caused by the Ebbinghaus conditions should be bigger than the differences caused by other bubble plot displays.

4. METHODOLOGY

4.1 Research design

This study was a quantitative experiment in which participants were asked to judge the size of a series of circles presented to them in various bubble plot display conditions. The experiment aimed at firstly finding out whether people were able to make accurate judgements of circle size in different bubble plot settings. Secondly, if there were distortions, were there any patterns to those distortions, and did these patterns correspond to the theoretically predicted distortions that you would occur if an Ebbinghaus type illusion was present.

The independent variables in the experiment were **four** different bubble plot conditions and **two** test circles. The four bubble plot conditions consisted of three plots constructed based on theoretical knowledge of the Ebbinghaus illusion and one random bubble plot (Details of the construction below). The two test circles (**A** and **B**) were identical in size, and their positions remained the same in all plots, one located near the bottom left corner, and the other near the top right corner of the plot. The participants were asked to judge the magnitude of one of the two test circles (**A** or **B**) in each round.

Participants were given response sheets where they were asked to fill out their answers on a seven point circle size scale (Figure 9). The bubble plot experiment conditions were projected on to an overhead screen and for each set. The circle which the participants were asked to judge was indicated by a laser pointer. This was done for 16 sets: four different bubble plot conditions with two test circles being judged in each condition, and each condition being repeated twice in the experiment. The four different conditions were as follows: two of the bubble plot conditions were constructed to elicit an Ebbinghaus type illusion, distorting each test circle either making it appear bigger or smaller, one condition was constructed for the purposes of minimising the illusion, and one was generated at random. The order in which the plots were presented was randomised. The seven point circle scale (Figure 9) used to measure circles size had four different variations in the presentation of circles, each being a randomised order, rather than being presented as a scale from smallest to biggest circles.

4.2 Sample

The sample obtained in this research was a convenience sample from university students at the UKZN Pietermaritzburg campus. These students came from an undergraduate Psychology 301 lecture. The sample size was 52 students who volunteered to stay behind after the lecture. The sample cannot be seen as representative and findings should be tested on a more representative sample before they can be generalised to the wider population. It is however likely that any effect due to an Ebbinghaus type illusion will be due to fairly low level perceptual processes which are less likely to vary drastically amongst cultures and environments.

Table 2: Demographic information of the sample

Age	**Mean**			
	22			
Gender	**Female**	**Male**		
	46(88.5%)	6(11.5%)		
Race	**Black**	**White**	**Coloured**	**Indian**
	36(69%)	13(25%)	2(3.8%)	1(1.92%)
Nationality	**South African**	**Other**		
	42(80.8%)	10(19.2%)		

All participants were students from the university and therefore had a high level of education. As can be seen from Table 2 , 80.8% of participants were from South Africa and 88.5% of them were female. The majority classified themselves as African. Their mean age was 22-years.

4.3 Procedure

4.3.1 Data collection

4.3.1.1 Construction of the bubble plot conditions

Four different bubble plot graphs were constructed (Figure 8 shown below), each of them had two standard test circles (**A** and **B**), and these circles were the same size and remained in the same locations in all the plots. In Figure 8 they are labelled A and B but they were not labelled during the experiment. Around these two test circles the four different plot conditions were constructed based on the Ebbinghaus illusion.

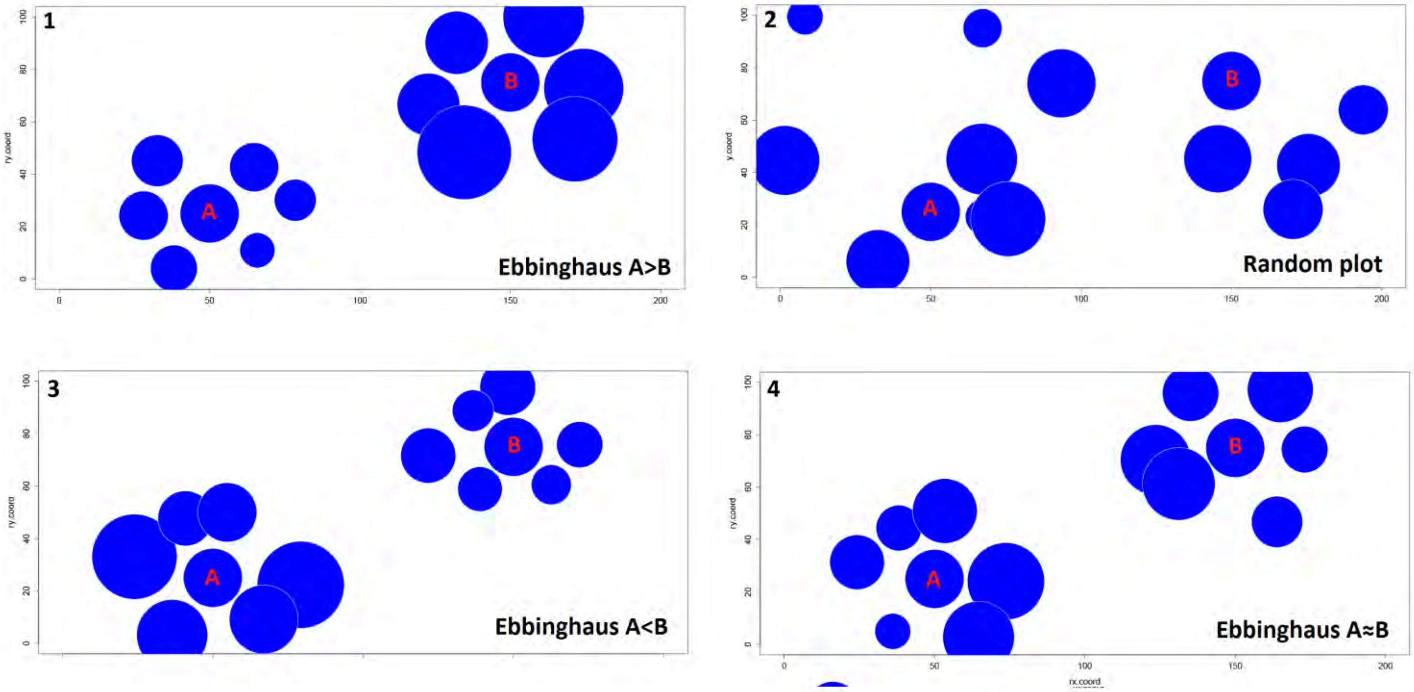

Figure 8: All the Bubble plot conditions

The first bubble plot (**Ebbinghaus A>B)** was made to mimic the Ebbinghaus illusion with **Circle A** in the bottom left corner being surrounded by circles smaller than itself and **Circle B** being surrounded by circles bigger than itself. The second bubble plot **(Random plot)** was a random experimental condition with only the test circles' (**A** and **B**) positions being planned with the rest of the circles being placed at random (with randomly varying sizes). The third bubble plot condition **(Ebbinghaus A<B)** was the mirror of **(Ebbinghaus A>B)** with **Circle A** being surrounded by bigger circles than itself and **Circle B** being surrounded by circles smaller than itself. The fourth condition **(Ebbinghaus A≈B)** was constructed in order to minimize the effect of an Ebbinghaus type illusion. An effort was made to ensure that the circles surrounding the test circles were similar in position and size.

The bubble plots were generated using R statistical software (R Core Team, 2014). Every bubble plot condition (1-4) always contained the same two tests circles, **Circle A** was position just near the bottom left corner of the plot and **Circle B** mirrored this in the top right corner. The value 300 was chosen as an arbitrary starting value for **Circles A** and **B**; this value represented the area of the circles with regards to the scale of the axes on the plot they were located in. When actually plotting the test circles it was necessary to convert the area into the radius by dividing it by π and square rooting it. This resulted in circles with the radius of 9.77. What this meant was that no matter how big the graph or display you were showing the bubble plot on, the circle would always have the height and width of 9.77 and an area of 300 when measured against the scale of the x and y axes. For this research circle area was used as the best way to measure circle size and from here on any numbers mentioned are measures of area with regards to the axes (Cleveland et al., 1983).

In **Ebbinghaus A>B** the process of building the plot started with mimicking the prototypical Ebbinghaus illusion around the two test circles. Once this was done the position and sizes of the surrounding circles were offset by small random margins generated using R's random number generator. This produced a bubble plot that was sufficiently similar to the Ebbinghaus illusion but sufficiently different to make them not instantly recognisable (Plot 1 in Figure 8). The **Random plot** was generated from scratch with the two test circles being surrounded by randomly generated circles, these circles positions and sizes were generated using the R number random generator (Plot 2 in Figure 8). **Ebbinghaus A<B** was generated in the same manner as **Ebbinghaus A>B,** except the initial Ebbinghaus illusion was reversed between circles **A** and **B** distorting the circles in the opposite direction, then a bit of random variation was added in the same manner as mention above (Plot 3 in Figure 8). **Ebbinghaus A≈B** was constructed in order to minimize any Ebbinghaus illusion effect. In order to achieve this effect the two test circles were surrounded by circles of the same size and position (Plot 4 in Figure 8), which in theory should not distort the judgements of differences between the two test circles. A small amount of randomness was added to this condition in order for it to not be instantly recognisable.

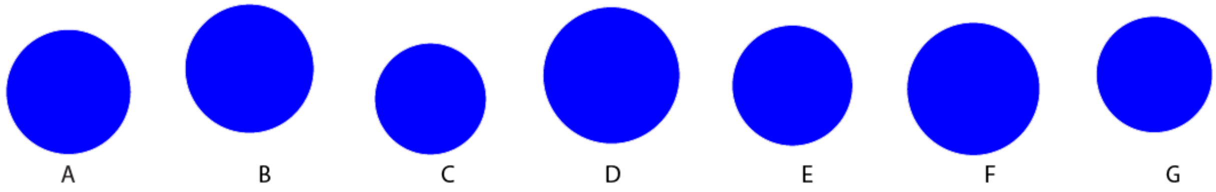

Figure 9: Seven point response scale

Underneath these plots was the seven point circle scale (Figure 9) that consisted of seven circles of varying sizes Participants were asked to judge which of them was closest in size to the indicated test circle. There were four versions of the scale, each with the same seven circles but in different randomised orders. Circles were arranged in a horizontal jittered line. The jittering was done in order to make it easier for participants to tell the difference between circles in the scale. One of these circles was the same size (area) as the test circles (**A** and **B** = 300), the rest varied in intervals of 20 from 300, the smallest being 240 and the biggest being 360. The scales were then added to the bottom of the bubble plots in an alternating order that ensured a wide variety of combinations between the scales, bubble plots, and test circles. The circles were labelled A to G from left to right regardless of their order. Four examples of the full layouts including the bubble plot conditions and measurement scales are shown in Appendix A.

Sixteen bubble plots in total were produced in this way, with each experimental condition being judged twice. For example **Circle A** was judged twice in the **Ebbinghaus A>B** condition, firstly in the first set **(Set 1)** and then was judged again in a later set **(Set 12)**, resulting in two responses for **Circle A** in the **Ebbinghaus A>B** condition. This was the case for every test circle for all the different bubble plot conditions. When switching between bubble plots the fact that the test circles stayed in the same position and retained the same size became obvious, being the only constant on the screen while everything else changed. To solve this problem a distracter screen was shown in between each switch. The distracter screen consisted of many different circles of different colours and sizes randomly placed on the screen, the rationale behind this was that it would break up the transition between different conditions making participants less likely to notice the similarity between the conditions. This worked well enough judging by the participants surprised reactions when they were told that all the circles they had been asked to judge were exactly the same size and in the same positions.

The response sheets that were given to the participants consisted of sixteen multiple choice questions. Each question gave them the options A to G corresponding to the seven circles on the scale present underneath each bubble plot. The response sheet is shown in Appendix B.

4.3.1.2 Collection of data

At the end of the lecture students were asked to stay behind to take part in a psychological experiment. A total of 52 students took part in the study; they were told that it was about the communication of data using visualisation, and the accuracy with which people could judge those visualisations. Response sheets were handed out with informed consent forms, and participants were asked to fill in their demographic information. Once this was done they were presented with an example bubble plot where the procedure for answering was explained to them. The participants were then shown the first bubble plot condition and asked to judge which circle on the seven point response scale was the same size as **Circle A.** They filled in their response on their response sheet, and then were presented the next plot. A laser pointer was used to indicate whether **Circle A** or **B** was to be judged for each condition. Participants filled in their responses on the response sheet and when they indicated that they were finished the next bubble plot was shown. This was continued for sixteen repetitions. Response sheets were then collected and the participants were debriefed, and the rationale of the experiment explained to them.

The responses from the questionnaires were entered into a Microsoft Excel file and the A to G responses (Response scale) were coded corresponding to the size of the circle that they represented in the particular repetition. This resulted in answers being in the form 240 – 360 based on the area of the circle associated with the letters the participants indicated.

4.3.2 Data analysis

Quantitative data was produced from coding the response sheets. The answers in the form of letters A to G were converted into the numerical values they represented, namely a measure of circle size (area). Once this was accomplished the data was in the form of sixteen columns representing sixteen judgements of circle size. On two occasions there were participants who had given two responses to a particular question. In each case one of the answers was chosen at random; being such a low number (2 out of 832 responses 0.2%) it is unlikely that this random imputation would adversely affect or bias the current study (Gelman & Hill, 2007).

Half of the 16 columns measured the same experimental condition as the other half and therefore were combined and averaged. This resulted in 8 columns of averaged judgements of circle size for each of the experimental conditions. A Wilcoxon signed-rank test was used to check the consistency of the two judgements before they were combined. A non-parametric test was used rather than a t-test due to the assumption of normality being violated in the two groups. This allowed us to get some indication of how reliable the method of measuring was at representing the true perceived circle size that it was designed to measure. If most of the measures measuring the same condition were significantly different from one another this would indicate that the method used to measure circle size was not reliable.

The next analysis was conducted in order to see if the judgement of circle size in each experimental condition was significantly different from the actual size of the circle judged. This was accomplished using a one sample Wilcoxon signed-rank test compared to the median of 300 (area of the actual test circle). If the bubble plots do distort circle size interpretation then there should be evidence of this here and if the distortion is non-random there should be patterns emerging at this stage.

The next step in the analysis was comparing circle size judgements of the two test circles in the same bubble plots. For instance is there a significant difference between **Circle A** and **Circle B** in **Ebbinghaus A>B** and if so, does this difference follow the theoretically predicted direction? Instead of just testing whether single circle size judgement is distorted this will tell us whether comparisons between two circles within a plot are distorted. This is important in data visualisations where one is encouraged to make many comparisons. The double distortion that occurs when both circles are distorted can lead to even greater bias in interpretation. In order to test this hypothesis a Wilcoxon signed-rank test was conducted between measures of **Circles A** and **B** in all four bubble plot conditions. If these were significant they revealed a distortion in judgement between test circles and furthermore if the direction in which the distortion occurred was in the same direction as theoretically predicted by the Ebbinghaus illusion this would provide support for the hypothesis that an Ebbinghaus illusion occurred in the bubble plot

The last part of the analysis tested the differences between the differences in circle size judgement. How much does the difference between **Circle A** and **Circle B** vary based on the different bubble plot conditions? To test this hypothesis the differences between **Circle A** and **B** in all the bubble plot conditions, for each participant, were worked out by subtracting Circle B from Circle A, and this resulted in four columns representing each bubble plot condition's difference score. A One-Way ANOVA was performed on these difference scores and post hoc analysis was conducted to find out in which conditions the difference scores most differed from each other. Tukey's HSD procedure was used for the post-hoc analysis, which not only allowed comparison between all experimental conditions but also corrected for the problem of multiple comparisons (Howell, 2009).

If an Ebbinghaus type illusion occurred in the bubble plots, then **Ebbinghaus A>B** should exhibit a positive difference score, because it was constructed so that **Circle A** would be distorted to look larger and **Circle B** would be distorted to look smaller. With the **Random plot** being randomly generated the distortion could vary in any direction and the difference score could also vary in an unpredictable direction. **Ebbinghaus A<B**'s distortion should be the opposite of **Ebbinghaus A>B** but the difference score should be comparable. **Ebbinghaus A≈B** should theoretically have the smallest difference score as it was constructed in order to appear equal. The biggest difference in difference scores should be exhibited in the bubble plot conditions that were built to mimic the Ebbinghaus illusion and they should have opposite signs.

4.3.3 Ethics

There were no major ethical problems with the research. The topic of the research was not one that required any special ethical considerations. None of the materials used in the research could be considered offensive or damaging to the participants.

Participants were informed that their participation was voluntary and that they could withdraw at any time or ask that their data be excluded from the study. Informed consent forms (Appendix B) were signed by each participant and these were stored separately from the response sheets so that participants responses could not be identified using them.

Contact details for my supervisor and I were on the consent forms, and if any of the participants wished to complain or have their data removed from the study they could contact us. The data produced by the research was only accessible by me and was backed up on a Drop Box folder also only accessible by me.

5. RESULTS

The results section is split up into three sections. The first section looks at the consistency between measures of circle size interpretation in the same experimental conditions. This is in order to assess the suitability of combining them into an averaged measure. The second section consists of analysing the differences between participants' judgements of a circle size and the actual size of that circle (the distortion in their perception of a single circle). In this section we will also look at whether those distortions can lead to significant differences in perception when comparing two test circles in the same plot. The third and final section of the results will compare how each bubble plot condition distorts the comparisons between two circles. We will do this by comparing the **difference scores** in judgements of size between **Circle A** and **Circle B** and how much they vary between the different bubble plot conditions.

5.1 Consistency of the measures

Sixteen sets of judgements of circle size were made (Q1-Q16), half of these judgements were repetitions of the same conditions and were combined and averaged. In order to judge the consistency of these repetitions a Wilcoxon signed rank test was conducted between the two matching responses. Table 3 shows the results.

Table 3: Consistency of measures

	First mean	Second mean	p_1
Ebbinghaus A>B A (Q1–Q12)	316.54	300.38	0.01
Ebbinghaus A>B B (Q6-Q14)	282.69	282.69	0.97
Random plot A (Q8-Q16)	292.69	295.77	0.60
Random plot B (Q2-Q9)	315.00	293.46	0.00
Ebbinghaus A<B A (Q3-Q11)	295.77	292.69	0.93
Ebbinghaus A<B B (Q5-Q15)	307.69	309.62	0.71
Ebbinghaus A≈B A (Q7-Q13)	306.92	306.15	0.91
Ebbinghaus A≈B B (Q4-Q10)	288.85	290.77	0.59

1 p.values come from a Wilcoxon signed-rank test

Most of the measures did not show significant differences between the first and subsequent judgements. Only **Ebbinghaus A>B** when judging **Circle A,** and in the **Random plot** when judging **Circle B,** showed significant differences. Therefore there is evidence for the consistency between most of the two measurements. It is not clear what the reasons for the discrepancies in the measures for **Ebbinghaus A>B** and **Random plot** are, although they may be the result of a small sample size. Statistically significant findings amongst many hypothesis tests tend to be overestimates (Gelman & Weakliem, 2009). If we use a Bonferroni correction (Howell, 2009) to correct for multiple comparisons on α = 0.05 we get α/8 = 0.006 and this results in all the above tests being non-significant.

5.2 Distortion in the judgement of circle size

Using the averaged combination of the two measures we looked at whether they show significant differences from the actual circle size area of 300. Then we looked at comparisons between the two test circles present in the same bubble plot conditions and see if they are distorted to be statistically different from each other. To achieve this, each individual circle was compared using a One Sample Wilcoxon signed-rank test to the median 300 (area) and then a Paired Wilcoxon signed-rank test was conducted on the differences between the test circles (**Circle A** and **B**) in each bubble plot condition. Figure 10 summarizes the results.

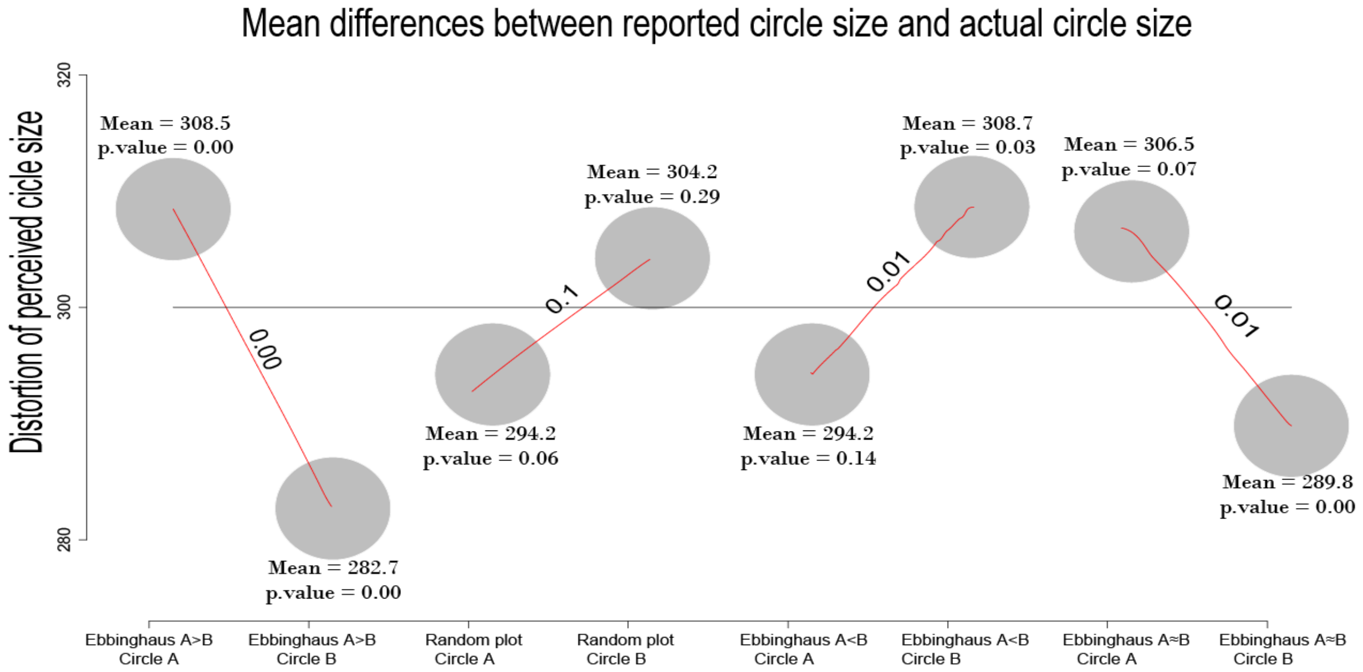

Figure 10: Single circle and comparison plot

In the above figure, means and p-values for One Sample Wilcoxon signed-rank test are reported near the circle they apply to. Paired Wilcoxon signed-rank test p-values for the differences between **Circles A** and **Circles B** in the same bubble plots are reported on the lines connecting the relevant circles.

5.2.1 Single circle distortion

As shown in Figure 10, significant distortion in judgements of single circles was found in four of the circles judged. **Circle A and B** in **Ebbinghaus A>B** were significantly distorted with **A** having a mean of 308.5 (p = 0.00), and **B** having a mean of 282.7 (p = 0.00). **Circle B** in **Ebbinghaus A<B** showed significant distortion (mean = 308.7, p = 0.03). **Circle B** in **Ebbinghaus A≈B** also showed significant distortion (mean = 289.8, p = 0.00). The bubble plots that were built to evoke the Ebbinghaus illusion (**Ebbinghaus A>B and Ebbinghaus A<B**) distorted the circles in the predicted direction with 3 out of 4 circles being significantly distorted. Circles in the random condition (**Random plot**) showed little distortion, not reaching significance. One of the circles in the condition that was constructed to be equal (**Ebbinghaus A≈B**) showed significant distortion in **Circle B** (mean = 289, p = 0.00) but not **A** (mean = 306.5, p = 0.07)**.**

5.2.2 Comparisons between circles in the same plot

Significant differences were found between **Circles A** and **B** in all the bubble plot conditions except the **Random plot** condition as show in Figure 10. The difference between **Circle A** and **B** in **Ebbinghaus A>B** (p = 0.00) was in the predicted direction based on the Ebbinghaus illusion. The distortion was reversed in **Ebbinghaus A<B**, with there being significant difference between **Circle A and B** (p = 0.01) in the direction theoretically predicted. **Circles A** and **B** in **Ebbinghaus A≈B** were significantly different (p = 0.01) even though this plot was constructed to be equal. **Circles A** and **B** in the **Random plot** (p = 0.1) did not show a significant difference.

5.3 Did different bubble plot conditions vary how circle size was distorted?

The next analysis examines the variation in the differences between **Circle A** and **Circle B** in the different bubble plot conditions and this was accomplished using a One-way ANOVA.

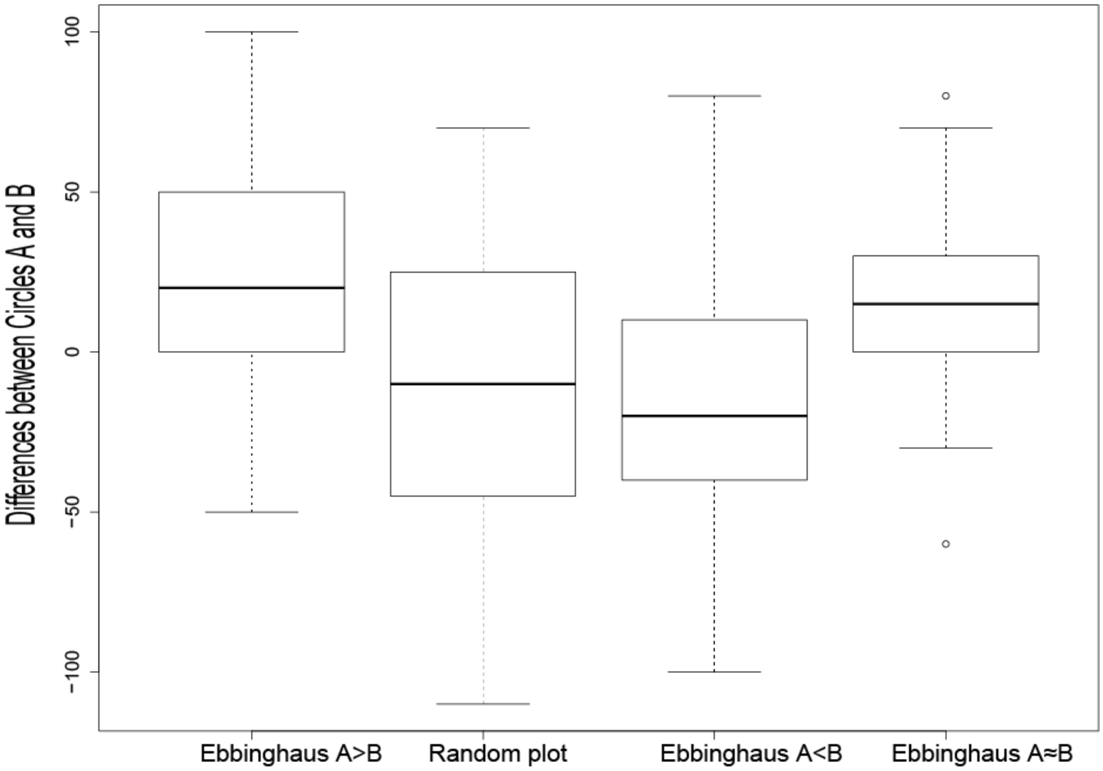

Figure 11: Box plots of differences between A and B

The box plot in Figure 11 shows that the differences between **Circles A** and **B** within each bubble plot condition is roughly normally distributed. ANOVA is robust against large deviations from normality (Glass, Peckham, & Sanders, 1972; Harwell, Rubinstein, Hayes, & Olds, 1992; Lix, Keselman, & Keselman, 1996) and using ANOVA is appropriate here. Bartlett's Test for homogeneity of variance was performed and was found to be significant (K-squared = 13.39, p = 0.00). This means that the assumption of homogeneity of variance was not met. A Welch corrected p-value for the ANOVA was added to the analysis to correct for this problem.

Table 4: ANOVA: Differences between differences

	Df	Sum Sq	Mean Sq	F value	p-value	Welch p-value	Eta=squared
Bubble plots	1	22898	22898	15.23	0.00	0.00	0.183
Residuals	206	309653	1503				

Table 4 shows that the main effect of the One-way ANOVA of differences between bubble plot conditions was found to be significant (F = 15.23, p = 0.00, Welch p = 0.00). This means that there was significant variation in distortion between bubble plot conditions. This supports the hypothesis that an Ebbinghaus like illusion can occur in a bubble plot and that the effect on the judgement of circle size is not a random phenomenon. The effect size of the variation between bubble plot conditions was Eta squared = 0.183.

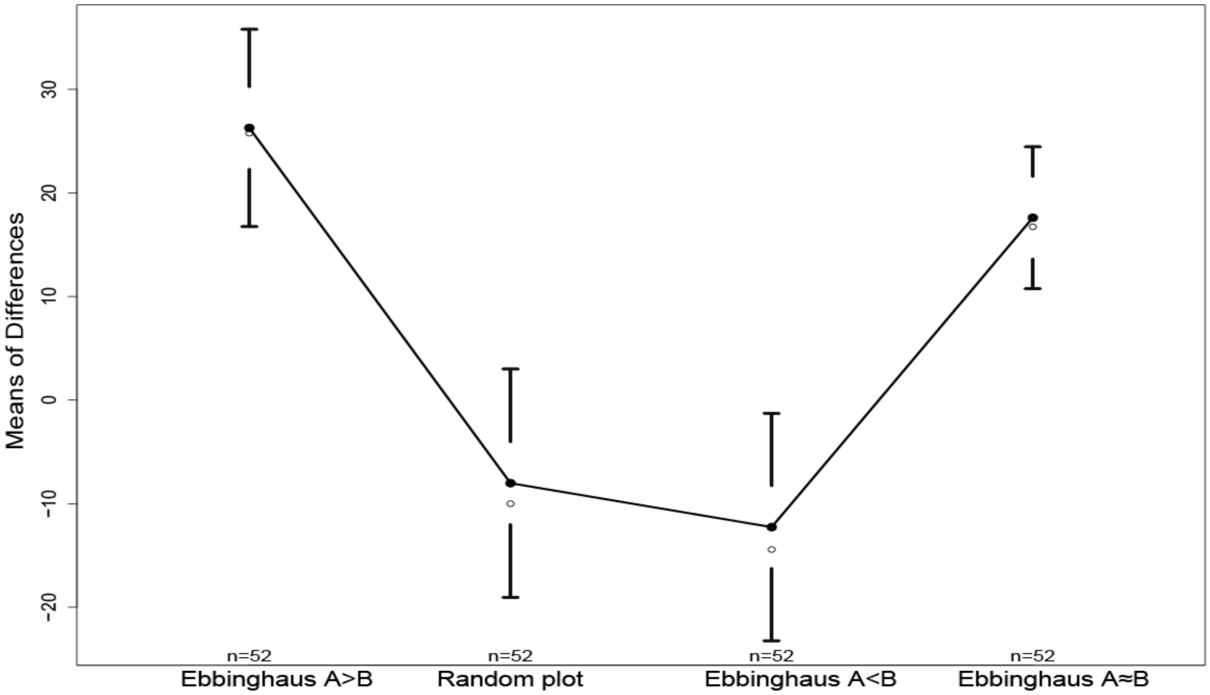

Figure 12: Mean plot of differences between Circles A and B

Figure 12 shows the means of the differences between Circles **A** and **B** for each bubble plot condition. **Ebbinghaus A>B** and **Ebbinghaus A<B** show differences in the directions theoretically predicted.

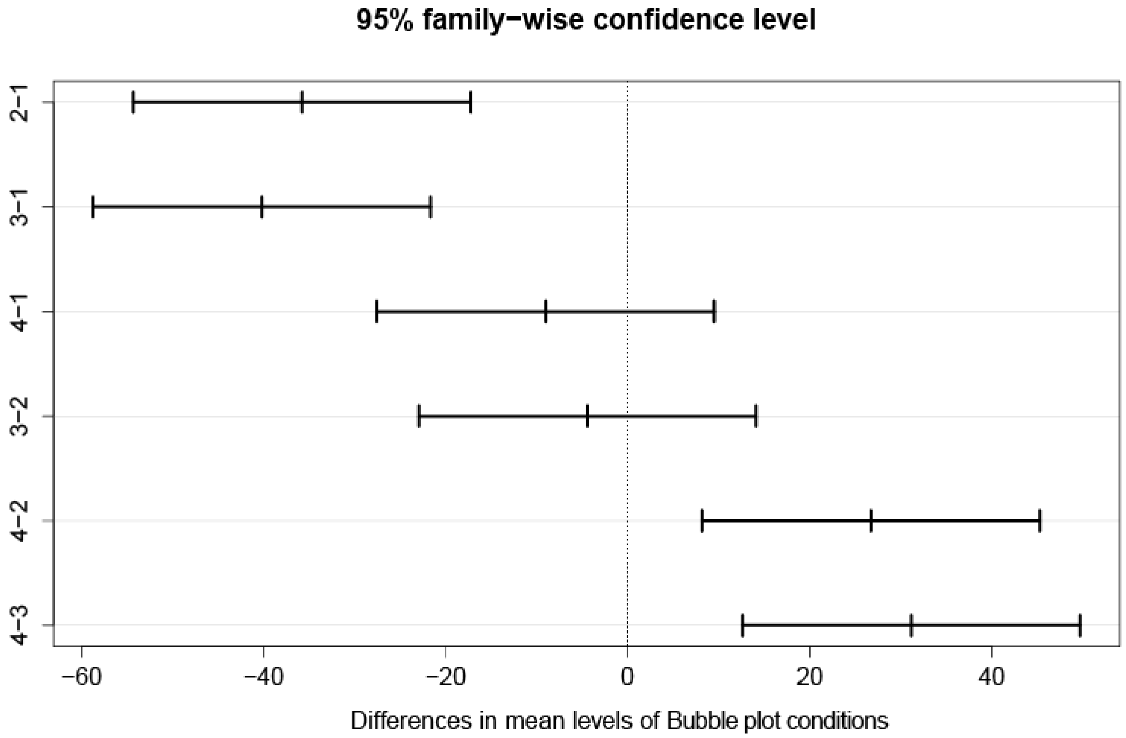

Figure 13: Tukey HSD showing differences between plots

The Tukey's HSD plot in Figure 13 shows that there were significant differences between plots even when correcting for the family-wise error. The difference between plots **1-2** (**Ebbinghaus A>B and Random plot**) was -35.77(p=0.00). The difference between plots **1-3** (**Ebbinghaus A>B and Ebbinghaus A<B**) was the greatest being -40.2 (p=0.00). There was not a significant difference between plots **1-4** (**Ebbinghaus A>B and Ebbinghaus A≈B**) and plots **3-2** (**Ebbinghaus A<B and Random plot)**. There was a significant difference between plot **4** (**Ebbinghaus A≈B**) and plot **2** (**Random plot**) (diff=26.73, p =0.00) and **3** (**Ebbinghaus A<B**) (diff = 31.15, p = 0.00). Comparisons between the two Ebbinghaus inspired plots showed the greatest differences. Comparisons between **Ebbinghaus A>B** and **Ebbinghaus A≈B** (constructed to minimize distortion) did not show any differences and no significant differences occurred between **Random plot** and **Ebbinghaus A<B.**

6. DISCUSSION

This research sought to answer the question about the suitability of the use of circles to display extra dimensions of the data in bubble plots. More specifically it focused on the possibility that an Ebbinghaus like illusion could be present in bubble plots, thus distorting accurate interpretation of the data. It also sought to assess the ‘damage’ caused by this distortion, based on various guidelines for assessing good graphical displays. We asked whether the distortions caused by the illusion are serious enough to consider the bubble plot as an unreliable and invalid way of displaying data, or whether there are occasions when its use is justified.

The current research has supported previous research indicating that circle size is difficult to judge and is susceptible to many sources of distortion (Cleveland et al., 1983). We found that in all the bubble plot conditions except the **Random plot** condition, there was distortion in judgement of single circles. These distortions made sense in the conditions built to mimic the Ebbinghaus illusion, but the distortion of circle size judgement in the **Ebbinghaus A≈B** condition, where the plot was designed to minimize the illusion, indicates that circle size interpretation may be difficult even when an illusion should not be present. This distortion is perhaps due to other causes not measured in this research. Because of this observation, it is important in the current research to make the case that the distortions that were present in this experiment were due to the Ebbinghaus conditions and not due to some other unknown causes. To do this we will look at the magnitude and the theoretically predicted directions of the circles and whether the results match what you would expect if the illusion caused the distortion.

6.1 Ebbinghaus distortion

Before looking at whether the evidence in the current research suggests that an Ebbinghaus like illusion was present, we will discuss whether an Ebbinghaus effect is likely to occur in ‘real world’ bubble plots. It is one thing if they occur in artificially constructed situations, such as the current experiment, but what are the odds of them occurring in everyday research? One way of answering this question empirically would be to collect as many published bubble plots as possible and examining them for the presence of the illusion and evidence that distortions occur due to the illusion. This would be an interesting empirical exercise but unnecessary because we argue that the necessary conditions for an Ebbinghaus like illusion are likely present in all bubble plots, and that it is only a question of magnitude. The conditions the illusion requires are that there be a circle surrounded by other circles, a common occurrence in bubble plots. The surrounded circle can be any of the circles on the plot and is not limited to a predefined one. You could rate areas of bubble plots by their similarity to the illusion and this would likely correlate with the strength of the distortion. Circles that are not surrounded by any circles would likely not show much distortion, whereas a circle surrounded by many circles, bigger and smaller than itself will likely be distorted, subject to the summed effects of the influence of the circles surrounding it. It is because of this that it is likely that many bubble plots displays do exhibit an Ebbinghaus like illusion.

The current research focused on whether it is possible to deliberately design bubble plots to produce the illusion. In both **Ebbinghaus A>B** and **Ebbinghaus A<B** we see significant distortions of circle size in the directions theoretically predicted by the illusion. In single circles the effect is clear in all but one of the circles (**Circle A** in **Ebbinghaus A<B**), where the circle is distorted in the correct direction but not in a statistically significant way. This could be due to the effect being smaller in that particular arrangement of circles or the research may lack enough power to measure this effect accurately. When we compare circles **A** and **B** the effect is even more pronounced and in the correctly predicted direction. These findings support the conclusion that it is possible to successfully replicate the Ebbinghaus illusion in deliberately designed bubble plots.

6.1.1 Was the distortion caused by the illusion greater than that of the other conditions?

There is evidence that the difference in distortion between the two Ebbinghaus inspired conditions produced the largest differences found in the research. This supports the idea that Ebbinghaus illusions can be seen as a major cause of distortion in bubble plots over and above other causes of distortion, making it a serious issue to consider when creating bubble plots. Despite this there is also evidence that it is not the only cause of distortion, as the other plot conditions also showed distortion at almost the same magnitude as the Ebbinghaus inspired conditions. This is perhaps most surprising in the condition designed to minimize the illusion (**Ebbinghaus A≈B**); this condition showed a significant difference when looking at the single circles as well as when comparing the difference between **Circles A** and **B**. The **Random plot** condition only showed a significant difference in the single circle condition but not in the comparison between **Circles A** and **B**. This was interesting because it was the least similar to anything looking like the Ebbinghaus illusion. The plot condition that was designed to minimize the illusion (**Ebbinghaus A≈B**) still retained the feature of surrounding a test circle with other circles albeit ones of similar size. It seems this was enough to provoke an illusion. This evidence suggests that the closer your display is to resembling the Ebbinghaus illusion the more likely it is to be distorted.

6.1.2 Conditions affecting the illusion

On the whole this research supports the hypothesis that the Ebbinghaus illusion is likely to be a major driver in any misinterpretations of circle size in bubble plots. This is supported by the evidence above that shows that plots more similar to Ebbinghaus constructions are more likely to be distorted. We will now go through a tentative list of necessary conditions for inducing the illusion in a bubble plot and discuss their likely causes based on what we know about perception and the proposed causes of the Ebbinghaus illusion.

The conditions are:

1) A circle distortion is more likely if the circle being judged is surrounded by other circles.
2) That distortion is likely due to the summed effect of the circles and the edges surrounding it.
3) This effect is mediated by the distance between circles.

6.1.2.1 Circle distortion is more likely if the circle being judged is surrounded by other circles

The most obvious condition seem to be that circle distortion is more likely to occur if it is surrounded by other circles. The Ebbinghaus illusion is an illusion caused by context (Coren & Miller, 1974) which is most clearly evident in the current research in the difference between the **Random plot** and the other plots. An explanation is needed for the influence circles have when closely surrounding another circle, and do not have when they are not surrounding a circle. As we have seen above there are perhaps two main interacting causes of the Ebbinghaus illusion and they are likely both top-down and bottom-up effects (Coren & Miller, 1974; Jaeger, 1978; Rose & Bressan, 2002). They are respectively cognitive contrast and contour integration and both are likely to be affected by the position of the contextual (surrounding) circles. The cognitive contrast explanation of the illusions relies on the similarity between the surrounding circles and the inner circle. In order for this to happen the brain has to make a judgement that the circles are part of the same conglomerate or whole, and this is more likely to happen when the circle is surrounded by other circles rather than those circles being at random distances and positions away from it. Well known gestalt laws of proximity and similarity are likely contribute to this effect (Wertheimer, 1938). Circles that are not in close proximity to the circle being judged may still exert an effect on it but it is likely to be small compared to circles in closer proximity to it. We also have reason to believe that contour integration adds to the effect of the distortion, with the edges of the test circles being attracted to the outer edges of the surrounding circles (Jaeger, 1978). The distortion here is a sensory low level phenomenon and is likely caused by the design of the visual system and is not affected by gestalt considerations. Here it is quite obvious that closely surrounding circles exert more pull in terms of contour integration on the inner circle than circles that do not surround the inner circle closely.

6.1.2.2 The summed influence of the surrounding circles

The summed influence of the surrounding circles needs to be taken into account. This explanation is only needed when the surrounding circles vary in different ways. When the surrounding circles are uniform in size and position it is probable that they have the same effect on the inner circle, but when they differ in terms of size and position it is likely that effects can vary in size and direction. The effect of the cognitive contrast on the illusion will likely be due to the averaged interpretation of the scene created by the surrounding circles, and it is within this framework that the inner circle will be judged and distorted (Coren & Miller, 1974; Rose & Bressan, 2002; Weintraub, 1979). Therefore, it is likely that the varying sizes and positions of the surrounding circles will result in varying interpretations of the scene. Contour integration also relies on the distance between the outer edges of the circles, and in accordance with this the differing sizes and positions of the surrounding circles can alter the profiles of those edges and any attraction or repulsion they exert towards the inner circle (Field et al., 1993; Jaeger, 1978). The effects of contour integration namely the attraction and repulsion of edges can be summed resulting in many combinations of overall effects, on occasion cancelling out the effect due to conflicting attraction and repulsion. It is therefore important to take into account the summed influence of all the surrounding circles.

6.1.2.3 The effect is mediated by the distance between the circles

The distance between the surrounding inducer circles mediates the magnitude of the illusion. The **Random plot** was not distorted much due to many of the circles being far away from the judged circles, whereas the other plot conditions were designed to have surrounding circles that were near the inner test circles but varied in different ways. The close distance between the inner and surrounding circles contributed to the conglomeration being seeing as a single whole based on the gestalt laws of proximity (Wertheimer, 1938) and also resulted in contours of edges being close enough to exert influence on the inner circle. Each circle's influence is likely to decrease in two ways as it gets further from the inner circle. Firstly, the contour integration effect will gradually diminish until it is close to zero. Secondly, a categorical effect is likely where at a certain distance the circle will be judged to not be a part of the whole associated with the inner test circle, resulting in a decrease in the cognitive contrast effect.

If a person is deciding on whether or not to display data using a bubble plot they will need to take into consideration these three conditions and assess the extent to which they are present in their current display and will distort its perception.

6.2 Violation of visual display guidelines

Another aspect that must be taking into account when deciding whether or not to use a bubble plot is the extent to which the distortions of circle size interpretation violates various guidelines for making good graphical displays. We will now look at how circle size distortion can be seen as violating various guidelines.

6.2.1 Violation of Tufte’s guidelines

The most important feature that defines a good visual display of data is the accurate representation of the data, namely, whether the effects or differences shown in the display correspond to the effects or differences in the actual data (Tufte, 1983). If this condition is not met the display is liable to mislead the viewer, and depending on the context can have serious repercussions. However this condition is also subject to pragmatic considerations. If the display′ s purpose is not affected by the distortion then its use could be justified. This could occur if the differences from actual and displayed effects are too small to be seen as an adequate violation, or if the distortion does not affect the main focus of the display.

In the current research the distortions caused by the Ebbinghaus illusion in the bubble plots can be assessed by way of Tufte’s lie factor (Tufte, 1983). Clearly circle size distortion can affect the lie factor. Circles that are distorted to look smaller than they are will have a lie factor of less than 1.0 and circles distorted to look bigger will have a lie factor of more than 1.0. However it is hard to interpret this measure. It is a useful when assessing or critiquing displays but when creating displays you also need to be aware of the pragmatic nature of the display. How big a lie factor is tolerable depends on the purpose of the display and whether the benefits of the bubble plot outweigh the costs. One of the benefits that bubble plots have is that they embody one of Tufte’s recommendations, that of small multiples (Tufte, 1983). You can quickly compare aspects of data by comparing circle size. This is useful in that multiple aspects of the data can be summarised and compared in the same display.

6.2.2 Violation of Kosslyn’s guidelines

We can also use Kosslyn’s guidelines to get a sense of the impact the Ebbinghaus type illusions have on bubble plot displays, and the seriousness of the violations that they cause (Kosslyn, 1989). The violations here are likely not ones that occur in the framework or background of the display. This research did not include labels, but labels could possibly affect the distortion due to semantic and affective influences on the illusion. The current research focused on the specifier of the display, and it is clearly the distortion of the specifier that is of most interest in this research. It is the circle size specifying some aspect of the data which is distorted. The distortion is clearly at the syntactic level but has repercussions at the semantic and pragmatic levels as well.

6.2.2.1 Syntactic

Syntactically the circles are interpreted as different from their actual sizes. This means a requirement for accurate discriminability has not been met (Kosslyn, 1989). If circles are shown to be poor at conveying small differences then their use is inadvisable for displays of data where noticing small differences are crucial. There is perhaps a minimal size difference that circles are good at accurately conveying. The marks on a ruler are good at measuring distances to the accuracy of a millimetre, but differences in between those marks are not accurately discriminable and the use of a ruler is inappropriate to measure them. The same is perhaps true for the use of circles in displays; big differences are safely displayed using them whereas small differences are lost and subject to any small distortion causing effects present in the plot. Contour integration and cognitive contrast are likely to be the main causes distorting the syntactic level properties of the specifier (Coren & Miller, 1974; Jaeger, 1978). Displaying differences in a bubble plot depends on how much distortion is present due to those two causes. There is a relationship between the presence of the two main causes − cognitive contrast and contour integration − and the minimal safe size differences in circles that can be shown in a bubble plot. In other words, displays with high distortion present in them are less suitable for accurately displaying differences than those with smaller distortion. Since the amount of distortion varies in each bubble plot, one cannot suggest a minimal threshold difference that would be acceptable for a bubble plot display. In certain situations minimal distortion could be present and small differences could be accurately judged, but in other situations the interpretation of even large differences can be inaccurate due to high levels of distortion being present in the display.

6.2.2.2 Semantic

The semantic level is undoubtedly affected by the syntactic level. Every difference in the specifier at the syntactic level should be accompanied by a corresponding difference in interpretation at the semantic level (Kosslyn, 1989). Larger circles mean that the corresponding value of the data that the circle is displaying should be larger. In the current research the semantic level was not specified. Circle size and their positions were not labelled and therefore there was no real semantic interpretation of the graphs. This was in an effort to isolate the syntactic causes of the distortion in bubble plots, but basic semantic interpretations such as 'greater than' and 'less than' or still likely to be made. Semantic causes of the distortion may also feedback on to the syntactic level. An extreme example of how this could affect circle size interpretation would be if you were explicitly told that the circles were all the same size but they were just different distances away from you. However there seems to be very little evidence of any explicit semantic causes of distortion in the current research.

6.2.2.3 Pragmatic

The most interesting level to look at the distortions caused by the Ebbinghaus illusion is that of the pragmatic level. This is the level that tends to matter the most in the real world. It looks at what are the real world consequences of a distortion in the display (Kosslyn, 1989). It is deeply related to the syntactic and semantic levels and adjudicates the seriousness of violations at those levels. One of the questions we want to ask is what do people do with the data presented in the display. If the data were representing daily nutritional guidelines then we would want it to be accurate and lead to consumers making informed choices about their diets (Geiger, Wyse, Parent, & Hansen, 1991). Distortions in interpretation of the message conveyed by the display could lead to real world health problems. Do Ebbinghaus like illusions in bubble plots lead to undesired consequences like this? How do the distortions shown in the research relate to the real world and what consequences can they have?

Using Kosslyn's guidelines we can examine the current research displays using the acceptability principles to get a better idea of where bubble plots might be lacking (Kosslyn, 1989). The first aspect 'purpose compatibility' looks at whether the display makes it explicit about what is needed to be extracted from the display (Kosslyn, 1989). This involves various things such as the appropriate amount, content and format being used. In what settings are bubble plots most likely to be fruitfully used? In an academic setting the amount of ink present in the plot usually seeks to follow Tufte's data-ink ratio (Tufte, 1983), i.e., getting rid of any needless features that do not convey important information. Bubble plots are in line with this feature in that they do not add unnecessary frills. However, in certain other settings such as displays used in newspapers they can easily be modified with decorations to serve a different purpose. Use of a bubble plot to display data is most routinely used as a way of conveying data to an audience, and it is not likely to be used in a setting where the display's purpose is to help find something out. It is difficult to compare circle sizes, and informative findings could be hidden from the researcher because of this difficulty. It is therefore not likely to be used in scientific or statistical settings where the goal is to use the displays as epistemic tools (Blakemore et al., 1990). Appropriate content is a relevant factor. In certain settings 'chart junk' and related features may be ideal for use in displays and data-ink ratios can be ignored. However, in an academic setting where small details need to be conveyed 'chart junk' can distract (Tufte, 1983). Researchers need to calibrate their decisions about displays based on what content is appropriate. Researchers need to ask themselves whether the content embodied by bubble plots is appropriate for displaying their data. Using the appropriate format is also important, and certain formats are better at displaying certain things. Interactions in regression analysis are best displayed in line graphs and many other displays are ideally suited to different settings (Kosslyn, 1989). In the present research, the display of differences in circle size to represent differences in real world features can be appropriate when those differences are large enough, and in this case distortions may only have a negligent effect upon interpretation. Bubble plots are well suited for when the variable that you are using circle size to display has a high uncertainty and only a vague idea of its value is needed; an example of this is population estimates of countries where the given number is almost certainly wrong but a vague estimate is all that is need to be conveyed. When this is not the case bubble plots can be inappropriate. One of the main attractions for using a bubble plot is that it displays an extra dimension of the data and this is a benefit that needs to be weighed in favour of using it against the various distortions that can occur due to its use.

The idea of the invited inference is also important to consider, and this is the higher level message that the display is trying to convey (Kosslyn, 1989). Some displays may not have an intended meaning and they are just used to discover aspects of the data, but ones that are published tend to have a purpose, an invited inference that the author wishes to convey. The suitability of using a bubble plot depends on this goal. A person, if so inclined, could use the distortions caused by the Ebbinghaus illusion to convey a false message. Most of the time, it is likely that they want to convey the variation of three aspects of the data, and if this is the case, and they are satisfied that it does this adequately despite whatever distortions may be present, bubble plots can be highly effective.

We have seen that the appropriateness of the use of bubble plots is mediated by many things. The main themes of the above discussion are those of purpose, and setting or context. It is important to take these into account when deciding whether or not to use a bubble plot. The consequences of the distortions in circle size caused by the illusion vary in seriousness based on these considerations. Displaying small detail differences may not be the purpose of the display and in a non-academic setting and accurate interpretations may not be the ultimate goal. In other settings these could be vital requirements for displays, and in these cases bubble plot should not be used.

Bubble plots seem to be more prevalent in certain settings and this may be related to the fact that different software defaults are used in different settings. Microsoft Excel offers users the option of making bubble plots, whereas IBM SPSS does not offer this option. The settings that these two products are used in can be very different. Excel may be used in a financial setting but SPSS is usually in an academic setting (Cleveland, 1984). We would have to ask the question of whether bubble plots are good at communicating financial data and whether any distortions in the interpretation they convey can have serious real world financial consequences (Cleveland & Fisher, 1998).

6.3 Limitations

The current study suffered from a number of limitations and its conclusions need to be independently replicated to ensure that they are valid and reliable findings. Firstly the sample size needs to be increased in order to test whether the conclusions of this research are valid and to get a more accurate measure of the effect. Any replication should have at least 2.5 times the current number of participants, based on recommendations by Simonsohn (2013). The sample was made up of mainly undergraduate Psychology students and the generalisability of the research cannot be assessed with this unrepresentative sample. Research has shown that the Ebbinghaus illusion effect does vary in some cultures and age is also known to affect it (De Fockert et al., 2007; Weintraub, 1979). However, in other cultures familiarity with interpreting graphical displays of data might be limited, making distortions in perceived circle size the least of the problems to consider when using the displays to convey information. This raises the question of whether it matters if these effects are not generalisable to certain cultures. If those cultures are not using graphical displays of data, then the research likely only affects those in cultures that are familiar with graphical displays, and these cultures are more likely to be similar to the participants used in the current research. We also have reasons to believe that at least some causes of the illusion are universal features of the human visual system.

6.3.1 Limitations in measurement

The method used to measure circle size in the current research, namely comparing the test circle to a scale of other circles of varying size, and saying which one is the same size as the test circle has been shown to be a valid and reliable way to measure circle size, but better ways to measure circle size have been developed (Coren & Girgus, 1972). These methods have been shown to have a greater validity and give more accurate measures of what the person perceives to be the size of the circle. However these methods were not practical for the current research which displayed the bubble plots using a projector.

Another limitation of this research was in the measurement procedure. The bubble plot conditions and the scale used to measure the circles were shown to the participants using a projector, projecting the images on to a screen in the lecture room. A question that needs to be asked is if this procedure in any way biased the measurements. Did the position of where the participants sat have any effect on their judgements of circle size? Replication attempts could use a different procedure to test if the conclusions obtained in that way match the current research. However, the measures were shown to be relatively consistent and there is every reason to believe that the effects are real based on prior research – nothing highly unlikely was found in this research.

The research conclusions seem valid in that they measured syntactic variation in bubble plots where Ebbinghaus illusions were present. However there was no measure of semantic or pragmatic distortions. This was because there were no real semantic interpretations of the displays, because it was designed to be a measure of syntactic variation only. Semantic and pragmatic effects could be measured by giving labels to the plot conditions and then asking the participant questions about the graphs and then seeing if their responses were consistent with being affected by the illusion (Kosslyn, 1989). The reliability of the research can only really be judged by replications, but the measures were well behaved and the findings consistent with previous research.

7. CONCLUSON

In conclusion to the question of whether bubble plots can produce an Ebbinghaus like illusion, we must answer in the affirmative, and that this illusion can distort the way people interpret bubble plots. Certainly at a syntactic level this is the case; people misjudge circle size even when the conditions for the illusion are not present. However when they are present the distortion is likely to be large and can be multiplied by the illusion being present in multiple areas in the bubble plot. The current research bears this out with circle size interpretation being unreliable for both single circle interpretation and interpretation of differences between circles. When the Ebbinghaus illusion was present it showed variation in the theoretically predicted direction indicating strongly that the distortion was due to the illusion.

The way that the visual and perceptual system works did not evolve for accurate judgements of circle size, indeed the likelihood of needing to know if two circles are the same size for our survival seems very small. The natural world seems to lack mass produced exact replicas of things (Pinker, 2008). The perceptual system only needs to be able to accurately tell the difference between things that have much dissimilarity. It is perhaps because of this that high similarity between objects is a thing that the perceptual system uses to group things into single entities (Wertheimer, 1938). All these features of the visual system serve to either magnify or lessen differences between circle sizes in the bubble plot conditions. A multitude of causes from contour integration to cognitive contrast explanations serve to make our limitations in this task plain.

The seriousness of these distortions is not clear from the current research. The semantic and pragmatic violations that circle size distortion cause are something that will likely vary between different contexts and expressed purposes. They are highly connected to syntactic violations but can in some cases be insensitive to them, either when they are too small or when they do not affect a higher goal of the display. It is this question that needs to be addressed next.

7.1 Further research

Ideas for further research could be the testing of semantic and pragmatic violations that may occur due to the Ebbinghaus illusion. It would be important to test these in a wide variety of settings and purposes. Only in this way will we be able to tease out where the violations are most serious. In order to do this the plots will need to be given meaning, so that questions can be asked that will reveal distortions in any semantic or pragmatic interpretations of the plots. Another way to do this would be for participants to perform actions based on information they interpret from the bubble plots. Future research can look at the different ways of measuring the judgements of circle size, and it can also test if using a projector can bias the interpretation of circle size in any way.

Undoubtedly there are times when the distortions in circle size interpretation do not matter and the benefit of displaying more than two dimensions is worth the risk of using circle size. However, in certain conditions when small differences are crucial to display, the use of bubble plots is not recommended. Further research will be needed in order to determine when these occasions occur.

Further research could look at alternatives to the bubble plot and compare them in terms of the criteria used above. Where these alternatives may not be susceptible to the Ebbinghaus illusion, they may also have their own problems, which will make it necessary to weigh up the strengths and weaknesses of the displays when deciding which display is better for a certain setting.

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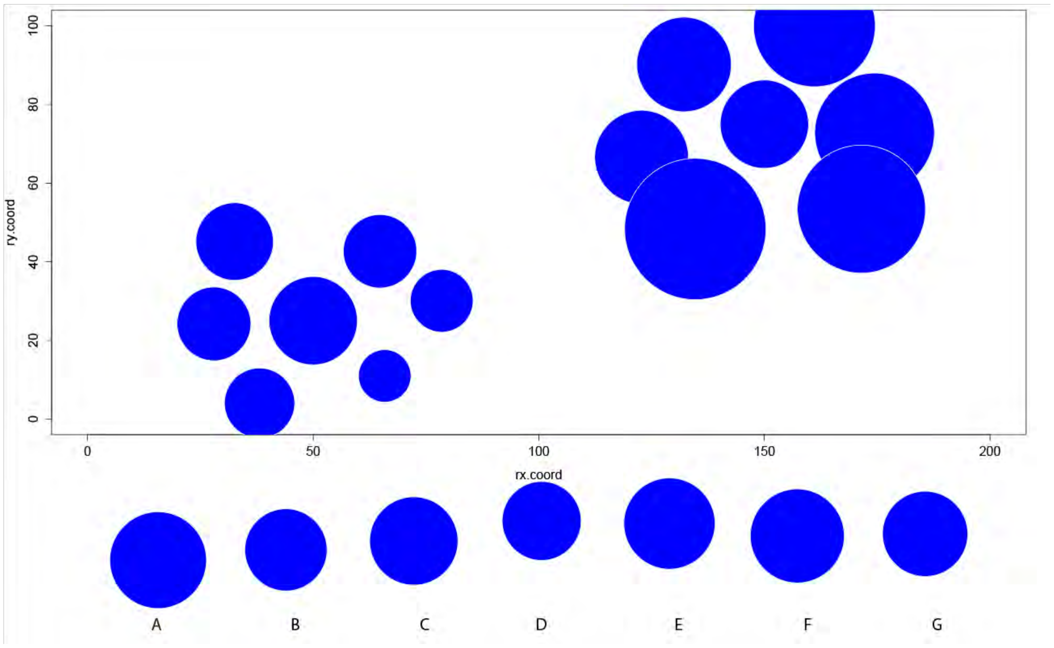
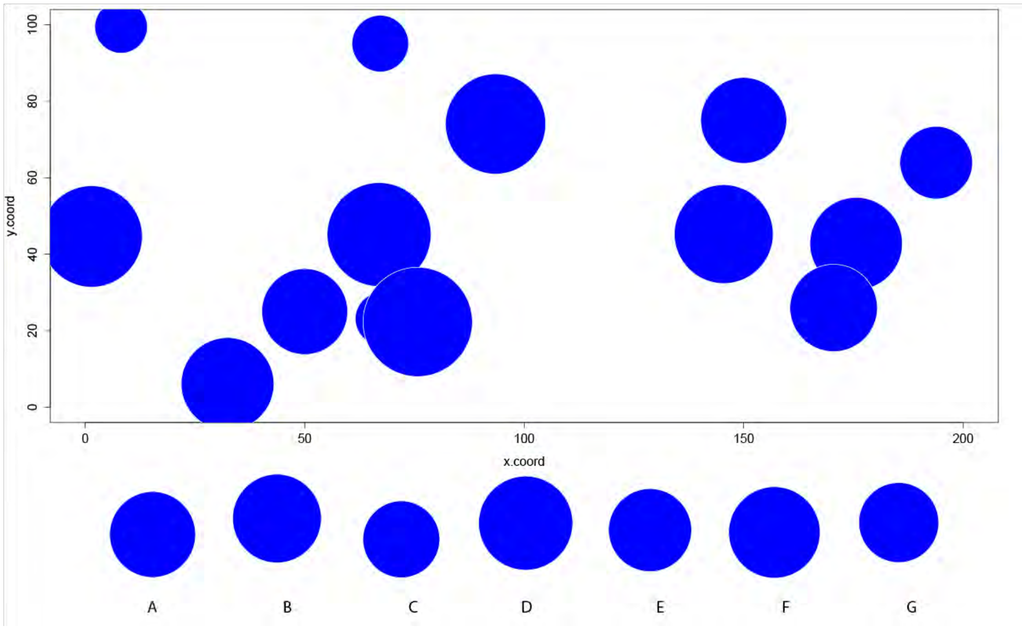
9. APPENDIXES

9.1. Appendix A: Ebbinghaus plot conditions

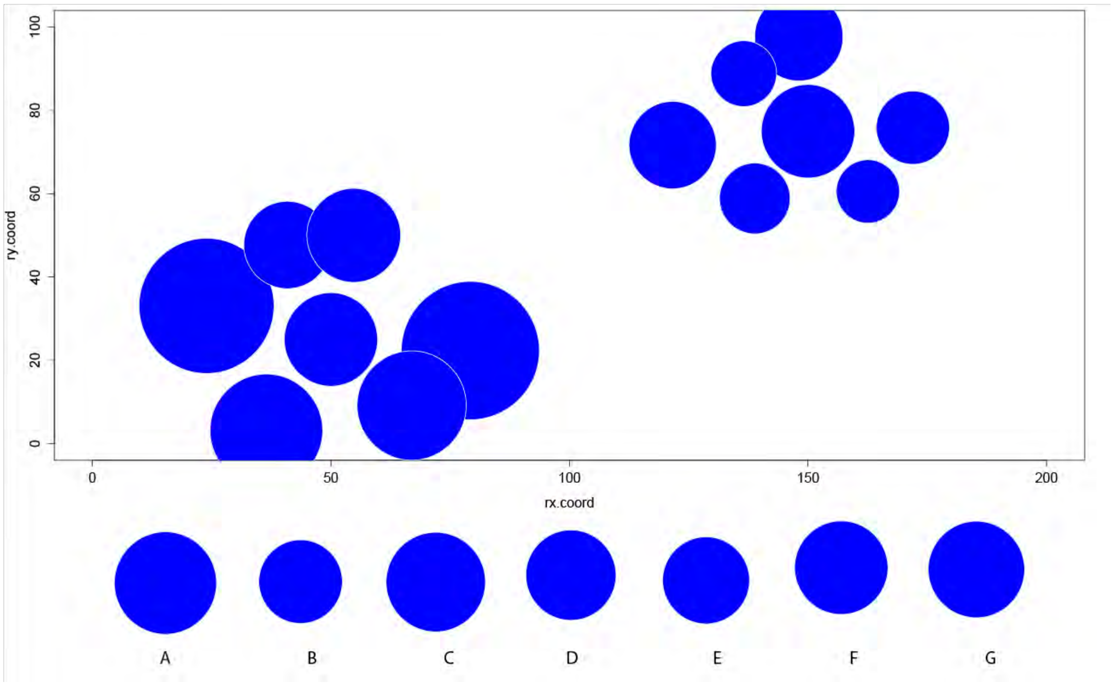
Ebbinghaus A>B using variation 1 of the measurement scale



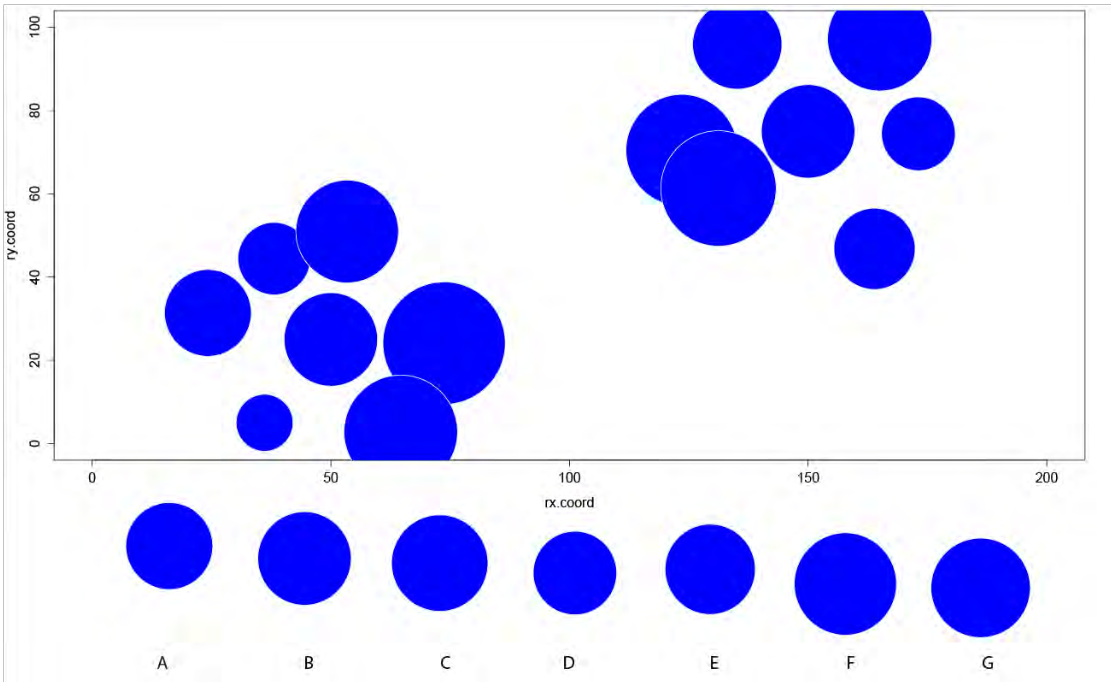
Random plot using variation 2 of the measurement scale



Ebbinghaus A<B using variation 3 of the measurement scale



Ebbinghaus A≈B using variation 4 of the measurement scale



100
80
60
40
20
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50
100
150
200
rx.coord
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B
C
D
E
F
G

9.2. Appendix B: Informed consent sheet and responses sheet

Informed Consent Form

Dear Participant

I am a Psychology Masters student asking you for your participation in this research, which forms the basis of my Masters Research project required for me to complete my Masters degree.

The information collected will be kept confidential at all times, stored in the form of a computer database and no names will be stored. The informed consent form will be separated from the questionnaires and the data will not be able to be traced back to you.

This study is voluntary and you are able to withdraw at any time from the study without any negative repercussions. Should you have any concerns related to this research, you should not hesitate to bring them to my or my supervisor's attention.

Stephen Olivier
solivier85@gmail.com
Cell: 084991192

Supervisor
Prof. Lance Lachenicht
Lachenicht@ukzn.ac.za

I……………………………………………………………(full names of participant) hereby confirm that I understand the contents of this document and the nature of the research project, and I consent to participating in the research project.

I understand that I am at liberty to withdraw from the project at any time, should I so desire.

SIGNATURE OF PARTICIPANT DATE

…………………………………… …..…………….

Age	
Gender	
Race	
Nationality	

Please circle the letter corresponding to the circle you think is the same size

	Response						
1	A	B	C	D	E	F	G
2	A	B	C	D	E	F	G
3	A	B	C	D	E	F	G
4	A	B	C	D	E	F	G
5	A	B	C	D	E	F	G
6	A	B	C	D	E	F	G
7	A	B	C	D	E	F	G
8	A	B	C	D	E	F	G
9	A	B	C	D	E	F	G
10	A	B	C	D	E	F	G
11	A	B	C	D	E	F	G
12	A	B	C	D	E	F	G
13	A	B	C	D	E	F	G
14	A	B	C	D	E	F	G
15	A	B	C	D	E	F	G
16	A	B	C	D	E	F	G

9.3. Appendix C: Ethical Clearance letter

9.4. Appendix D: Turnitin

Turnitin Originality Report

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paper text:

1 Popping the Bubble: Do bubble plots distort interpretation of circle size Stephen Olivier (206518683) UKZN – PMB Campus Supervisor: Prof. Lance Lachenicht Submitted in partial fulfilment of the requirements of the degree of Masters of Arts in the School of Psychology in the University of KwaZulu-Natal, Pietermaritzburg. Abstract This research tested the hypothesis that an Ebbinghaus illusion can occur in a Bubble plot display and distort the interpretation of circle size. In order to do this we tested participants' ability to judge circle size in different Bubble plot conditions. These conditions varied based on how likely they were to cause an Ebbinghaus illusion to be present in the plot. The research found that conditions that were more similar to the Ebbinghaus illusion showed greater distortion and were distorted in the correctly theorized direction. The seriousness of these distortions was then assessed based on theoretical guidelines of good visual displays of data. DECLARATION Submitted in partial fulfilment of the requirements for the degree of Master of Arts in the Graduate Programme of Research Psychology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

11. The research reported in this thesis, except where otherwise indicated, is my original research. 2. This thesis has not been submitted for any degree or examination at any other university. 3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons. 4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then: a. Their words have been re-written but the general information attributed to them has been referenced b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced. 5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

____________________ Stephen Olivier ____________________ Date

____________________ Professor Lance Lachenicht ____________________ Date Contents

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25 October 2011

Mr S Olivier (206518683)
School of Psychology

Dear Mr Olivier

PROTOCOL REFERENCE NUMBER: HSS/1050/011M
PROJECT TITLE: Popping the Bubble. Do bubble plots distort interpretation of circle size?

In response to your application dated 26 September 2011, the Humanities & Social Sciences Research Ethics Committee has considered the abovementioned application and the protocol has been granted **FULL APPROVAL.**

Any alteration/s to the approved research protocol i.e. Questionnaire/Interview Schedule, Informed Consent Form, Title of the Project, Location of the Study, Research Approach and Methods must be reviewed and approved through the amendment /modification prior to its implementation. In case you have further queries, please quote the above reference number.
PLEASE NOTE: Research data should be securely stored in the school/department for a period of 5 years.

I take this opportunity of wishing you everything of the best with your study.

Yours faithfully

……………………………………………………………………
Professor Steven Collings (Chair)
HUMANITIES & SOCIAL SCIENCES RESEARCH ETHICS COMMITTEE

cc. Supervisor – L Lachenicht
cc. Mrs B Jacobsen