THE APPLICATION OF PRACTICAL GEOMETRY AND THE GOLDEN RATIO IN PRODUCT DESIGN

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MARCH 2014

Declaration

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree. However, the thesis incorporates to the extent indicated below, material already submitted as part of required coursework and/or for the degree of:

Doctor of Philosophy

In Engineering and Design

which was awarded by University of Sussex

Signature:...

Acknowledgements

I would like to take this opportunity to thank a number of people who have assisted, supported and enabled me to complete my thesis. Firstly, I must thank my supervisors, Dr Christopher Long, Ms Diane Simpson-little and my external advisor Mr Richard Morris who all supported me academically in a positive way during the research period. Secondly, my deepest gratitude goes especially to Mr Gary Feeney for proofreading my thesis and without whose help and emotional support this research would not have been possible.

Finally, I wish to thank my parents (Dr Boem Kweon and Mrs Soon Ja Bak) and my brother (Woong Koh) for their love, encouragement and for their financial support throughout my venture in Italy and England since 1997.

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SUMMARY

There have been numerous researchers who, over the years, have explored the relationship between the golden ratio and how it relates to the human perception of beauty. Although the golden proportion is one of the aesthetic characteristics contained in many masterpieces of art and design, it is still largely thought of as little more than an aesthetic guideline, that is, if indeed it is even being considered at all.

This thesis asserts that golden proportion and practical geometric knowledge can be used as an extremely effective means of codifying the creative process, inspiring and influencing creative design decisions. This thesis is concerned with examining the application of practical geometric knowledge as an integral part of the design process. It also documents the development of the author's geometric refinement tools and discusses the results of their performance in testing by scrutinizing the opinions of design students and professional designers who both had their designs modified by the author's refinement tools. The relationship between geometric knowledge embedded in design classics and bestselling items was also examined.

This thesis describes a mixed methods approach with multiple analyses, from which qualitative and quantitative data (about the implementation of applying geometric knowledge) was gathered via two geometry workshops, interviews with the professional designers, as well as an analysis of visual materials consisting of two hundred selected design examples. Based upon the process of employing geometric knowledge and its experiments, the thesis presents a descriptive analysis of the data to test theoretical propositions and draw conclusions about the value of applying practical geometry as design knowledge and as a practical tool for a design in the modern context.

The significance of this thesis is that it elucidates upon the use of the golden ratio, and practical geometry as a practical design refinement tool, with the ability to transform the perception of practical geometry from being merely an aesthetic guideline which appears

in masterpieces from the past, to a directly applicable practical design technique.

The main contribution this thesis makes to the field of design practice is that it attempts to further understand the results achieved by codifying designing styles and design decisions, a process which can be described as objective rational knowledge in practice. This thesis frames individual design participants' perspectives of the golden ratio and the relationship between modern designs and the masterpieces of history. Thereby, hopefully providing a historical perspective and a modern context for the golden ratio. Further to that, it is the author's hope that this work will provide inspiration to today's designers, motivating them to begin implementing practical geometry into their designs and in the future generations of design education to come.

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1. INTRODUCTION

1.1 THE FOCUS OF THIS RESEARCH PROJECT

This research focuses on the application of the golden ratio and practical geometric knowledge in design. Although the golden proportion was regarded as one of the most visually pleasing aesthetic guidelines often appearing in masterpieces, so far much of the previous research into the relationship between the golden ratio and aesthetic perception has proven inconclusive at best. The problem facing those who wish to use golden ratio and geometric knowledge effectively is the matter of knowing when and how to apply it to the design process. This thesis is an examination of the implementation and utilization of practical geometric knowledge as an aesthetic refinement tool for designers during the design process. More specifically, the author questions how, and to what degree, were the aesthetic decisions of design professionals influenced after seeing the results of the golden proportion, and other ratios, being applied to their own designs? This research will also investigate how deeply geometric knowledge has become embedded in what are considered to be design classics and in bestselling items amongst consumers.

1.2 RESEARCH INTENT & RESEARCH AUDIENCE

There seems to be a lack of regard for incorporating knowledge of geometry in product design education and few theoretical researchers to date have examined the relationship between geometric knowledge and design forms. The intention of this thesis is to develop geometric knowledge of design and find out how it can be effectively and practically applied to the design process. Providing design students with experience of learned geometric principles can be a way to support aesthetic decisions, providing objectivity and a rationale for designs.

This research is aimed at design students, designers and design educators, and will provide an approach to design analysis and geometric refinement through the research participants' own designs, and it will show how geometry can be utilized effectively in the design process. Not only for analysing proportions of designed forms, but also for articulating aesthetic decisions and explaining them rationally. This document will provide an account of the design student's own experiences with using geometric knowledge and the authors' geometric refinement tools, which will help to lead them to the development of their own design style.

The findings of this thesis would provide useful resource for design students and design educators alike. Because, in reflecting upon their own experiences with golden ratio and considering the outcomes of this thesis, design students and educators may come to a more complete understanding of why well-conceived design is proportionally pleasing to the eye.

1.3 RESEARCH AIMS & THE PURPOSE OF EACH CHAPTER

The purpose of this research was to develop effective design tools which focus on the use of geometric knowledge as a design practice to further develop visual coherence, and as a basic for rational decisions in the design process. Although the golden ratio has been used as a way to perceive aesthetically pleasing structures, it is the author's opinion that there has been insufficient attention paid to the benefits of implementing the golden ratio and practical geometric knowledge into the field of design as a fundamental procedure. In this research, applying geometry to the design process will be approached from the perspective of visual analysis to increase understanding of how to create designs with frequently used geometric ratios. Secondly, to use geometry to encourage designers to align the artifacts they design more with the geometric blueprint found in nature and to improve their awareness of proportions in the natural world.

Three hypotheses have been tested on product design students in order to investigate how design students perceive geometry in their design practice and how the golden ratio in designs may be utilized to recognise harmonious geometry.

This research also suggests an approach to developing effective design refinement tools which are based on the concepts of the Golden ratio, Dynamic symmetry and Fibonacci sequential numbers and how they can be utilised in design. A set of geometric refinement tools were developed and applied to the designs of various professional designers for the purposes of analysis of their designs. The results of the experiments clearly show that applying this set of geometric refinement tools can be an effective technique for design refinement. The designers' views on the application of the refinement tools to their own designs are also discussed.

THE AIMS OF THIS THESIS:

1. To appraise the importance and potential value to designers of utilizing geometry in the design process and ascertain how geometry can provide effective design techniques which can be practical and directly applicable in any design situation.
2. To ascertain how and when design students (and professional designers) may apply the golden ratio to their designs to best effect, to maximize the success of using geometric knowledge as a practical method in design education.
3. To discover the significance of the golden ratio and geometric knowledge in superior designs (*'Phaidon Design Classics'*) and everyday objects (bestselling items), and to investigate the uses of geometry and aesthetics in design practice.

The thesis' basic research questions are: a) To what degree are geometric principles currently being used in design education and practice? b) How could that geometric knowledge be more successfully implemented as a practical method for designers?

The thesis's research questions are:

1. What is the value to designers of developing effective design tools based on knowledge of geometry and then applying them in product design education?

2. How can geometry be useful as a practical method in design for developing visual coherence?

3. What are the perceptions of design students regarding the implementation of geometric principles as a means to recognize their own level of visual knowledge?

4. How do professional designers consider applying geometric knowledge in their design process?

5. How frequently do geometric ratios and golden ratio appear in best consumer choice products and expert designers' designs?

Research Objectives: There are three objective steps, and each step describes how this thesis will achieve its aims.

Objective Step 1: to review previous related research as to how the golden ratio has been used in science, art and design. Chapter 2 discusses the use of the golden ratio as an analytical method for investigating aesthetic beauty, proportion in natural beauty and in artefacts. The thesis' Literature Review examines the central argument in the field of design regarding the golden ratio, and what the related geometric knowledge and practical methods in the design process are. Thus, the thesis' Literature Review will provide directions on how to utilise practical geometric knowledge as an effective design tool in the design process.

Objective Step 2: There will be two methods used to teach basic geometric knowledge to the research participants. Firstly, Geometry workshops which aim to introduce geometric knowledge to design students. It will focus on examining what makes geometry and the golden ratio useful practically in the design process and how can their effectiveness be tested in terms of usability with regard to further development. Thus, the participants learn practical geometry and apply it directly to their own designs to experience first hand the refinement of their design style. This experimentation process will test the thesis hypotheses and attempt to measure how geometric knowledge can influence design decisions made by design students. Secondly, after the geometry workshops, the author's geometric refinement tools will be developed and used to experiment with professional designers' designs. This experiment will be completed with two interviews of the participating designers and therefore there is a need to provide a clear instruction on how to implement geometric knowledge and geometric analysis in order to explain its codifying process for the professional designers.

Objective step 3: To apply the author's geometric refinement tools to the selected modern designs (from 100 '*Phaidon Design Classics'* and 100 Bestselling items sold via Amazon online retailer) in order to investigate what relationship exists between geometric knowledge, design classics and bestselling items.

1.4 CONTRIBUTION TO NEW PRACTICAL KNOWLEDGE

This thesis has revisited geometric knowledge and the golden ratio in order to articulate the process involved in aesthetic refinement of modern designs. This thesis is significant as it moves beyond the golden proportion as an aesthetic guideline and uses it as analytical method. It focuses on the practical use of geometric knowledge, developing geometric refinement tools for both design students and professional designers alike. The key contribution of this thesis is to further our understanding of how to support aesthetic design decisions, by codifying evolving design styles. These processes attempt to harmonize artefacts with nature as a fundamental design theory through practical geometry. This thesis has helped frame some of the design activities of the research participants from the perspective of their experience of implementing geometry in support of their subjective aesthetic design decisions, providing them with new ways to objectify their approach to aesthetics.

1.5 THESIS STRUCTURE OUTLINE

This thesis is divided into seven chapters and each chapter has been designed to answer the research questions and aims to build the argument to meet the study's broad aims. Table 1-1 consists of each chapter and outlines how this thesis contributes new practical knowledge to design education. It also contains the purpose of the chapter as well as a summary. In addition, discussions about the data gathered are included in Chapter 4, 5 and 6. Chapter 7 is thesis' conclusion.

Table 1-1 Thesis structure

Chapter 1 Introduction: This chapter presents the overall thesis' outline and it includes, research aims, research questions, objectives, limits of the research and an outline of each chapter.
Chapter 2 Literature Review: The intended outcome of this literature review is to highlight the synthesized findings and to develop research questions that will establish the framework of this empirical study. It should also lead to a better understanding of how geometry and knowledge of the phenomenology of designing might produce better results. Chapter 2 will provide the answer to research question 1 and reviews how previous researchers have used geometric knowledge in design to establish what the essential points of applying geometric knowledge into design practice are. In this section, thesis' research questions have been developed and presented.

Chapter 3 Research Design & Methodology:

This chapter outlines the methodological framework which has been applied to this thesis. The chapter is divided into 5 main sections. Section 3.2 reviews different theories of knowledge and illustrates the philosophical assumptions of this thesis. Section 3.3 considers mixed research methods and what methods would be appropriate for the thesis' research area. Section 3.4 presents the study of the research design. There are three research stages in this thesis: 1) The first one is the experimental procedure of testing three hypotheses; 2) The second involves experimenting with a set of the geometric refinement tools with professional designers; 3) The third is a geometric analysis of popular consumer choice products and expert designers' designs (modern design classics). Section 3.5 describes how data gathering will be carried out. Section 3.6 presents the thesis' analytical processes.

Chapter 4 Testing Hypotheses:

In this chapter the three hypotheses of the thesis are tested in order to examine unconscious application of geometric ratios and how gained geometric knowledge influences aesthetic design decisions. Thus, the 'Geometry workshop' illustrates the process of how to apply the golden ratio and other geometric ratios into design practice, ultimately raising the design students awareness of golden ratio as a practical method of analysing their own design forms, rather than limiting its use to that of an aesthetic guideline. The results of the experiments manifest how geometry can be useful as a practical method for the design students for developing visual coherence and helping them to recognize their own level of visual knowledge.

Chapter 5 Experiments with Geometric Knowledge:

The purpose of this chapter is to examine the notion of how professional designers should consider pro-actively applying geometric knowledge into design. The process of developing a set of geometric refinement tools and applying them into the design process could reveal the value of implementing the golden ratio and related geometric knowledge into the professional design environment. The author's geometric refinement tools are used for the

analysis of the professional designers' designs and the considered opinion of the designers are evaluated in order to clarify how to fit into the broad range of design methods used during any design process.
Chapter 6 Modern Classic Designs & Bestselling Products: The purpose of this chapter is to investigate the characteristic proportion of modern classic designs and popular products. It also aims to consider what geometric ratios are related to both bestselling and classic designs. Following the criteria for Geometric refinement set out in chapter 5, this chapter utilized the geometric refinement tools as a method to examine to which degree the frequently used geometric proportions occur in masterpieces (1, $\sqrt{\Phi}$, $\sqrt{2}$, Φ, $\sqrt{3}$, $\sqrt{4}$ & $\sqrt{5}$) and how deeply the golden ratio is embedded in design classics. The results of geometric analysis of both the classic designs and bestselling products could indicate how geometric knowledge in the professional world has been implemented.
Chapter 7 Conclusion: This chapter includes an overview of the thesis by considering theoretical arguments and logic developed throughout the thesis which has led to the thesis making an innovative and original contribution to new design knowledge. It points out what next steps would, or could be taken and provides the thesis' perspective on any future development of this idea.

2. LITERATURE REVIEW

This chapter will review the existing relevant literature used to develop a set of five research questions as a starting point for an empirical study and a critical re-thinking of design education and practice.

The objectives of this Literature Review are firstly, to establish the main argument and address how there has been a lack of research carried out into the implementation of geometric knowledge in design practice. Secondly, to respond to the basic research question *“a) To what degree are geometric principles currently being used in design education and practice?”* via reviewing the relevant literature which has already examined the connection between geometric principles and science art, and design. Lastly, to achieve a set of discreet research questions which will identify the gaps in current design knowledge and practice, and which will illustrate how geometric theory might impact upon design students in order for them to create their own style aided by the use of basic geometric subdivisions.

This Literature Review is divided into five sections:

1) Geometry in science: Presents some existing research into the subject from diverse sources.
2) Golden ratio and facial beauty: Reviews the relationship between golden proportion and the aesthetic beauty of the human face.
3) Geometric relationship to Fibonacci numbers: Focuses on Fibonacci numbers which have been used for mathematical explanations to examine the proportion, structure and growth of nature. How and why is the Fibonacci sequence relevant to the design process through geometric articulation?

4) Aesthetic preferences of the golden ratio: Scholars have long since argued about the aesthetics of geometric proportions. This section discusses their conflicting views on the subject.
5) Geometry in design: The final section reviews previous research regarding perception of the golden ratio and the application of geometric principles. Also it includes a reference to other approaches used in design practice for developing design forms, such as the use of design history (reference to past products) and the development of visual brand language. It contains a rational explanation for why geometry is a credible method for increasing the understanding of a design practitioner's experience of designing.

2.1. GEOMETRY IN SCIENCE

This section will present some of the most notable examples of scientific research to date which examine the geometric relationship between the natural world and man-made artifacts, and asks why, and how, these are connected with art, architecture and design. The use of geometry in design highlights necessary scientific rationality, leading to the establishing of a logical framework for the research. It explains why there is a lack of resources regarding the implementation of scientific knowledge of geometry into design theory and practice.

Geometry is one of the oldest sciences and a branch of mathematics which has been widely used in art, architecture and design since ancient Egypt and Greece. The denotation of geometry is simply 'measure of the earth' and *'the study of spatial order through the measure and relationships of forms'* (Lawlor 1982). Artists, architects and designers have also applied and used geometry as a basic theory for their own works of art. Plato acknowledged that geometry and number are the most concise and vital philosophical language. Number can be transformed into a medium for philosophical contemplation. Geometry can act as a bridge to reconnect science and art, and if used as a vehicle for developing practical theories in design, geometry could facilitate a deeper understanding of the similarities and differences between the man-made world and nature, which can only be of benefit to both in the long term.

> *'Geometry deals with pure form, and philosophical geometry re-enacts the unfolding of each form out of a preceding one. It is a way by which the essential creative mystery is rendered visible. The passage from creation to procreation, from the unmanifest, pure, formal idea to the 'here-below', the world that spins out from that original divine stroke, can be mapped out by geometry, and experienced through the practice of geometry.' (Lawlor 1982, p.10)*

According to research from the field of quantum mechanics, every animate or inanimate object vibrates regardless of man's ability to perceive it or not. Matter in the world consists of a certain amount of atoms assembled in geometric formations. When tiny particles of atoms are constantly changing formation, they produce energy or resonance, so in other words it could be said that 'Existence is vibration' (Emoto 2001). All substances consist of atoms, and in solids, liquid, gas and plasma, all of which join together efficiently *'because nature prefers configurations that minimize energy'*(Stewart 1998, p.32).

During an experiment with atomic structural changes of a gold cluster, Sugano and Koizumi (1998) discovered that atomic clusters naturally assemble into platonic solid formations. They noticed that there is a connection between the geometric shape of a cluster and the number of atoms. A sequence of atomic clusters holds critical information regarding the cluster's electronic and ionic spatial organization (Sugano et al 1987). Atomic clusters are symmetrical geometric configurations of atoms, such as cubic, hexagonal and icosahedral, too miniscule to be perceived by the human eye. From the perspective of vibration and resonance, all objects both animate and inanimate in existence appear to have very definite and specific geometric patterns.

Dr. Ibrahim Karim is the originator and developer of a relatively recent science known as BioGeometry. He combined micro-vibrational physics, ancient Egyptian architectural knowledge and a study of the earth's energy grid, to develop his own method of measuring the subtle energy of colour, sound, smell, touch, taste and shape (Karim 2010). More specifically, BioGeometry is concerned with utilizing these principles effectively to construct harmonious environments that have a positive physical and mental effect upon human beings. BioGeometry focuses on reproducing the harmonizing qualities that support life and it recognises design as another way to maximise human health and well-being through the subtle energetic effect of patterns and shapes.

Adrian Bejan, professor of mechanical engineering at Duke University has been working on how living organisms are shaped. His theory of *'Constructal law'* states; *"For a finite-size flow system to persist in time (to live), its configuration must evolve in such a way that provides easier access to the currents that flow through it."* (Bejan 2012, p.3). The constructal law is one of the first principles of physics to explain the designs in nature and articulates why designs arise and predicts how they will evolve in the future. It can be applied to any system anywhere. The constructal law states that every flow system is destined to remain imperfect as nature evolves. It is noted that the constructal law in nature and golden proportion (Φ) are both naturally occurring phenomena. The golden ratio is an irrational (never-ending decimal) number approximately equal to 1.618. When there are two ratios, ('a' and 'b') and a>b and the longer part ('a') is divided by 'b', it is also equal to the whole length (a+b) divided by the longer part (a), $\frac{a}{b} = \frac{a+b}{a}$ =1.618…=

Φ.

Bejan applied the constructal law of the golden ratio to common designs of rectangle images and he found that the proportion of the designs were close to the golden ratio, but did not exactly represent the golden ratio. Bejan's method was based on the human binocular field of vision. The human eye can scan both the vertical and horizontal axis of images and can scan the horizontal faster than the vertical. According to Bejan, the proportions of these images were close to the golden ratio. Others, such as Stone & Collins (1965) and McWhinnie (1989) found evidence in their research that provides substance for there being a preference for rectangles which have proportions similar to that of the golden proportion. Collectively, these researchers' theories shed light on why the golden ratio has been regarded merely as an aesthetic guideline for millennia, and why it appeared so often in masterpieces of classic design inspired by the natural world.

2.2 GOLDEN RATIO & FACIAL BEAUTY

Golden proportion in the human body has been used by researchers, dentists and cosmetic surgeons in the area of facial perception to identify facial attractiveness (Marquardt 2001, McDonnell & McNamnara 2003, Jefferson 2004, Pallett 2010, Schmid et al 2008).

Dr. Eddy Levin, a pioneer of implementing phi ratio (Φ) in aesthetic dentistry patented the 'Golden Mean Gauge' and 'Phi Dental Grid' which were both based on golden proportion. The proportion of the two incisor teeth conform to the golden section rectangle (see figure 2-1). Levin discovered that the four teeth, from the central incisor to the first premolar are all in golden proportion to each other (figure 2-2).

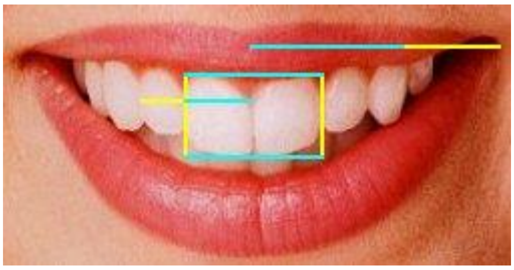


Figure 2-1 Golden proportion in teeth

(Downloaded from: http://www.goldennumber.net/face/, accessed date: 17/07/2013)

Figure 2-2 The width of incisor and lateral incisor

(Downloaded from: The width of incisor and lateral incisor, http://www.goldenmeangauge.co.uk/, accessed date: 17/07/2013)

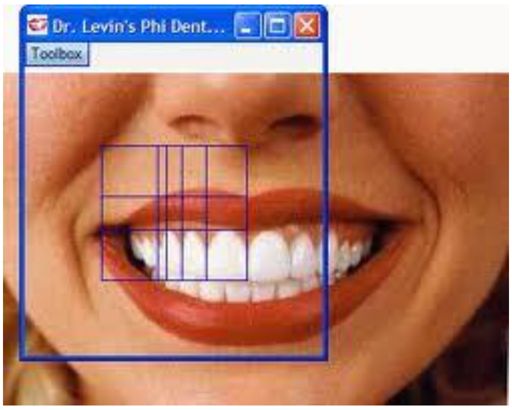


Figure 2-3 Phi Dental Grid (Downloaded from: The width of incisor and lateral incisor, http://www.goldenmeangauge.co.uk/, accessed date: 17/07/2013)

Levin's golden proportion in beautiful teeth has been suggested in many articles and textbooks as a guideline method for replacing teeth in aesthetic dentistry.

Dr. Stephan Marquardt, an oral surgeon in California developed a 'Golden Decagon' mask which was based on golden ratio. He claims that visual perception of the face was two-dimensional. He developed an acute golden triangle with sides of 1.618 and a base of 1, or an obtuse golden triangle with a base of 1.618 and side of 1, which together form a golden pentagon which can be duplicated, inverted and superimposed on itself forming of the golden decagon (Gottlieb 2002, Marquardt 2001, Cleese 2001) (see figure 2-4).

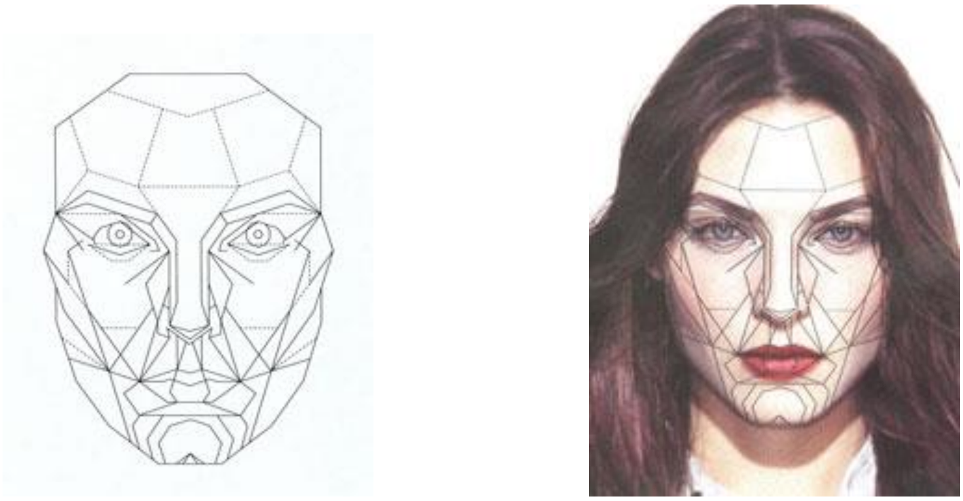


Figure 2-4 Left is Golden Decagon Mask, right is a beautiful face with Golden Decagon Mask applied (Downloaded from: http://www.beautyanalysis.com/index2_mba.htm, accessed date: 17/17/2013)

Marquardt's mask appealed to many plastic surgeons and designers as an example of an aesthetically pleasing face. He claimed that all face types conform to his mask, universally, regardless of race, age or nationality. Marquardt's method was also documented through a BBC documentary called *"The Human Face"* from 2001. It presented the complexity of the human face and the relationship between the golden ratio and facial attractiveness. McDonnell et al (2003) and Schwind (2011) used Marquardt's golden decagon mask in order to create beautiful 3D facial models by using computer software programmes, although evidently, some drawbacks were experienced by Schwind with the suggestion that this approach may not be suitable for all racial features, and for various facial expressions (Schwind 2011).

Schmid et al (2008) utilized three principles: symmetry, conformance to Neoclassical Canons and golden ratio, in order to identify the determinacy of beautiful faces and developed a quantitative method for measuring facial attractiveness.

Four hundred and two images of faces were taken from the Facial Recognition Technology (FERET) Database and thirty two popular movie actors and actresses from between 1930s and the present day were also chosen, with an equal number of male and female faces used. Figure 2-5 shows twenty nine feature points of FERET and figure 2-6 illustrates how to measure the proportions of face: Figure 2-6 shows 'A'- the ideal result which was 1.6, almost exactly the golden ratio; 'B' - three equal proportion of facial segments of equal proportions from forehead hairline to a spot between the eyes, from the eyes to the bottom of the nose, from the bottom of the nose to the chin; 'C'- the length of ear is equal to the length of nose, and the width of an eye is equal to the distance between the eyes.

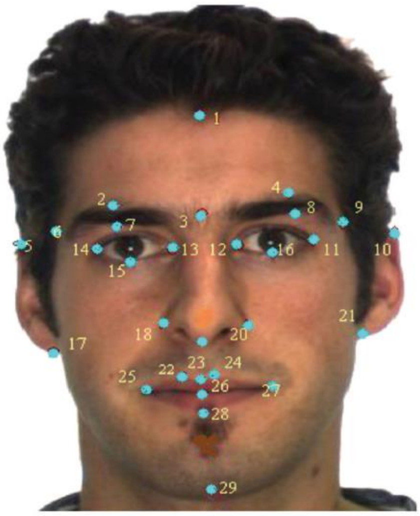


Figure 2-5 Feature points on an image (Schmid 2008, p.7)

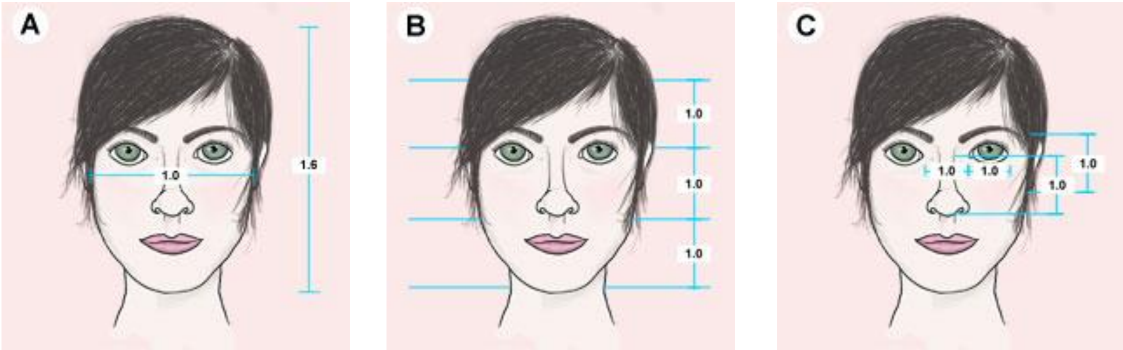


Figure 2-6 Measuring length and width of face

(Downloaded from: http://www.oprah.com/oprahshow/Measuring-Facial-Perfection-The-Golden-Ratio, accessed date: 17/07/2013)

Schmid et al discovered that facial beauty can be measured on a scale of one to ten. Most people scored somewhere between four and six, but no one ever scored a perfect ten. They also claimed that most celebrities were clearly scoring higher than six which would seem to suggest in this experiment at least, the greater the degree of conformity to symmetry, golden proportion and neoclassical cannons a face had, the greater the degree of preference was expressed (Schimid et al 2008, p.2715). The golden proportion is clearly applicable when examining facial beauty. So therefore, if it can prove effective given the complexity of human features, then surely it should be safe to assume that inanimate objects would be relatively straightforward to analyse very effectively using the same method.

Other researchers (Ghyka 1946, Ricketts 1991, Baker et al 2001, Jefferson 2004, Saraswathi 2007) presented analyses of faces based on the golden proportion, which also claimed that the golden ratio is related to aesthetics and biology. People who have longer faces have a tendency toward a conclusion known as long face syndrome, meaning they have a greater chance of being diagnosed with certain medical conditions, such as upper airway obstruction and 'mouth-breathing'. People who have shorter faces tend to experience a greater incidence of craniofacial pain and migraine (Jefferson 2004). So therefore it can be said that this simple application of the golden proportion in human faces has proved to be both aesthetically beneficial and conducive to deeper understanding and the treatment of various health problems. (Jefferson 2004, Saraswathis 2007).

2.3 GEOMETRIC RELATIONSHIP TO FIBONACCI NUMBERS

This section examines the relationship between the Fibonacci sequence in nature and geometry.

Artists and designers are inspired by geometric patterns in nature and have throughout time, tried to imitate the forms of plants and animals. This is perhaps because nature shows the perfect balance of aesthetic principles of unity, symmetry and asymmetry. Gnomic growth, or logarithmic spiral growth, in nature appears in visible patterns such as seashells, pine cones and sunflower seeds. An ancient Greek mathematician and engineer, Hero of Alexandria defined a gnomon as '*any figure which, when added to an original figure, leaves the resultant figure similar to the original.'*(Lawlor 1982, p.65). The publications, *'The curve of life'* (1914) by Theodore Andrea Cook and D'Arcy Thompson's *'On Growth and Form*' (1917) were influential resources for understanding the principles of the laws of nature. Thompson's spiral geometry investigated the connection between geometry and numerology in living organisms. The law of biological growth in animals, plants and most living organisms, is to grow without changing their shape only increasing in the ratios of the golden number; phi (1.6182) and the golden angle (137.50776˚).

> *"Any plant cure proceeding from a fixed point (or pole), and such that the vectorial area of any sector is always a gnomon to the whole preceding figure, is called an equiangular, or logarithmic, spiral… it is characteristic of the growth of the horn, of the shell, and of all other organic forms in which an*

equiangular spiral can be recognised, that each successive increment of growth is similar, and similarly magnified, and similarly situated to its predecessor, and is in consequence a gnomon to the entire pre-existing structure." (Thompson 1917, p.184)

The Fibonacci number appears everywhere in nature, from leaf arrangements, branching plants, breeding pattern of rabbits and the ratio of males to females in honey bee hives.

Ian Stewart explains, in his book 'Life's other secret', what botanical research into Phyllotaxis (the arrangement of leaves on a plant stem) has discovered regarding the relationships between botanic spiral patterns, numbers and energy efficient structure formation.

"At the centre of the tip is a circular region of tissue called the "apex"; around the apex, one by one, tiny lumps form, called "primordial." Each primordium migrates away from the apex-more accurately, the apex grows away from the lump, leaving it behind-and eventually, the lump develops into a leaf, petal or the like. Moreover the general arrangement of those features is laid down right at the start, as the primordia form. So the heart of the problem is to explain why you see spiral shapes and Fibonacci numbers in the primordia, as all the varied Fibonacci features of plants are simple consequences of this basic geometric structure."(Stewart 1998, p.124)

In fact these spirals known as "parastichies" do not represent the actual pattern of plant growth and they consist of neighbouring primordia. However the most important spirals are the generative spirals which actually are formed by the mathematical patterns of primordia in order of their appearance (Stewart 1998). He provides two French mathematicians, Adrien Douady and Yves Couder's investigation in 1992 regarding Fibonacci numerology in geometric growth of plant. According to Douady & Couder, *'the dynamics of the appearance of the new primordial at the place of lowest repulsive energy* *creates a final structure of minimum global interaction energy.'*(Douady & Couder 1992). This theory can be seen in the symmetric pattern of sunflower. Helmut Vogel in 1979 examined the case of sunflower seed patterns through his computer experiments. Stewart explains that a small sunflower' capitulum consists of 34 clockwise and 55 counter clockwise arcs which are interwoven tightly at an angle of 137.5˚ and the figures of 34 and 55 are set constantly in the Fibonacci sequence, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55…e.g. For example 34/55=0.6182 which is close to phi (Φ). The Fibonacci number is related to the golden angle. *"take consecutive numbers in the Fibonacci series, such as 34 and 55; form the corresponding fraction 34/55, and multiply by 360˚"*(Stewart 1998, p.126) The result of it is approximately 222.5˚ which is bigger than 180˚. So then, the golden angle is subtended by the smaller angle, which is 137.5˚. The golden angle is the principle arrangement of leaves and branches around the main stem of many plants and in the case of sunflower seed head, packed without any gap at the angle of 137.5˚ (figure 2-8, the middle picture). While the angles of 137.3˚ and 137.6˚ show greater gaps between seeds (figure 2-8, the left and the right pictures). This angle is known to be the most efficient for packing the plant's head strongly and solidly with seeds.

Figure 2-7 Sunflower seed head

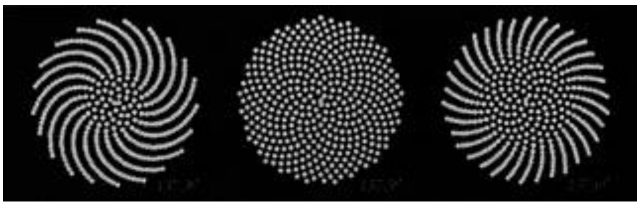


Figure 2-8 The left 137.3˚, the middle 137.5˚, the right 137.6˚

It is not only plants that conform to these principles. Figure 2-9 shows that human bone lengths in the finger, hand and arm show their relationship to the Fibonacci number sequence (Lawlor 1982). In more recent years geometric formations in the natural world have been exhibited more clearly as a double-helix model of DNA structure which has a logarithmic proportion of the golden section or phi. Furthermore other scientific research reveals the ratio of growth in organisms as 1.618 which is very close to 1.665, the value of the binocular field of vision in humans (McWhinnie 1989).

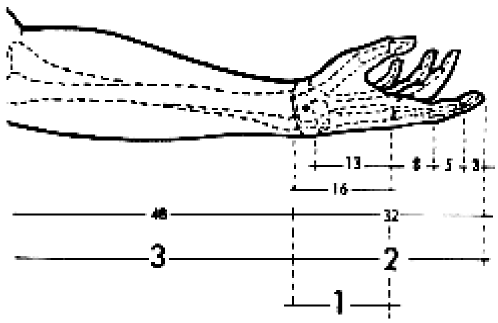


Figure 2-9. Human bone lengths in the finger, source from Lawlor (1982, p.59)

When experienced through the sensory organs we are surrounded by a natural world which consists of varying degrees of aesthetic attraction. However, when viewed through mathematical systems and the laws of physics, we do in fact, live in a fractal world composed of patterns of gnomic growth.

> *"Sensory systems generally have a very mathematical structure. Why? Senses have to process incoming data rapidly and reliably to extract information about the outside world. To do this they must be engineered rather carefully. They must respect the underlying patterns of the outside world."(Stewart 1998, p.160)*

Expanding his theory to include human perception which has a tendency to be biased towards recognition of patterns in the universe. We are surrounded by nature which consists of patterns and systems.

> *"Senses produce internal patterns of neural activity in brains; in order to be useful, those patterns must correspond, in some manner, to significant patterns in the outside world. Therefore, the neural nets used in sensory perception must*

be organized in a way that reflects the deep patterns of the external universe…the universe is based on symmetries…The human brain and its sensory organs have evolved together in this wonderfully symmetric universe. In order to survive in a hostile world, we have evolved the ability to use our brains to detect what will happen next. So it is only to be expected that the symmetries of the universe should somehow be imprinted on our sensory apparatus."(Stewart 1998, p.166)

It is not at all unlikely that our consciousness follows these natural patterns and neuroscientific research would suggested that the development of the human brain has evolved through gnomic growth patterns (MacLean 1986, 1990). Forms that develop as a result of gnomic growth always retain some residual element of the past, therefore this process does not merely represent the evolution of matter but also of consciousness, with our perceptive apparatus inclined to the recognition of these gnomic growth patterns and the resultant forms.

Thus, with normal human senses we cannot experience the geometric formation of atoms nor the resonance of atomic particles and yet through geometry and the golden section these concepts not only were known, but also have been embedded in art, architecture and design before the formal acknowledgement of these discoveries was announced by the scientific establishment. It can be said that these scientific discoveries; logarithmic spirals which are based on the golden section and its relation to Fibonacci series, and the gnomic growth of plants and animals; are useful principles to apply to design in order to avoid subjectivism (Padovan 1999).

Geometrical symmetry is a principle of proportional form in art, design and science and it is used to understand nature and the whole universe. Geometric proportion and symmetry are carefully applied in arts and design to express emotion and also to present logical reason via proportional harmony. Geometry can be approached as a theory of design or a method for developing efficient forms for productivity, as it also has useful practical applications, not merely aesthetic applications.

2.4 AESTHETIC PREFERENCE OF THE GOLDEN RATIO

The purpose of this section is to review some of the previous research on the subject and to put professional perceptions of the golden ratio under closer scrutiny.

The golden ratio has been recorded in use as a guiding principle of aesthetic beauty and proportion in arts and design since ancient Egypt and Greece (Berlyne 1971, Benjafield 1976, Huntley 1970, McManus 1980, Lefebvre 1992, Davis & Jahnke 1998) and perhaps even before. For example, a plan of Stonehenge shows how it conforms to the root five rectangle, which consists of a square and two reciprocal rectangles with a ratio 0.618 attached to the each side of the square. (Doczi 1981) Researchers in aesthetics and psychologists have investigated geometric forms as stimulus objects in order to understand the aesthetic qualities of the objects. The first researcher who studied the aesthetic preference of the golden section rectangle was the famous German psychologist Gustav Fechner, in 1876. His subjects chose their most–preferred to least-preferred among ten rectangles of varying proportions from 1:1, 5:6, 4:5, 3:4, 7:10, 2:3, 5:8(the golden section proportion), 13:23, 1:2, to 2:5. He gathered a total of 347 responses and his experiment shows that 35 % of people preferred the golden section rectangle and that no subject chose the golden section rectangle as their least favoured choice. The least preferred rectangle chosen by the subjects was the 2:5 with 35.7%. Other researchers repeated the experiment, such as Witmar (1894), Lao (1908) and Thorndike (1917) and all outcomes remained similar to the original.

Not all studies done would agree, however, that people are attracted to the golden section rectangle. For example, Berlyne's work (1970) suggests that cultural factors could be influential toward the chosen preference of different sized rectangles or squares. This was the result of his experiment which showed evidence that Japanese high school girls preferred squares rather than the golden section rectangle. Fischler (1981) claimed there was no sufficient documentation to support the theory that an artist used the golden ratio as the theoretical basis of his work. Davis and Jahnke's research (1991) would also suggest there is not enough solid data gathered to be a decisive factor in terms of aesthetic preference for the individual choice. They concluded that their experiments "provide no basis for the golden section as an aesthetic ideal" (Davis and Jahnke 1991). Whilst both these studies produced results that seem to place less emphasis on the golden ratio as a design concept, the results are by no means conclusive in any way. Fischler, and Davis and Jahnke in their own words both mention a lack of sufficient data when attempting to write a conclusion to their research. In other words their findings do not constitute conclusive proof of anything. There are as many, if not more, examples of the reverse scenario actually being the case (Piehl 1976, 1978, Benjafield 1976, McManus 1988).

Aesthetics researchers used various shapes of stimulus with a broad range of stimulus ratios in order to gain determinant results. Yet their conclusions could be described as inconclusive regarding the methods used to obtain the results.

Boselie (1984) researched the perception of the golden proportion in visual patterns. He wanted to know whether it lead to an aesthetically pleasing state. As with other psychologists, Boselie used undergraduate students for his subjects. He showed ten pairs of polygons (some with internal lines) to fifty male students, which contained golden proportion. The results were not conclusive enough to show that the golden ratio was the most influential determining factor justifying its visual preference in a pattern. He concluded that the presence of the golden ratio does not in itself influence the aesthetic preference of a pattern and generally agreed that people perceive patterns while searching for symmetry and repetition. However, although it appeared to Boselie that there was no significant amount of visual preference expressed for the golden ratio. Unless other features in the geometric shape were also harmoniously divided.

Boselie (1992) tested the visual preferences of the golden proportion compared to ratio 1.5. In the first experiment, he used Mondrian-like rectangles divided into different proportions, yet it did not provide any conclusive findings regarding the visual preference between the golden ratio and 1.5. The reason for this being it can be argued that all works of art have many perceptual dynamics which could result in preference for golden ratio, just as any of the other proportions could also be considered the preferential ratios.

For the second experiment, eight golden rectangles and eight rectangles of ratio 1:1.5 were used. Each rectangle contained one interior line creating two equal proportions. The other remaining fourteen rectangles were divided into different proportions. Twenty five subjects were asked to rank them from the most preferred to least preferred. The result of the second experiment presented findings that the golden section rectangles and rectangles ratio 1.5 were almost equally preferred. In the third experiment, he used thirty subjects who were asked to compare six pairs of plain rectangles. Each pair, which consisted of a golden section rectangle and the other a 1.5:1 rectangle, were divided into two, some vertically and some horizontally. From the results of the third experiment, the 1.5 rectangle was preferred over the golden ratio rectangle, (59% and 41% respectively). Whilst Boselie concluded from this that golden ratio did not have any special aesthetic qualities which made it an obvious preference, it can be argued that the subdivisions of small rectangles in 1:1.5 and the golden section rectangles may have been an influential factor in terms of the visual preferences of the 6 pairs of rectangles. Boselie repeated testing the aesthetic preference of geometric proportions but the three individual experiments did not lead to a comprehensive conclusion. This is an important factor to consider because Boselie's conclusions were drawn almost exclusively from his third experiment.

Davis (1931) was one of the few researchers to use the preferred rectangles, drawn by research subjects, in order to look at the perceived beauty of the rectangles. In total, three hundred and ten subjects enrolled on the philosophy of aesthetics course were asked to visualize the most pleasing proportioned rectangle and then draw it freehand on five inch square blank paper provided. After a forty minute interval the subjects were asked to repeat the process. The results of two repeated experiments were treated as independent preferences. According to Davis, about three percent of the total subjects had drawn their preferred rectangles which were proportionally from 1.55 to 1.64. There were three clear groups of rectangles with ratios of √3:1, √4:1 and √5:1 which were drawn as the subject's preferred rectangles. Although Davis' results were far from the golden proportion, the three groups of proportions used are ratios which form the basis of practical geometry.

Schiffman (1966, 1969, 1978) experimented regarding visual preference of golden proportion. In an experiment to discover if the shape of the field of binocular vision was responsible for the aesthetic preference of the golden proportion, he used thirty six psychology students and they were asked to draw the most aesthetically pleasing rectangle that they could on a sheet of paper. Ninety seven percent of subjects drew horizontally oriented rectangles, the average ratio of which were 0.525 (Schiffman 1966).

Schiffman (1969) repeated this experiment. For the first experiment he used the same method as previous researchers, but with a higher volume of test subjects. Of the one hundred and fifteen male psychology students, ninety percent of subjects drew horizontally oriented rectangles the average ratio of which was 0.489. In the second experiment however, he approached the subjects with a different method. He showed twenty five male subjects six pairs of different proportioned rectangles, oriented in both horizontal and vertical positions and of varying ratios. The subject's instructions were as follows: "Pairs of rectangles will be shown against this screen. Carefully examine the two rectangles and choose the one that appears the most aesthetically pleasing". The results of this experiment showed no significant preference of any rectangles, yet the most preferred rectangle ratio was 0.518. There was an overall preference of vertically oriented rectangles, rating fifty seven and three percent. In the third experiment, he used five pairs of rectangles, dropping the ratio to 0.818, and the result was the same as the second experiment. His first experiment showed that the majority of subjects drew horizontally oriented rectangles as their preference, which correlates with Bejan's conclusions related to the field of binocular vision. Yet he concluded there was no conclusive aesthetic preference for the golden ratio. It can be argued that the first method was a more natural, uncontrived approach to finding out how the binocular field of vision and the golden ratio were related. There could also be a case for arguing that designed stimulus for subjects may influence preferences and therefore may add a degree of bias to the researcher's conclusions.

Konečni (2003) used a similar method of freehand drawings by the test subjects in an experiment designed to examine the visual preference and immediate response towards golden proportions and how the accuracy of geometric proportion can be an important factor for professional artists. On this occasion professional painters with at least seven year's experience participated. In total twenty seven photographs of simple golden proportion and other proportioned vases were used. Paintings by a young and relatively unknown painter called Kodama, who was known for implementing the golden ratio in his paintings, as well as classic paintings by Mondrian and Whistler, who were also well known for implementing the golden ratio in their works, were also used. Thirty seconds were allowed for sketches of the vase and sixty seconds for the paintings by Kodama, Mondrian and Whistler. The results showed that more accurate sketches appeared from the images of Mondrian and Whistler's work than of Kodama's. It is clear that there are physical connections between the golden proportion, nature and the human body which are reviewed in previous section 2.1 and 2.2. However, there are few researchers who investigated the importance of geometric knowledge and its application into art, architecture and design. The following section, will review the work of geometry in design in order to understand how principles of geometric knowledge can be implemented into the design field.

2.5. GEOMETRY IN DESIGN

As previously mentioned there are few researchers in product design who have seriously examined the relationship between forms and reasoning in the design process. Nor how geometric forms of designs can be rationally justified through the visual and verbal media or other forms of aesthetics based communication. In fact, visual forms in design derived from geometric patterns in nature have been utilised in various areas of study, such as physics, engineering, art, architecture and design etc. since ancient times. In design education, both "Industrial design" and "Product design" courses require design knowledge and artistic skills to be designer in modern times. Industrial design might be considered to be the process of creating and developing new concepts. It optimizes the function, appearance of products and usability usually associated with craft design to that of mass produced objects (Morris 2009). Product design might be considered a more technological and innovative approach to develop products. Its process is involved with the efficiency and effectiveness of a developing idea for a new product, through the use of electronic and mechanic technology (Morris 2009, Loughborough University n.d. p.6). In terms of designing objects in the design process, there are many methods and approaches used, such as mood boards, researching past products and the development of visual brand language all of which deliver an aesthetic style of product. These methods tend to focus on developing aesthetic forms in the design process, whilst there is a lack of methods or tools to effectively analyse the aesthetic appearance of the designed creation at any stages.

So far surprisingly few researchers in the field of design have emphasised an in-depth analysis of how to implement and apply geometry in product design education in order to examine the relationship between visual perception and design forms. Thus, aesthetic beauty of visual forms and logically designed forms can be codified through knowledge of geometry. It can be said that a new approach to implementing geometry, as a vehicle for establishing a philosophical background to understand the visual relationship between physical objects in the outer world and the inner world of visual perception, has not yet been firmly established, and not fully explored.

This section reviews why and how geometry has been used to understand the principles of art, architecture and design since ancient times. It attempts to understand how successfully geometric forms, structures, proportions and growth have been implemented into art, architecture and design and why this is so. It will explain how geometric shapes relate to our conception, perception and aesthetics, and then how the golden ratio [or any of its other titles: the golden section (Coxeter 1953), the divine proportion (Huntley 1970) and the golden number (Fischler 1981)], symmetry and geometric progression (Sir D'Arcy Thompson) is the structure of form and proportion which exists within living organisms, animals, and the human body (Lawlor 1982). In particular, the golden ratio has been used in art and architecture, since ancient times. More modern examples are A.M. Cassandre's works of art (between 1920th to 1930th) Charles Eames' Plywood Chair (in 1946), Deter Rams' designs (since 1960th) and Apple designs by Jonathan Ive (since

2001). All of which are respected works of art, architecture and design. Are these examples mentioned considered masterpieces of art and design due to the fact they used the principles of geometry and the golden ratio? How does our perception interpret these artifacts, and what attracts our perception to the forms within geometry and the golden ratio? Or can it be said that because the golden ratio is biologically imprinted upon us, we have a natural inclination towards artifacts which conform to the principles of the golden ratio? As Jay Hambidge suggested:

> *"It is the symmetry of man and of plants, and the phenomenon of our reaction to classic Greek art and to certain fine forms of other arts is probably due to our unconscious feeling of the presence of the beautiful shapes of this symmetry." (Hambidge 1967, p.xvi)*

Hambidge - who analyzed Greek vases to research his own theory of 'Dynamic symmetry'- discovered that the root rectangles (√2, √3 and √5) and the golden section rectangle were used for Greek vase design. His research material was obtained from three areas; 1) Greek and Egyptian arts. He wanted to understand and learn how the geometric rhythm was used for design during two of the greatest artistic periods in history. 2) The symmetry of man and plants. Which guides us to recognize how nature employs the same rhythm in living organisms, 3) Study of the five geometric solids; the cube, the tetrahedron, the octahedron, the icosahedrons and the dodecahedron present the fundamental geometrical material for his study. He coined the term 'Dynamic symmetry' for the first time and his research was basically analysing how the golden ratio and root rectangles (√2, √3, √4 and √5) were applied in ancient Greek architecture and design. He suggested that ancient Greek artists and designers were consciously experimenting with geometry and frequently used the golden ratio and the root rectangles, all of which are deeply embedded in ancient Greek design. The most significant feature of his research was to stress the importance of the diagonal line of the golden rectangle (the whirling square rectangle) and root rectangles. The diagonal acts as a vital feature of tension which impacts upon surface areas of designs. According to his geometric principles, the construction of "Dynamic symmetry" consists of the diagonal of a rectangle and the diagonal of a reciprocal rectangle *"the reciprocal of a rectangle is a figure similar in shape to the major rectangle but smaller in size. The end of the major rectangle becomes the side of the reciprocal"* (Hambidge 1967, p.30). He claimed that the designs and proportions of many Greek vases, such as Amphora, Kalpis, Hydria, Skyphos, Oinochoe and Lekythos, all conform to a specific arrangement of the rhythmic subdivisions, "Dynamic symmetry"(see figure 2-10) and he suggested that Greek artists were able to understand how to implement this harmonious geometric knowledge (the diagonal of reciprocal and the diagonal of designs) in their work. In fact the diagonal of reciprocal in design forms guides designers to construct the golden spiral which illustrates the logical outgrowth of patterns geometric progression in nature (see figure 2-11).

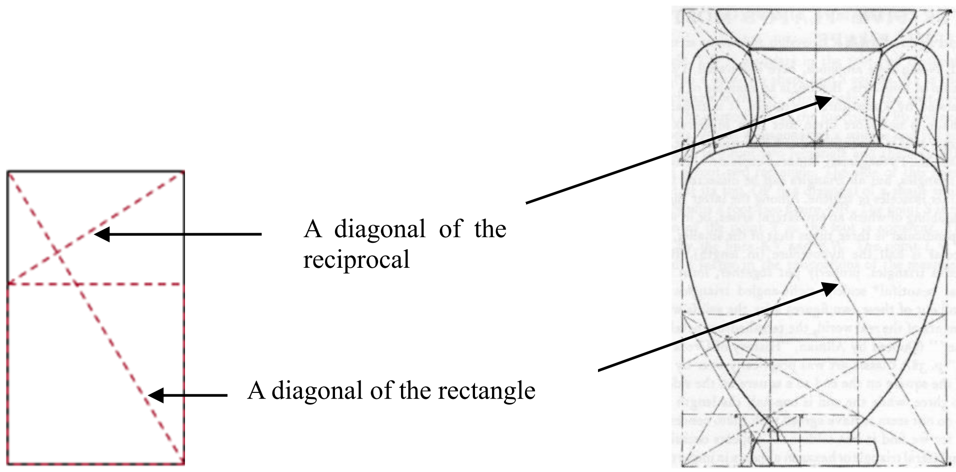


Figure 2-10. The golden rectangle (left) and Amphora in a root three rectangle (right) (Hambidge 1967, p.60)

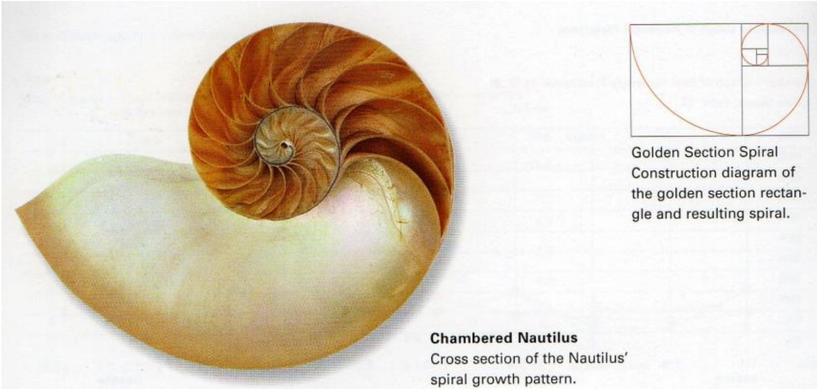


Figure 2-11. The golden spiral in nature (Elam 2001, p.8)

> *"Dynamic symmetry in nature is the type of orderly arrangement of members of an organism such as we find in a shell or the adjustment of leaves on a plant…The dynamic is a symmetry suggestive of life and movement… its great value to design lies in its power of transition or movement from one from to another in the system. It produces the only perfect modulating process in any of the arts... it is the symmetry of man of plants, and the phenomenon of our reaction to classic Greek art and to certain fine forms of other art is probably due to our unconscious feeling of the presence of the beautiful shapes of the symmetry... "(Hambidge 1967, pp. xii-xvi).*

Thus he addressed that the superiority of "Dynamic symmetry" in Greek art works are fundamentally different in comparison to the "Static symmetry" of Roman times.

> *"The dynamic rectangles, which we obtain from the growth phenomena, are distinguished by this property of area measurableness. It is this characteristic which lies at the base of the rhythmic theme conception and gives the dynamic scheme its greatest design value. Because of the persistence of the normal ratios of phyllotaxis the conclusion is inevitable that the measurable are themes posses life and all the qualities that go with it, while areas which do not have this peculiar property do not have life. They are "static" or dead areas, at least as far as design is concerned. If the testimony of Greek art has value this would seem to be so. We know that one characteristic of Greek design is just this life-suggesting quality…we know also that Roman art, by comparison, is lifeless."(Hambidge 1967, pp.10-11)*

It appears that his application of both geometric and mathematical knowledge into art and design was recognized as an important addition to the field of design knowledge. Presumably due to the fact that it was based on following the logic of natural progression. Even if many artistic works do not belong to nature and are artificially created, at the very least, design principles regarding form and structure need to be considered. It is still the case however, Hambidge's contribution to art and design using geometric principles has not been acknowledged in design circles. His geometric analysis may be useful for the analysis of the aesthetic appearances of the product designs when designers may not be sure which designed objects can be their determined forms.

There are other aesthetic refinement approaches to design, such as the development of visual brand language and referencing to design classics or past products. Dieter Ram's work with Braun electronics is the most renowned example of how visual brand language developed. Ram is one of most influential product designers who worked with such grid systems. He and his team at Braun established their own design style which has been applied to all Braun products in Germany since the 1950s. His design philosophy is to minimize details and clarify function by avoiding unnecessary extra detail and his limited use of colour in products (primarily black and white) supplied Braun's own brand language with simple and monolithic appearances. In terms of referencing past designs, Johnathan Ive and the Apple design team are among the few who have managed to carry Ram's exacting aesthetic rigour without compromising usability (Parson 2009, pp. 52-61). For example, G4 PowerBook, iPod and iPhone exhibit an aesthetic rigour akin to Rams' designs at Braun, with simple geometric lines like Rams'. Thus, it can be said that Rams' and Ive's aesthetic refinement approaches are the product of an evolving process of aesthetic forms, which can be seen as a means to a less subjective end. It is very rare for a designer to provide a fine product without any evolving aesthetic refinement process. However, it can be said that in terms of aesthetic styles, contemporary design forms have a tendency to rely on designer's intuitive and subjective artistic skills to make a final aesthetic decision, among a range of similar styles, rather than applying the golden ratio in order to examine which appearance of the design proportion would be the best for harmonizing manmade objects and the natural environment.

Whilst not all of Le Corbusier's works exhibited the deliberate use of geometry and the golden ratio, other works, such as Chaise Lounge (1929), Façade of the Arsenal of the Piraes (1931) and Villa Savoye (1931) were definite examples of deliberate and intentional application of the golden ratio. Le Corbusier published his book *'The Modulor'* in England in 1954, in which, he created a system of proportional measurement to solve communication problems among engineers, architects, craftsman and designers in Europe. His approach reconciled Euclidian geometry and Vitruvius human body measurement in order to establish dimensional standardisation and a system of proportional measurement. He illustrated biological and mathematical connections between architecture and geometry (Le Corbusier 1954, Ostwald 2001). However, the proportional system was a result of trying to solve his initial basic geometric mistake with his young collaborators, Hanning and Mlle Elisa Millard:

> *"To solve Le Corbusier's conundrum, Hanning started with the central (overlapping) square and then generated a golden section arc (from a diagonal of half the square) in one direction and another arc (form the diagonal of the full square) in the opposite direction. These arcs then generate two new contiguous squares which are also defined by a right-angle triangle with its right angle passing through the common boundary between the two newly-formed squares, the idea being that the resulting form can be used to create a series of golden section rectangles at the multiple scales; except that it doesn't work geometrically. The final "squares" generated by the golden section and the arc are rectangles not squares; they are very close to being square*

> *(sufficiently close to fool armature geometers) but are not equal-sided …"(Ostwald 2000, p.146)*

It appears that he focused on only the golden section and showed his limited mathematical knowledge in terms of applying geometry in the *Modulor*. He realised his mistake while consulting Millard's geometric solution with M. Montel, Dean of the Faculty of Science at the Sorbonne, otherwise he would have known that creating two golden section arcs from the central square is one of the methods of constructing a root 5 rectangle in geometry (Le Corbusier 1954, p.43). Le Corbusier faced criticism from both art critics and designers alike for a lack of practicality. Also for some reason, he used the height of an English policeman, i.e. roughly 1.82 meteres tall, as the basis for determining a man's height in '*The Modulor'* rather than the average height of a French man which was approximately 175cm. He also provided little in the way of explanation behind his reasons for regulating human body measurement thusly, yet he responded that:

> *"The reasoning is simple: the objectives manufactured on a world-wide scale with the aid of the 'Modulor' are to travel all over the globe, becoming the property of users of all race and all heights. Therefore it is right, and indeed imperative, to adopt the height of the tallest man (six feet), so that the manufactured articles should be capable of being employed by him this involved the largest architectural dimensions; but it is better that a measure should be too large than too small, so that the article made on the basis of that measure should be suitable for use by all." (Le Corbusier1954, p.63)*

It appears that the body measure he used, which was based on the English policeman, was purely arbitrary. A standard body measurement with a comfortable margin would have been more appropriate than his one example. Le Corbusier was also chastised by those who were of the opinion that use of geometry would restrict creativity, preventing artists and designers from sufficiently developing their imagination (McWhinnie 1986). If geometry and the golden ratio were to be a restriction to artistic creativity then these masterpieces for instance; Michelangelo's the Creator, Santa Maria del Fiore by Brunelleschi, the Sydney Opera House by Jørn Utzon and Pedestal Chair by Eero Saarinen, all of which conform to the golden ratio and root rectangles, would hardly be considered noteworthy works of art, let alone be considered masterpieces.

> *"Whether the golden ratio taps into some inherent aesthetic preference or is simply an early design technique turned tradition, there is no question as to its past and continued influence on design. Consider the golden ratio when it is not at the expense of other design objectives. Geometries of a design should not be contrived to create golden ratios, but golden ratios should be explored when other aspects of the design are not compromised."(Lidwell et al 2003, p.96)*

Despite this, Le Corbusier's mathematically based golden proportional system disappeared in his later designs (Padovan 2001). What Le Corbusier's research presents, is that perhaps it is very difficult to apply geometry in every aspect of design and it takes practice to master the geometric knowledge sufficiently in order to apply it to its fullest potential as a creative design principle. His latest designs from the 1950s, such as the chapel of Notre Dame Du Haut in France and Legislative Assembly in Chandigarh in India, were regarded as *"the last great works of architecture inspired and determined by a system of proportion."* (Padovan 2001, p.335). Despite criticism Le Corbusier's approach to his work was advanced in terms of design and also reflected a way to use golden ratio as an artistic feature to reconcile the artificial world and nature.

Matila Ghyka explained both the mathematics and the geometric construction of the concept of the golden proportion, in his book *'The Geometry of Art and Life'* (1977). It also showed geometric knowledge of root rectangles, other polygons and geometric shapes in three-dimensions, as well as the relationships between geometry and the logarithmic spiral in nature and its growth patterns. As Hambidge and Le Corbusier analysed ancient architecture, Ghyka discovered harmonic analysis of ancient Architecture and paintings while implementing Hambidge's 'Dynamic symmetry' and exploring geometric knowledge (see figure 2-12)

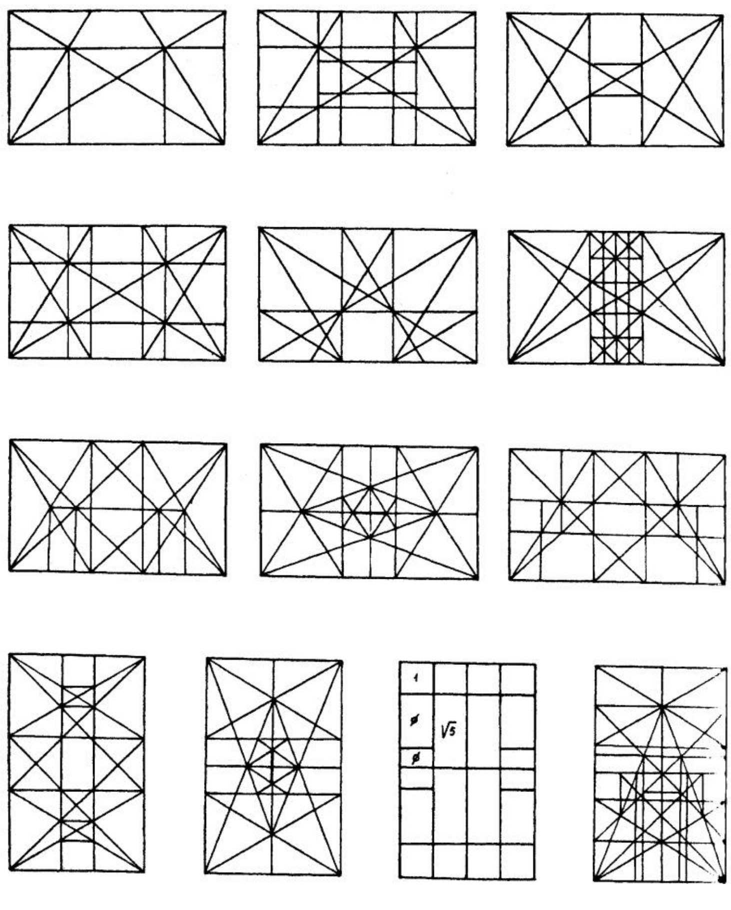


Figure 2-12 Harmonious subdivision patterns (Ghyka 1977, p.130)

He argued that *'most of modern cubists were blissfully ignorant of geometry of regular solids and corresponding interplay of proportions'* (Hambidge 1977, p.156). However, he criticised the "geometric feeling" of harmonious subdivisions in Seurat's paintings; Le Pont de Courbevoie (1886-1887), Parade (1887-1888) and Le Cirque (1891), all of which either intentionally or subconsciously manifested the use of golden proportion. He asserted that all the great periods of European Art were characterised by the use of harmonious geometric subdivision.

Gyorgy Doczi (1981) described geometry as a system that determines the form of both man-made and natural structures. Doczi's system of harmonic proportion analysis which he names 'Dingery', was derived from the golden proportion, the Fibonacci sequence and the forming process of natural patterns in nature. He discovered that not only were the golden proportion and root ratios embedded in ancient classic arts and architecture in Europe, but also represented in many more ancient masterpieces from virtually all other continents. He illustrated how harmonic proportion of the growth patterns were already appearing in modern architecture and design, such as Sydney Opera House and Boeing 747 (see figure 2-13). 'Dingery' was an example of quantifying forms in a mathematical manner based on the aesthetic principle of the golden proportion and it explained how the link between the mathematical number, 1.618 and geometric patterns in both nature and the man-made world, were equally measurable in terms of quantifying aesthetic beauty.

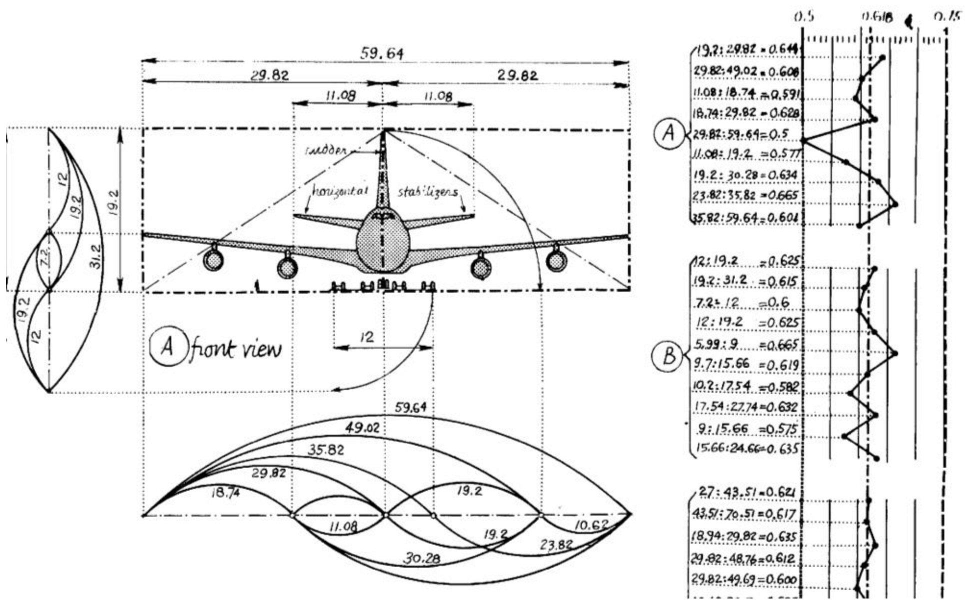


Figure 2-13 Boeing 747 (Doczi 1981, p.131)

Author (*'Sacred Geometry: Philosophy & Practice* (1982)) and researcher of geometry, Robert Lawlor, also approached geometry as practical knowledge to analyse the forms in nature and artificial designs. His research showed that a vast area of studies from astrology, numerology, religion, mathematics, biology, physics, philosophy, art and architecture are interlinked by geometry. He explained how ancient thinkers in places like Egypt, Greece, India and China recognized that geometry can unite nature and the manmade world. He claimed that ancient masterpieces were not only aesthetically pleasing, but also being designed based on the same geometric principles as nature, they are therefore an expression of the divine. Lawlor clearly saw geometry as being capable of harmonizing and bridging the gap between the diametrically opposed worlds of man-made things and nature.

More recently, Kimberly Elam in her book 'Geometry of Design' describes how geometry can be a useful tool for analyzing designs. Her choice of resources were fourteen different individual designers' works along with some designs by the German company Braun from the period between 1877 and 1997. There were a total of 26 graphic designs and product designs carefully analysed by applying the golden section rectangle, root rectangles, the golden section triangle and ellipse. For example, Elam used A.M Cassandre's L'intransigeant Poster from 1925 (see figure 2-14), in order to illustrate how artistic creativity had been expressed under consciously planned geometric composition, proportion and harmonious subdivisions. The visual format of the original poster shows a square inside of a root two rectangle with the face and neck organized inside of the square.

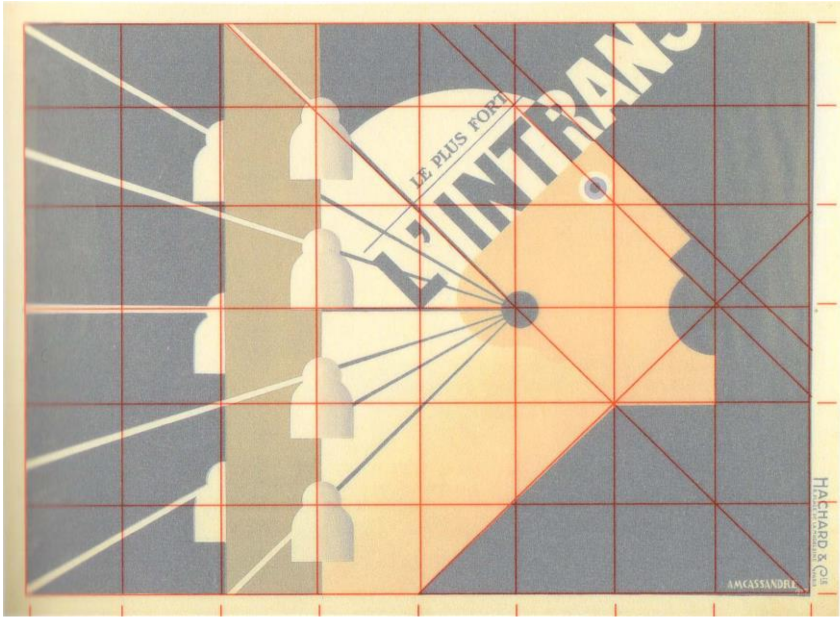


Figure 2-14. L'intransigeant poster (Elam 2001, p.51)

Thus, Elam's application of geometric analysis into modern graphic art and product design could help designers and students to recognize the harmonious construction of forms in design. Furthermore, geometric analysis is an example of adopting the 'thinking with your hands' approach (hands-on method) (Heimer 2008) in order to develop creativity at the same time. So it is difficult to see how the golden ratio and symmetry in design could be a limitation or a hindrance in terms of creativity:

> *"Geometric organization in and of itself does not yield the dynamic concept or inspiration. What it does offer to the creative idea is a process of composition, a means of interrelationship of form, and a method for achieving visual balance. It is a system of bringing the elements together into a cohesive whole."(Elam 2001, p.101)*

Although Elam illustrates the importance of geometric organization and proportion in both graphic and product designs, her examples of geometric analysis do not include guidance as to how designers could be able to design based upon the principle of gnomic growth and Fibonacci sequence, which are exhibited at the beginning of her book. Perhaps an oversight on her part, but perhaps it would have been appropriate to provide some examples which would help readers and designers to have a more practical understanding of the process, for example, how the Apple logo design clearly conforms to the Fibonacci principle (see figure 2-15A). It appears that the circle 8 is in the same proportion as the blue circles, ‘a’, ‘b’, ‘c’ and ‘d’ which are the curve shapes of the logo (see figure 2-15A). Circle number 5 (as marked in pink) is used for drawing curve lines of the logo’s bottom part and a circle 3 is proportionally located between circle 8 and circle 5 in the inner proportion of the logo (see figure 2-15B).

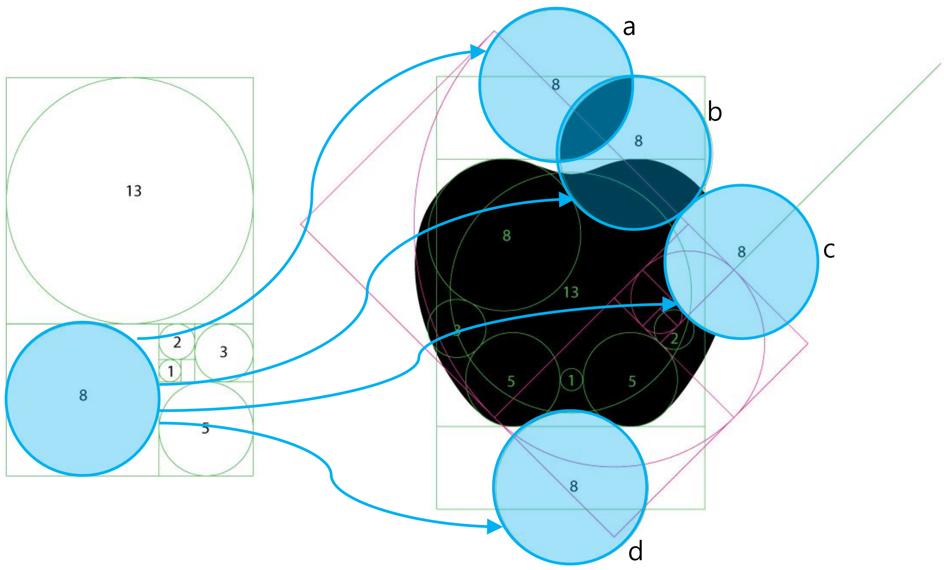


Figure 2-15A Fibonacci sequence in the Apple logo. (Downloaded from: https://dhs.stanford.edu/big-data/finding-fibonacci-apple/, accessed date:07/04/2012)

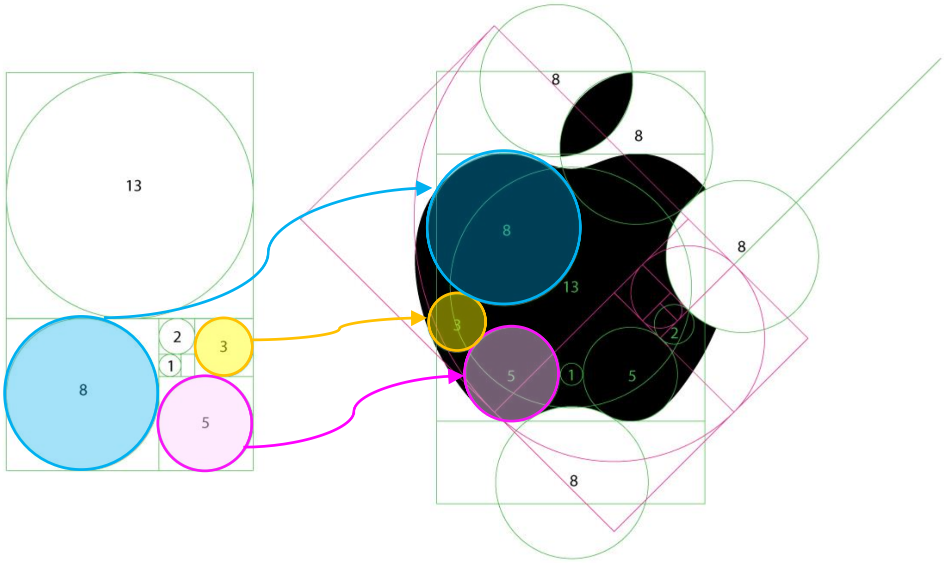


Figure 2-15B Fibonacci sequence in the Apple logo. (Downloaded from: https://dhs.stanford.edu/big-data/finding-fibonacci-apple/, accessed date: 07/04/2012)

She provides a clear explanation of Hambidge's *'Dynamic symmetry'*. According to her, the differences of 'Static symmetry' and 'Dynamic symmetry' can be explained with rational and irrational numbers. The former consists of static rectangles, which have ratios of simple fractions, such as ½, ⅔, ¾, etc. However, the later consists of dynamic rectangles which have a ratio of irrational fractions and an infinite number of digits, such as √2 (1.4142···), √3 (1.732···), √5 (2.236···) and Φ (1.618).

> *"static rectangles do not produce a series of visually pleasing ratios of surfaces when subdivided. The subdivisions are anticipated and regular without much variation. However, dynamic rectangles produce an endless amount of visually pleasing harmonic subdivisions and surface ratios when subdivided, because their ratios consist of irrational numbers."(Elam 2001, p.32).*

The subdivision of a static rectangle (1:2) (figure 2-16) does not show harmonious proportion compared with the golden section rectangle (figure 2-17) which is a dynamic rectangle. Elam illustrates only the construction of the harmonious subdivisions of dynamic rectangles which originated from Ghyka's works (see figure 2-12). It can be argued that there needs to be more visual references regarding the uses of dynamic subdivision into designs and what is the impact upon them when dynamic subdivision is applied.

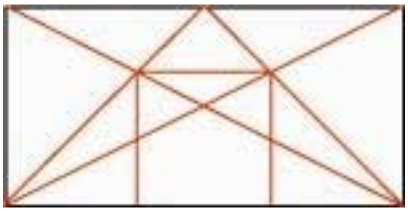


Figure 2-16. Static rectangle's subdivision

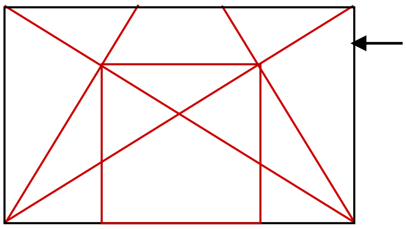


Figure 2-17. Dynamic rectangle's subdivision

For instance, figure 2-18A shows how the smart car modified to conforms to the golden proportion. The composition of the design parts can be analysed by using the harmonious dynamic subdivision which is applied on top of it. It seems that the part in the left top corner and the door handle are in the sky-blue diagonal. The fuel door and the door handle are designed on the yellow line and the rear wheel and side mirror are almost entirely composed on the green line (see figure 12-8B)

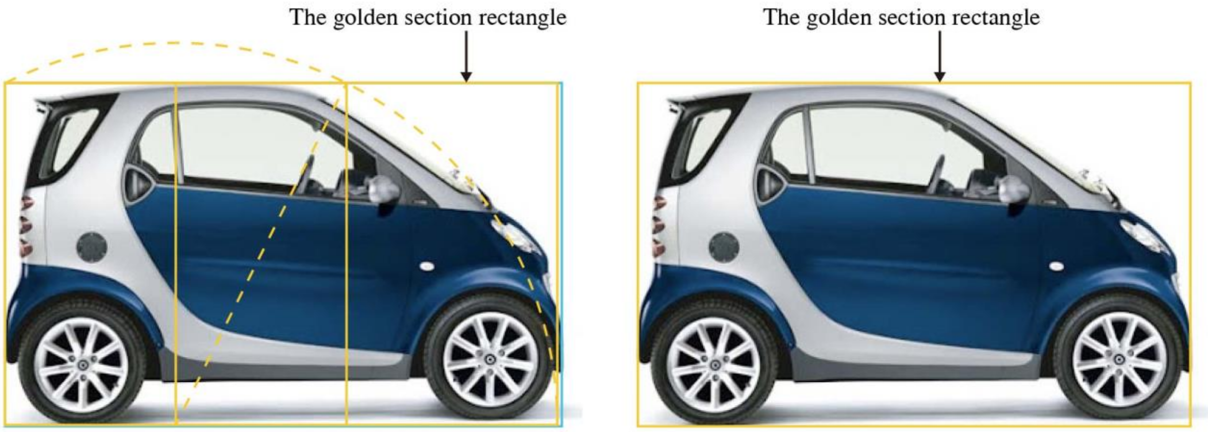


Figure 2-18A. The application of golden section rectangle
(Downloaded from: http://www.treehugger.com/cars/smart-car-how-smart-is-it.html, accessed date 23/09/2012)

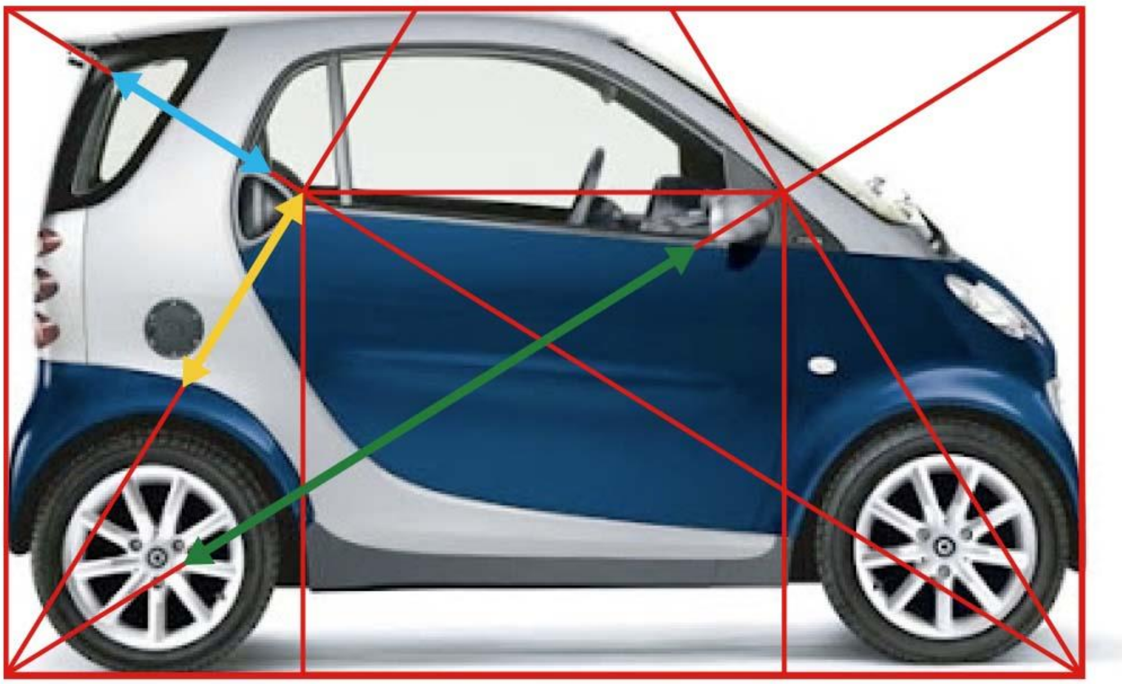


Figure 2-18B. The application of dynamic symmetry
(Downloaded from: http://www.treehugger.com/cars/smart-car-how-smart-is-it.html, accessed date 23/09/2012)

She concluded that learning geometry in design disciplines, geometry in mathematics and the arts have had a long relationship. Now however, these disciplines have become divorced to some degree and it is to the detriment of both areas of study.

> *"Architecture has some of the strongest educational ties to geometric organization because of the necessity for order and efficiency in construction, and the desire to create aesthetically pleasing structures. The same is not true of art and design. In many schools of art and design the study of geometric organization begins and ends with a discussion of the golden section relationship to the Parthenon in an art history course. This is due to in part to the separation of information that is a part of education. Biology geometry and art are taught as separate subjects. The content area of each that is congruent to the other is often neglected and the student is left to make the connections on their own. In addition, art and design are commonly viewed as intuitive endeavours and expressions of personal inspiration. Unfortunately, few educators will bring biology or geometry into the studio, or art and design into the science or math classroom. "(Elam 2002, p.101)*

It appears that few designers either consciously seek to apply geometry in their work or bother attempting to further understand the geometric implications. There are different forms of visual language used in different arenas, so in arts and design, in order to apply the golden ratio, designers need to learn the language of geometry. Moreover, it means not only knowing how to draw the golden ratio and how to apply it to artistic works, but also to be aware that the use of geometry provides a visual language for delivering effective design means and provides an explanation to viewers. Not to mention the fact that it is an ideal tool for helping designers understand and develop their own aesthetic style.

As previous examples of ancient arts works and modern designs illustrate, irrational emotion and innate thoughts can be effectively expressed via abstract geometric forms, the golden ratio and symmetry in art and design. The golden number, its irrational number and its incommensurable ratio in mathematics is regarded as a proportion of extraordinary beauty and the guiding principle of beauty in arts, architecture and design.

Elam's work is one of the few examples of an academic who implements geometric principles in design education. It seems that although there are resources in design which explain the notion of the golden proportion including examples where it appears in masterpieces, the golden ratio is still mainly known as a reference for early design technique turned into tradition and it has been approached as "Geometry of a design should not be contrived to create golden ratios, but golden ratio should be explored when other aspects of the design are not compromised" (Lidwell, Holden and Butler 2003, p.96). Thus, the resource used in this section do not provide enough support for research question a) to what degree are geometric principles used in design education and practice? It is necessary to explore the uses of geometric principles in design education and practice in future work.

2.6 DEVELOPED RESEARCH QUESTIONS

Examining the literature review suggests that geometry is the bridge for connecting art, science and design. Applying geometry at product design degree level is a way of considering and developing both the aesthetic principles and practicalities of geometry in product design. It does not mean geometry is the sole determining and defining factor when developing a product. But rather, implementing geometric principles in the design process can only be of help to design students enabling them to rethink visual composition and design proportion, and where necessary, to make form-giving decisions. Product design forms are abstract forms to be expressed through geometric principles accompanied by aesthetic 'logic'. This process may help design students to recognize how their aesthetic consciousness can evolve. It appears that geometric knowledge should be considered a valuable tool which can support aesthetic reasoning when analysing forms of product designs and for developing the creativity of design students.

Through the literature review the thesis' research questions are developed:

1. What is the value to designers of developing effective design tools based on knowledge of geometry and then applying them in product design education?
2. How can geometry be useful as a practical method in design for developing visual coherence?
3. What are the perceptions of design students regarding the implementation of geometric principles as a means to recognize their own level of visual knowledge?
4. How do professional designers consider applying geometric knowledge in their design process?
5. How frequently do geometric ratios and golden ratio appear in best consumer choice products and expert designers' designs?

2.7 CHAPTER SUMMARY

In this chapter the purpose of the literature review was presented to develop the basic research questions which were used to establish an empirical study.

As reviewed various related works the relationship between geometry in science, art and design could facilitate a deeper understanding of the man-made world and nature. It could be said that the golden ratio appears in nature and master pieces as well as in human body. The golden ratio and how it relates to aesthetic beauty is one of the core principles in how the golden ratio has been used effectively amongst cosmetic surgeons and dentists in order to examine the characteristics of facial beauty. Although the different views of psychologists regarding the aesthetic perception of the golden proportion. It is possible, however, that the various results of these experiments had much to do with the methods used and the difference in personality between psychology students and professional artists. There is little doubt that the golden proportion is an effective and aesthetically important proportion amongst artists, architects and designers. In addition, this chapter reviews the uses of geometric knowledge in the design field and how it is to be modernized for a more practical approach, emphasizing the aesthetic tools in order to analyse the design styles by designers themselves as a practical design skill. It seems that it is necessary for investigating how geometric knowledge and the golden ratio can be developed as an effective and practical method to explore. In what ways can this knowledge can support design students and professional designers when they may face uncertainty of making the aesthetic design decisions? Furthermore, throughout history the golden ratio has been considered most pleasing to the eye and frequently the golden ratio appeared in modern classic design and bestselling objects, what practical geometry has been embedded in from classic designs to everyday objects.

In chapter 3, traditional design research, methodologies, and how they helped to develop this thesis, will be discussed. The purpose of chapter 3 is to respond to research question 2 and illustrate the method of testing the hypothesis and the details of implementing geometric knowledge in product design education through a number of Geometry workshops. Chapter 3 contains the method of gathering data for the thesis and analytical procedures.

3. RESEARCH DESIGN & METHODOLOGY

3.1 CHAPTER PURPOSE

The purpose of this chapter is to introduce the philosophical assumptions underpinning this research. During the process of writing this thesis the author adopted the most appropriate methods for achieving the aims of this thesis. The methods used were each chosen to fulfil specific criteria for collecting data.

This thesis' research plan involves three components; firstly section 3.2 outlines philosophical worldviews on design. Section 3.3 addresses an appropriate approach this thesis should take and an overview of the research design, as well as its chosen methods. Section 3.4 presents how the data was gathered and section 3.5 describes the analytical process of this thesis. Ethical considerations are presented in section 3.6 and lastly the summary of the chapter is included in section 3.7.

3.2 PHILOSOPHICAL WORLDVIEWS

This section explores four different philosophical worldviews, each with different research roots, which helped to choose this thesis' research approach and methods used.

There are three major components in any research process; Ontology, epistemology and methodology. A research paradigm is an all-encompassing system of interrelated practice and thinking that defines the nature of research foundations along these three dimensions (Terre Blanche and Durrheim 1999). According to Ruddock :

> *"ontology and epistemology are significant in that they illustrate how research begins by outlining theoretical suppositions that are taken as given by the research. Ontology relates to how we understand the nature of reality… epistemology refers to a theory of knowledge. It is related to ontology in that the nature of reality you set out to explore influences the sort of knowledge that you can have of it…methodological implications follows. Observation, measurement and interpretation depend on the understanding of the*

ontological and epistemological nature of the work at hand" (2001, p.27)

Ontology is the science or theory of 'being' and is concerned with the question of how the world is built. It questions 'what is the nature of reality', whilst epistemology is *"a way of understanding and explaining how we know what we know"* (Crotty 1998, p.8) and explores what the relationship is between the researcher and that which is being researched (Creswell and Clark 2011, p.42).

Methodology is a systematic procedure to find information which is applied to a specific branch of knowledge and describes the techniques used to gather and analyse data in order to answer research questions or hypotheses.

In philosophy, classical empiricism and classical rationalism are two traditional views of human knowledge. The former sees the source of ultimate knowledge as a purely sensory experience. It was supported by Bacon (1620), Locke (1688), Berkeley (1710), Hume (1748) and Mill (1961). However, the later source of knowledge was the intellectual intuition of clear reason, and distinct ideas, as supported by philosophers such as Descartes (1637) Spinoza (1677) and Leibniz (1714). The birth of modern science and modern technology derive from this epistemological optimism and were supported by both Bacon and Descartes. It is said that each person gains the source of knowledge either through man's perception of careful observation, his or her use of powerful intellectual intuition which he or she may use to discern true knowledge from deceptions.

Karl Popper rejects classic empiricism and induction as a scientific method which he addressed with his view of an epistemological philosophy, termed 'Critical Rationalism', which means that knowledge can and should be rationally criticised. He replaced the term Critical Rationalism with 'The Theory of Falsification' and the widely known method of *'Conjecture and Refutation'.* Popper argued experiments can only provide scientific validation of a theory or hypothesis if they are falsifiable. This falsifiable approach is useful for exploring conjecture and helps to synthesize essential information. Rationally criticised knowledge is generated by the creative imagination in order to solve problems. Empiricism, objectivity and induction may be placed after the formulation of an explanatory conjecture. Popper's critical rationalism was brought into design research and it seems to have predominantly been adopted in the field of design science (Cross, Naughton & Walker 1981, p.196). This is perhaps that *"the process of forming an explanatory hypothesis [...] is the only logical operation which introduces any new idea"* (Peirce, Hartshorne and Weiss, 1998) and the nature of design involved in developing new artefacts. As Gregory noted: *"The scientific method is a pattern of problem-solving behaviour employed in finding out the nature of what exists, whereas the design method is a pattern of behaviour employed in inventing things of value which do not yet exist. Science is analytic; design is constructive"* (Gregory 1967, p. 323).

3.2.1 Three Epistemologies in Research

According to Crotty, there are three epistemologies in research: objectivism, constructionism and subjectivism (Crotty 1998, pp. 2-9) as his knowledge frameworks are illustrated in table 3-1.

Table 3-1 Crotty's knowledge frameworks.

Epistemology	Theoretical perspective	Methodology	Methods
Objectivism	Positivism Post-positivism	Experimental research Survey research *etc.*	Sampling Measurement and scaling Statistical analysis Questionnaire Focus group Interview *etc.*
Constructionism	Interpretivism • Symbolic Interactionism • Phenomenology • Hermeneutics Critical inquiry Feminism	Ethnography Phenomenological research Grounded theory Heuristic inquiry Action research Discourse analysis Feminist standpoint research *etc.*	Qualitative interview Observation • Participant • Non-participant Case study Life history Narrative Theme identification *etc.*
Subjectivism	Postmodernism Structuralism Post-structuralism	Discourse theory Archaeology Genealogy Deconstruction etc	Autoethnography Semiotics Literary analysis Pastiche Intertextuality *etc.*

Source from Crotty (1998, p.9)

Objectivism is the notion that a meaningful reality exists 'mind-independently', having real existence or carrying intrinsic meaning within them as objects. This objective truth can be discovered if it is gone about in the right way (ibid, pp. 2-9). Constructionism is the notion that meaning is formed through people's minds interacting with the world, which implies that people of diverse cultures or different time periods construct meaning in various ways, even in relation to the same phenomenon. Subjectivism maintains that meaning is influenced by our minds without the contribution of the world and there is no truth or meaning that exists independent of the mind.

Crotty's epistemologies were usefully related to the theory of design and design practice. In general, design research questions the relationship between what designers do and what designers know (Feast and Melles 2010). The objectivist position was presented by Ken Friedman, he framed the conditions for theory construction in design (2003). He claimed *"Critical thinking and systemic inquiry form the foundation of theory. Research offers us the tools that allow critical thinking and systemic inquiry to bring answers out of the field of action. It is theory, and the models that theory provides, through which we link what we know to what we do"* (2003, p.512). Thus, he rejected both tacit knowledge and reflective practice as the construction theory in design research. For him developing a theory of design needs to be a robust and sophisticated system for generating knowledge through tacit knowledge into explicit knowledge. The subjectivist position was presented by Christopher Frayling's model for research of art and design (1993). He claimed that there are a lot of common similarities between scientific research and the works of art and design from history, when artists worked in a cognitive and rather expressive manner, such as Leonardo Da Vinci with his drawings of the human anatomy, George Stubbs's animal anatomy paintings. However, he rejected the objectivity and associated research in art and design as personal, practice-based, subjective knowledge. The constructionist position was illustrated by Donald Schön and Nigel Cross. Schön brought Popper's critical rationalism into the heart of the understanding of professional knowledge and constructionist epistemology. He suggested that in the process of learning and acting, practitioners are pre-occupied with a kind of reflection on their pattern of action, on the situations in which they are performing and on the know-how implicit in their performance'. This approach influenced researcher Nigel Cross, in the field of 'design thinking research'. Cross explained 'Designerly ways of knowing' as *"The aim of studying outstanding designers to gain knowledge of design activity at the highest levels at which it is practised. This knowledge might enable us to transfer and diffuse* *'best practice' more widely across the design professions, thus raising general levels of performance."* (2001, p.50)

3.2.2 Four Philosophical Worldviews

There are four most common philosophical worldviews suggested by Creswell and Clark (2011) for designing research. As table 3-2 illustrates, each worldview has its own characteristic ontology, epistemology and methodology.

Table 3-2 Three Elements of Worldviews and Implications for Research Practice

Worldview Element	Post-positivism	Constructivism	Participatory	Pragmatism
Ontology (what is the nature of reality?)	Singular reality (e.g., researchers reject or fail to reject hypotheses)	Multiple realities (e.g., researchers provide quotes to illustrate different perspectives)	Political reality (e.g., findings are negotiated with participants)	Singular and multiple realties(e.g., researchers test hypotheses and provide multiple perspectives)
Epistemology (What is the relationship between the researcher and that being researched?)	Distance and impartiality (e.g., researchers objectively collect data on instruments)	Closeness (e.g., researchers visit participants at their sites to collect data)	Collaboration (e.g., researchers actively involve participants as collaborators)	Practicality (e.g., researchers collect data by "what works" to address research question)
Methodology (what is the process of research?)	Deductive (e.g., researchers test an a priori theory)	Inductive (e.g., researchers start with participants' views and build "up" to patterns, theories and generalizations)	Participatory (e.g., researchers involve participants in all stages of the research and engage in cyclical reviews of results)	Combining (e.g., researchers collect both quantitative and qualitative data and mix them)

Source from Creswell and Clark (2011, p.42)

Post-positivism is often associated with quantitative approaches. Researchers often claim that knowledge is based on a) determinism, cause and effect thinking; b) reductionism via narrowing information from variable to interrelated; c) detailed observation and measures of variables; d) testing theories or hypotheses that are continually refined (Slife and Williams, 1995).

Constructivism is associated with qualitative approaches. The meaning of the world is constructed through participants' subjective worldview. The participants provide their understanding. They speak from meaning shaped by social interaction with others which form their own personal histories. Participatory worldviews are influenced by political concerns in order to bring changes into practice, and this is often associated with qualitative approaches rather than quantitative approaches. This view is used for improving our society. Researchers engage with participants as active collaborators in their enquiries. Pragmatism does not determine one system of philosophy, and reality and is concerned with 'what works' in practice. Pragmatists use multiple methods, different assumptions and different methods of data collection and analysis. Thus, researchers, Tashakkori and Teddlie (1998), Morgan (2007) and Creswell (2008) were concerned for the application of what works when solving research problems, and using all methods rather than focusing on research method alone. As Creswell (2008) suggests, pragmatism is the best philosophical worldview for adopting a mixed methods approach, this is the most suitable philosophical world view for this thesis because the main focus of this research is to develop effective and practical design tools for use in real design practice.

3.3 MIXED METHODS APPROACH

A quantitative approach is often associated with the epistemology of classic empiricism, positivism, post-positivism or critical rationalism. It appears that the knowledge of science gathers data under logical experimentation via experiences. Thus, a quantitative approach can be applied, usually starting with testing a hypothesis and a questionnaire as a quantitative strategy. Social science research however, is based largely on a qualitative approach in order to understand and explain why people have different experiences, and to understand the constructions and meanings through experience. Thus, the qualitative approach is associated with interviews, and observation can be considered to be a qualitative technique. The best approach for design research is associated with both science and social science research methodologies. Visual materials, such as, visual diaries, photos and films are often used in design research as ways of answering research questions, with visual culture of social conditions, and effects of visual objects, presented in these materials (Rose 2007).

The context of this thesis considers developing effective design methods. It includes testing professional designer's aesthetic perceptions regarding the golden ratio and hypothesizes the implementation of the golden proportion in the participants own designs. It explores the author's geometric refinement tools and evaluates how practical geometric knowledge can be systematically codified through professional designers' perspectives. It also examines how geometry and specifically the golden proportion have been embedded in both modern classic designs and bestselling products. The aim of this thesis is to establish practical geometry as a tool for increasing a designer's own "knowing" while providing critical rationalisation and systematic procedure. This thesis also derived from the concept that designer's subjective aesthetic knowledge can be transformed via geometry to develop objective reasoning in the practical design process. Thus, the mixed research approach is the most appropriate approach to adopt in order to explore the premise of this thesis as seen in figure 3-1. In this thesis design knowledge of practical geometry is approached through post-positivist, critical rationalism and the design epistemology which shaped the investigation of how designer's knowledge of geometry and their instinctual application of applying practical geometry in design practice.

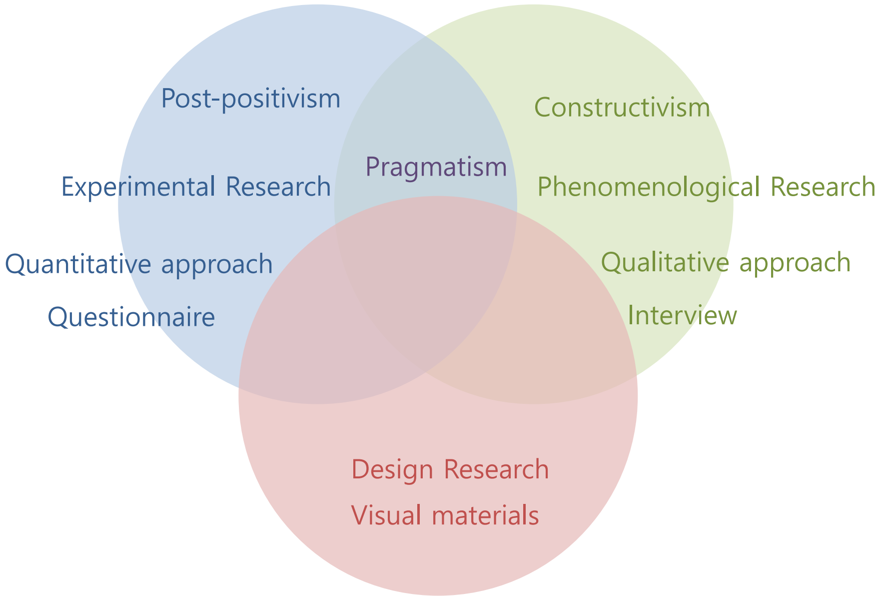


Figure 3-1 The thesis' mixed research approaches

Therefore, this thesis' philosophical view was, in part, derived from the epistemological philosophy of understanding how design students and professional designers come to know what they know, and how can that process be facilitated. This research considers implementing both geometry as knowledge, and as a practical method to support designers when the need arises to rationally criticize the aesthetics of their own design.

Thus, this thesis explores how geometric knowledge can improve the aesthetics of designs while providing a method of codifying the elusive creative reasoning process when designing forms. An individual designer's knowledge can be articulated, and implemented geometry as practical knowledge identifying their style via their own aesthetic knowledge being rationally articulated via geometric forms.

Unfortunately the participants' ability to apply geometric knowledge is still at the entry level rather than the expert level of geometry application. This may be due to the fact that geometry in design education has not been utilized as well as perhaps it could have been. As it tends to be thought that of as merely an aesthetic guideline: its potential benefit to designers as a practical design method or theory gets over looked.

Geometry workshops tested the hypotheses of this thesis and used both open and closed-questions in questionnaires, as the appropriate research method for obtaining data and thesis content. This data will help achieve a greater understanding of how geometry is used in the design process. Different methods used in science and social science, were reviewed as well as some specific methods used by design researchers.

This thesis is likely to be collecting numerical data in reasonably large quantities (30 subjects or more) to more broadly explore the participating design students and professional designers' perception of using geometric knowledge gained. In addition, qualitative data also will be gathered through Geometry workshops and interviews examining their reaction to the golden ratio and other practical geometric ratios. Both quantitative and qualitative research data will be more appropriate for this research as a 'mixed method' seems the best choice of procedure for collecting both qualitative and quantitative data, in order to understand a research problem more completely (Creswell, 2002).

3.4 RESEARCH DESIGN

This section outlines a strategy for answering research questions. One of the most popular mixed methods designs in educational research, "sequential explanatory mixed methods" design will be adopted for this thesis (Creswell 2002). This thesis consists of three distinct steps in order to respond to research question 3, 4 and 5 respectively:

- Step 1 is the experimental procedure of testing hypotheses.
- Step 2 contains the experiment with the author's geometric refinement tools with professional designers.
- Step 3 is a geometric analysis of popular consumer choice products and expert designers' designs (modern classics).

In step1, two questionnaires will be used as part of the quantitative approach as well as a visual assignment involving analysis of the students' designs. This data will be collected at the 'Geometry workshops'. In general, a workshop is used as one of the methods of participatory action research and is defined thusly: *'as usually a brief, intensive educational program, relatively a small group of people in a given field that emphasizes participants in problem solving efforts.'*(Steinert 1992). This educational method provides effective learning experiences for students in the class room and also may offer an opportunity to encourage students to generate creativity or discover new ideas.

Thus, workshops will be an appropriate approach for implementing new knowledge or theory in order for participants to explore its practicality. The data collection will provide a response to research question 2, *'How can geometry be useful as a practical method in design for developing visual coherence?'* and research question 3, '*What are the perceptions of design students regarding the implementation of geometric principles as a means to recognize their own level of visual knowledge?'*

The aim of step 1 is to identify potential and useful geometric knowledge which can be used for developing the author's refinement tools. In step 2, quantitative and qualitative data gathered will be used through individual semi-structured interviews and questionnaires, as well as visual materials, to help explain why certain external and internal factors through the professional views, obtained in the first step, may be significant predictors of the potential success of implementing geometry in the design process, providing evaluation through the professional designers' views in order to respond to research question 4, *'How do professional designers consider applying geometric knowledge in their design process?'* Step 3 will be used for collecting quantitative data through examining the proportions of product designs, which responds to research question 5, *'How frequently do geometric ratios and golden ratio appear in best consumer choice products and expert designers' designs?'* This last process, to explain the distinctive features of masterpieces, can be highlighted through geometric proportion used in modern designs. All three steps will use visual materials for the purpose of hypothesis, interview questions and collecting quantitative data. The visual model of the procedures for the sequential explanatory mixed methods design of this thesis is presented in figure 3-2. The majority of design research in this thesis came about through the quantitative methods, because the qualitative research presents the major aspect of data collection and refines the participants' views which focus on in-depth explanation of quantitative results.

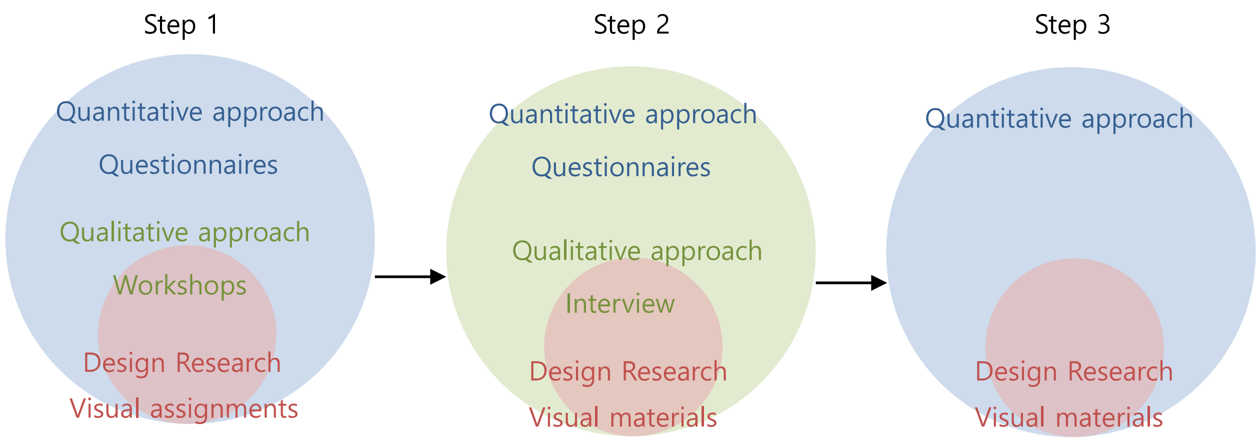


Figure 3-2 The thesis' explanatory sequential research design

3.5 DATA COLLECTION & ANALYSIS

Thesis' data will be collected from three different sources, employed individually, for research purposes to explain the rational choice of specific techniques and data analysis. Triangulation techniques will be used in data collection. '*Data triangulation*' is the use of a research design which involves various data sources to explore the same phenomena. Data can be collected from different comparison groups, or different points in time, or from a range of settings. Ultimately a triangulated study has the potential to achieve in-depth understanding and completeness, if triangulation is approached less as a strategy for confirmation (Arksey and Knight 1999).

- The three process used for collecting data:
    1) Geometry workshop: Two groups of design students
    2) Semi-structured interview: Five professional designers
    3) Visual analysis : Visual materials of artifacts

3.5.1 'Geometry workshop' will be designed for gathering quantitative and qualitative data regarding aesthetic perceptions of various proportions of shapes and at the same time testing the hypothesis for the effectiveness of implementing learned geometric knowledge into their own designs. This workshop method will provide an introductory practice for implementing practical geometric knowledge and its perception. The participants will be required to complete questionnaires and visual assignments. The details of the workshop procedure will be presented in Chapter 4.

a) Paper self-completion questionnaires will be designed to be completed by both design students and professional designers. The questionnaires will ask only one piece of information at a time, using concise sentences. Questions must be carefully designed to yield valid information and must be worded appropriately, intelligently, precisely, they must be relevant and unbiased (Leung 2001). The advantages of using this method are numerous and can include the use of descriptive materials, such as written description, pictures of new ideas and products or ideas. The participants will have time to read and digest these materials before giving their responses and they have time to consider their answer. Yet in this thesis, there will be a definite disadvantage in using this method of data collection as the participants will have limited time in which to consider their answers. Added to which, the geometry workshops will be under the author's supervision.

b) Visual assignments will be designed to test the hypotheses of the students. During the geometry workshops, the participants will learn basic practical geometry and use it to refine their own designs. Thereby the students get to use their own designs as visual materials for the implementation of their newly acquired geometric knowledge. Thus, visual assignments will combine images of their designs, the details of the process of analysing designs and an explanation of their own thoughts on geometry as a practical design tool which 'measures' aesthetic processes, which is valuable for communicating their rational findings to an audience. The author will be able to collect in-depth data which can be articulated via the participant's own interpretation.

3.5.2 Semi-structured interview is considered the most common and most diverse of the three forms; structured, semi-structured and unstructured. Semi-structured form is designed for following a specific plan and will have pre-designed questions beforehand. Therefore, the interviews are partially structured through the interview guidelines, which consists of key questions. Interviewers are free to follow-up ideas, probe responses and ask for clarification or further elaboration if necessary (Arksey and Knight 1999). The interview questions will focus on gathering data on the perception of applying practical geometric knowledge to improve design style. 'Scaling' will be used for the questions in order to clarify responses and to accommodate the participants who do not have strong views regarding the questions asked.

The interviewed professional designers are as follows:

Mr. Paul Davey.

CEO of MK Windsurfing
http://www.mkwindsurfing.co.uk/
Experiences: over 20 years

Mr. George Diamantidis
Designer –Brighton wave
http://www.brightwave.co.uk/
Experiences: over 5 years

Mr. Owen Evans
Director– Furnace design
http://furnacedesign.co.uk/
Experiences: over 15 years

Mr. Max Lilley
Designer–Sussex Innovation Centre
http://www.sinc.co.uk/home/index.html
Experiences: over 5 years

Ms. Claire Potter
Lead designer and founder of Claire Potter Design
http://clairepotterdesign.com/index.html
Experiences: over 15 years

Five professional designers participated in the implementation of geometric knowledge into their own designs. Four of the five designers obtained their undergraduate degree in England and one designer graduated in Greece. Although the participating designer's education background are in product design, all of them are experienced in designing both product designs and graphic designs. Moreover, this thesis will focus on refining the aesthetics in designs without trying to provide better functional solutions by adjusting form or researching how components could be fixed. Thus, interviewees require experience of developing products and the visual knowledge which any professional designers would have used for refining the aesthetics of their own designs. The reliability of small groups of subjects was discussed by researchers who found that tests using only five subjects are sufficient, in usability testing terms, to eighty percent of usability problems that maybe encountered (Faulkner 2003, Nielsen 2000). The author is certain that these experienced designers will be able to find any glitches when implementing the author's refinement tools and using practical geometric knowledge in their design process. The primary concern is what qualifies them to be considered 'professional designers'. Their experience is taken into consideration for this matter, and all participants were experienced designers who had been practising professionally for at least 5 years. The semi-structured interviews will take place between October 2012 to January 2013. The duration of the interviews is about an hour and all are audio-recorded, with the transcription confirmed by all participants involved. The details of applying the author's refinements tools, interview questions, and the transcription of the interview will be displayed in Chapter 5.

3.5.3 Visual materials: In this thesis, there are two types of visual materials used, 1) *'Phaidon Design Classics'*. 2) items sold via Amazon.com online retailer. In total 200 visual images will be used for collecting data and analysed geometrically. *'Phaidon Design Classics'* (3 volume set) was published by one of the world's leading publishers of books in visual arts, Phaidon Press in 2006. In this thesis, volume three includes three hundred and thirty three designs selected by a group of design experts at Phaidon press. The features of design classics are to be considered of a superior level, such as quality of execution, enduring qualities and restraint (Hill 2006). The selected designs of '*Phaidon Design Classics'* certainly meets these considerations and so one hundred product designs were chosen from volume three, the most recent designs being between 1980 and 2004. They will be used as visual materials for data collection and the process of geometric analysis i.e. the application of the author's refinement tools will be illustrated in chapter 6. One hundred bestselling items in March 2013 according to the world's largest online retailer, Amazon.com will be used. These items are representative of the largest number of everyday objects sold. The lists of Amazon bestselling items presents a good indication of how well a product sold and is not necessarily an indicator of quality. Yet it presents more recently updated information regarding consumer choices and regarding what items most stand out in their category. Two different groups categories of design will be used to contrast how and if the golden ratio, and other geometric ratios, are embedded in superior modern design classics chosen by the experts, with the geometric ratios of bestselling items which represent everyday objects chosen by ordinary people.

3.5.4 Analysis methods

The purpose of data analysis is to search for patterns in data and for ideas which help explain why those patterns are there in the first place. Interpreting data is done by finding patterns (Bernard 2000). There will be two types of analysis used in this thesis, geometric analysis and descriptive analysis. The former will be employed for analysing the participants' design works and visual materials. The latter, descriptive statistical analysis will be used for presenting the main features of data, in a numeric and visually simple to understand graph. This thesis investigates the deeper understanding of professional designers and design students and the more practical aspects of applying geometric knowledge. The findings will be reported in the form of a discussion and will provide information in percentages as to how much variance is accounted for via Chi-squared test analysis for the statistical significance and probability (or p value). All statistical analysis of the quantitative results will be conducted with the Excel software, version windows 2007.

3.6 ETHICAL CONSIDERATIONS

Ethical problems will also be addressed in the study. The data gathered from both the design students and five professional designers in the context of this thesis does not fail in the sensitivity category, and all participants (the subject population) are over eighteen years old. This thesis' experiments would not reasonably be expected to distress or harm the design students and was conducted in a classroom setting. They were informed as to the nature of this thesis' experiment in advance and all data gathered from the participating students will be anonymous and therefore informed consent can be skipped. Moreover, the professional designers were informed of the purpose of the research, the duration and all procedures before completing the questionnaires and interview questions. All the participants' confidential information will only be used for this thesis and there will be no exchanging of information and gathered data with any other entity.

All data including visual material of designs was provided by both design students and the professional designers. Both groups agreed to use their designs for this research prior to the research commencing. The questionnaires, the visual assignments, the professional designers' designs, interview tapes and transcripts will be kept carefully for at least five years. The designers have agreed and confirmed that their interview scripts and their designs could be used for this thesis. The designer's consent forms, all questionnaires used and interview scripts are attached in this thesis' appendix. A geometric analysis of both modern classic designs and bestselling items is also shown in the appendix.

3.7 CHAPTER SUMMARY

The philosophical standpoint of this thesis is based on various worldviews, post-positivists' critical rationalism and constructivism. Pragmatism is included in these various views and the nature of this thesis takes three different approaches, science, social-science and design research. Thus, pragmatism is the most appropriate world view for this thesis. The experimental exploration in the present study adopts a mixed-methods approach for examining the practical geometric knowledge and its perceptions of the participants. Also, 'geometry of proportions' both classic and bestselling designed items were measured. Data collecting procedures consisted of three steps: Geometry workshops, semi-structured interviews and visual analyses of the selected designs. The details of data collection procedures and the methods will be presented in Chapter, 4, 5 and 6.

4. TESTING HYPOTHESES

4.1 CHAPTER PURPOSE

The purpose of this chapter is to provide a logical response to the research questions which are central to this thesis. *"How can geometry be useful as a practical method in design for developing visual coherence?"* and also *"What are the perceptions of design students regarding the implementation of geometric principles as a means to recognize their own level of visual knowledge?"* It also illustrates how geometric relationships can be implemented in design practice as a tool for analysing design appearances. The aims of using a 'Geometry workshop' was to demonstrate how practical geometry can be an effective design tool for improving the aesthetics of artefacts and also in turn, provide designers with the means to demonstrate their rational design decisions during the design process. It then goes on to test three hypotheses which examine the sense of design proportion in design students and how it can be evaluated through gained geometric knowledge via the Geometry workshop.

4.2 METHODS

In this chapter the two methods used for obtaining data were a questionnaire and visual assignments. Questionnaires are one of the most effective methods of gaining information because straight forward questions can almost immediately provide useful data for analysis. Thus questions are employed as a tool to gather overall information about the views on the golden proportion and frequently used geometric shapes. For the participants, there were various visual assignments, such as creating a poster, photo essays and keeping visual diaries. The idea of keeping visual diaries, however, was abandoned as, in practice, it proved somewhat difficult to encourage the students to devote the requisite time and effort into a voluntary, extra-curricular activity that was not part of their course, and therefore did not contribute to their final mark. Thus, the specific concept of visual assignments was introduced to the participants in order to manifest how they implemented geometric analysis rationally in their designs and because it appeared to be a useful way to record their approach and create effective visual communication.

4.3 GEOMETRY WORKSHOPS

Geometry workshops were carried out in the Creativity Zone at the University of Brighton and in the Design Studio at the University of Sussex in England as well as in the Design studios of the second and third year student's at the Cheon Buck National University in South Korea twice between 2011 and 2012 for two hours each, with each workshop being, two hours in duration. The product design students in U.K and industrial design students in South Korea were recruited to test the application of geometric knowledge because they had at least more than one year of working on their own design projects which could be used in the workshops immediately. In terms of artistic skills, the Industrial design students in South Korea trained basic design skills in the first year, such as 'design depicting', 'design representing techniques', 'design drafting' and 'modelling'. However, both the product design courses in U.K. focused on the integration of technology into products, such as 'materials and manufacturing process', 'mathematics for product design', 'principles of engineering design' and had trained less in the basic design skills compared with the students in South Korea. Thus, it seemed to appropriate to gather data from students who had different skills and strengths to see how effective a tool geometric knowledge would be.

For the workshops, a group of sixty three, second and third year BSc Product Design students (1/3rd female and 2/3rd male), who study at the University of Brighton and the University of Sussex. The students from Cheon Buck National University in South Korea

BA Industrial Design students (2/3rd female and 1/3rd male) to analyse their own designs using geometry and the golden ratio. The geometry workshop explored ways to expand creativity through a series of exercises, including learning how to use and apply the golden ratio and geometric analysis. This workshop aimed to show students how to be able to apply geometry to their own designs naturally in order to develop visual coherence through geometry practices and to help design students to communicate effectively – and where necessary – to support design decisions with rational explanation. Ultimately each design practitioner will be able to find their own way towards using geometry as a design tool for stimulating their artistic skills, creativity and sensitivity.

- **The workshop process had three steps:**

1) Completing questionnaire: the purpose of the questionnaire is used the data to investigate the students' awareness of the golden ratio and visual preference of proportions. The participants were encouraged to complete the questionnaire as quickly as possible by themselves.
2) Learning geometry and using geometry for analysis: the participants were introduced the concept of geometry and the golden ratio before being asked to learn and implement geometric knowledge into their own designs.
3) Reviewing assignments and discussion regarding the pros and cons of implementing geometry into their own design: The last process examines how design students would perceive the use of geometry and geometric analysis as effective design rules.

4.3.1 QUESTIONNAIRE

All participants were introduced to the purpose of the Geometry workshop, and were told that they needed to complete three exercises and the visual assignments before filling in a questionnaire

- Question 1 – Asked students whether they were familiar with the 'Golden section', the 'Golden ratio', the 'Golden mean', the 'Golden number' or the 'Divine proportion' (all terms refer to the same concept).
- Question 2 – Asked students for the specific numerical ratio or value of the 'golden section'.
- Question 3 – Was a test asking students to choose a favourite from 'A' to 'F' (see figure 4-1). 'C' was the only option which conformed to the golden Ratio. None of the students were aware of which of rectangle was the golden section rectangle.

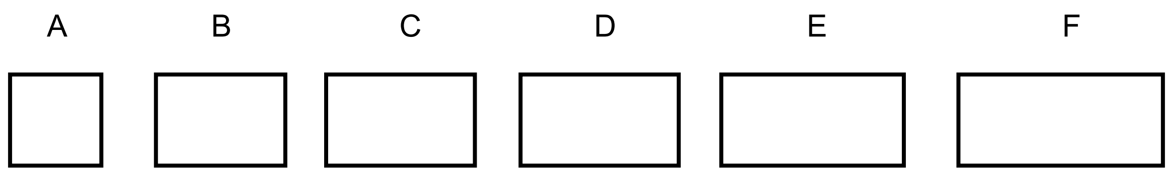
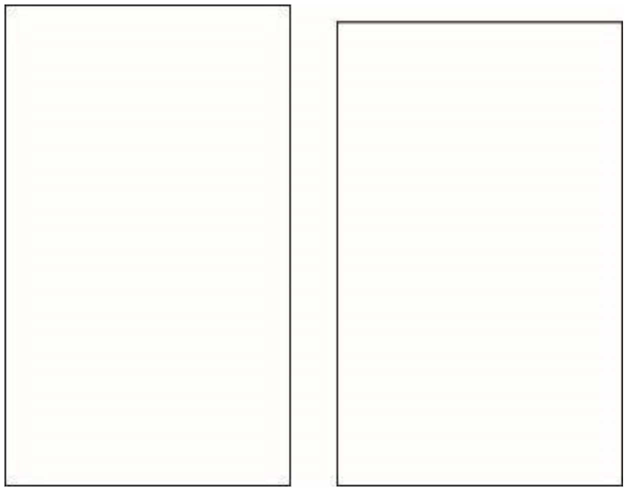


Figure 4-1. Question 3

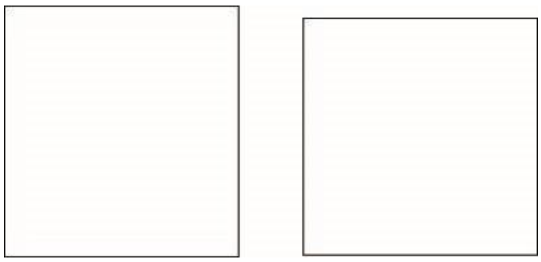
- Question 4 – students were asked to choose their favourite rectangle between 'A' or 'B'. Rectangle 'A' is the same ratio as the iPod classic (1.67) and 'B' is a rectangle constructed from rectangle 'A' which has been modified to conform to golden ratio proportions (1.618) (see figure 4-2).



A B

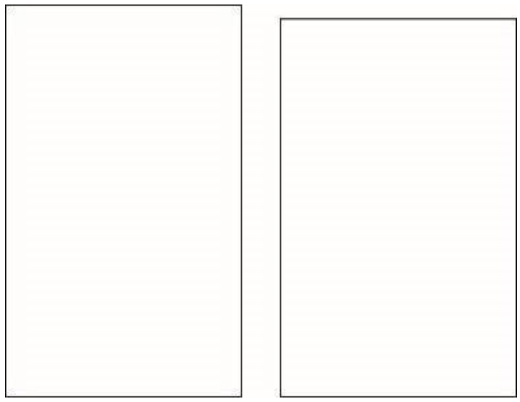
Figure 4-2. Question 4

- Questions 5, 6 and 7 – students were asked to choose their favourite rectangle between ‘A’ or ‘B’ (similar to question 4). An effort was made to keep the difference in ratio between rectangles equal throughout all question 5, 6, 7. i.e. Question 5, ‘A’ is a rectangle with a ratio of 1.052 (see figure 4-3) and ‘B’ is a square; Question 6, ‘A’ is a rectangle with a ratio of 1.784 (see figure 4-4) and ‘B’ is a √3 rectangle and Question 7, ‘A’ is a rectangle with a ratio of 2.288 (see figure 4-5) and ‘B’ is a √5 rectangle.



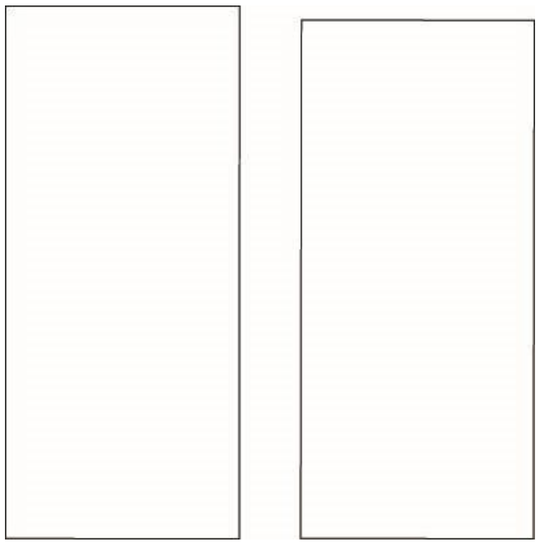
A B

Figure 4-3. Question 5



A B

Figure 4-4. Question 6



A B

Figure 4-5. Question 7

4.3.2 RESULTS

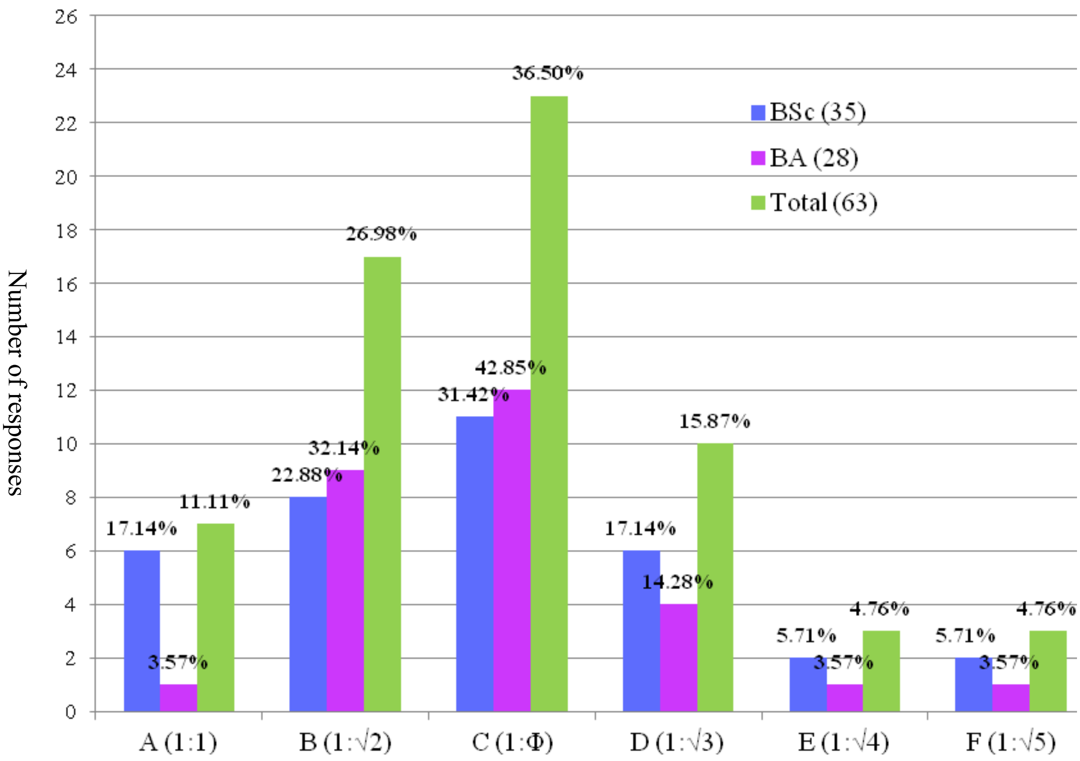
All sixty three students (who study BSc Product design at the University of Brighton and the University of Sussex in England and BA Industrial design at Cheon Buck National University in South Korea) completed the questionnaire regarding geometry and the golden ratio. Although the majority 80.95% (51) of students, were familiar with the concept of the golden ratio, only twelve students (19%) knew the actual numerical value of the golden ratio, ('1.618') and twelve students (19%) had no prior knowledge of the concept whatsoever. From data collected in question 3 it appears that the golden section rectangle was the most attractive geometric shape amongst participants in both groups and their second favourite choice was the √2 rectangle (see table 4-1).

Table 4-1 the results of question 3

	BSc Students (U.K.)	BA Students (South Korea)	Students preferred choice
A (1:1)	6 (17.14%)	1 (3.57%)	7 (11.11%)
B (1:√2)	8 (22.88%)	9 (32.14%)	17 (26.98%)
C (1:Φ)	11 (31.42%)	12 (42.85%)	23 (36.50%)
D (1:√3)	6 (17.14%)	4 (14.28%)	10 (15.87%)
E (1:√4)	2 (5.71%)	1 (3.57%)	3 (4.76%)
F (1:√5)	2 (5.71%)	1 (3.57%)	3 (4.76%)
Total number of students	35	28	63

However, rectangles, 'A', 'E' and 'F' were chosen as the least favourite by one of the BA students (3.57%). The least favourite choices of the BSc students were rectangles 'E' and 'F', chosen by two students (5.71%) (see chart 4-1).

Chart 4-1 the results of question 3



Chi-square (often written x^2) is calculated to test whether the distribution of a series of counts is likely to be a chance occurrence or not and '*p*-value' is the figure given to indicate the probability of any deviation from the expected results being due to chance. The formula $x^2 = \Sigma \frac{(O-E)^2}{E}$ was used to obtain the *p*-value. This *p*-value is called the '0*.05(5%) level of significance'* (Russell Bernard 2000, p 530). A *p*-value of 0.01 is usually considered statistically *'very significant'* and 0.001 is often labelled *'highly significant'*. The x^2 result of question 3 is calculated as follows: $x^2(5, N= 63) = 4.01$, *p*-value= 0.54, which means that the *p*-value for x^2, in this case, is 0.54. This would mean there is a 54% chance that the difference between the data sets is due to chance.

The result of question 4, shown in chart 4-2 is that a higher number of students - fifty four of sixty three (85.71%) - chose the golden section rectangle and a drastically smaller figure of nine students (14.28%) chose the rectangle that does not conform to golden ratio principles. This is an important result as one would have expected a much more equal division of choice considering there was no pronounced difference between the sizes of both rectangle options. Also the chi-square for the results of question 4 is 0.07, with the *p*-value for x^2 being 0.78 ($x^2(1, N = 63) = 0.07$, *p*-value = 0.78). Meaning that if this particular test was completed a thousand times, the distribution of results could be expected to match the results of this test about 78% of the time.

Chart 4-2 the results of question 4, 5, 6 & 7

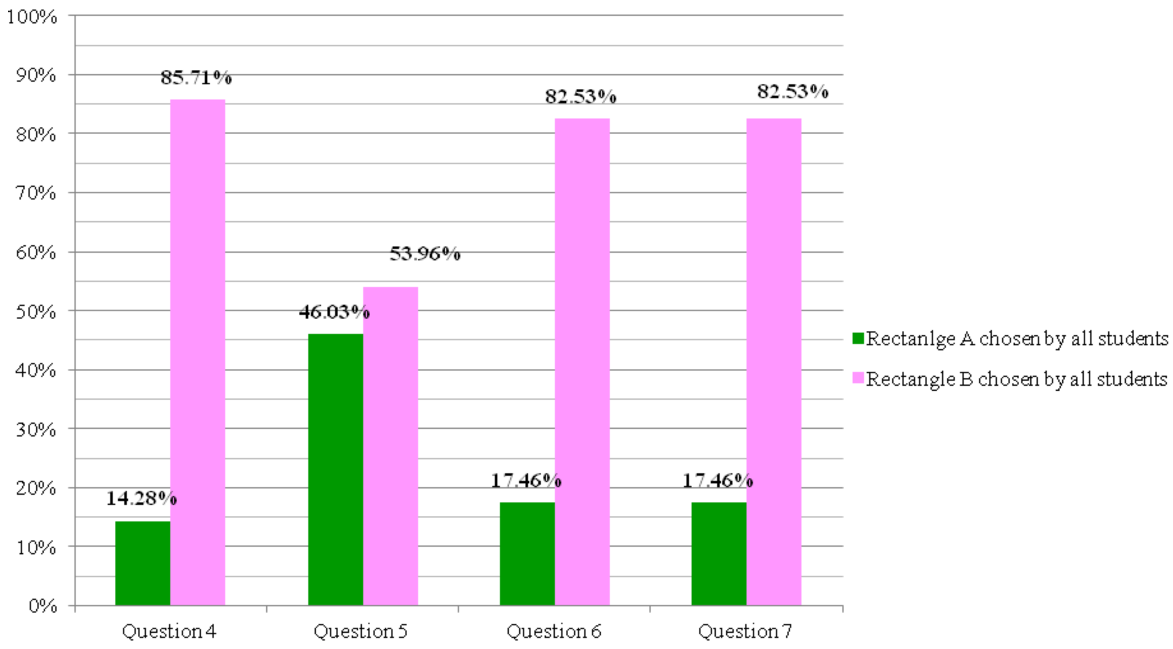
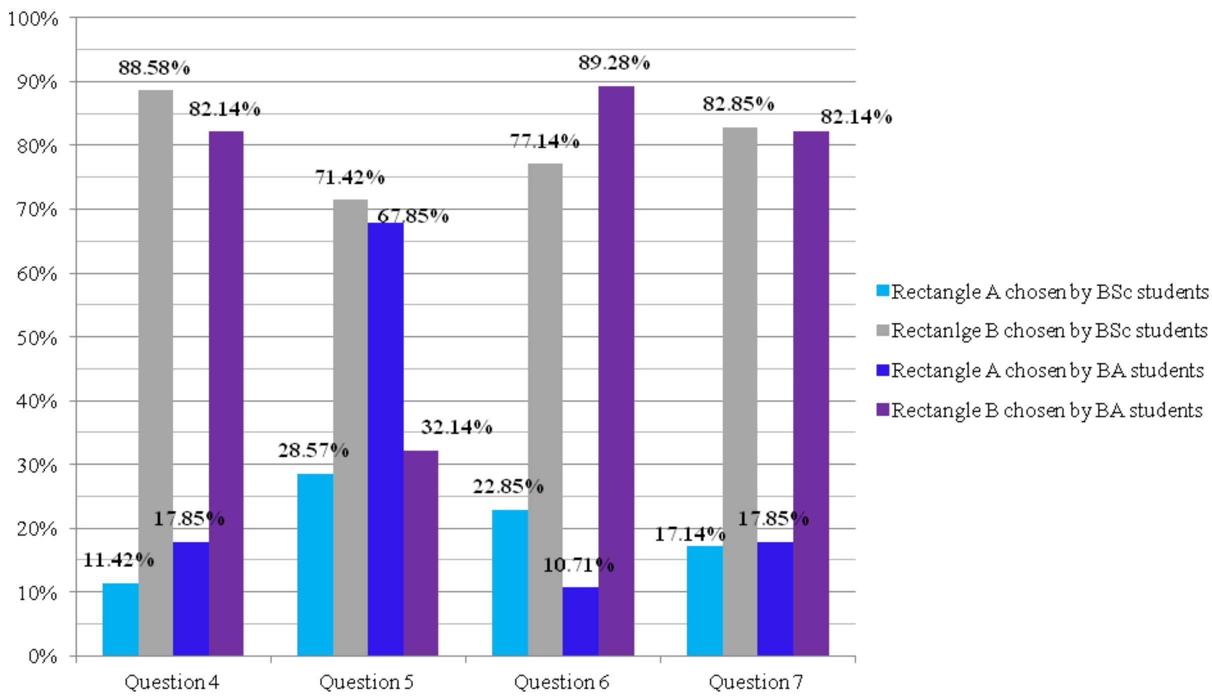


Chart 4-3 the results of the question 4, 5, 6 & 7 by comparisons



In contrast, the results of question 5 in chart 4-2 show there was no significant difference expressed by any of the students in their choice between 'A' and 'B'. Nine out of twenty eight BA students chose 'B' which was a significantly lower number than BSc students of which twenty five of thirty five chose 'B'. These results are reflected in question 3 (table 4-1) where BA students chose 'A', square (1:1) as one of three least favourites whilst BSc students chose it as their favourite square with an equal number of students also choosing 'D', or root 3 (1:√3), as their favourite. The results of the chi-square test and its p-values in question 5 are considered statistically significant, $x^2(1, N = 63) = 9.66$, *p-value*=0.0019 due to the p-value being less than 0.01. This means that there is less than a one in one thousand chance of the stated result being incorrect based on observed error.

The results of question 6 and 7 both share an equal percentage of 82.53% (x^2(1, N = 63)= 0.132, *p-value*=0.71), meaning that if you ran this test on a thousand separate occasions, you would still expect to get a distribution like the one in the results for question 6 and 7 approximately 71% of the time. Fifty two of sixty three students preferred 'B' as their favourite choice of rectangle in both questions. This was also similar to the results of questions 4.

4.3.3 DISCUSSION

The results of the questionnaire suggest that the concept of the golden ratio was a well-known reference for the design students and it was statistically the most popular choice among all shapes used. These results show that using geometry as a method of developing aesthetic visual coherence for designers has far-reaching implications and should not be overlooked in design education.

There are three major findings from the results of the questionnaire which are distinctive from the previous research presented in Chapter 2.

Firstly, although the golden ratio is still one of the most important aesthetic principles in existence, the majority of the design students were not aware of the numerical value of the golden proportion. This implies that the popular perception of the concept of the golden ratio in design education as a practical, modern and current design consideration is somewhat lacking. Instead, it is seen rather as purely an 'out-dated' aesthetic principle associated with ancient and classic designs from history. However, the result of question 3 (table 4-1) in the questionnaire indicates that the golden section rectangle was still the most preferred rectangle amongst the frequently used geometric ratios. In this respect the author's research reflected similar results to previous research, Fechner (1876), Lalo (1908). More recently, Berlyne (1970), Benjafield (1976) and Piehl (1978) which focused only on visual perception, regarding first favourite choice of a rectangle by subjects who were mostly psychology students as opposed to art and design students. Ten different ratios of rectangles from 1 to 2.3 or 2.5 were used and the golden section rectangle was the first choice among all other rectangles. However, the questionnaire in this current thesis attempted to examine the level of awareness regarding the golden ratio and the visual preferences of the design students. In fact the awareness of the golden ratio was higher (80.95%) yet only a small number of the students (19 %) knew its actual numerical value. This indicates that the importance of practical geometry is not a consideration in main stream design education.

Secondly, even though there was only a small difference in proportion between rectangles 'A' and 'B' in questions 4, 5, 6 and 7, there was a marked preference for golden rectangles in both the groups of participants. These results clearly manifest that even the smallest difference in numerical ratio may influence the aesthetic decisions of the design students. In particular they were very definitely inclined to choose the rectangles Φ, $\sqrt{3}$ and $\sqrt{5}$ which are constructed by following a precise geometrical procedure compared with other rectangles. These are very interesting results considering the design students were not aware of the ratios of the rectangles, and yet the majority of them preferred the rectangles which precisely conformed to Φ, $\sqrt{3}$ and $\sqrt{5}$. The significance of these results is that the measuring of features may be a useful practice for designers to identify characteristic elements in style and create a range of designs within similar aesthetic parameters. Also, individual designers could ensure distinctive design features will not infringe upon the defining aesthetic characteristics of that for example other brands. A good example of this particular point is the ongoing legal battle between the Apple 'iPhone' and the Samsung 'Galaxy' over design and patent (Warman 2011, Rancombe, Hicks and Mullineus 2012).

Lastly, cultural background may have influenced the students choice of rectangle in questions 3 and 5. In question 3, the South Korean BA students chose the golden section rectangle as their favourite which clearly differs from the results of Berlyne's research (1970). Even though he noted in a cross cultural test that Japanese high school girls preferred squares over other rectangles, whereas only 5 % in total of forty four Japanese girls preferred the golden section rectangle. Based on that research, Berlyne (1970) generalized that Asians preferred ratio was 1:1 suggesting that cultural influence was the reason for this preference. However, the results of question 3 from this author's research seem to suggest it is not possible to generalize in such a manner because the square was not universally preferred by Asians when there were other choices of rectangle available, such as golden section rectangle. It appears that golden ratio and $\sqrt{2}$ may be universally preferred by the design students and thus it can be said that knowledge of how to construct them may be useful and practical for designers if they wish to use similar proportions in their designs. In addition, cultural influence appeared to affect the results of question 5. There were only small differences in geometric ratio between rectangle 'A' (1:1.052) and square 'B' (1:1). Yet this clearly influenced both groups of design students in England and South Korea, as 71.42% of design students in England preferred rectangle 'B' whilst 67.85% of South Korean students chose 'A'. However, there were no cultural influences detected in the results of questions, 4, 6 and 7 as both groups preferred rectangles 'B', which conforms to frequently used ratios, Φ, $\sqrt{3}$ and $\sqrt{5}$ respectively.

4.3.4 LEARNING AND APPLYING PRACTICAL GEOMETRY IN DESIGN

During the introduction of 'Learning and Applying Practical Geometry in Design', the participants were informed as to how the golden proportion and Fibonacci sequences are related to the natural world and the human body. Moreover, It was also explained how and where the golden ratio was imbedded in both master pieces and modern classic designs, such as the Stonehenge (2000 -1600 B.C.), the Parthenon (447–432 B.C.), the Sydney opera house (1973), Eero Saarinen's Pedestal Chair (1957) and the logo of Apple (1998-2000).

The students learned how to construct frequently used measures in geometry, such as √2, √3, √4 and √5 rectangles and the golden section rectangle as well as the golden spiral. After learning the basic geometry, students attempted to apply what they had learned in order to analyse design examples. Figure 4-6 illustrates a basic step-by-step approach to applying geometric analysis to designs and the students applied this geometric analysis to find out how their intuitive geometric ratios are reflected in their designs.

1. Obtain the original dimensions of the work to be analyzed
2. Draw a "frame" around the work that is at a tangent to, or touches, the work to be done. Usually, this frame is rectangular. Once this is done a ratio can be calculated. It is important to note that any measuring system will work. Whether in inches, centimetres, the ratio always comes out the same. Simply divide the lesser measure to the greater.
3. Draw the two diagonals, which will give you the centre point.
4. From the centre, bisect the four angles of the two diagonals. In a square, these angles are 45° but in a rectangle, these four angles can vary in size, depending on the ratio of the rectangle. These bisected lines will give the vertical and horizontal mid-lines of the rectangle, parallel to the sides.
5. If desired, do the constructions for the other fractional parts of the rectangle. These will include fifths, sixths, eighths, tenths, etc. For example, if fifths, are found, three of them will yield 3/5 = 60%. This is very close to the golden section, which is .618033...= 61.8033% of the height or width.
6. Another suggestion in the analysis is to apply the golden section(s) and other frequently used sections, such as √2, √3, √4 and √5 to the work.

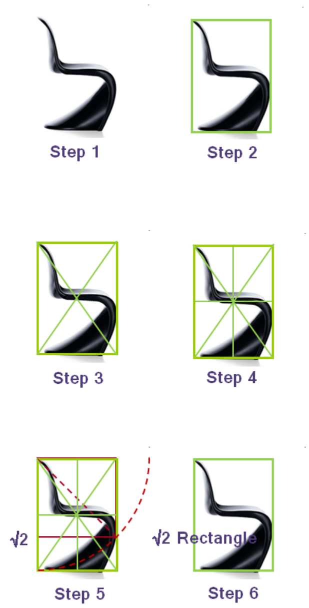


Figure 4-6 A basic step-by-step to applying geometric analysis to design

The participants were asked to use a compass and ruler to follow the steps of constructing √2, √3, √4 and √5 rectangles first and then the golden ratio as well as the golden spiral. Whilst learning how to construct the root rectangles and the golden section rectangle, they were also repeatedly advised not to confuse the process between the construction of root rectangles and the golden section rectangle. Three exercises of classic modern designs were given to the students, 'S-chair' by Verner Panton (figure 4-7), 'Smart City-Coupé' by Smart design team (figure 4-8) and 'iPod' by Jonathan Ive (figure 4-9).

Figure 4-7 Exercise 1

Figure 4-8 Exercise 2

Figure 4-9 Exercise 3

All of which were used for examining geometric proportion and geometric analysis. The participants were asked to complete the geometric analysis of each exercise and find the proportions of it in the ten minutes allotted for each exercise. As a result of the exercises, the students identified that each design conformed to ratio √2, 1.618 and 1.673 respectively. Most students managed to use geometric analysis easily in Exercise 1, as obviously the design was used when the author explained the 'basic step-by-step' process for applying geometric analysis to design. However, most participants were often confused between the construction of √2 rectangle and the golden section rectangle when they attempted to apply the golden section rectangle to Exercise 2. It seems that this could be a common problem for anybody who is experiencing practical geometric application in design practice for the first time. Moreover, during the analysis of Exercise 3, they examined how the classic 'iPod' design, well-known for its appearance which adopted the concept of the golden proportion, did not conform the golden ratio.

During the workshops three hypotheses were also tested regarding applying geometric analysis to design.

- Hypothesis 1: '*Is an intuitive understanding of what constitutes good design* *linked to a fundamental relationship of geometry?*'

- Hypothesis 2: '*Does a formal knowledge of geometric rules and visual coherence improve design skills?*'
- Hypothesis 3: '*Does bad design result when the geometric rules are ignored*?'

Hypotheses 1 was used to examine how their perception is linked to geometry and in particular the golden ratio. Also, if design students show a higher level of visual coherence in their designs, do they use geometry and the golden ratio more effectively? And finally, how should design students effectively learn and use geometry and the golden ratio in order to analyse designs and also to develop their visual coherence? Hypothesis 2 investigated how design students perceive this geometric exercise in terms of finding their own personal style and to find out if knowledge of geometric proportion has been helpful to them as designers. For Hypothesis 3, students were asked to try not to use geometry in design in order to experiment with their conception and perception and see how they have progressed. This final hypothesis is to analyse whether geometry is useful to them and how intuitively they apply geometric principles without intending to do so. Thus the students completed four experimental assignments which were designed to test the hypotheses.

- Assignment 1(A1) – to apply geometric analysis to your design and find out what your intuitive geometric ratio is.
- Assignment 2 (A2) – to refine your original design through applying the golden ratio.
- Assignment 3 (A3) – to avoid geometric knowledge gained while redesigning your original design.
- Assignment 4 (A4) – to display all three designs from assignment 1-3 and chose a favourite design and explain the reason for that choice. (see figure 4-10)

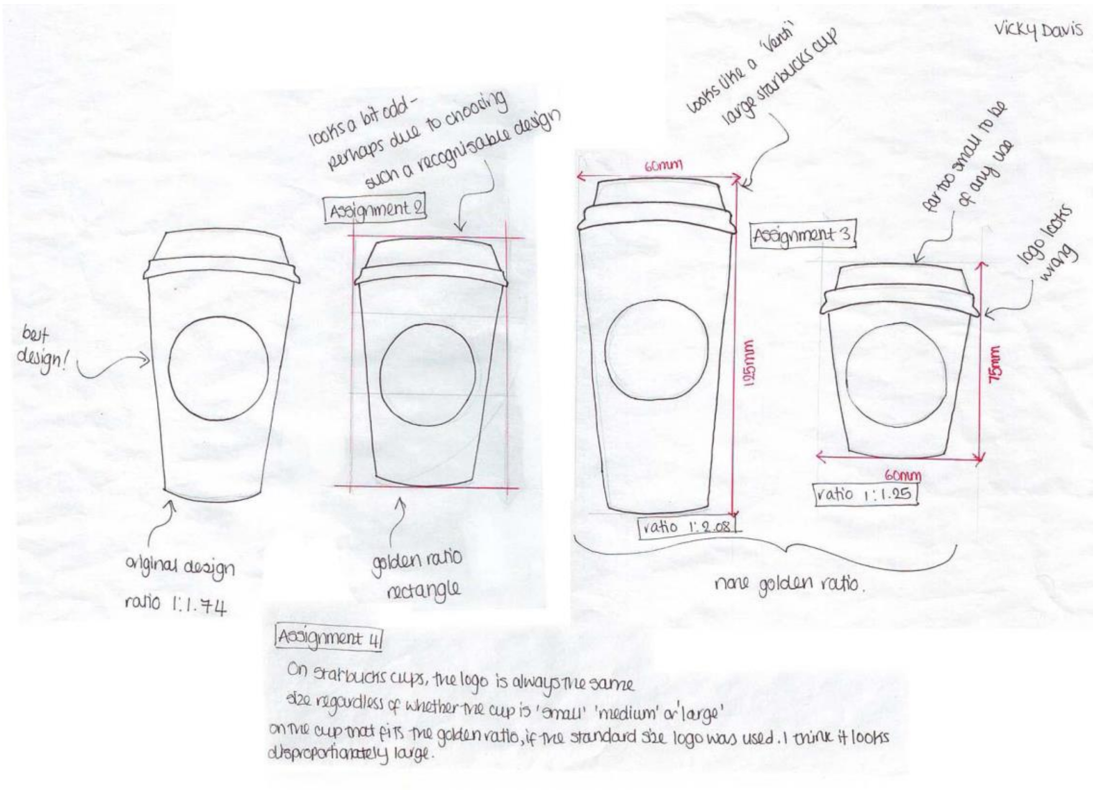


Figure 4-10 Assignment 4

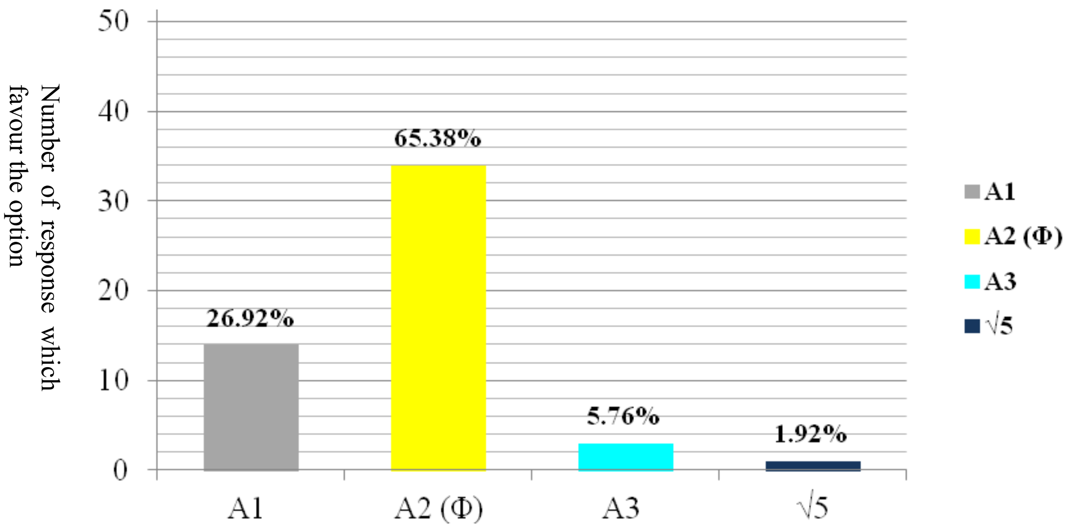
4.3.5 RESULTS

Twenty four BSc and twenty eight BA students out of sixty three students completed the assignments. Thirty four out of fifty two students chose their refined original design modified to conform to the golden ratio as their favourite design and only one student chose their favourite design as one which conforms to root 5 ratio (see table 4-2). The chi-square of the results were calculated as follows: $x^2(3, N=52)=3.83$, $p\text{-}value=0.28$, meaning there is a 28% likelihood of the results being due to chance. Only fourteen out of fifty two students chose their original unrefined designs as their favourite, but it is interesting to note their design ratios were remarkably close to root rectangle ratios and phi group ratios (see the grey marked ratios in table 4-3 & 4-4). In assignment 2 the students did not necessarily express a marked preference for their 'golden ratio' modified designs, five (BSc) and four (BA) of the fourteen students chose the golden section rectangle as their favourite in question 3 and 4 of the questionnaire.

Table 4-2. Favourite design choice

Designs	BSc	BA	Total
Assignment 1	7 (29.1%)	7(25%)	14 (26.92%)
Assignment 2 (Φ)	16 (66.6%)	18 (64.28%)	34(65.38%)
Assignment 3	0 (0%)	3(10.71%)	3(5.76%)
Refined design to conform to √5	1 (4.16%)	0 (0%)	1(1.92%)
Student Number in total	24(46 %)	28(54%)	52 (100%)

Chart 4-4 The results of assignment A1, A2, A3 &√5



The original design ratios of the students' designs show that their intuitive design ratios almost entirely conform to the golden ratio and other common geometric numerical quantities (see table 4-3 & 4-4). Thus in total 67.3% of the students preferred their refined design which conformed to the golden ratio and root 5. None of the BSc students chose the design from assignment 3, which had no geometric refinement applied, as their favourite design overall. However, three BA students preferred 'Assignment 3' while they avoided their own aesthetic principles and knowledge in order to redesign their original design, 'Assignment 1'.

Table 4-3. Original Design Ratios of BSc Product Design Students

Ratios	1:1	1:1.2	1:1.3	1:1.4	1:1.5	1:1.6	1:1.7	1:1.8	1:1.9	1:2	1:2.1	1:2.2
Frequently used ratios	1:1	1:1.272 (=√Φ)		1:1.414 (=√2)		1:1.618 (=Φ)	1:1.732 (=√3)			1:2 (=√4)		1:2.236 (=√5)
Original design ratios	1.03	1.2		1.404	1.58	1.612	1.72	1.805	1.918	2.09	2.18	
	1.008	1.23		1.414		1.625	1.74	1.83	1.987			
	1.096	1.231		1.44		1.631	1.79					
				1.454		1.661						

Table 4-4. Original Design Ratios of BA Industrial Design Students

Ratios	1:1	1:1.2	1:1.3	1:1.4	1:1.5	1:1.6	1:1.7	1:1.8	1:1.9	1:2	1:2.1	1:2.2	others
Frequently used ratios	1:1	1:1.272 (=√Φ)		1:1.414 (=√2)		1:1.618 (=Φ)	1:1.732 (=√3)			1:2 (=√4)		1:2.236 (=√5)	
Original design ratios	1	1.2	1.384	1.440	1.552	1.621	1.712					2.291	2.39
	1	1.214	1.389	1.445	1.58	1.623	1.731						2.54
	1.097	1.225		1.45		1.623	1.77						2.875
	1.139	1.258				1.625							3.56
		1.29											

A3: 1.514 A3: 2.22 A3: 1.25

It is also interesting to note that the students favourite choices of ratio in 'Assignment 3' were 1.25, 1.514 and 2.22 (marked in green in table 4-4) which were very close to √Φ (1.272), √5 and 1.5. These ratios of their original designs were 2.875, 1.139 and 1.29 respectively which had a pronounced difference compared to their preferred ratios. Thus, the favourite choice of ratios applied in design by the students were either golden ratio (Φ) or their original design ratios which were very close to √Φ, √2, 1.5, √3, √4 and √5. In addition, table 4-3 and 4-4 demonstrate that 73 % of the original design ratios were in the frequently used group yet only 27% of the original ratios were not in the frequently used category. These results show that the majority of the design students intuitive sense of proportion correlated closely with the frequently used ratios of practical geometry, in particular 17 original ratios (about 32 %) were close to the golden ratio group, $\sqrt{\Phi}$, Φ ($1.618 = \frac{1+\sqrt{5}}{2}$) and $\sqrt{5}$. In addition, each seven students' original ratios were close to ratio 1 and $\sqrt{2}$, and other 6 ratios were proximate to $\sqrt{3}$ but only one student's original ratio was close to $\sqrt{4}$.

4.3.6 DISCUSSION

On the basis of the data gathered from visual assignments, a large number of frequently used geometric ratios were found in the participants' original designs and the majority of the design students preferred their refined design, which conformed to the golden ratio over their original ratios. It is noted that applying geometric analysis to their ongoing projects, both design students in U.K and South Korea could be more aware of the characteristics' of their designs which may be more effective when analysed, in order to refine their designed proportion alongside referencing the golden ratio. Also the Geometry workshop was conducted in a limited time frame. Moreover, it was noticeable that the BA students in South Korea were more advanced in basic artistic skills such as, drawing effectively and were more able to quickly refine their designs. Moreover, their original designs also showed that they were more competent with using marker pens in comparison to the participating students in U.K. There are three significant findings:

Firstly, the ratios of the students' original designs were very close to commonly used geometric ratios. These results mean that there was a geometric relationship between design students' aesthetic perception and the frequently used ratios which were usually found in masterpieces of art, architecture and design. They used the ratios in their designs without prior knowledge and experience of practical geometry. This is an extremely important finding. The results of assignment 4 manifested that they were naturally implementing these ratios, or ratios very close to golden ratio, so it could be argued that with the knowledge of how to refine their designs and utilize the golden ratio and root ratios, they could easily expand the possibilities at the creative stage of design, and measuring and refining at the completion stage. This highlights and emphasizes that there is value in implementing practical geometry in design education. The visual assignments showed practical geometry was useful as a practical method in design for identifying aesthetically pleasing proportions. Geometric analysis can be a means of self-analysis for finding a design's strengths and weaknesses. Through this process design students may gain more awareness of how design proportions can help to improve visual coherence and also how the process of gaining geometric knowledge may be of benefit in relation to "trouble shooting" and identifying aesthetic problems.

Secondly, it is important that the design students experimented with the creation of their own ideas of geometric refinement from which to analyse their own innate sense of geometric proportion by themselves, through drawings. This process may produce different results to the previous research completed on this subject. For instance, Boselie (1992) noted that between the two stimuli, ratio 1.5 and the golden proportion, 1.5 was the most often preferred choice over the golden ratio and concluded that *"the golden section has no special aesthetic attractivity"* (Boselie, 1992, p16).

In addition, Raghubir & Greenleaf (2008) believed that proportion 1.38 was more attractive to consumers in such a context with regard to this research. There are three facts to be considered: 1) These researchers used their subjects in order to observe geometric shapes for testing their hypotheses; 2) The stimuli used were already designed by researchers and provided for the subjects and; finally, 3) Students of psychology and undergraduate students enrolled on the marketing course were used as their research participants. Perhaps that could be the reason why their results differ from the results of the hypotheses tested in this chapter. In fact, the vicinity proportion of 1.38 was found in two designs and 1.5 was found in three of the original designs (see table 4-3 and 4-4) and these results were totally opposed to Raghubir & Greenleaf's conclusion regarding the attractiveness of golden ratio. It suggests that the golden proportion was the most attractive ratio to the design students and other irrational numbers, √2, √3 and √5 were also popular. These proportions can be extremely useful for refining designs. However, when the basics of this type of refinement become ingrained in the designers and become more familiar to them through practise, then the practical and aesthetic possibilities increase dramatically, as would the ease-of-use of this approach.

Lastly, the results of the hypotheses in fact correlate with the findings from question 3 and 4 of the questionnaire and patently manifest a high number of students inclined to the golden section rectangle. In addition, after having learned about the golden ratio, when they were then asked to redesign their original design (assignment 3) without using what they had learned about geometry, they struggled with the task. It is interesting for the purposes of this research to observe that once they had designed using geometric principles they found it difficult to work without them. It appears that their intuitive perception of geometry has emerged and has become a design consideration in a very short space of time.

4.3.7 FEEDBACK

The three student comments below are typical of the general consensus of opinion amongst subjects after being exposed to golden ratio principles and exhibit their feelings regarding applying geometry in product design.

> *"It is beneficial to have an understanding of geometry in design as it may help the proportion and ratio of your design that previously did not look right before. It is practical and it will take practice to apply it to my own work." - Product Design Year 2, University of Sussex.*
>
> *"It is very interesting to see that behind a beautiful design there is geometry, ratios, shapes. Sometimes it is hard to believe that someone actually planned this geometry into mysterious design…I think it can be very beneficial when you are carrying out a design and something does not feel right you can actually try to apply geometry to your design and "fix" what was wrong with it" - Product Design Year 2, University of Sussex.*
>
> *"Aesthetically it can be good but I am interested to see if geometry and the golden ratio still make the function better" - Product Design Year 3, University of Brighton.*

Since being introduced to the idea of using geometry as a design consideration according to student feedback they would all consider applying geometry to their design as a way to refine their work. Learning geometry and successfully applying it to the design process takes time and requires practice. At the end of the geometry workshop the students have more idea how to compare their design styles and forms through geometric analysis. Thus geometry provides a method of analyzing designs and develops an ability to express design concepts rationally when needed. A possibly more effective approach to help design students would be to set specific tasks which involve engaging with and observing geometry in nature and their surroundings, to experience how these frequently used ratios are common place in the natural world e.g. plants, shells snowflakes.

The geometry workshops have demonstrated how to apply geometry and the golden ratio into product design as a design tool for analysing or refining designs. The results of the questionnaire and the hypotheses appear to show that the golden ratio is one of the favourite design ratios chosen by design students. Also the original design ratios of the design students are close to common geometric ratios which explains how every designer has their own intuitive sense of geometric organization i.e. whether intentional or not, they produce designs that conform to geometric principles.

However*, "in design and architecture it is far less intuitive and far more often a result of knowledge that is thoughtfully applied."*(Elam 2001, p101). The point of learning about geometry and how it relates to design is not to use it as a substitute for the creative process, but rather as a means of obtaining a deeper understanding of it and enhancing it. Without the initial spark of imagination and creativity, geometry on its own will not make a good design, nor is that the claim being made by this thesis. The motivation behind this thesis is to re-introduce the idea and perhaps increase the positive perception of using golden ratio as a practical design consideration in modern design education.

One of the aims of this workshop was to explore and analyze students' intuitive sense of geometry. Then, to discover ways to apply geometry to designs in order to produce an end result of a coherently designed product. It is clear that only a few workshop sessions may help design students to obtain tangible benefits from learning how to apply geometric analysis to their designs. In the short term, it would be a useful approach to review their designs to improve them in terms of proportion and composition. For the longer term, using geometry would lead to gaining true benefits when it comes to developing creativity and imagination. As Albert Einstein once said *"Imagination is more important than* *knowledge. For knowledge is limited to all we know now and understand, while imagination embraces the entire world, and all there ever will be to know and understand"*(Viereck 1929).

4.4 CHAPTER SUMMARY

This chapter has tested the awareness of the golden ratio and the hypotheses in order to provide logical responses to the research questions. The results of the questionnaire and assignments showed that there was strong relationship between practical geometric ratios and the design students' original ratios. Moreover, in particular, the golden ratio was the most pleasing proportion according to feedback, and it can be a useful method for refining design proportions. During the assignments they attempted to utilize geometric knowledge they had acquired and to effectively implement it for refining their designs. This process may develop design students' self-skills i.e. how to analyse their designs and to identify their design style and how they create artefacts. The purpose of this process was for them to realize their own level of visual knowledge. The next chapter will investigate professional designers' thoughts on implementing practical geometric knowledge in real world. It will examine their awareness of the golden ratio and practical geometry.

5. EXPERIMENTS WITH GEOMETRIC KNOWLEDGE

5.1. CHAPTER PURPOSE

The purpose of this chapter is a response to research question 4, *"How would professional designers consider applying geometric knowledge in their own design process?"* This chapter examines the notion of how professional designers should consider applying geometric knowledge into design as an integral and fundamental process, and this chapter sets out to evaluate the effects of applying geometric knowledge in designs via the considered opinion of professional designers. The process of developing a set of geometric refinement tools and applying them into the design process could reveal the value of implementing the golden mean and other related geometric knowledge into design. This thesis being documented here also involved the testing of a theoretical assumption in a practical and rational way.

The concept of the golden ratio in art, architecture and design is known as one of the fundamental aesthetic principles of today. Many researchers in mathematics and aesthetics consider the golden ratio to be the most pleasing visual ratio to human beings. However, few researchers focus on examining how geometric knowledge, (i.e. the golden ratio) can be utilised practically in the design process. This chapter examines to what degree professional designers are aware of the concept of the golden ratio and in what way can the golden ratio and geometry be implemented in design. In addition, it investigates their perspectives regarding the implementation of three elements of geometric knowledge; the golden ratio, dynamic symmetry and Fibonacci proportional sequence.

5.2 AIMS

The aim of this chapter is to generate an effective design tool that supports the further development of embedding geometric knowledge into design education. It also infers how geometric knowledge can be implemented as an effective design tool for professional design environments and scrutinizes what problems, if any, may arise. A set of geometric refinement tools were developed by the author in order to be utilized to analyse designs. The tools have been evaluated via professional designers having their designs refined and their feedback scrutinized carefully to determine the usefulness of the tools in practical situations.

The following section 5.3 illustrates the application of geometric knowledge and the set of geometric refinement tools for examining the aesthetic appearance of selected products. How can the tools be applied to improve the aesthetic appearance of those original designs? This section demonstrates how effective design technique can modify the appearance of a design, and supports design decisions by providing related geometric knowledge and helping to articulate rational reasons for aesthetic decisions.

Section 5.4 examines professional designer’s perceptions of the proportion of various common geometric ratios. It also experiments with the geometric refinement tools the author devised. The designers were asked to complete questionnaire one and two for testing design students’ perception of aesthetics, after which they were interviewed in an attempt to evaluate the efficacy of the geometric refinement tools and to assess their geometric knowledge in designs. Section 5.5 includes a discussion of the results of the questionnaires and the experiment. Section 5.6 is a summary of this chapter.

5.3 APPLYING GEOMETRIC ANALYSIS & GEOMETRIC KNOWLEDGE

The visual materials the designers provided, were drawings of their original designs and images of same. Information regarding the relationship between the aspects of mechanical functions and the geometric appearance of the designs, choices of the materials and the colour combinations used in the designs, was not provided by the individual designers. Thus, the analysis is only concerned with the shapes and proportion in the designs.

5.3.1 THE SET OF GEOMETRIC REFINEMENT TOOLS

The purpose of developing a set of geometric refinement tools is to find a way to explore how the golden ratio can be effectively and easily utilised in design as a practical and applicable theory. It also focuses on a method for analysing the appearance of both new and mature products in five steps.

Step 1 – Decomposing designs

The designer either provides an image (figure 5-1) or an outline (figure 5-2) of one of their original designs. It is possible to identify the concept of the design in figure 5-1, yet in figure 5-2 it is not as easy to identify what the design might be. This is an example of a design provided by a participating designer who had a tendency to not give full details of their own designs. The use of the visual materials in this chapter is to examine the proportion of designed forms and there is no intention to investigate how and where any functional problems might influence the appearances of the designs. Thus, the image of figure 5-2 is suitable material for analysing design proportion. Where an image is supplied an outline must be drawn in order to simplify the details of the design (figure 5-3).

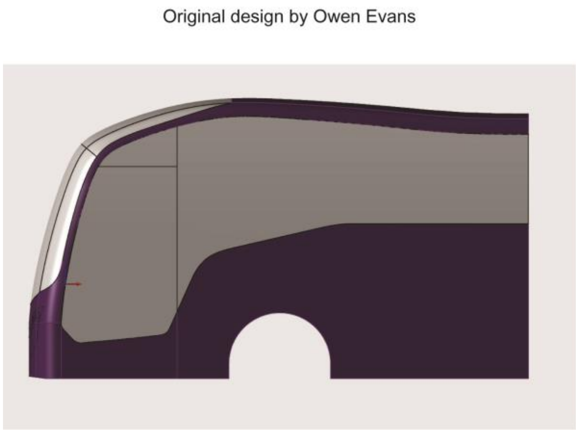


Figure 5-1

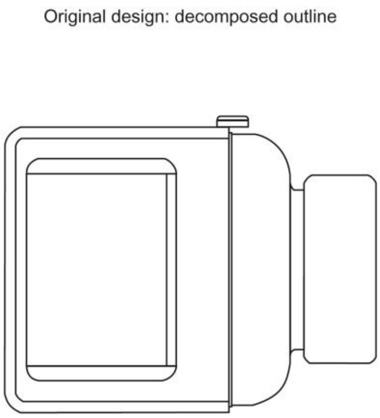


Figure 5-2

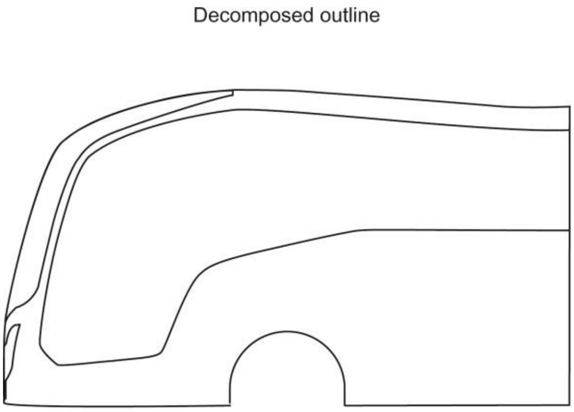


Figure 5-3

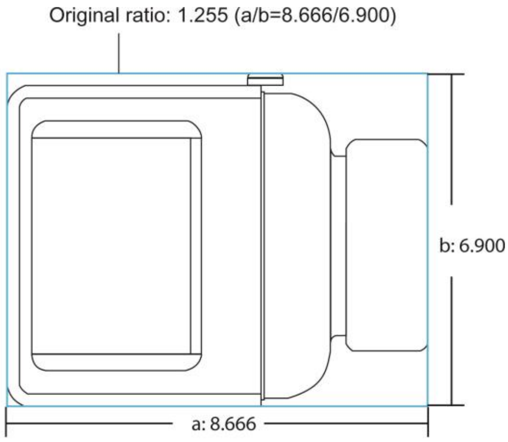


Figure 5-4

Step 2 – Applying geometric analysis

This step is to obtain details of the geometric ratios in the design. The design is framed within a rectangle in order to obtain its geometric ratio by dividing 'a' into 'b' (a>b). For example, figure 5-4 shows that the original design ratio is a/b=1.255, a/b (8.666/6.9). Figure 5-5 shows each individual geometric shape of the design outlined within rectangles in order to find the geometric ratios. Figure 5-6 demonstrates the geometric ratios of the parts in the design within rectangles with the original outline removed.

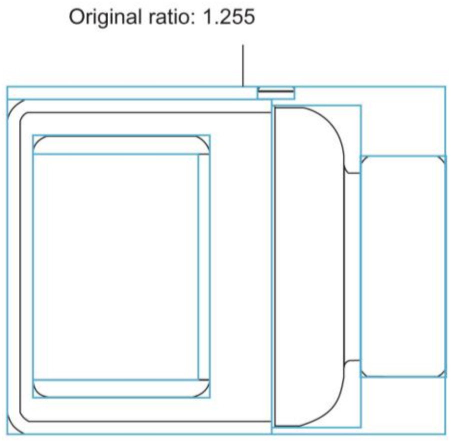


Figure 5-5

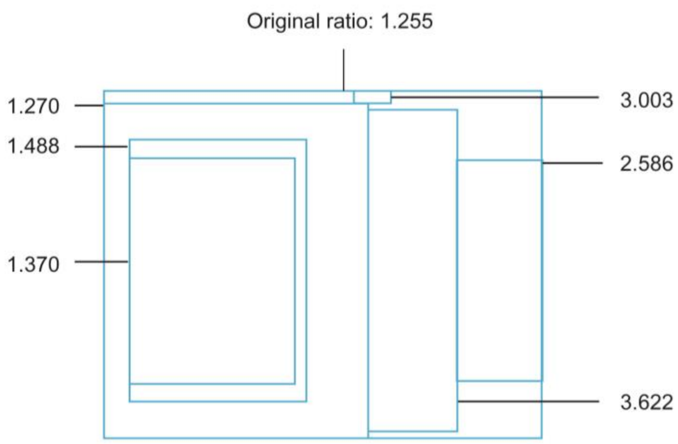


Figure 5-6

Step 3 – Applying frequently used geometric ratios

These existing designs must be modified so they adhere to the frequently used geometric ratios, of the golden proportion, ratio 1, Root 2, 3, 4 and 5. Figure 5-7 to figure 5-10 shows how Root 2 section rectangle is applied to the original design.

a) From figure 5-8, a square of side 1 (in red) is constructed on the left side of the outline of the original design.

b) In figure 5-9 an arc is drawn of radius √2. The centre of the arc is at 'A' and the arc is extended to point 'C'.

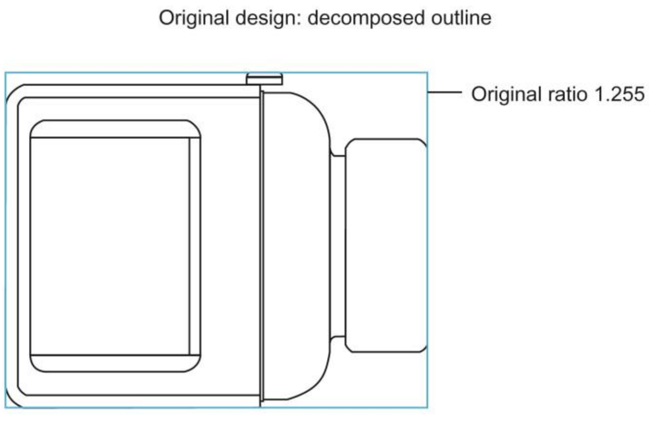


Figure 5-7

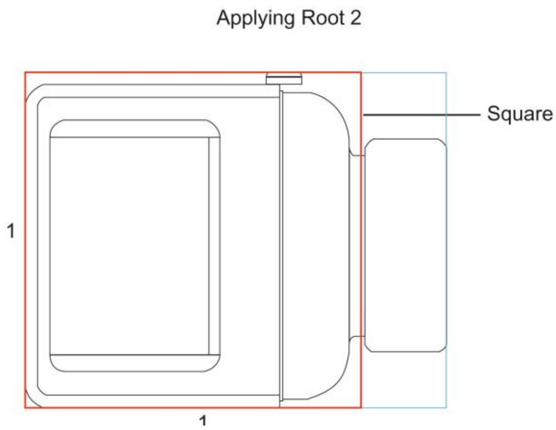


Figure 5-8

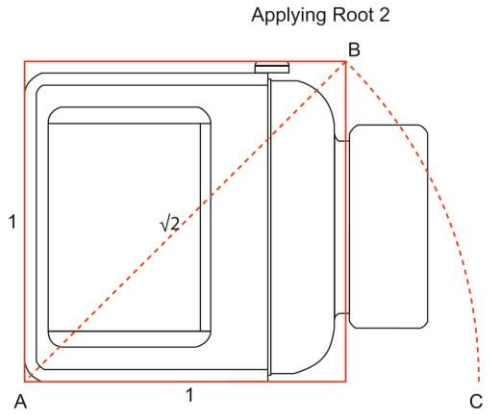


Figure 5-9

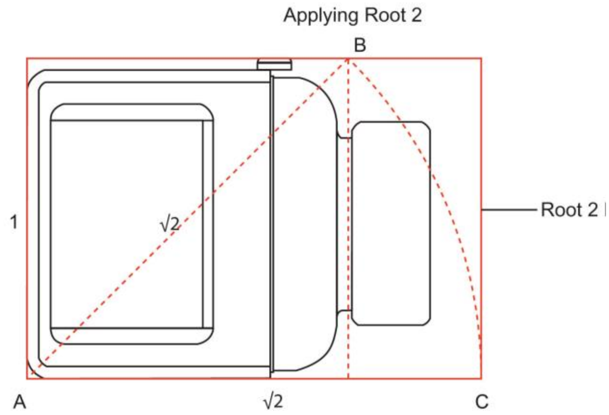


Figure 5-10

c) The rectangle in figure 5-10 is now a Root 2 rectangle which will hereafter be referred to as “Rec1”. The original design is then framed within “Rec1”. The distance between the edge of the design and the border of “Rec1” is now equal on both the left and right hand sides (figure 5-11). The original design is now stretched horizontally to conform to the sides of the Root2 rectangle. The details of the construction to allow this are given in figure 5-12 and the final result in figure 5-13.

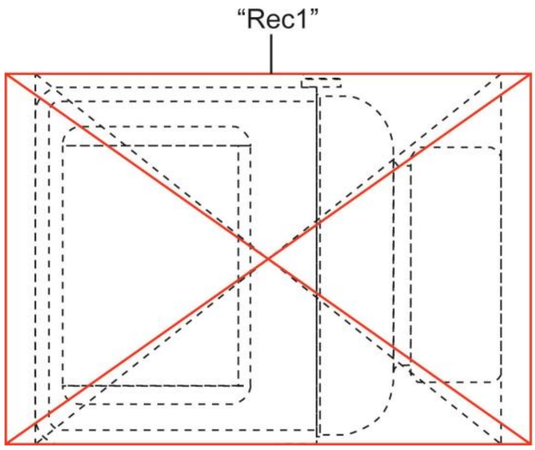


Figure 5-11

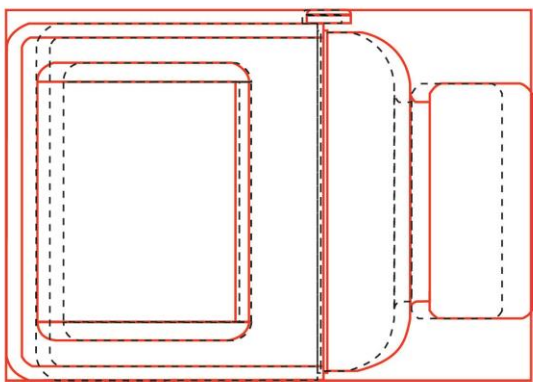


Figure 5-12

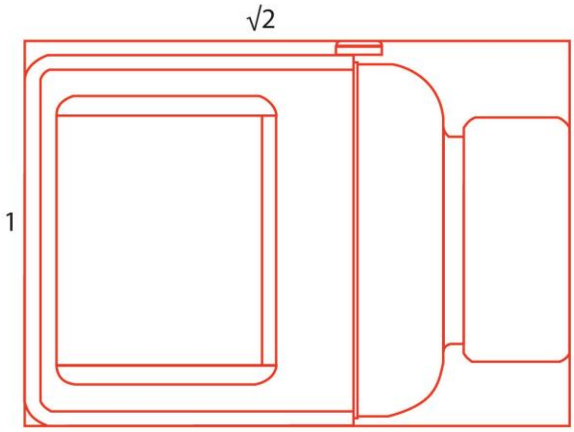


Figure 5-13

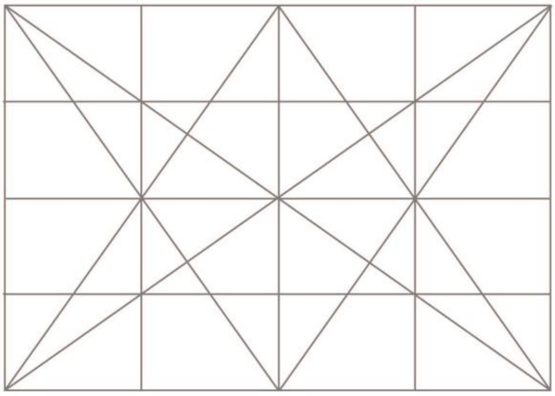


Figure 5-14

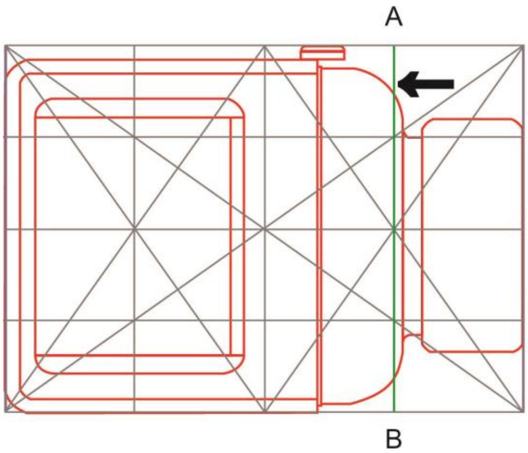


Figure 5-15

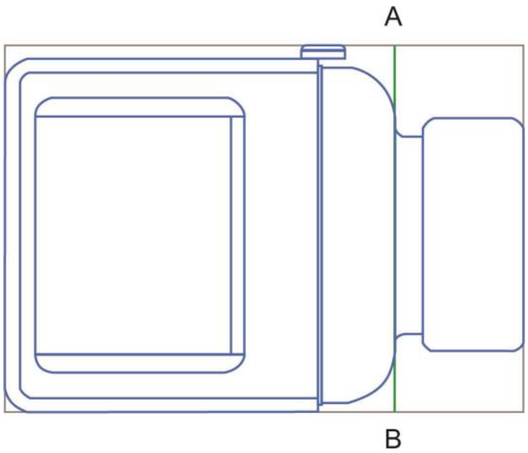


Figure 5-16

d) Figure 5-14 shows the application of the harmonic subdivisions of Root 2 Dynamic symmetry rectangles to the refined design (red line in figure 5-15). The Root 2 rectangles are subdivided into sixteen smaller Root 2 rectangles which are always related to the proportion of the original Root 2 rectangle.

e) Figure 5-15 demonstrates the refined design changed to proportionally fit into the harmonic subdivision line 'AB' and outlined in blue figure 5-16 shows the refined design which now conforms to Root 2 ratio and Root 2 dynamic symmetry.

Step 4 – Applying the Golden Ratio and Dynamic symmetry of the Golden proportion

a) The method used to apply the Golden ratio is broadly similar to the Root 2 section rectangle. It starts with the same process used to obtain the first square of "Rec1" as per figure 5-8. Two diagonal lines are then drawn inside the square to find the centre. A line is drawn from the centre of the square to one of the horizontal axis of the original design and this is the midpoint 'A' of the square.

b) Figure 5-18 demonstrates how the square is divided into two rectangles with an arc from point 'A' to pass through point 'B' of the square. The radius of the arc is $\sqrt{5}/2$.

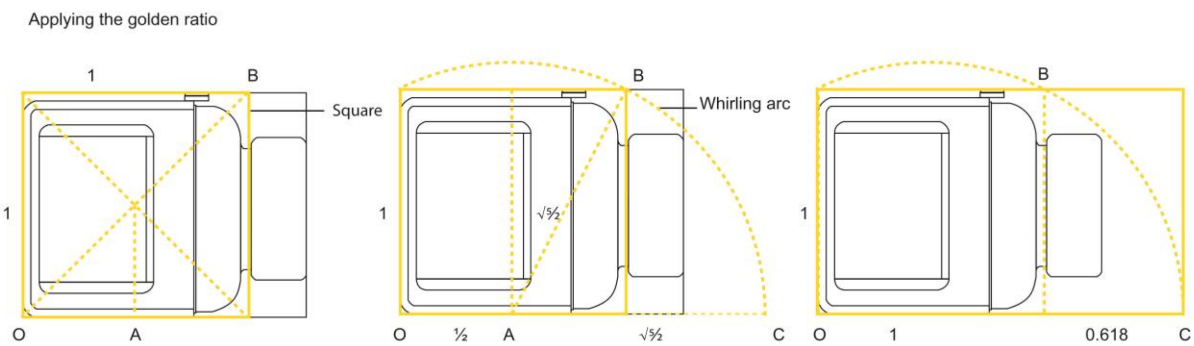


Figure 5-17 Figure 5-18 Figure 5-19

c) Now the square is extended to the point 'C' and 'OC' becomes one side of a golden section rectangle (see figure 5-19).

d) Figure 5-20 shows the original design within using a black dotted line which has been positioned at the centre of the golden section rectangle. The original design is then extended to conform to the new golden ratio proportions (see the yellow line of figure 5-21). Figure 5-22 shows the resulting new design which now follows the golden section rectangle.

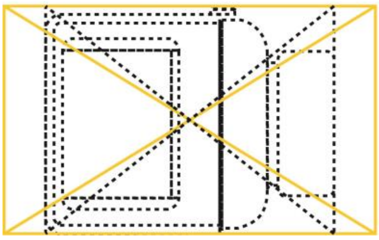


Figure 5-20

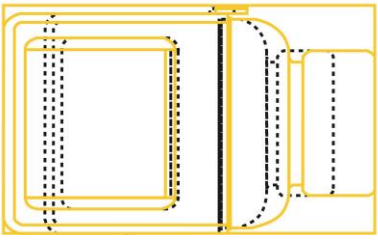


Figure 5-21

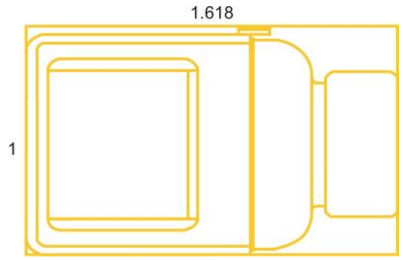


Figure 5-22

e) Golden ratio Dynamic symmetry is then applied to the composition of the refined design figure 5-23. The outline of the refined design (in yellow) is then moved to proportionally fit into the harmonic subdivision lines ‘AB’, ‘CD’ and ‘EF’ (figure 5-23). Figure 5-24 now shows the result of applying Dynamic symmetry proportion to the design.

f) Figure 5-25, 5-26 and 5-27 explain how Dynamic symmetry can be used as a tool to refine the small proportions of each part of the design by following the harmonic subdivision lines in green (‘AB’, ‘CD’ and ‘EF’) and the colour key clearly shows both “before” and “after” the refinement process.

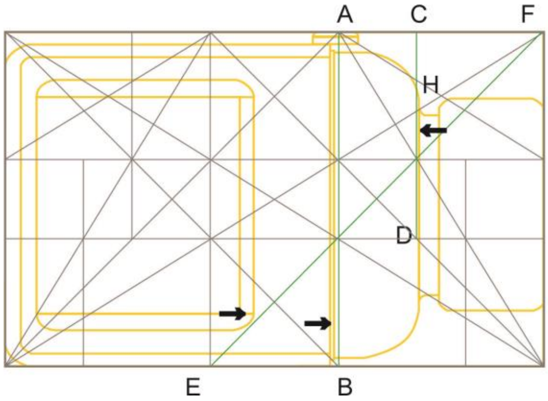


Figure 5-23

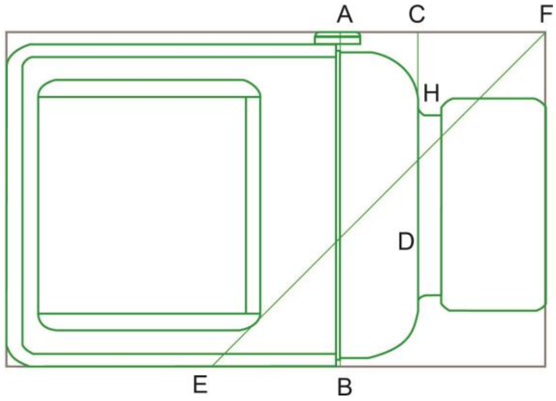


Figure 5-24

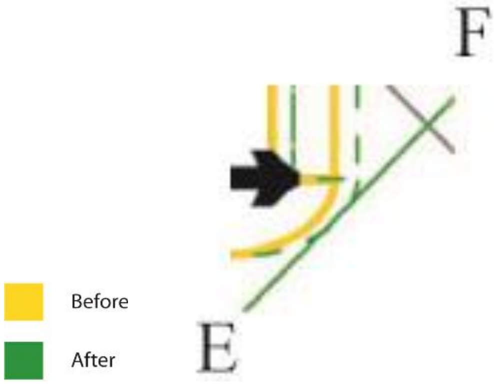


Figure 5-25

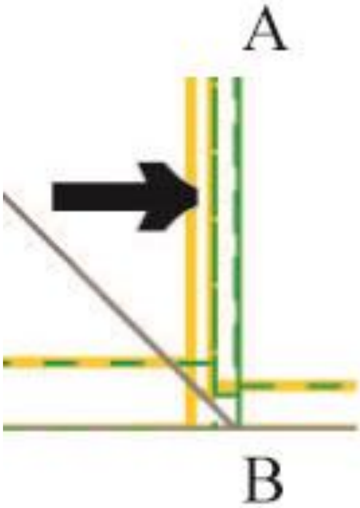


Figure 5-26

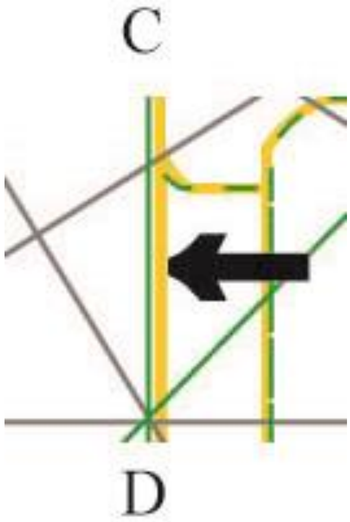


Figure 5-27

Step 5 – Applying Fibonacci sequential proportions

a) The Golden ratio is closely related to and intimately interconnected with Fibonacci sequential numbers. Figure 5-28 shows the proportional properties of the squares in the Golden section rectangle which are formed using the Fibonacci sequence. For example Square 1 (yellow), Square 2 (green), Square 3 (sky blue), Square 5 (purple), Square 8 (pink) and Square 13 (black).

b) Within a Golden section rectangle are contained an infinite number of other Golden section rectangles. For instance, after creating square 13 from the Golden rectangle in figure 5-28 what remains is another Golden rectangle which is shaded in grey. In figure 5-29, square 8 is also attached to another Golden section rectangle (shaded in purple) and so on and so on to infinity. Figure 5-29 demonstrates the Golden section rectangles which will be used to modify the individual components of the design to conform to the golden ratio. This further refinement of individual components parts of the design is necessary in order to retain the integrity of harmonious proportions.

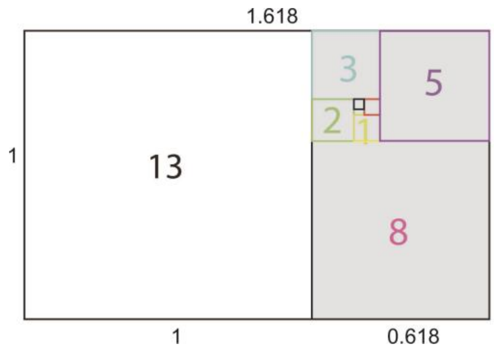


Figure 5-28

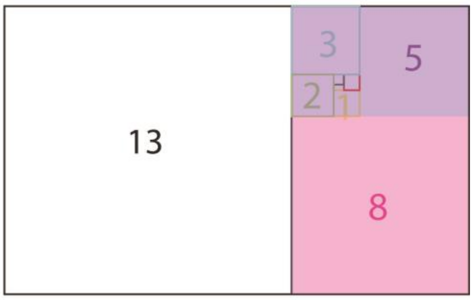


Figure 5-29

c) The design now conforms to the golden section rectangle which can be seen in figure 5-30. It has been modified by implementing Fibonacci proportions (Square 8) and the golden section rectangle drawn from square 5(see 5-31).

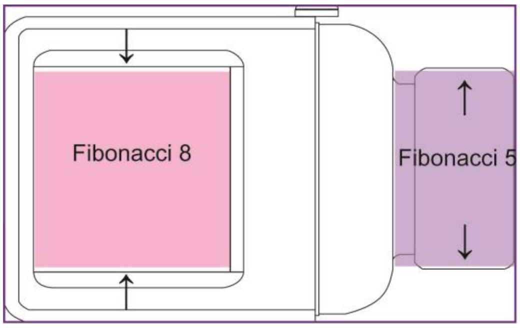


Figure 5-30

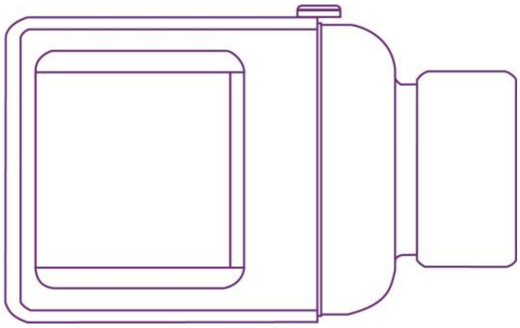


Figure 5-31

5.4 METHODS

In this chapter, two questionnaires and one interview were completed by five designers between October 2012 and December 2012. The first interview took between fifteen to twenty minutes. In the first meeting, the participating designers were informed of their roles during this experimental process and each participant was asked to complete the questionnaire as quickly as possible. In total 30 designs were used for analysis by implementing the author's geometric refinement tools. Each designer provided images of six of their designs with no product information other than a top, front and side view of each design. Moreover, they were asked to send an electronic image file (JPEG, PNG or PDF) of their individual designs to the author. The designs were then analysed by the author using the geometric refinement tools. Thus, each design was analysed using from 'Step1' to 'Step 5' of the geometric refinement tools by the author. The individual analysis of each design took approximately one hour to complete. At the second meeting, the designers were asked to complete questionnaire two also as quickly as possible. After that they were immediately informed their choices of favourite designs amongst other refined designs by the author. Finally, the designers were interviewed by the author, regarding their own views of applying the geometric refinement tools, and the interview took approximately an hour to complete. The interviews reviewed the results of the feasibility study to test aspects of applying practical geometry and the refinement tools. Five participants should be a sufficient number to discover approximately 85% of the problems one could encounter regarding the usability of tests (Nielsen 2000). Thus, the feasibility study was carried out by five professional designers.

5.4.1 QUESTIONNAIRE ONE (Q1)

Question 1 & 2 – asked 5 designers whether they were familiar with 'the 'golden ratio' and if they knew the specific numerical ratio or proportion of the 'golden ratio'.

Question 3– the designers were asked to choose their favourite between designs 'A', ‘B’ or ‘C’. Rectangle ‘A’ is the iPod classic (1.67) and ‘B’ shows the iPod classic design modified to conform to golden ratio proportions (1.618). ‘C’ has the same proportions as ‘B’ but with the circle in the centre repositioned in order to equalize the distance both above and below the circles (see figure 5-32).

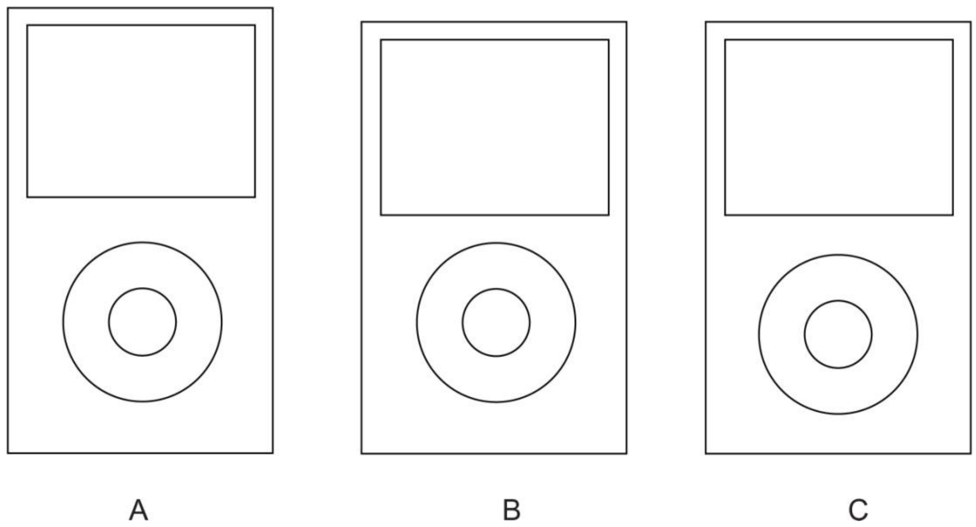


Figure 5-32: Question 3 in Questionnaire One

5.4.2. THE RESULTS OF QUESTIONNAIRE ONE

Four of five designers were familiar with the concept of the golden proportion however; none of designers were able to provide the numerical ratio of the golden ratio (approximately 1.618) when asked. None of designers had previously learned how to construct the golden section rectangle and other root rectangles, however, the four designers were aware that the golden proportion was an aesthetic proportion embedded in master pieces. In Question 3, three of five designers chose ‘C’ as their favourite design but two designers chose ‘A’ as their favourite. Whilst not all designers chose ‘C’ it still illustrates that the designers’ visual preference for Golden ratio proportions overpowered their preference for the original ‘iPod’ design which has been regarded as one of the most iconic designs of modern times. Whilst, it could be said that there is not much numerical difference between the ratios 1.67 and 1.618, in geometry and in relation to aesthetic appeal however, the effect is quite pronounced. This result suggests it would be interesting to look at how Golden ratio can be implemented in design to improve the aesthetic quality of a design's appearance.

5.4.3 QUESTIONNAIRE TWO (Q2)

The aim of Q2 investigates each designer's impression of implementing frequently used geometric ratios and geometric knowledge to refine their own designs. The notion of "favourite" in the Questionnaire two referred only to the aesthetic preference of the design appearance. So, the designers were informed by the author as to their preferred designs and it was emphasised that they should not consider any functionality aspect of the designs, but instead purely aesthetic considerations. The designers were asked to choose, three of their most favourite and three of their least favourite among their own designs. This request was to explore, firstly how close each of the individual designers' natural, intuitive sense of geometric proportion was to golden ratio. Secondly, it also exhibits whether the designs themselves adhere more closely to the golden ratio than their least favourite designs. After obtaining visual materials of their own designs, the author's set of geometric refinement tools were applied to the designs in order to modify them to conform to the frequently used ratios, using harmonious subdivisions of dynamic symmetry and Fibonacci sequential proportions by the process already described earlier. Q2 consists of six questions. Each question asks the designers to reorganize the designs in order starting with their most favourite to their least favourite among 'A', 'B', 'C' and 'D'. Figure 5-33 presents design options in one of the questions in Q2 ; 'A' is the original design, ‘B’ has √2 ratio applied, ‘C’ has been modified to conform to the golden ratio and follows harmonious subdivisions of golden ratio dynamic symmetry. Fibonacci proportions have been applied to modify ‘D’.

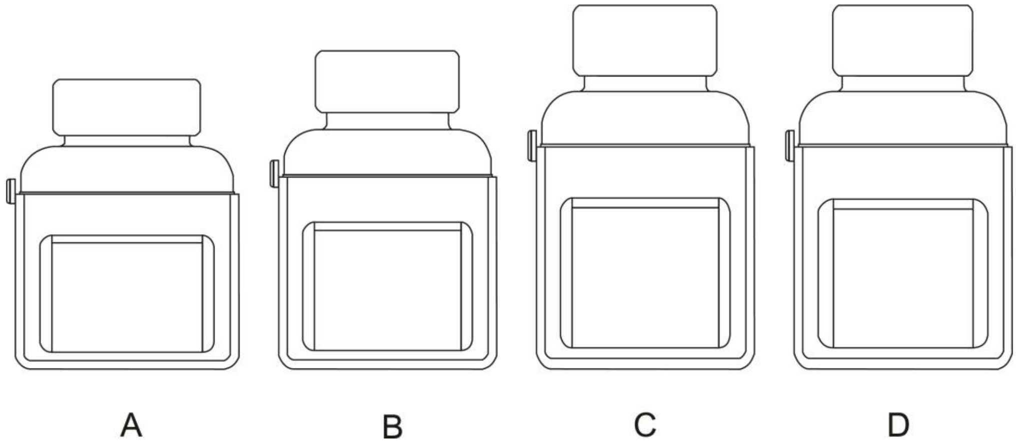


Figure 5-33: An example of Questionnaire Two

After completing Q2, it was explained to them how the set of geometric refinement tools had been used to modify their designs and they were informed of the results of their choice (see figure 5-34).

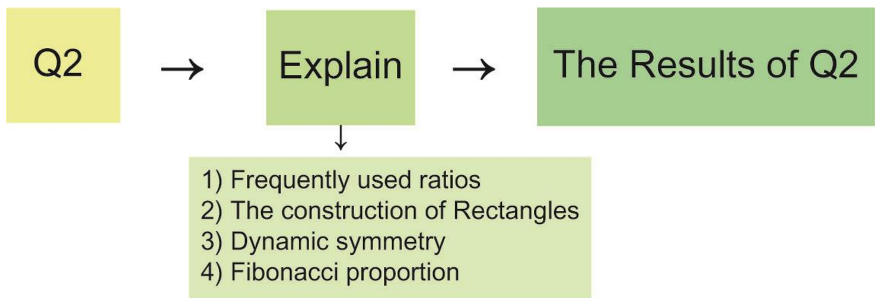


Figure 5-34: The process of applying the geometric refinement tools

5.4.4 THE RESULTS OF QUESTIONNAIRE TWO

Table 5-1 shows that of the thirty total refined designs, twenty one were chosen by the designers as their first choice of favourite design over their own original designs, which gives a very significant value of 70% ($x^2(4, N = 30) = 12.65$, p-value=0.013) as the p-value of the x^2 is about 0.01. This means that there is approximately a one in one thousand chance of the stated result being incorrect based on observed error.

The author was not informed of the functional aspects and mechanical characteristics of the designs due to the concerns of the participating designers regarding confidentiality and intellectual property rights.

Table 5-1 Choice of refined designs

Designers	**Education**	**Years of Experience**	**Choice of refined designs(%)**	**Total**
Mr. Davey	Mechanical Engineering(BSc)	20	5/6 (83.3%)	21/30 (70%)
Mr. Diamantidis	Graphic Design(BA)	5	4/6 (66.6%)	
Mr. Evans	Mechanical Engineering (BSc & MSc)	15	2/6 (33.3%)	
Mr. Lilley	Automobile Engineering (BSc)	5	4/6 (66.6%)	
Ms. Potter	Interior Architecture(BA)	15	6/6 (100%)	

Table 5-2 shows the thirty original design ratios compared with the ratios of first choices of refined design ratios. Various geometric ratios were used for individual design concepts. It is noted that the designers' perception which constitutes their aesthetic decisions was linked to golden ratio. Even though not all the designs conformed to the golden ratio, one design of each designer was very close to 1.618 (marked in yellow). These results patently manifest that the golden ratio appeared in their own designs without their knowledge of its numerical ratio and with no knowledge of how to apply it to their design.

Table 5-2 Design ratios

- Original design ratios which are close to Golden ratio (1.618)
- First choice of original design ratios
- First choice of original design ratios which are close to √2 (1.414), Φ (1.618) and √3 (1.732)

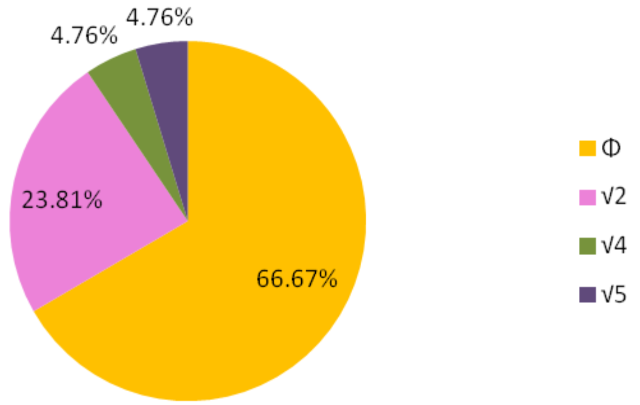
Designs	Design ratios	Designers				
		Mr. Davey	Mr. Diamantidis	Mr. Evans	Mr. Lilley	Ms. Potter
*MFD1	Original	3.042	1.629	1.782	2.583	1.5
	Preferred design	Refined (ϕ×2)	Original (1.629)	Original (1.782)	Original (2.583)	Refined (ϕ)
*MFD2	Original	1.35	1.206	5.608	1.886	1.626
	Preferred design	Refined (√2)	Original (1.206)	Refined (ϕ×3)	Refined (√4)	Refined (ϕ)
*MFD3	Original	1.604	1.285	1.255	1.551	1.926
	Preferred design	Refined (ϕ)	Refined (ϕ)	Refined (ϕ)	Refined (ϕ)	Refined (ϕ)
**LFD1	Original	3.467	1.5	1.663	1.673	1.021
	Preferred design	Refined (ϕ)	Refined (ϕ)	Original (1.663)	Refined (ϕ)	Refined (√2)
**LFD2	Original	1.238	1.285	1.42	2.392	1.193
	Preferred design	Refined (ϕ)	Refined (ϕ)	Original (1.42)	Refined (√5)	Refined (√2)
**LFD3	Original	1.166	1.179	2.711	1.201	1.045
	Preferred design	Original (1.166)	Refined (√2)	Original (2.711)	Original (1.201)	Refined (√2)

*Most Favourite Design (MFD), **Least Favourite Design (LFD)

The results also show that only nine of the total of thirty unrefined original designs were chosen as the designers favourite compared with the new geometrically modified designs. It is also interesting to note that four of those nine were also remarkably close to the golden ratio (1.618). One was close to √2 (1.414) and one was close to √3 (1.732) (see marked green). When these six unrefined designs - i.e. the four original designs that were virtually identical to golden ratio proportions and the ones virtually identical to - √2 and √3 - are added to the previous 21 refined designs that were preferred by the designers even over their original designs, it results in a figure of 83.33% of preferred designs either conforming exactly to or extremely close to, golden ratio and other commonly used ratios. This significant finding goes a long way to suggest that the golden ratio is an extremely important geometric proportion which can improve design and the fact that it has influence over aesthetic design decisions would also suggest there is an affinity between human beings and the divine proportion found in nature. The relationship between geometric ratios and designer's design decisions, however, is not entirely governed by aesthetics, some designers choices were heavily weighted in favour of functional aspects e.g. the original designs of Mr Davey's LFD 3, Mr Evans, LFD 2 and LFD 3 were designed carefully with their specific functional factors in mind which overpowered aesthetic design decisions. That said however, the figures of 70% and 83.33% would suggest that functionality does not have to be sacrificed when designing a product that is also aesthetically pleasing and based on golden ratio principles.

Chart 5-1 demonstrates the ratios of twenty one designs which were chosen by designers as their preferred choice. Fourteen of twenty one designs were modified by utilising the concept of golden proportion, which works out at about 66.67%. Five of the twenty one refined designs conformed to √2 (23.81%), one √4 (4.76%) and one √5 (4.76%) respectively. These results are very significant because even though all original designs were carefully designed to meet client's criteria the individual designers preferred the modified designs which conform the golden proportion as opposed to their original designs, suggesting that golden ratio can be the most effective ratio used for modification and the second most effective ratio being √2.

Chart 5-1 The ratios of 21 modified designs



5.4.5. DISCUSSION

Details of the three major findings from Questionnaire one and two are as follows.

Firstly, although the awareness of the concept of the golden ratio and its effective implication into designs were acknowledged by four of five designers, none of the designers had any prior practical experience of using geometry. One had no previous experience nor knowledge of golden ratio whatsoever, and none of them knew how to construct golden section rectangles nor how to utilize them in their design process. However, the frequent appearance of commonly used geometric ratios in their original designs seems to concur with previous scholars' findings regarding innate design preference, which is that individuals seem to be naturally drawn to golden proportion (Doczi 1981). Could it be that human beings are drawn to the golden proportion due to its occurrence in organic forms in nature? (Mayall 1968, Papaneck 1984). Moreover, across cultures, beautiful human faces quasi-conform to the golden proportion (Cleese 2001, Marquardt 2003). The human face could be thought of as one of the most complex and difficult things to alter cosmetically, whilst still maintaining aesthetic integrity. The golden ratio seems to be very effective at helping many modern cosmetic surgeons solve this problem. Today the golden ratio is used as an aesthetic guideline for exactly this type of work (i.e. Marquardt's beauty mask). Perhaps the subliminal influence of natural forms and aesthetic perception of beauty results in inherent visual preferences for design professionals, which then in time become the basis of their 'know how', known as *'Reflection in-action'* (Schön 1991). This phrase describes a process of conscious activity which allows designers to reform what they are working on, while they are working on it, indicating what designers really know about designing and how they perceive beauty and proportion of artefacts. When the professional designers were presented with a choice between various examples of their work geometrically refined by the author's refinement tools, the results expressed a definite preference among the designers for golden proportion and other frequently used geometric ratios. Which is an example of their conscious 'know-how', or 'reflection in-action' being expressed in their design choices.

Secondly, the designers' own inherent aesthetic judgement reflected in their original designs seems to be rather incomplete, otherwise the figure 70% of designers who preferred the modified designs (using the author's refinement tools) would not have been so high. Overall it seems that practical knowledge of geometry and the concept of the golden ratio can provide effective improvement of the designs. The process of applying the author's refinement tools for geometric analysis of designs may be a way to help designers overcome uncertain aesthetic knowledge. It is rare for designers to describe design decisions in quantifiable terms. Thus geometric knowledge can help to support designers in uncertain areas of design. Schön (1991) argues that professionals were not satisfied with how they described and expressed their knowledge of aesthetics. He pointed out that they assumed it without question or rational interpretations. It appears to be rather important how designers are trained to use practical geometry effectively.

Lastly, functional aspects overpowered the designer's aesthetic judgements. Although Questionnaire two was aimed purely at the aesthetic preference of the designs, two of the designers were from a mechanical engineering background and thus were not able to ignore functional aspects of their designs while completing Q2. A possible explanation for this is visual appearances and other values, such as quality, performance, ergonomic efficiency, manufacturability and safety are more interwoven. Schoormans and Snelders (2008) pointed out that depending on professional designers' experience and educational background a significant effect on styling in design decisions would result. Designing ideal forms is not simply related to designers from an art background having a greater sensitivity to aesthetic concerns compared with designers with no art-training in their design background. Although the differences in course work and the level of basic art skills were found between the participating students in U.K and South Korea (see p.81), considering three of five designers in the experiment had a BSc qualification in engineering, it is possible to conclude that their educational background did not significantly influence their aesthetic decisions during this experiment.

From the literature review, chapter 2, however, the aesthetic appearance of a design is the biggest factor effective in influencing consumer decisions when purchasing products, when products are otherwise equal in terms of price and quality. Also consumers are attracted to objects which conform to the golden ratio more than other ratios used in design (Nicolik 2011) because the human eye perceives the golden ratio more quickly than other ratios (Bejan 2009) and brain scan studies have discovered that the visual perception of an attractive artefact can provoke the part of the motor cerebellum which controls hand movement (Hosey 2012). A large proportion (60%) of senior design managers consider aesthetics to be the most important determining factor for new product sales with only 17% mentioning price (Bruce and Whitehead 1988).

Considering the professional designers' original designs used in Questionnaire two, their responses were sufficient to suggest that the refinement tools could be an effective geometric styling method used to help support design decisions, as the visual appearance of products can influence both consumers and brand identity. The refinement tools can be useful, strategically, as a ploy to identify aesthetic features for branding and promote familiarity of designs.

5.5 FEASIBILITY STUDY

The feasibility study was part of the iterative process involved in testing the refinement tools and applying geometric knowledge. The aim of using an interview was to evaluate how practical geometric knowledge and the tools are, and also what other potential problems need to be considered when applying them. What else can be implemented in design to support the visual perception and aesthetic judgments of designers? Interview questions were designed for obtaining valuable feedback regarding applying geometric knowledge to refine designs. It included five closed questions with a rating scale from 0 to 10 to indicate more accurately how useful the designers thought the geometric refinement tools are and to provide an overall view of how they should best be applied in the design process. Also the responses gave rational reasons and clear explanations of how, and why, they rate the process of implementing geometry in design.

5.5.1 INTERVIEW QUESTIONS

1. *In your opinion, on a scale of 0 to 10, how useful is geometric analysis in design?*
   Not useful at all 0 1 2 3 4 5 6 7 8 9 10 Extremely useful

2. *On a scale of 0 to 10, how would you rate applying geometric ratios (such as the golden ratio and root 2, 3, 4, and 5) to the design process, and could you briefly explain the reasons for your answers?*
   Not useful at all 0 1 2 3 4 5 6 7 8 9 10 Extremely useful

3. *On a scale of 0 to 10, how would you rate applying Dynamic symmetry in design and the design process?*
   Not useful at all 0 1 2 3 4 5 6 7 8 9 10 Extremely useful

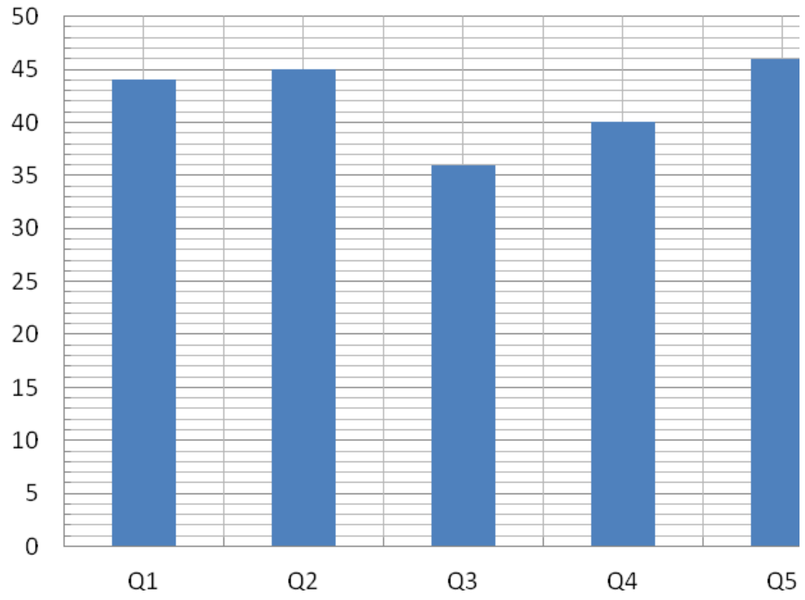
4. *On a scale of 0 to 10, how would you rate applying Fibonacci sequence proportions in design and to the design process?*
   Not useful at all 0 1 2 3 4 5 6 7 8 9 10 Extremely useful

5. *On a scale of 0 to 10, using the knowledge gained from geometry, how would you rate consider using geometry for your design and design process?*
   Not consider at all 0 1 2 3 4 5 6 7 8 9 10 Extremely considerable

5.5.2 THE RESULTS OF THE INTERVIEW QUESTONS

Chart 5-2 shows the results of the interview questions. Interview questions 1, 3 and 4 were rated in total forty four, thirty six and forty out of fifty respectively. Question 2 in the interview *'Applying geometric ratios in design'* was the most significant in terms of gauging how useful the set of refinement tools are, rating forty five out of fifty. It can be said that the golden ratio principle influenced the designers to a greater degree than other ratios due to its relative ease of use. The construction of Dynamic symmetry rectangles perhaps appeared to them to be a relatively time consuming process because it consists of drawing many complex lines as opposed to other geometric section rectangles. This could perhaps explain why it proved to be least popular. Interview Question 5 *'considering using geometry in design'* was rated forty six out of a total of fifty by the designers. However, the score of Interview Question 5 suggests that gaining geometric knowledge through the experiment process was effective and beneficial for the designers in order to utilize it in design.

Chart 5-2 The results of the interview questions



5.6 DISCUSSION

The feedback regarding the application of geometric knowledge and the refinement tools revealed that all five designers definitely found practical geometry a useful consideration for design purposes. However, the designers had specific concerns with the process such as:

1. It is important to consider the economic value of time consumed applying geometric knowledge and the refinement tools.
2. They addressed that it was rather significant for them to find appropriate projects with which to utilize their gained practical geometric knowledge.
3. Applying practical geometry in the design process needs to be approached in a

flexible way either in an earlier stage or later as part of an evaluation process.

In the feedback obtained from the usability of geometric analysis, the professional designers commented that it would take time to learn and apply practical geometric knowledge in their design process. It should be said that despite their perception of geometric knowledge being a time consuming process to learn and apply, practical knowledge obviously will require a certain amount of time to learn, and practice to perfect. Once the knowledge is gained however the students will find the process of applying it to their designs easy, beneficial and ultimately effective. However, having said that, during the course of the Geometry workshops in this thesis, it required only four hours in total for the students to learn the basis of practical geometric knowledge and to apply it effectively in design. After which, the design students manifested the ability to modify their designs while applying practical knowledge gained. So whilst it may appear to be a time consuming process initially, to the professional designers, the results of the experiments in chapter 4, and this chapter, showed that, after even a mere few hours of learning, geometric knowledge was an effective tool that could produce pleasing results, even in the hands of a novice when modifying the physical appearance of a design.

The individual designers understanding of geometric knowledge may be the biggest determining factor in how effectively geometry can be utilized in practical situations. Whether or not geometry was intentionally used in order to find suitable projects, it is apparent that the concepts of Golden ratio and Fibonacci proportions have been prevalently implemented in design since ancient times, the results of which, was the production of masterpieces of art and architecture that are still being revered as the benchmarks of design up until the present day. Today it appears that there may be a link between economic success of brand designs and the Golden ratio. Some companies consider it useful for their initial set of design constraints when designing products (Bloch 1995). Perhaps this is because the number of recent market research studies discovered that the ratio that most appeals to consumers is the Golden ratio (Nikolic, Cosic, Pecujlija & Miletic 2011, Raghubir & Greenleaf 2006).

The professional designers commented that there is a point to using the refinement tools and knowledge gained, either at an earlier or later stage, in their design procedure. Although it was suggested that practical geometric knowledge and Gestalt principles could be useful for managers who are involved with design decisions (Bloch 1995), it could also be effective for individual designers to be acquainted with this knowledge to aid the evaluation of their design, because in this instance a method to judge aesthetics of design needs to be constructive and rational rather than purely intuitive. Thus, geometry can be applicable at any design stage, yet it does seem that the level of a designer's geometric knowledge and experience, which could influence their decision to apply them at the appropriate stage, is certainly a significant factor in the degree of benefit that can be gleaned from using geometry as a refinement tool.

All five designers addressed the importance of using geometric knowledge and how it would be practical to use in design situations. Although the concepts of the refinement tools have been in use since ancient times, modern design as an entity has overlooked the potential value of applying geometric knowledge into design practices. It seems that using geometry in design can be an approach to developing aesthetics in design. Some artists and scholars may dispute that geometry could be a hindrance to artistic creativity, but that is missing the point. Geometric knowledge is not intended to be a substitute for the creative process, rather a means to enhance it. Golden ratio is not the determining factor in design, yet, nature and the human body are so closely related to the golden ratio. Of course, it may be too bold an assertion to say that the golden ratio is a determining factor in product design, but the reverse scenario seems equally unlikely i.e. given the proliferation of the golden ratio in our surroundings, in nature, and indeed in the human body, it seems equally unlikely that there is no connection and no influence upon designers.

5.7 CHAPTER SUMMARY

This chapter details the results of applying geometric knowledge and the refinement tools. It has been rigorously tested through five professional designers and the feedback gathered. The results from the questionnaires reveal that the golden ratio was the most effective ratio and design principle in the refinement tools. From the feedback, the professional designers were highly positive and enthusiastic about considering using and applying gained practical geometric knowledge in their design process. It showed that geometry can be effective knowledge for design students yet it is also important to judge the value of applying the golden ratio in design. The next chapter investigates the relationship between geometry and both one hundred classic modern designs and one hundred popular designs in recent history and responds to research question 5 *"How frequently do geometric ratios and golden ratio appear in best consumer choice products and expert designers' designs?"*

6. MODERN CLASSIC DESIGNS AND BESTSELLING PRODUCTS

6.1 CHAPTER PURPOSE

The purpose of this chapter is to investigate the characteristic proportions of modern classic designs and popular products. Following the criteria for geometric refinement set out in Chapter 5, this chapter utilized the refinement tools as a method to examine to which degree the frequently used geometric proportions (1, √2, Φ, √3, √4 & √5) occur in classic masterpieces and are embedded in design classics. It also aims to consider what geometric ratios are related to popular modern product designs. This is also to answer research question 5, *"How frequently do geometric ratios and golden ratio appear in best consumer choice products and expert designers' designs?"* This process facilitates the application of the frequently used geometric proportions and show how they can be implemented to improve popular designs and to embed the superior proportion of the classic designs in more mundane consumer goods. A geometric analysis was carried out of both one hundred items of design experts' choice and bestselling consumer choice designs. Selected classic designs from recent modern times were chosen in order to identify and analyse the geometric proportion of classic aesthetics in designs, and how their proportions would differ from bestselling products. *'Design status is earned not created'* and *'classic status is earned based on quality of execution, enduring qualities and restraint.'*(Hill, 2006). Thus, it can be said that design classics should not merely meet purely functional requirements but should also embody aesthetic values clearly manifested in products and as a result should be an expression of how classic design has influenced the aesthetics of product designs of the present time and those of the future. Bestselling products were chosen based on the largest number of sales which reflected consumer behaviour and how they were influenced by a considerable number of factors, such as quality, value for money, brand preference, environmental concerns and the aesthetics of the products. However, this chapter only attempts to highlight how the geometric proportions of bestselling products as everyday objects reflected the visual perception of consumers' purchases and how they are related to the frequently used geometric ratios.

6.2 METHODS & DATA GATEHRING

In total, two hundred designs were analysed by utilizing step1, 2 and 3 of the geometric refinement tools in chapter 5.

- Step 1 – Outlining design
- Step 2 – Applying geometric analysis in order to obtain "Design ratio".
- Step 3 – Applying golden section rectangle

For example, figure 6-1 and figure 6-2 show the steps of geometric analysis to collect design ratios as thesis data.

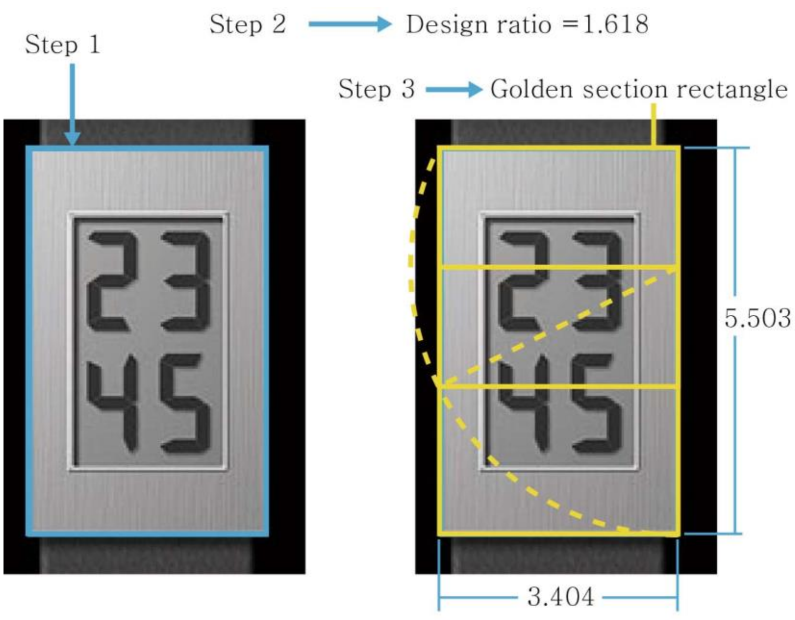


Figure 6-1 Geometric analysis of Flemming Bo Hansen's "WATCH"

Figure 6-1 illustrates the process of collecting the design proportions of Flemming Bo Hansen's "WATCH", from the design classics category. The outline of the design conformed to the golden section rectangle and therefore its geometric proportion was 1.618. The iPod Classic which is also in the design classics category did not conform to the golden proportion as indicated by the yellow rectangle in figure 6-2 which indicates the golden proportion. Thus, the geometric proportion of the iPod Classic was 1.673, which is 0.055 larger than 1.618.

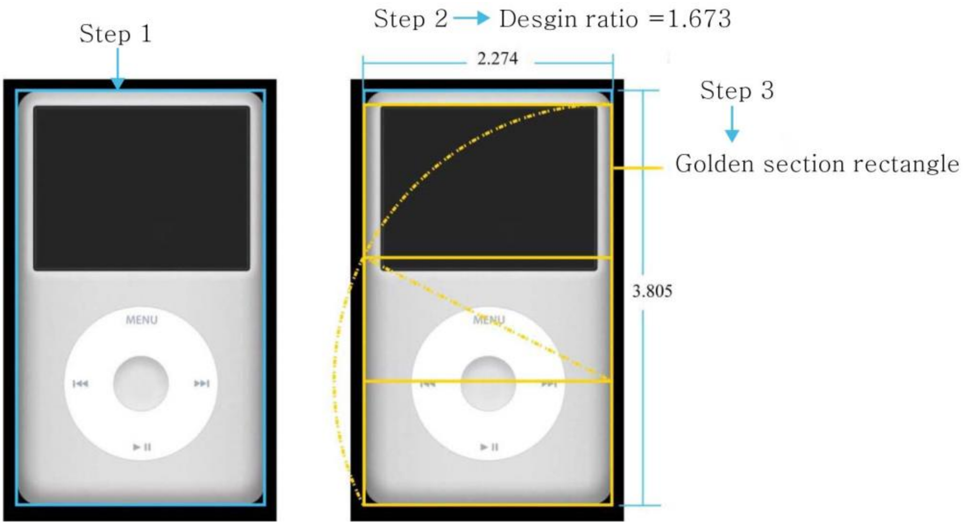


Figure 6-2 Geometric analysis of iPod Classic

One hundred superior designs were selected from *'Phaidon Design Classics'* (a three volume set) compiled from choices made by a panel of academics, journalists, architects, auctioneers, critics, curators and designers who carefully elected what, in their considered opinion, were the ultimate classic designs from the last two hundred years. The third volume of the *'Phaidon Design Classics'* was used for this chapter and all products were designed between 1980 and 2004. Electronic products were the items of highly advanced technology used to represent the status of popular consumer culture at the time. This is one of the best sources that can be used to investigate the trends in consumer choice, to then be compared and contrasted with the *'Phaidon Design Classics'*. The one hundred electronic items selected were the top twenty bestselling products across five categories of bestselling items sold through the online retailer 'Amazon.co.uk'. The categories were, MP3, Smartphone, Digital camera, Tablet PC and Laptop. The details of the items selected for the one hundred *'Phaidon Design Classics'* and the one hundred best-selling products are presented in the appendix section of this thesis.

6.3 Results

In total, one hundred and sixteen of the total two hundred (58%) were proportionally very approximate (maximum 0.076) to the frequently used geometric ratios (FUGR), 1, $\sqrt{\Phi}$, $\sqrt{2}$, Φ, $\sqrt{3}$, $\sqrt{4}$ and $\sqrt{5}$ whilst eighty four designs (42%) were not as close to the FUGR. As shown in chart 6-1, the larger number of product proportions in the classic designs category were closer to FUGR at rate of 64 % out of a total of 100 designs. However, only 52 % were close to FUGR in the best-selling category.

Chart 6-1 Frequently used geometric ratios in the classic & the bestselling designs

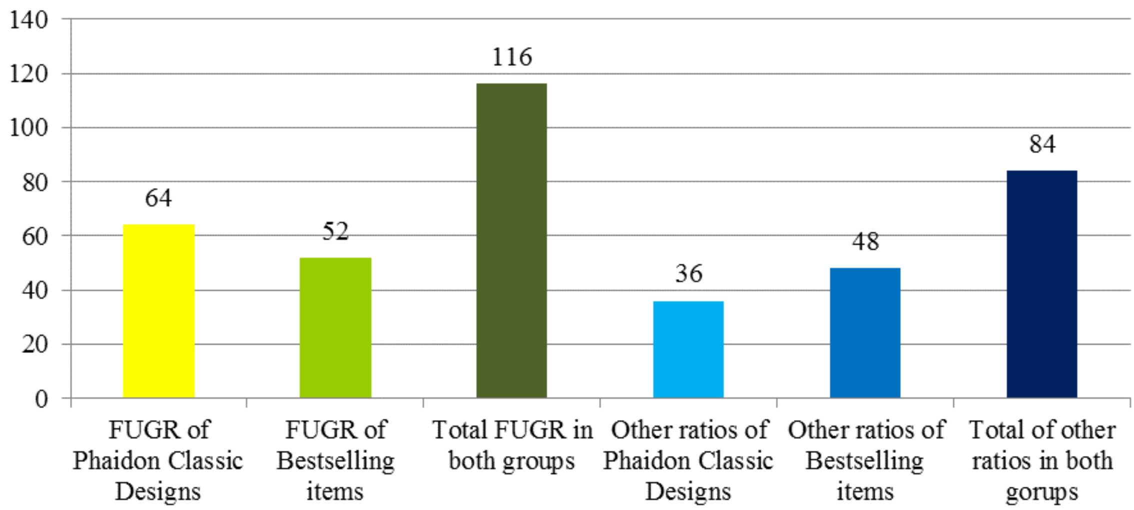


Chart 6-2 demonstrates how the *'Phaidon Design Classics'* and the bestselling items were divided into categories based on their geometric ratios from 1:1 to 1:2.2. Frequently used geometric ratios, √Φ, √2, Φ, √3, √4 and √5 were included in ratios 1.2, 1.4, 1.6, 1.7 and 2.2 respectively on the graph. The most commonly used geometric ratio in the both design groups was √2, with thirty three designs (16.5 %) were extremely close to √2 in proportion (between 0.013 and 0.076). Next, the largest number of the geometric proportions found was 1.5 and 1.6 rated 13% and 10 % respectively. The least commonly used ratio groups were 1.1 and 2.2 rated 2.5% and 1.5 % respectively. The chi-square of the results (x^2(14, N = 200) = 36.81, *p-value*=0.0008) is considered to be extremely statistically significant, as the p-value is less than 0.001. This means that there is less than a one in ten thousand chance of the stated results being incorrect based on observed error.

Chart 6-2 Geometric ratios of the *'Phaidon Design Classics'* & the bestselling designs

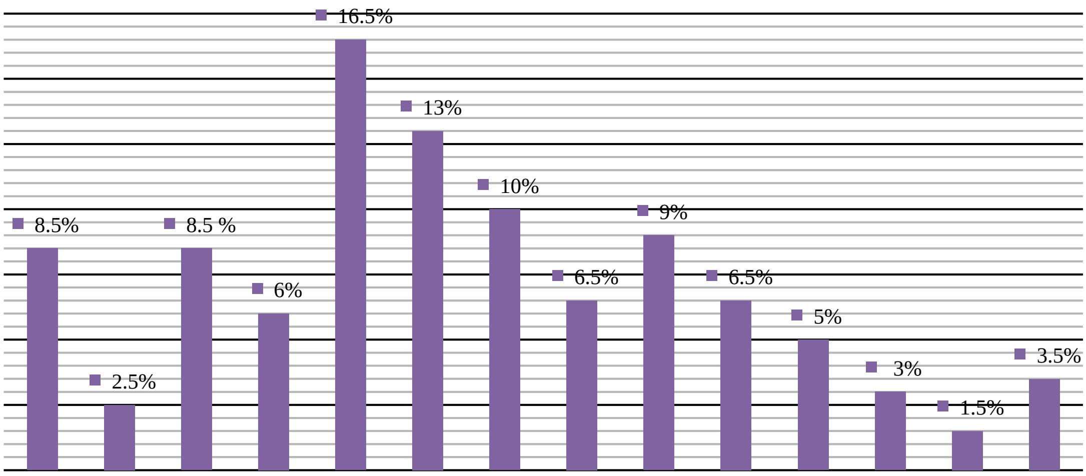
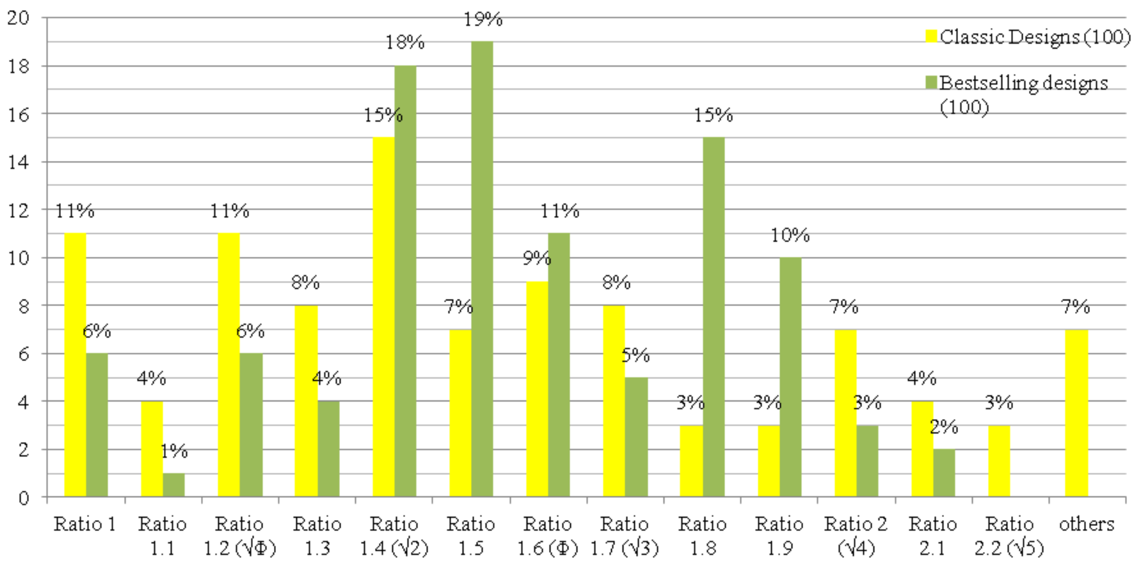


Chart 6-3 shows the comparison of geometric proportions in both the classic and the bestselling products. The larger numbers of geometric proportions in the classic designs were geometric ratios groups, 1, 1.2 and 1.4. However, the most commonly used ratios in bestselling designs were close to 1.4, 1.5 and 1.8. Although ratios of the Φ group (√Φ, Φ, √5) were used in ancient art, architecture and design, the classic and bestselling designs rated 23% and 17% respectively. None of bestselling designs were close to √5, yet there were three classic designs which were extremely close to √5 in their construction.

Chart 6-3 Geometric ratios of the classic & the bestselling designs



Furthermore, there are only eight classic designs which conformed to the FUGR as marked in yellow in table 6-1. In contrast no bestselling item conformed to any FUGR (see table 6-2).

Table 6-1 Geometric ratios of the classic designs

Ratios	1:1.0	1:1.1	1:1.2	1:1.3	1:1.4	1:1.5	1:1.6	1:1.7	1:1.8	1:1.9	1:2	1:2.1	1:2.2	others
Frequently used ratios	1:1		1:1.272 (=√Φ)		1:1.414 (=√2)		1:1.618 (=Φ)	1:1.732 (=√3)			1:2 (=√4)		1:2.236 (=√5)	
Geometric ratios of classic designs	1.096	1.102	1.22	1.375	1.413	1.5	1.618	1.736	1.875	1.989	2.071	2.131	2.2	2.87
	1	1.142	1.219	1.361	1.457	1.5	1.683	1.776	1.864	1.942	2.06	2.157	2.2	2.5
	1	1.172	1.23	1.321	1.401	1.555	1.666	1.78	1.837	1.979	2.032	2.19	2.25	8.75
	1	1.101	1.275	1.382	1.471	1.574	1.68	1.777			2.027	2.176		9.25
	1		1.25	1.308	1.482	1.5	1.681	1.709			2.021			2.898
	1.066		1.285	1.303	1.454	1.52	1.63	1.705			2			2.467
	1		1.25	1.333	1.428	1.5	1.66	1.76			2.021			6.571
	1.074		1.268	1.3	1.49		1.654	1.776						
	1		1.285		1.428		1.694							

	1.061 1.013		1.217 1.281		1.44 1.407 1.437 1.458 1.41 1.444									
Number of Classic designs by ratios	11	4	11	8	15	7	9	8	3	3	7	4	3	7
Total number of classic designs	100													

Table 6-2 Geometric ratios of the bestselling designs

Ratios	1:1.0	1:1.1	1:1.2	1:1.3	1:1.4	1:1.5	1:1.6	1:1.7	1:1.8	1:1.9	1:2	1:2.1	1:2.2	others
Frequently used ratios	1:1		1:1.272 (=√Φ)		1:1.414 (=√2)		1:1.618 (=Φ)	1:1.732 (=√3)			1:2 (=√4)		1:2.236 (=√5)	
Bestselling design ratios	1.089 1.089 1.089 1.089 1.022 1.039	1.18	1.295 1.279 1.287 1.298 1.215 1.288	1.372 1.302 1.302 1.33	1.49 1.408 1.408 1.408 1.468 1.466 1.468 1.408 1.455 1.468 1.466 1.431 1.406 1.451 1.431 1.411 1.445 1.454	1.5 1.571 1.575 1.5 1.5 1.5 1.59 1.509 1.522 1.509 1.56 1.515 1.509 1.534 1.546 1.504 1.534 1.522 1.547	1.674 1.6 1.674 1.641 1.688 1.694 1.684 1.64 1.635 1.666 1.671	1.722 1.777 1.78 1.777 1.742	1.884 1.884 1.877 1.884 1.824 1.817 1.863 1.876 1.835 1.893 1.864 1.888 1.864 1.854 1.816	1.9 1.936 1.931 1.934 1.934 1.929 1.929 1.903 1.942 1.903	2.098 2.098 2.014	2.103 2.112		
Number of bestselling designs by ratios	6	1	6	4	18	19	11	5	15	10	3	2		
Total number of bestselling designs	100													

6.4 DISCUSSION

After detailed comparative analysis of the geometric proportions between modern design classics and bestselling items, there appear to be five major findings.

Firstly, the FUGR appeared in modern design classics with a much higher frequency than they did in the bestselling items category. These results might suggest that Φ and other basic geometric proportions, √2, √3, √4 and √5 are, for whatever reason, not popular in mainstream product design at the present time. However the most commonly used design proportions in both design groups analysed was close to √2 ratio. These results differed from the results of previous experiments by Fechner (1876), Lalo (1908), Berlyne (1970), Godkewitsch (1974), Piehl (1976, 1978) and Benjafield (1976) who claimed that the golden ratio was the most preferred proportion whilst the results of others, such as Davis (1933), Schiffman (1966, 1969), Nakajima and Ohta (1989), Davis and Jahnke (1991) opposed that research saying that the golden ratio was not the most preferred proportion to other ratios. It must be noted however that all these experimental results noted above were based on simple geometric shapes, rectangles, ellipses and triangles and not actual products. A choice of simple geometric shapes, it could be argued, may have resulted in limited stimulus or indeed too broad a range of stimulus (Green 1995, Konečni 2003). Despite Schiffman (1966, 1969), Nakajima and Ohta (1989), Davis and Jahnke's (1991) results, it is not merely the geometric proportions that create the aesthetic beauty of a product design. Each product is designed with more than just one geometric shape. Harmonious composition and proportion are also necessary. Only a few researchers, Davis (1933) and Konečni (2003) have analysed the design proportions of participants own drawings, geometric shapes and painter's sketches and used them as a method of stimulus. Davis' participants were psychology students who drew their favourite simple rectangle, and Konečni's subjects were artists whose sketches were elaborate drawings, which were obviously more sophisticated than plain rectangles. As their results showed, participants' drawings were close to the golden ratio (71.4%) yet Davis' participants preferred √3, √4 and √5. These results would suggest that perhaps participants' artistic knowledge was the factor responsible for the significant influence on their perception of aesthetic preference. However it is important to note that the preferred proportions of both experiments were all included in the frequently used ratios. It can be said that because of the individual methods and procedures used by researchers, the results of their experiments were unable to conclude that the golden ratio was the determining aesthetically pleasing proportion.

However, the purpose of the above empirical research was substantially different to the purpose of this chapter's research. Here, an attempt is being made to examine both design classics and bestselling items, which were designed in various styles and proportions. Also, not all consumers are psychology students and are certainly from varied backgrounds. It is noted that the aesthetic guideline, the golden proportion, 1.618 appeared not to be the most commonly used proportion in both modern classic and bestselling designs. It is interesting to note that even though the golden ratio appeared frequently in masterpieces, the results of geometric proportion analysis showed that practical geometric knowledge and their exact proportions in product designs was less prominent, and perhaps the fact that the design ratios used were very often close to the commonly used geometric proportions, could be further evidence that they are intuitively utilized amongst designers, rather than being the result of their practical geometric knowledge.

Secondly, the largest proportion of geometric ratios used in each design group were close to ratio 1.4 in design classics and 1.5 in bestselling items. It is significant that there were a large number of designs close to ratio √2 (1.414) in both design groups. It is possible that designers were being subtly influenced by the wide spread paper grading system ISO (International Organization for Standardization). The series of 'A' paper is most commonly used today and it just so happens to be based on √2. Moreover, the dynamic symmetry subdivisions of √2 rectangles produce a variety of harmonious compositions and proportions which conform to various design classics (as noted in Chapter 6, a √2 rectangle possesses the special property of being able to be infinitely subdivided into proportionally smaller √2 rectangles. The proportion of a √2 rectangle is approximately 1.414 which is rather close to the golden proportion, 1.618) (Elam 2002, p.34).

It is also interesting to note that ratio 1.5 was mostly used in bestselling designs, (19%) compared with classic designs (7%). This result was similar to Boselie's experiments in 1992. In his second experiment, he used eight golden section and eight 1.5 rectangles each containing one interior line, presented in the horizontal orientation. He found equal preferences among subjects for 1.5 and the golden ratio and argued that it was a refutation argument for the preference of the golden proportion. In the third experiment, he used thirty subjects to compare six pairs of plain rectangles. One of each pair was of golden ratio proportion, the other was 1:1.5. In half of the pairs both rectangles had equal-length vertical sides. He concluded that 1.5 was most preferred choice of aesthetic preference and *'the golden section has no special perceptual aesthetic attractivity'* (1992, p16). It can be argued that the subdivided smaller rectangles for each pair may have influenced participants' preference, such as an equal division of a 1.5 rectangle, which produces two smaller proportioned 1.333 rectangles and a 1.618 rectangle produces two 1.236 rectangles. The former smaller rectangles were close to the √2 rectangle which was the most used geometric ratio in both design groups, according to the results of this chapter's experiment. Thus, it seems that the results of whether the participants were biased towards the proportion of 1.5 rectangle or the smaller rectangles in 1.5 were not clear. It may suggest that the reasons for ratio 1.5 being the most used in bestselling items were 1) there were only a few design resources presenting the method of geometric construction of the golden section rectangle, root rectangles and other geometric shapes as well as dynamic symmetry of harmonious subdivisions. 2) software design tools such as CAD, Adobe Photoshop, Adobe illustrator are based on distance and angles, as well as on a grid in square proportion, 1:1, rather than body proportion, 1:1.618. Moreover, geometric shapes, the golden section rectangles and ellipses, as well as other root rectangles, are not provided in the software. Thus, for designers it is more convenient for them to create geometric shapes which are based on what can be easily produced via the software.

Thirdly, there were more designs of 1.2 (11%) and 1.3 (8%) proportion in classic designs between 1980 and 2004 than bestselling items in 2013 (1.2 (6%) and 1.3 (4%)). Design ratios close to 1.5 and 1.8 in the number of bestselling items were higher compared to the classic designs, rated 19% and 15% and when added together it became 34 % in total of bestselling designs. This figure was significantly higher than in the modern design classics, which only appeared to be 10% in total of the classic designs. This may occur because designs close to ratios, 1.5 and 1.8 are influenced by the use of touch screen displays, which has been subconsciously and deliberately implemented in electronic designs for obvious reasons. This is perhaps one of the recent trends of the technological adaptation process manifested in product design. There have been increasing degrees of consideration regarding the size of high resolution and touch screen products which have led to electronics being designed with much bigger screens since 2008 (Bonnington 2013).

Bejan (2009, 2012) makes the claim that although design proportions were not the exact value of Φ, there are many designs which very closely resemble Φ and this could be due to biological and cultural, as well as technological, evolution which is governed by the 'Constructal law' of nature ('Constructal Law' is reviewed in Chapter 2, the literature review). According to him, the scope of binocular vision is close to the golden ratio and humans may, as a result of practical needs, have evolved to scan the binocular area faster and more efficiently to deliver information to the brain in the shortest time possible. For example, the first design of old computer and TV screens were close to proportion 1.33, now technology has brought wider screens close to the golden ratio and more recent high-definition television (HDTV) screen ratio is close to 1.8 (Bejan 2012, pp. 224-229). From his point of view, it could resolve the question as to why a significant number of masterpieces which conformed to the golden ratio, and the geometric proportions of art and architecture, produced a degree of beauty and aesthetic qualities which were pleasing to the human eye.

Fourthly, it seems that there are a plethora of other scientific references which can be considered in order to respond to the question of the golden ratio being an aesthetic principle, which, instead of being relegated to merely some quaint archaic aesthetic notion consigned to the dustbin of history, its potential should be more fully explored and implemented into design in modern times. Visual perception and cognition evolve together. Psychologists inferred that rectangle preferences were based on considering the proportion of the binocular field of vision, 1.665 (Borissavlievitch 1952, Stone and Collins 1965, Schiffman and Bobko 1978). On one hand, it may suggest that exploring the scientific relationship between the golden proportion and human field of vision could provide one of the most natural and organic methods for designing objects. It also may explain why master mason's works were designed to conform precisely to the golden ratio, and why works of great beauty were designed to withstand the passing of time. On the other hand, there were also countless researchers, David and Jahnke (1991) who found that there was a strong preference for equality of division; and Nakajima and Ohta (1989) concluded that the golden proportion was not preferred over other ratios (1989). Yet there is criticism of the conclusions drawn by these different experiments regarding visual perceptions being the results of methodological problems (Green 1995). It seems that it is difficult to conclude that the golden ratio was the preferred proportion based purely on aesthetics and psychological approaches relying on data gathered from individual preferences of geometric shapes. Other areas of study need to be considered too, such as how the relationship between the golden ratio and humans actually works and what are the implications thereof, if any. It is thought that the process of coding and organising information in the brain is based upon golden ratio principles (Weiss 2003) and the BBC programme "*The Human Face*" introduced Dr Stephen Marquardt's research regarding how the golden proportion is directly utilized in the field of cosmetic and dental surgery as a template for reflecting beautiful facial features and teeth in humans (http://www.bbc.co.uk, accessed 21 March, 2001). It seems that the previous opposing psychologists' research cannot be considered conclusive regarding the golden proportion as the preferred aesthetic proportion was also only based on two dimensional geometric shapes. In the real physical three-dimensional world, the golden ratio is utilized to produce both simple designs and even most the sophisticated designs. For instance, mundane items such as credit cards or debit cards, as well as processes in nature, including the cosmetic construction of the human face. As Dr Schmid discovered, facial attractiveness can be quantified based on proportion and symmetry, the length compared to the width of the face should be 1.6, i.e. the golden ratio. The highest scoring faces in terms of aesthetics are those of celebrities, such as Angelina Jolie, Brad Pitt and George Clooney (Schmid, Marx and Samal 2008).

Lastly, table 6-1 and 6-2 showed that there were only few designs in the design classics which conform to the exact value of the frequently used geometric proportions. This is a manifestation of how there were very few designers who utilized practical geometry in design even though the golden ratio clearly has a case for being the most pleasing geometric ratio to the human eye. There are successful examples of the golden ratio being embedded in prestigious designs throughout of history, such as Stradivarius violins (17^{th} century) and Flemming Bo Hansen's "WATCH" (1989). Depending on the condition, Stradivarius violins can be worth millions of dollars. But its value is not due to the fact that it is merely an antique. Among experts, the Stradivarius violin is famed for its unique tone and a quality of sound that has defied explanation. Flemming Bo Hansen's "WATCH" has also achieved both high sales and acclaim. More recently, the Aston Martin Rapid S (2013) and DB9 (2014) were developed by using the golden ratio in every part of their exterior design. All the above designs are considered bench marks for quality and luxury. If it seems that objects which reflect the golden proportion can be considered to possess superior aesthetic value, then surely it is apparent that designers should consider utilizing this and other proportions more frequently in their work. However, the results of the geometric analysis of the two hundred designs illustrates that perhaps the way to approach geometry is as a method to codify and maximize creativity. To utilize geometry to its fullest creative potential, designers must be encouraged to see it as a practical resource for artistic inspiration and creativity in everyday design practice. As Kimberly Elam said in her book *'Geometry of Design'* that '*geometric organization, in and of itself, does not* *yield the dynamic concept or inspiration, what it does offer to the creative idea is a process of composition, a means of interrelationship of form, and a method for achieving visual balance. It is system of bringing the elements into a cohesive whole"* (Elam 2001, p.101) Thus, geometry needs to be approached as a way to emphasise 'proportion' which can lead to achieving balance and harmony between nature and the human made artificial world.

The reason for analysing both design groups was to investigate the relationship between FUGR (1:1, 1:1.414(√2), 1:1.618 (Φ), 1:1.732 (√3), 1:2 (√4) and 1:2.232 (√5)), which are derived from Pythagorean theorem and Euclidean geometry, and product designs in modern times. From the results of data gathered from design classic and bestselling designs it can be said that the most commonly used ratios in the both design groups were extremely close to √2, and thus √2 is the most used proportion in modern design classics. The FUGR still appeared in design, yet the golden ratio has been regarded as an important aesthetic guideline for over 2000 years. It seems apparent that in modern design designers have adopted a more holistic approach to design, which encompasses both scientific references and aesthetic considerations.

6.5 CHAPTER SUMMARY

This chapter tested how the geometric proportions inherent in modern classic designs compared with those of bestselling designs. It is noted and accepted there will have been separate design considerations for both the former possessing superior aesthetic value than bestselling items, which are mundane consumer objects for everyday life. There were many designs in *'Phaidon Design Classics'* which were designed and constructed with ratios which closely resembled the golden ratio and the frequently used geometric ratios.

Yet there were few designs with the exact values of Φ or any of the other frequently used geometric proportions. As such it can be said that clearly the golden ratio and practical geometry tend not to be effectively utilized in modern classic designs in the past, nor in design at present. A considerably larger number of items in the bestselling category were close to 1.5 than they were to other frequently used ratios. This thesis means to examine how to implement practical geometry as a design method available to designers which takes into account both scientific references and aesthetic considerations. Chapter 7 presents a thesis' conclusion.

7. CONCLUSION

The purpose of this chapter is to summarise the principal findings gathered in this research project. It also explains the implications of these findings, elucidates upon strengths and weaknesses of the thesis, highlights problems encountered, the limitations of the research and makes suggestions regarding further research that may be undertaken in this field of study in the future.

This thesis appraised the potential importance to designers of utilizing geometric knowledge when designing and investigated how geometric knowledge can be transformed into effective design tools directly applicable in any design situation. It focused chiefly on the practical aspects of refining the aesthetic appearances of designs. The application of geometry was tested by the participating students and they learned just how easily the principles can be integrated into practice. In particular, the use of the golden ratio for analysing their (and the professional designer's) designs, indicating the differences in aesthetic proportions between their original designs and the same design refined to conform the golden ratio. As the golden ratio is one of the main aesthetic principles found in masterpieces, it is the author's assertion that the integration of geometric knowledge as a practical method in design education could prove to be beneficial and provide future design students with a more complete and intuitive understanding of aesthetics.

In order to gather data for analysis a series of workshops were conducted in both U.K. and South Korea. The results of the analysis of one hundred *Phaidon design classics* and one hundred bestselling everyday objects form Amazon contained in speak for themselves and signified that the geometric knowledge has not been fully utilized by designers who have the mass-market in mind.

Thus this thesis examined the application of basic geometric ratios in design as a rational approach to measuring the aesthetic value of designs. This is achieved by the use of a set of practical design tools derived from a basic geometric process. It is not intended to be a substitute for creativity, but rather a means of rationalizing and analysing the results of creativity, where appropriate. In this thesis, the collective opinions, of both design students, and professional designers, were examined in an attempt to explore the perception of the application of golden ratio and other common geometric ratios. Their views were collated and used to ascertain the efficacy of the author's geometric refinement tools in use, which could be seen as a valuable exercise in terms of revealing the potential contribution to both professionals and students alike in refining the aesthetic appearance of designs. The thesis also enters into a discussion of the problems and differing views surrounding the visual preferences of the golden proportion via the professional designers' evaluation of the process of implementing the author's refinement tools. Therefore It is the author's sincere hope that the concepts behind in this cross-disciplinary study will be considered a scholarly contribution to the field of design, and to the future of design education.

7.1 THE OUTCOMES AS ORIGINAL CONTRIBUTIONS TO KNOWLEDGE

This section states the findings of the thesis and reveals what the author considers to be an original contribution to practical knowledge in design practice and design education.

Research question 1 asked: 'What is the value of developing effective design tools based on knowledge of geometry and applying them in product design education?'

As was presented in the Literature Review, the knowledge of geometry embedded in ancient arts and architecture is largely overlooked in modern design education and practice. However research into the aesthetics of facial attractiveness has revealed the golden ratio to be an extremely effective tool for examining aesthetic beauty.

Bejan's theory of constructal law explains the golden ratio as a naturally occurring phenomenon, therefore, it is an important factor in the link between the evolutionary process of design and visual preference. Bejan appreciated that geometry can be used to generate a practical design theory enabling us to understand why, and how, the natural environment and manmade objects can be harmonized, because the environment is formed by, and consists of, both humans and objects.

World renowned Ethnobotanist Terence McKenna famously once said that *"Nature is the great visible engine of creativity, against which, all other creative efforts are measured."* (McKenna 1990). In fact, nature has been one of, if not the greatest sources of inspiration for many different areas of study. It is hard to imagine artists, architects, designers and scientists not looking to nature for inspiration either via a conscious process of investigation, or subconsciously due to the simple fact that we are all influenced, to a greater or lesser degree, by our immediate environment. Given that golden ratio is the only ratio repeated again and again throughout all natural organic environments, not to mention in the human body itself, it seems more likely than not that this ratio, in particular, has influenced the psyche of humans for millennia of their existence, surrounded by and co-existing with its proportions in nature. The pertinent question this thesis is concerned with is why are there a plethora examples of objects designed for the public or mass-market not conforming to golden proportion when its connection to human beings has long been an established scientific fact. It was shown in the Literature Review of this thesis that many researchers in various fields have been using the golden ratio as one of their most effective and precise analytical methods of examining aesthetic beauty. And yet surprisingly, however there is still clearly much convincing to be done of its harmonious potential when being used in the product design process. Its application has not been widespread in design education nor is it prevalent in designed objects. Therefore, this thesis enquires whether it is an untapped resource regarding its potential benefits, both when designing products and educating design students.

This led to the discussion of research question 2: 'How can geometry be useful as a practical method in design for developing visual coherence?' Original ways of applying geometry as an analytical method to measure the proportions of the designed objects were explored and how it can be developed as a design theory referenced to aesthetic preferences. The work presented in chapter 4, arising from geometry workshops, introduced specific geometric methods to the participants, such as geometric analysis, the construction of the golden section rectangle and its application for refining aesthetic appearances of designs, as well as other related geometric knowledge. These were all utilized for investigating the development of visual coherence while recognizing the proportions of own designs. Practical geometric knowledge was transformed to these analytical methods and they were directly implemented in the design process because, in general, the golden ratio was used as a resource for creativity or inspiration for designs. However this thesis' approach was to use it as an analytical methodology which could be used to aesthetically modify original designs. It can be said that this approach to design, using commonly occurring basic geometric ratios as a component part of the creative design process, is this thesis' contribution to design studies and presents findings that confirm the golden ratio can be articulated in various ways to create harmonious subdivisions.

Consequently, the applications of the specific methods were tested on design students in order to ascertain how effective these methods were and to investigate the relationship between golden ratio and intuitive design proportions responding to research question 3: 'What are the perceptions of design students regarding the implementation of geometric principles as a means to recognize their own level of visual knowledge?' The results shown in chapter 4 demonstrate that these practical geometric methods have produced intriguing results regarding them being an effective way to identify design proportion. At the same time, the process of applying geometric analysis has led design students to recognize their level of visual coherence. Therefore geometric knowledge in design practice could contribute to an effective self-analysing design method for design students by including the golden ratio principle in their design process.

Experimental methods, such as questionnaires and drawings were used in order to obtain data, from which, the vital information was gathered with regard to the author's hypothesis of the golden ratio being a significantly more pleasing ratio to the human eye and therefore we may benefit from a more widespread consideration of its potential properties when producing the designed objects that surround us.

In design practice and design education, the use of golden ratio and other related ratios has not been recognised as an analytical method for the purpose of aesthetically refining designed forms. This thesis has had some degree of success, shown in practice, with individual design student's views that it can, and indeed does, contribute to improving evolving design decisions as they are being made. Therefore, building practical design theory by incorporating geometric experiments into design, is an innovative approach to design practice. Analysis of the external appearance of products is, of course, always a rather subjective process yet practical geometric methods would support the design student's aesthetic decisions, making available a rational justification of the relative proportions used in a design. The experiment with the students led to the development of the geometric refinement tools for a further adjustment of aesthetics, which in turn assisted in evaluating the impact of geometry when applied to the professional design process.

Thus it was verified by the professional designers, and responded to in research question 4: 'How do professional designers consider applying geometric knowledge in their design process? The professional designers' perceptions were presented in chapter 5. Unanimously, they concluded that golden proportion was the most effective design tool amongst them. Furthermore, the professional designers views on applying geometric knowledge as an integral part of being creative was completely positive, as illustrated by the fact that, in terms of aesthetics, seventy two percent of designers preferred designs refined by the golden ratio and other commonly used ratios over their own design's original proportions.

The results of applying the geometric refinement tools to the professional designer's designs clearly had a strong correlation with the results obtained in visual perception tests by Konečni (chapter 2, p25). He used images ranging from simple geometric shapes of vases, to the work of an unknown artist, called Kodama, who used golden proportion in his work, as well as works of art considered classics by artists Mondrian and Whistler. He concluded that the effect of golden proportion may appear to be more pronounced when a work of art exhibits fine balanced qualities. Perhaps this could be one reason why research completed by psychologists, such as Davis (1933), Schiffman (1966, 1969), Boselie (1984) and David & Jahnke (1991) could not produce any conclusive findings regarding the golden ratio being the most aesthetically pleasing proportion. Their methods used relatively unsophisticated geometric shapes, either provided by the researchers or drawn by the psychology students who were themselves the subjects of the test. In addition, the work of other researchers, Ghyka (1977), Lawlor (1982), Hambidge (1977), and Doczi (1981) has manifested a clear tendency for the repeated occurrence of the golden proportion in what are considered to be the greatest works of art and architecture throughout history. Bejan's theory of constructal law explains golden ratio as a natural phenomenon, and he considers it to be an obvious factor in the link between the evolutionary process of design and visual preference.

This thesis applied practical geometric knowledge to the professional designers work to evaluate if the use of geometry could have a positive impact upon modern professional design scenarios. And there appears to be evidence to suggest the author's method of aesthetic refinement proved to be an effective method of codifying the notoriously elusive and intangible creative process, providing a means by which design decisions can be rationalized. As Simon Unwin emeritus professor of architecture at the University of Dundee, Scotland commented that *"Designing is a difficult thing [making] decisions about relative sizes is [hard]… If you adopt* *a rule-such as using the golden ratio whenever you can- life becomes easier. The decision is made for you by the rule you have adopted."* (Shan 2013).

For the purpose of this thesis, the author examined the geometric proportions of 100 classic designs since the 1980s and 100 bestselling products between 2010 and 2012 in order to respond to research question 5: 'How frequently do known geometric ratios and the golden ratio appear in best consumer choice products and expert designers' designs?' Ironically, the results as shown in chapter 6 were that the golden proportion did not appear to be the most used ratio in either category i.e. the classic designs and bestselling products. There were only a few classic designs that contained golden proportion and other frequently used ratios and none whatsoever that conformed to golden proportion in the bestselling designs category.

But what if these results are a symptom of a wider tendency that is a result of man's gradual retreat from nature and organic environments over time to live in, and be surrounded by, increasingly man-made high-tech environments. There are not many people these days, who, when faced with the prospect of being lost or stranded in a natural environment, could feed themselves and find enough clean water to stay alive even for a few days. This is obviously a more visceral and exaggerated example of our disconnect from nature, but on a more subtle level the author asserts it may be entirely possible that our intuitive affinity with the ratios of nature has also been incrementally eroded as time moves on.

Are consumers and suppliers becoming unwittingly locked into a false paradigm where choices are not an accurate representation of their actual preference and instead merely reflect a preference within the limited choice they are being presented with? It would be interesting to see the results of the bestselling product category for a market comprised of an equal amount of golden proportion products as non golden proportion products.

It may take a concerted effort to instigate the inclusion of the golden proportion and associated root ratios, as an integral part of the design process of objects for mass consumption. Designing and creating objects with these organic proportions in mind, whilst common-place in ancient times as the human body was the universal unit of measurement, has almost entirely been phased out of consideration as being useful, practical and most of all relevant to modern designers. And yet if the hugely lucrative cosmetic beauty industry is to be considered, cosmetic surgeons and dental surgeons alike have long recognised the importance of its proportions and have been utilizing the golden ratio regarding aesthetics when it comes to optimizing facial beauty for quite some time. However the benefits appear to be greater than the more superficial aspects of cosmetic surgery. There also appears to be many health aspects to the use of the golden ratio also (Chapter 2, p.29).

Given the subtle energetic effect of shapes on the human psyche, and considering we will be surrounding ourselves with these designed objects and products, it can only be beneficial to find a method for designing that satisfies both these considerations and incorporates them in a unified approach.

It is beyond dispute that many plants, animals, the human body and the binocular field of vision all share a common connection with the golden ratio (Stone &Collins 1965, McWhinnie 1989). And given the frequency with which it occurs around us and even in us, one wonders how we manage to continue to ignore that which is essentially part of our make-up and that of our surroundings, to produce objects which have no real harmonic correlation with the natural environment or the human beings who will use them.

There is at the very least a case to be argued that perhaps classic ancient works of art were almost a direct manifestation of nature, through the human beings, via the art. One does not have to go back very far in history i.e. the era of steam and when the first engines were built for commercial use, to encounter an infinitely, slower, quieter world where people followed natural processes largely because they had no option. Limited technological progress in the past forced people to follow and rely upon the natural cycles of time and events.

As the famous Austrian writer Karl Krauss once said; *"Progress celebrates pyrrihic victories over nature"*. It seems that no matter how far mankind wanders from nature we soon realise our separation from it, and our "power" over nature is illusory at best and an arrogant presumption at worst. Nature does not rely on intellect to produce its works of art. The golden ratio is manifested repeatedly in nature and in the human form, even in the grooves in our D.N.A conform to the 'Phi' ratio. It seems strange that such an important ratio concerning all cellular life on this planet should be so readily over looked when designing objects that will adorn our living spaces, and our working spaces.

Therefore in design, practical geometric knowledge of golden proportion can be seen as a vehicle with which to regain natural balance and to re-harmonize with the environment. Geometry can provide a creative approach and a specific technique of using experimental research to construct a practical theory which codifies aesthetic reasoning to make an original contribution to the field of product design studies, especially design education. In practice, it can be said that practical geometric knowledge has shown itself to be a useful resource for systematically analysing a design's aesthetic appearances.

Thus, the main recommendations in this thesis for the application of the golden ratio as geometric refinement tools are:

a) It is intended to be used as an aesthetic guideline which can be incorporated at any stage in design should any uncertainties arise. The author's refinement process has in practice proved to be practical and useful to both professionals and novices alike.

b) As explained in chapter 4 and 5 of this thesis, there are three key steps to follow when refining a design with geometry: 1) applying geometric analysis – drawing a rectangle which outlines a design to find out the ratio of the rectangle which the becomes the proportion of the design appearance, 2) applying the golden section rectangle on top of the design. 3) Refining the design to conform the golden ratio by modifying the original proportions.

c) The use of geometric refinement is merely a way to identify how the appearance of an original design can be refined aesthetically. Functionality is not what is being measured. Once analysis of the refined design has taken place the new refined design can be compared with the original and any necessary aesthetic improvements can be made. Perhaps the designer may prefer their original design but after a refinement process, at least now they know why.

7.2 STRENGTHS AND WEAKNESS OF THE STUDY

This thesis was an attempt to find a solution to the problem posed by the need to coherently quantify the aesthetic and creative process in design. Using the author's refinement tools, all designs can be examined equally from an academic perspective, and whilst the use of geometry is not intended to be a substitute for creativity, the nebulous nature of the creative process can now be successfully codified to some degree. Developing the design refinement tools was a challenging undertaking due to the fact that during the experiment the personalities behind the creative decisions which led to the evolution of each individual design, were extremely varied, as the outcome of the experiment shows. That being the case despite the differences in personalities, all the participants, both students and professional designers alike, found the refinement to be both an effective and straightforward method of refining their designs.

The outcome of this thesis regarding how it makes use of the golden ratio, geometric analysis and geometric refinement, will of course not solve functional problems in design, and only concerns itself with improving aesthetics. The practical geometry approach contributes to design theory and future cross disciplinary studies. However, the outcome stands to impact less upon the design audience who emphasize practical geometry as a method to solve or improve functionality. Perhaps this can be seen as a weakness of this thesis. However, its intended focus is as a practical tool to analyse designs in an aesthetic capacity, and to transform creativity offering a deeper level of understanding of using geometry and the implications thereof.

Two of the five designers had a tendency to ignore the author's advice regarding aesthetic appearance and insisted on choices based on 'functionality' rather than aesthetics. Although, during the experiment with the professional designers, the use of the term “favourite design” was referring to the most aesthetically pleasing design. It was clearly explained to the designers that functionality was not being considered at all. Although despite this being the case, some were unable to follow the guidelines provided and their choices reflected their fixation on the functional aspect of their design.

In summary, when a practical geometric knowledge approach is taken in order to address an aesthetic problem that has been established as relevant to practices, there is a requirement upon designers to adapt and there is the risk that the outcome affects the success of the original designs. However, in application, most designers preferred the new geometrically refined designs to their own originals. So this process of refinement does not appear to be a negative according to feedback and results collected. Once designers are able to apply the geometric refinement tools, they can provide effective results and a useful perspective from which to examine aesthetic problems, which can be seen as a strength of this thesis.

7.3 LIMITS OF THE RESEARCH

The research design illustrates a methodological and self-reviewing process in design. It also highlights design students and professional designers’ own perceptions of applying geometric knowledge to their designs. Although this thesis collected data through the use of questionnaires, geometry workshop assignments and semi-structured interviews, both groups of participants were complete novices when it came to applying geometry to their designs. Therefore they were limited to using fundamental geometry as opposed to a more advanced level due to time restrictions.

However, the use of practical geometric knowledge has not yet been fully included in design practice and design education. Therefore, it was necessary for this thesis to focus on experimenting at the beginner level of geometric knowledge in order to appeal to design students aiming to apply it to their own designing process as a refinement tool rather than investigating and examining how far geometry can be utilized to improve creativity.

Although the author's refinement tools were tested via the professional designers applying them, the designers could perceive learning the basic geometry as being a time consuming process if they are unfamiliar with these ratios and how to apply them. This may also be another limitation of this thesis. Because the experiment was not part of their course work, students did not have much time to devote to learning the basic skills required to use the geometric refinement process to its fullest potential. Initially it takes time to learn how to construct the various ratios and how to implement the process into designs and to reflect on progress being made. Being unable to motivate students to volunteer their free time resulted in a deficit of feedback data available for a deeper analysis.

7.4 OPPORTUNITIES FOR FUTURE STUDY

In the course of the research for this thesis, despite it being chiefly concerned with solving aesthetic problems encountered when designing objects, many more avenues of research opened up that would be worthy of scrutiny regarding the connection between the golden proportion, nature, human beings and the potential implications upon the human psyche of disrupting this balance. Firstly, the most glaringly obvious opportunity for further exploration would be the development of computer software that would enable the author's geometric refinement tools to be immediately accessible, and straight forward for anyone to use, even for those with no prior knowledge of geometry. Currently the author's refinement process is limited to a two-dimensional format whereas a three-dimensional computer software programme could be developed which obviously would provide designers with a more accurate and realistic idea of the end product almost immediately.

In addition, it can be suggested that there may be the opportunity for cross-cultural studies regarding the differences in performance between the students in U.K. and in South Korea. Some degree of differences in the approach and level of intuitive or artistic skills of the students may emerge from further investigation into these areas. Perhaps different examination standards and a different emphasis on course work could results in differences.

Other areas of further research that could be explored involve examining the depth of potential connection between the concept of resonance and human well-being which will draw from elements of the science of BioGeometry, the "subtle energy quality of shapes", which is at the core of the forming process in nature, and is responsible for maintaining harmony within the energy structures of all systems both animate and inanimate. BioGeometry is a holistic perspective, or a physics of the energetic quality of objects, and is concerned with inner and outer environmental qualitative balance. Ibrahim Karim postulates that BioGeometry points the way to a new approach to design which has been proven to be successful in research projects spanning some thirty five years.

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Appendix I Feedback

The purpose of the interview was to review how designers would like to see geometric knowledge, and the set of geometric refinement tools, implemented in the design environment. Here is a selection of the designer's own words on their experience of participating in the experiment of applying geometric knowledge to their own designs:

1. In your opinion, how useful is geometric analysis in design?

Mr. Davey: *"whilst I think there are so many other things, you need to consider not only geometry, I accept that you cannot ignore geometry"*

Mr. Diamantidis: *"I think it is extremely useful. I have realised that in general, designs are shapes, you cannot draw shapes without geometry."*

Mr. Evans: *"I would say extremely useful, certainly as a starting point I think I would use geometry a lot more going forward."*

Mr. Lilley: *"People's first initial point contact with a design, is what it looks like so geometric considerations can improve how the design looks."*

Ms. Potter: *"Until talking today probably I would say it wasn't that important but having looked your analysis, I actually think it's quite useful and quite interesting because it's obvious that I have been drawn to particular layouts for my original designs. So maybe it can an extremely useful thing to know."*

2. How would you apply geometric ratios (such as the golden ratio and root 2, 3, 4, and 5) to the design process, and could you briefly explain the reasons for your answers?

Mr. Davey: *"Well until now I probably wouldn't bother because I obviously did not know about it before, so I wouldn't have done it, but if a client invested a lot of money, then yes I would use it due to the significance of client satisfaction"*

Mr. Diamantidis: *"Sometimes I found hard to use it in terms of productivity for instance it seems when if I quite involved and need to do a quick design. But if time is not a factor then yes I'll use the golden ratio."*

Mr. Evans: *"It would be useful for layout, it is applicable to everything but you have to be free to ignore it if it does not make sense for particular projects."*

Mr. Lilley: *"It could be great, but it is quite tricky to draw correctly. Although you can apply it to everything."*

Ms. Potter: *"I think it is useful to apply it because I work with root 2 quite a lot which I never thought about at all. But now it would be interesting to look back at what I am doing, to see whether that is the way I design. So it is very useful. Maybe it is not practical all the time, depending on the project but it can be a useful tool for analysis"*

3. ***How would you apply Dynamic symmetry in design and the design process?***
   Mr. Davey: *"If I want to make sure something is going to conform to a specific design and set rule, I would use it just to make sure it looks ok"*

   Mr Diamantidis: *"Sometimes it can be useful and sometimes not useful"*

   Mr Evans: *"Yes very useful and more practical even if you deviate from the overall section you can still apply dynamic symmetry principles, I would say."*

   Mr. Lilley: *"It's useful for designing logos and branding. It's quite complicated to draw if you don't know how to. It can be learning process but yes it is applicable to pretty much everything."*

   Ms Potter: *"It is useful for 2D design and Graphic designs… it useful for analysis of designs and again depending on projects."*

4. ***How would you apply Fibonacci sequence proportions in design and to the design process?***
   Mr. Davey: *"It does seem to work with my logo design, when you scaled it down and divided it into smaller boxes, so I would say yes it is useful"*

   Mr. Diamantidis: *"Second most important after the golden ratio, it is easier than Dynamic symmetry. Everything is time, design is time, if you have time, you can design with it."*

   Mr. Evans: *"I have to give the same answer as I gave for dynamic symmetry because it is a similar process"*

   Mr. Lilley: *"It can be useful for all designs, it is easier to use than Dynamic symmetry"*

   Ms Potter: *"It's useful again I think depending on the project. If you have the right project, it would be useful. It comes down to selecting right projects. But then again a skilled designer could apply it to any project."*

5. ***Using the knowledge gained from geometry, how would you consider using geometry for your design and your design process?***

   Mr. Davey: *"It's very important, not the most important thing, but still important. In some cases aesthetics are more important than function. If something doesn't look right, you cannot sell it. So it is essential that something looks right and quite often items clearly don't, even if they do function well"*.

Mr. Diamantidis: *"I'll definitely use it"*

Mr. Evans: *"In the early stage of design certainly I would use it"*

Mr. Lilley: *"I will take more time and consideration to apply the geometric rules to my design in future"*

Ms. Potter: "*Up to today I would say geometry does not play huge part in my general design process. But it does, because you think about balance how things relate to other objects… I have not really thought about it is a driving factor in the way I design. After looking at the design analysis you have done I would seriously consider using it more and seeing whether there is a reason why I put something where it is, whether shifting something very slightly would actually be more aesthetically pleasing. So I think I would extremely and hugely consider using geometric knowledge in my design process."*

The feedback was grouped into three categories; "Negative", "Neutral" and "Positive". In total, sixty comments from the professional designers were collected and displayed in the table below.

The textual analysis of feedback

Negative	Neutral	Positive
1. Wouldn't bother 2. Did not know about 3. Wouldn't have done 4. Hard to use 5. Have to be free to ignore 6. Quite tricky 7. Quite complicated to draw	1. Need to consider not only geometry 2. Cannot ignore geometry 3. Cannot draw shapes without geometry 4. It wasn't that important 5. Depending on the project but it can be useful tool for analysis 6. Not practical all the time 7. Sometimes not useful 8. I would use it just make sure 9. Depending on projects 10. Design is time, if you have time, you can design with it 11. Depending on the project 12. Comes down to selecting right projects	1. Extremely useful 2. Would use geometry a lot more 3. Can improve how the design looks 4. Quite useful and quite interesting 5. It can an extremely useful thing to know 6. Would use 7. I'll use the golden ratio 8. Would be useful for layout 9. Applicable to everything 10. Could be great 11. Can apply it to everything 12. It is useful to apply 13. Would be interesting to look at 14. Very useful

	13. Not most important thing 14. I'll take more time and consideration to apply 15. Up to today I would say geometry does not play huge part in my general design process	15. Can be useful tool for analysis 16. Can be useful 17. Yes very useful 18. More practical 19. It is useful for designing logos and branding 20. Yes it is applicable to pretty much every thing 21. Useful for 2D design and Graphic design 22. Useful for design analysis 23. Seems to work with my logo design 24. Yes it is useful 25. Second most important after the golden ratio 26. Yes very useful 27. More practical 28. Can be useful for all designs 29. Easier to use than Dynamic symmetry 30. It's useful again 31. Skilled designer could apply it to any project 32. It would be useful 33. Very important 34. Still important 35. I'll definitely use 36. Early stage of design certainly I would use 37. I would seriously consider using it 38. Extremely and hugely consider using geometric knowledge
TOTAL= 60		

By far the largest group of the three was the "Positive" section. It seems that overall the designer's views on applying practical geometry in the design process was considered "practical", "useful", "applicable" and "important" knowledge for improving aesthetics in the design process.

However, some comments in the “Neutral” category should be given some consideration. Firstly, time is an important consideration in every designer’s design process. And unfortunately there is no escaping the fact that any designer unfamiliar with geometry will need to invest a certain amount of time and effort, initially, in learning how to effectively use the refinement process to its full potential. It can be argued that the professional designers’ may have considered it a time consuming process due to a lack of familiarity with process used.

Secondly, one designer felt that geometry may be only effective “depending on the project”. Although, it should be noted that through experience of applying it directly to a wide variety of projects, the designer will find themselves becoming quite adept at using the geometric process in every situation.

Lastly, as far as “Negative” comments, such as “quite complicated to draw”, “quite tricky” and “hard to use” are concerned, of course the designers’ opinions must be taken on board as it will be designers who will be using the refinement process in the end. Again, as already stated in the “Neutral” comments section, perhaps the reason for this is that while the designers may be highly skilled in their specific area of design, they are not yet expert at the application of golden ratio and geometric knowledge in the design process. So, whilst the views, such as “not applicable all the time” and “sometimes not useful” when applying geometry in design, are fair comments, there is certainly room for discussion. Just by way of a contrast, it is perhaps important to note that, as one designer asserted, “a skilled designer could apply it to any project”.

Thus, findings are:

1. Geometric knowledge can be a useful and practical tool for analysing aesthetics in design process.

2. Perhaps individual designers with a lack of experience of geometry, could find it a challenge to recognise its applicability with certain projects.

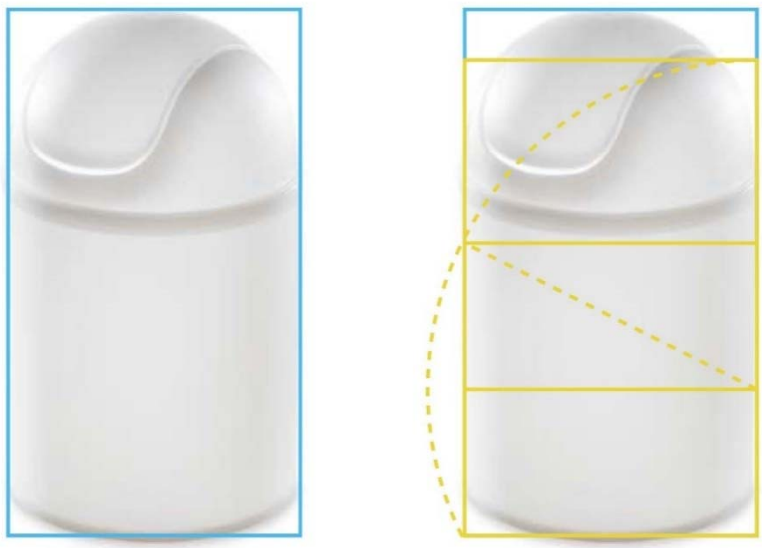
3. Time also appeared to be one of the most important factors in utilizing geometry in the design process, yet there is a case to be argued that as designers become more familiar with the geometric refinement process, they will inevitably achieve more successful results.

Appendix II The details of selected 100 ‘*Phaidon Design Classics*’

	Product	Companies/Manufactured years	Designers	Designed years	Ratio
1	9091 Kettle	Alessi/ 1983~	Richard Sapper	1983	1.096

Downloaded from: http://store.alessi.com/gbr/en-gb/catalog/detail/9091-kettle/9091, accessed date: 17/07/2013

2	Can Family	Authentics/ 1984~	Hansjerg Maier-Aichen	1984	1.736



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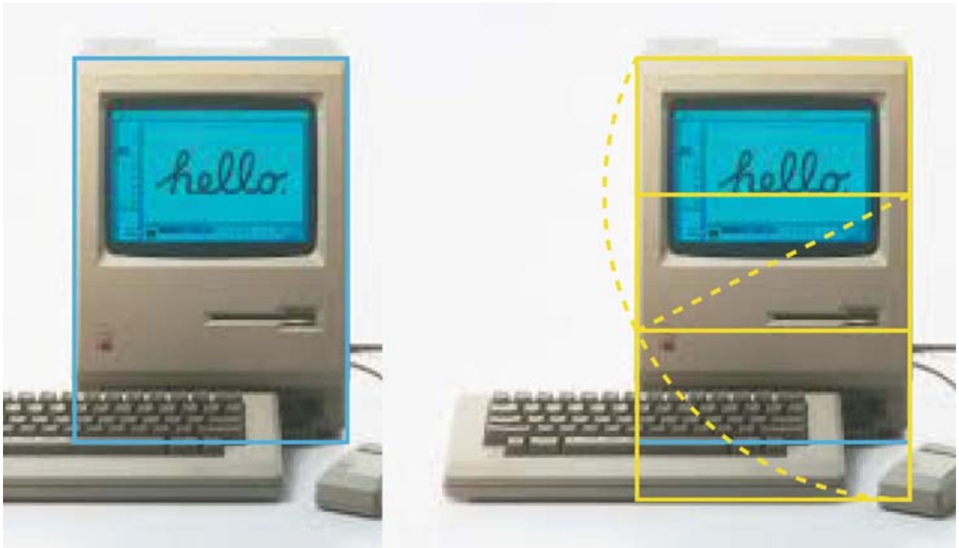
<tr><td>3</td><td>Apple Macintosh</td><td>Apple Computer/ 1984 -1987</td><td>Hartmut Esslinger</td><td>1984</td><td>1.413</td></tr>
<tr><td colspan="6">
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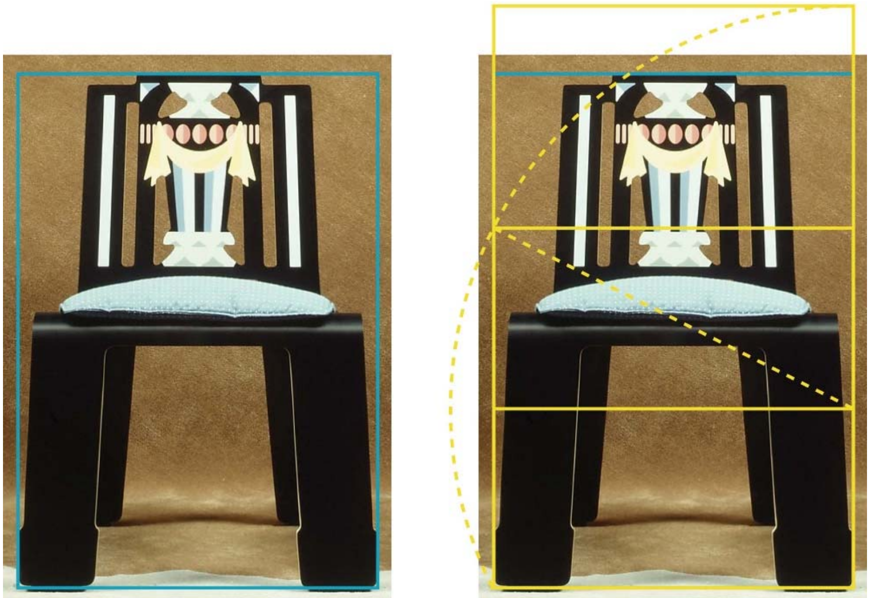
<tr><td>4</td><td>Sheraton Chair 664</td><td>Knoll/ 1984-1988</td><td>Robert Venturi</td><td>1984</td><td>1.457</td></tr>
<tr><td colspan="6"></td></tr>
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<tr><td>5</td><td>Pasta Set</td><td>Alessi/ 1985~</td><td>Massimo Morozzi</td><td>1985</td><td>1</td></tr>
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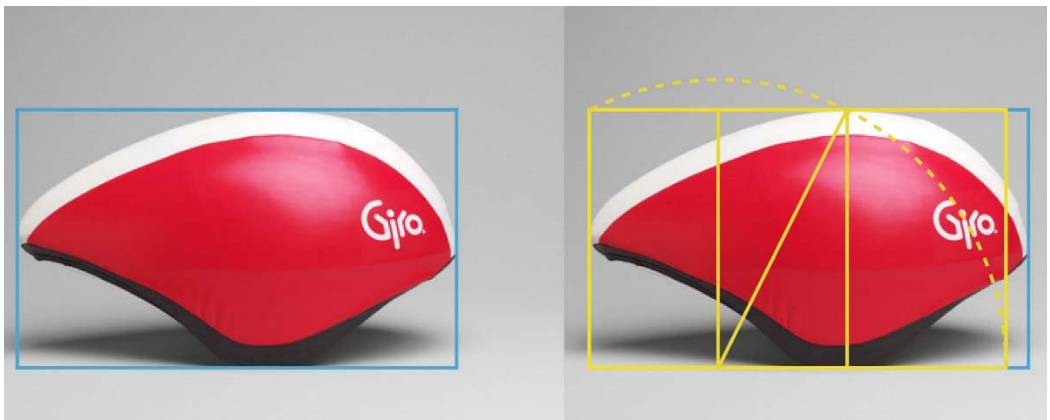
<tr><td colspan="6">Downloaded from: http://hivemodern.com/pages/product26/alessi-mssiomo-morozzi-pasta-set, accessed date: 17/07/2013</td></tr>
<tr><td>6</td><td>Aerohead Bicycle Racing Helmet</td><td>Giro/ 1985~</td><td>James Gentes</td><td>1985</td><td>1.776</td></tr>
<tr><td colspan="6">
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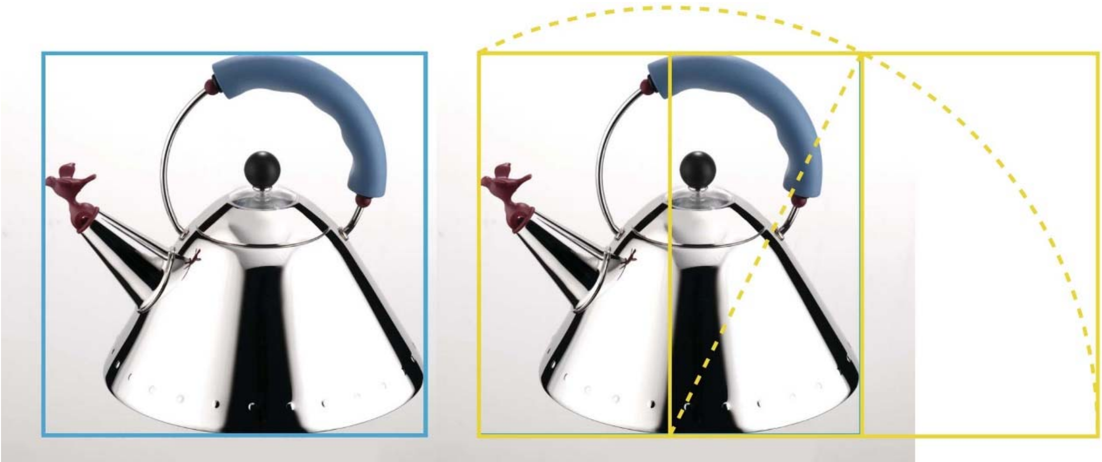
<tr><td>7</td><td>9093 whistling kettle</td><td>Alessi/ 1985~</td><td>Michael Graves</td><td>1985</td><td>1</td></tr>
<tr><td colspan="6"></td></tr>
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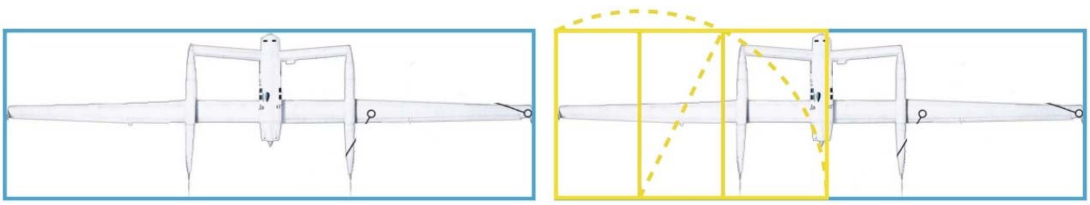
<tr><td>8</td><td>Rutan Voyager</td><td>Rutan Aircraft Factory/ 1986</td><td>Elbert 'Burt' Rutan</td><td>1986</td><td>2.87</td></tr>
<tr><td colspan="6"></td></tr>
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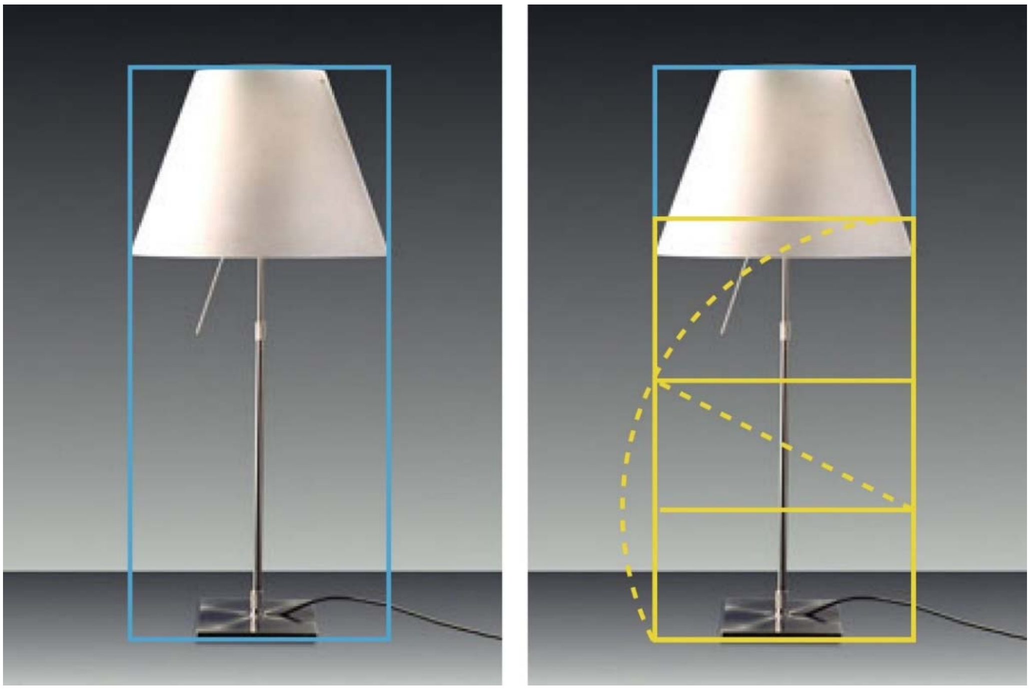
9	Costanza (Floor Lamp)	LucePlan/ 1986~	Paolo Rizzatto		2.5
					
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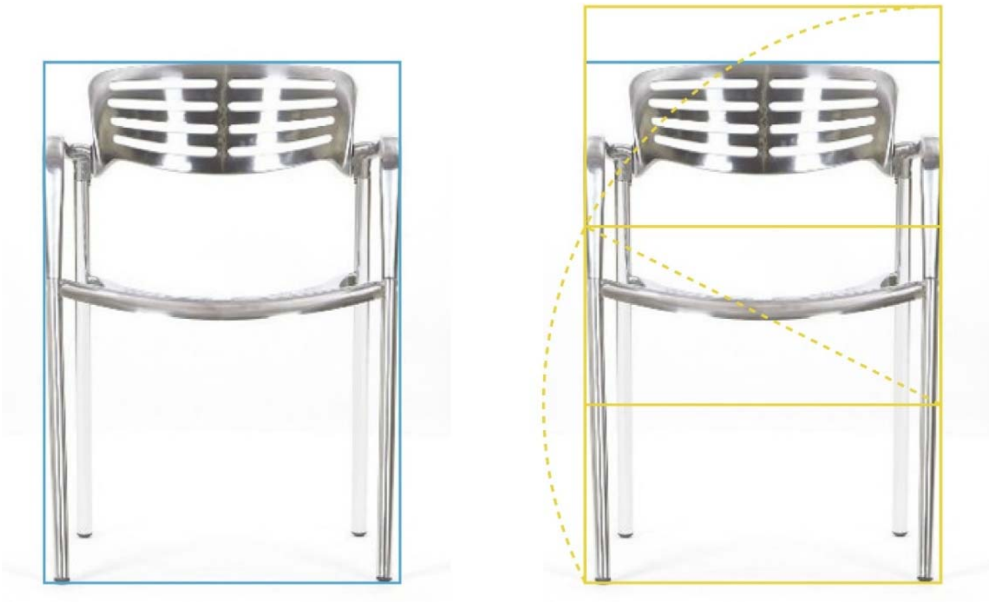
10	Toledo Chair	Amat/ 1988~	Jorge Pensi	1986-88	1.375
					
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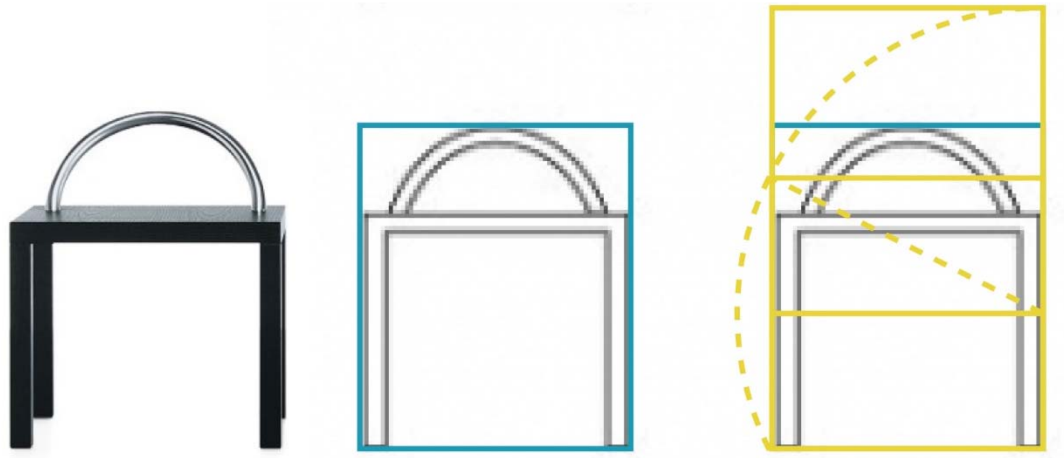
<tr><td>11</td><td>Ko-Ko</td><td>Cappellini/1986~</td><td>Shiro Kuramata</td><td>1986</td><td>1.22</td></tr>
<tr><td colspan="6"></td></tr>
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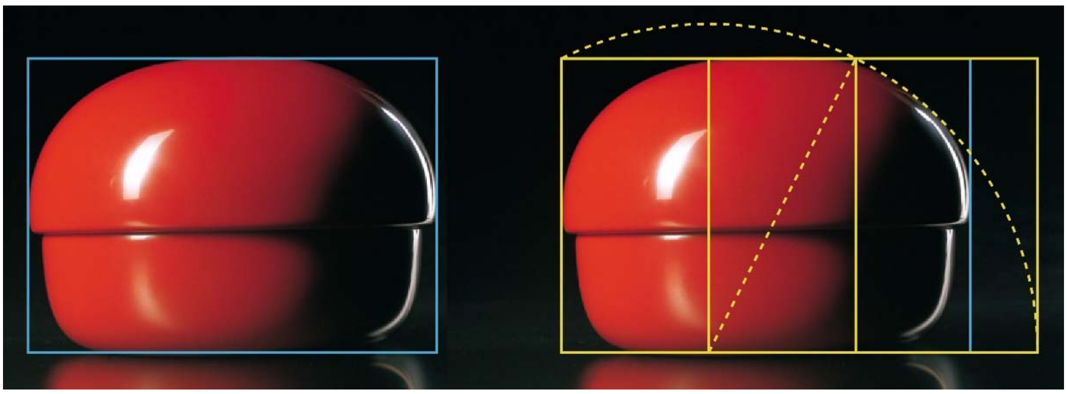
<tr><td>12</td><td>Wajima Ceremony Series</td><td>Ohmukai-Kosyudo/ 1986~</td><td>Toshiyuki Kita</td><td>1986</td><td>1.361</td></tr>
<tr><td colspan="6"></td></tr>
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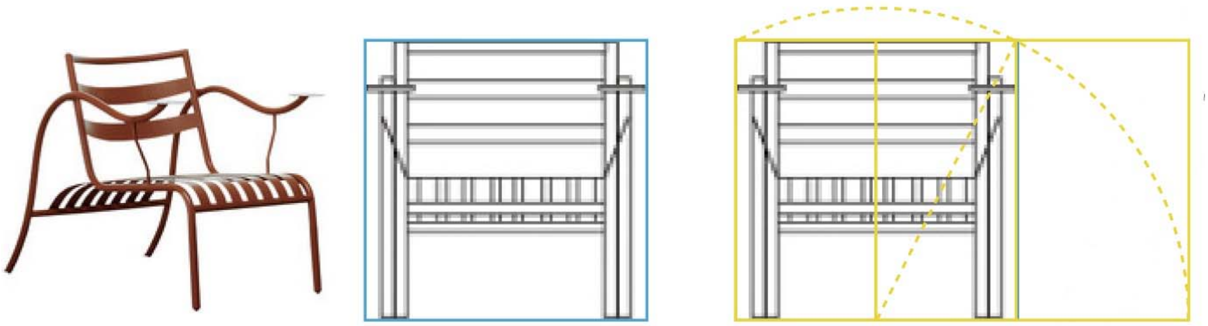
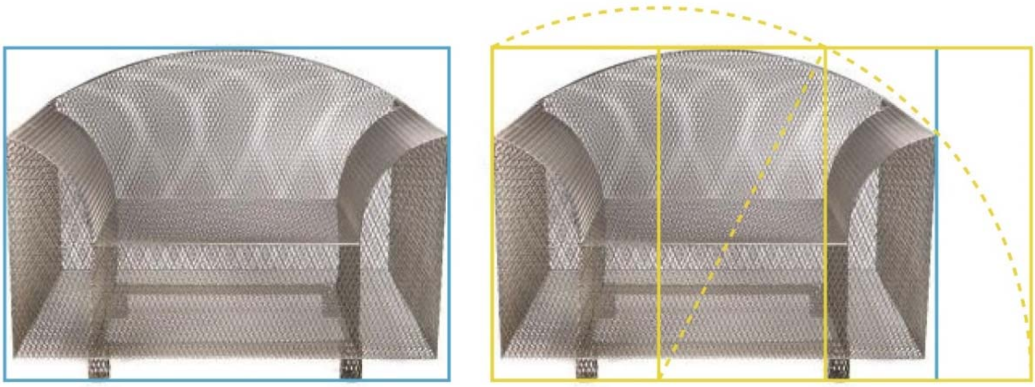
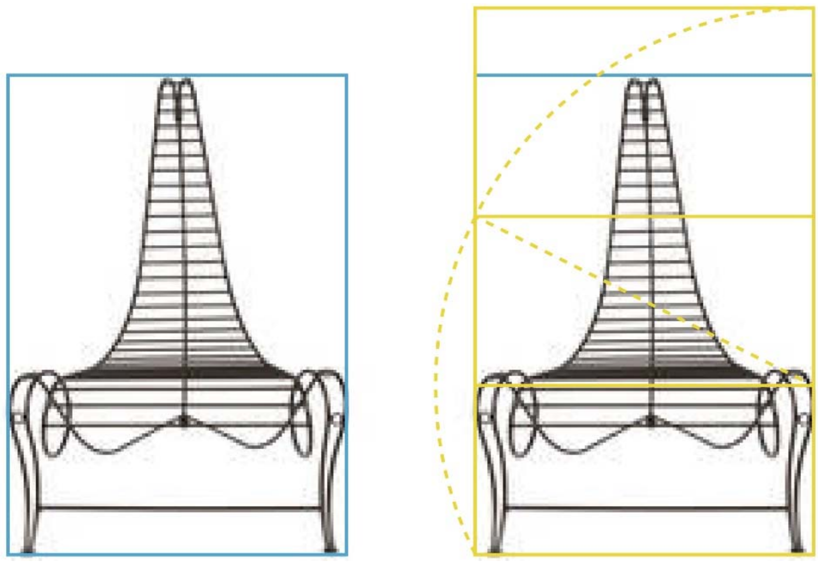
13	Thinking Man's Chair	Cappellini/ 1988~	Japser Morrison	1986	1.102
					
Downloaded from: http://cappellini.it/en/products/sofas-and-armchairs/thinking-mans-chair, accessed date: 19/07/2013					
14	How High the Moon	Vitra/ 1987~	Shiro Kuramata	1986	1.321
					
Downloaded from: http://www.bonluxat.com/a/Shiro_Kuramata_How_High_the_Moon.html, accessed date: 19/07/2013					

15	Spine Chair(A)	Ceccotti Collezioni/ 1988~	André Dubreuil	1986	1.417
					
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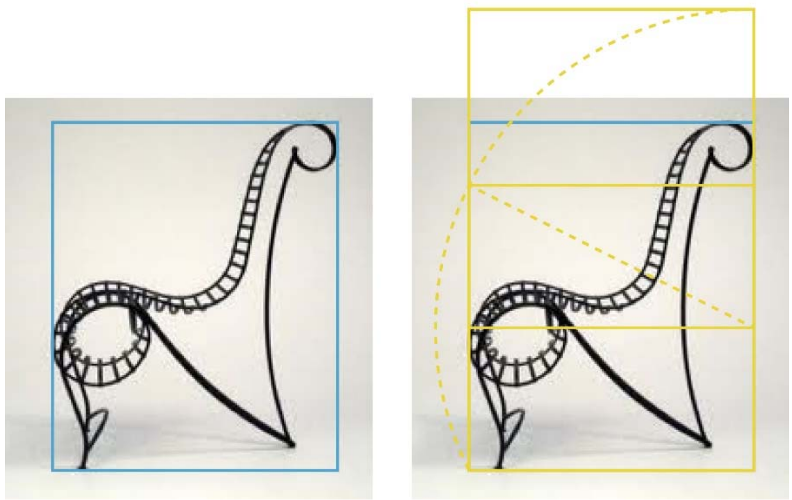
16	Spine Chair (B)	Ceccotti Collezioni/ 1988~	André Dubreuil	1986	1.219
					
Downloaded from: http://www.miniaturechairman.com/60/post/2010/03/first-post.html, accessed date: 19/07/2013					

17	Quicksnap Single Use Camera	Fujifilm/ 1986 to 1987	Fujifilm Design Team	1986	2.19

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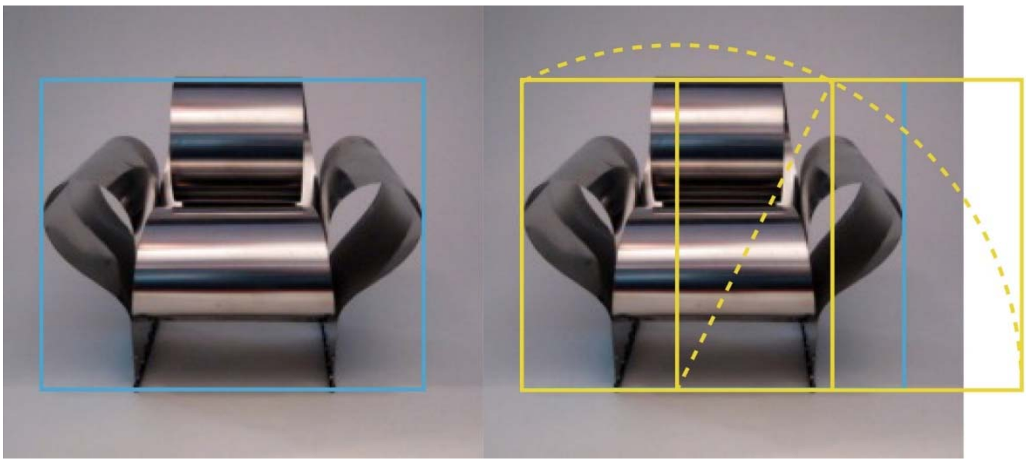
18	Well Tempered Chair	Vitra/ 1986-1993	Ron Arad	1986	1.23



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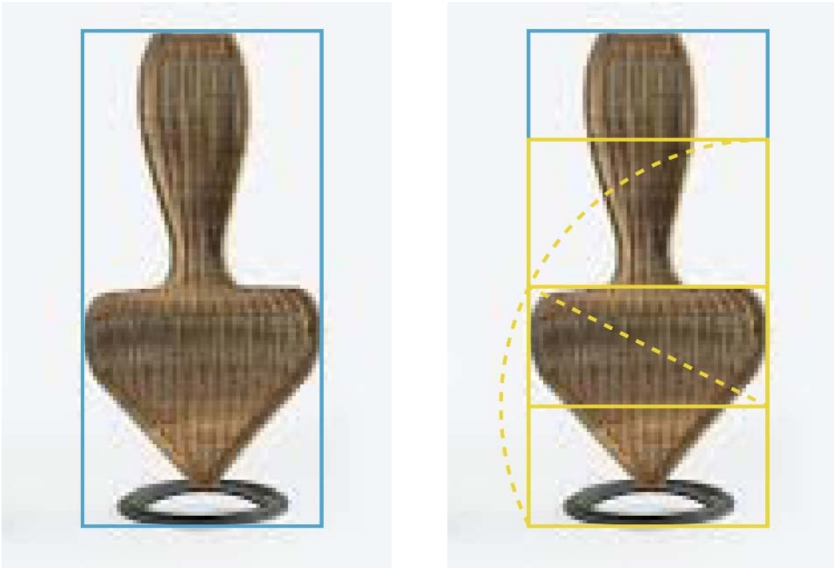
19	S chair	Cappellini/ 1991~	Tom Dixon	1987	2.104
					
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20	I Feltri (arm chair)	Cassina/ 1987~	Gaetano Pesce	1987	1.78
					
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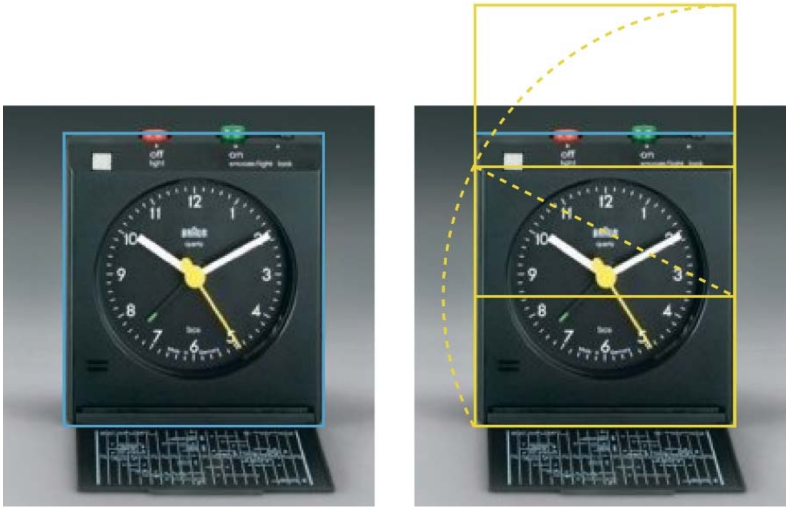
<tr><td colspan="6"></td></tr>
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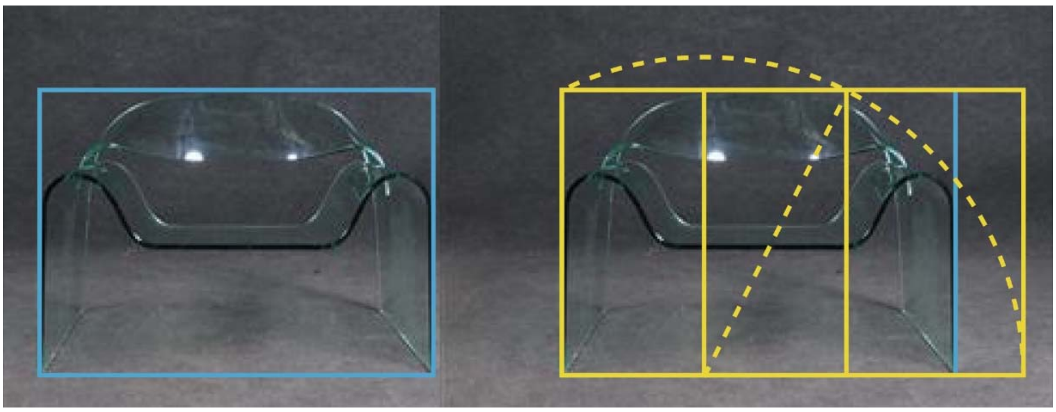
<tr><td>22</td><td>Ghost chair</td><td>Fiam Italia/ 1987~</td><td>Tomu Katayanagi</td><td>1987</td><td>1.382</td></tr>
<tr><td colspan="6"></td></tr>
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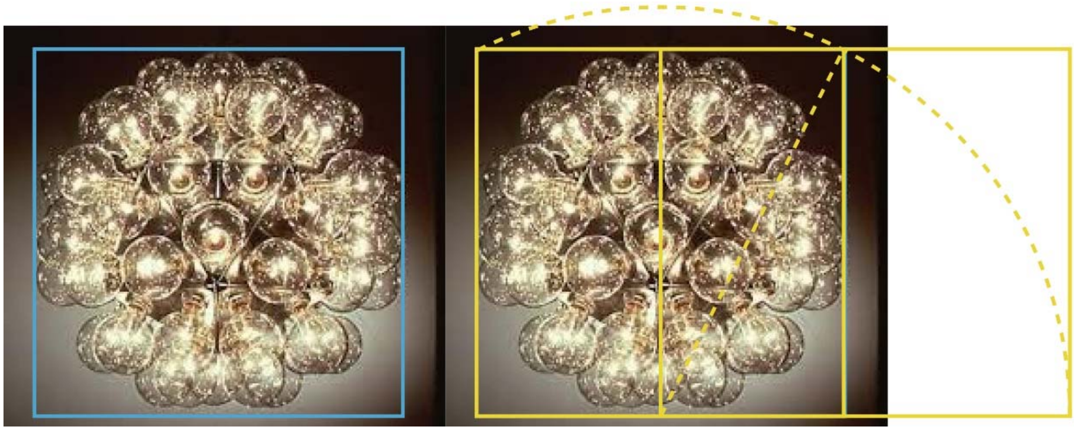
<tr><td>23</td><td>Taraxacum' 88 (light)</td><td>Flos/ 1988~</td><td>Achille Castiglioni</td><td>1988</td><td>1</td></tr>
<tr><td colspan="6"></td></tr>
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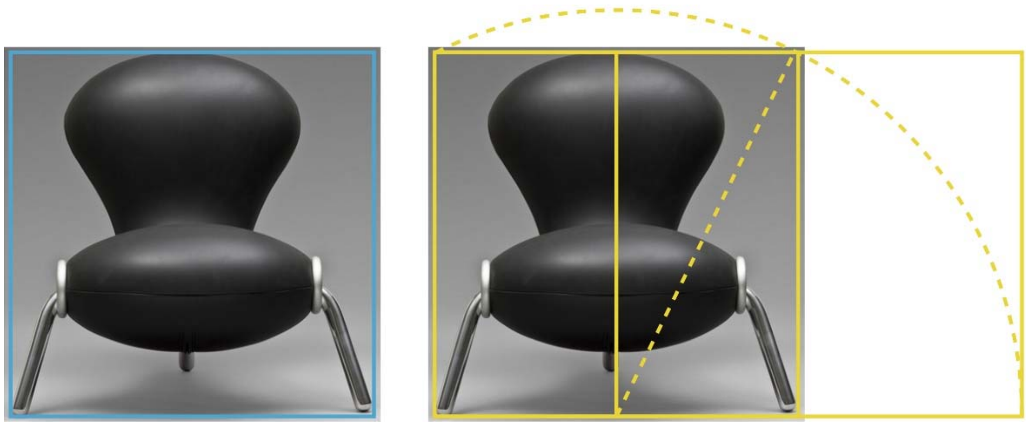
<tr><td>24</td><td>Embryo Chair</td><td>Cappellini/ 1988~</td><td>Marc Newson,</td><td>1988</td><td>1</td></tr>
<tr><td colspan="6"></td></tr>
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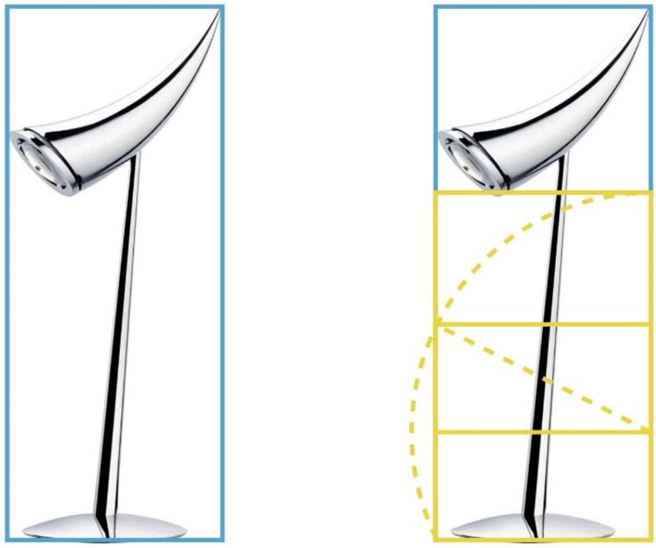
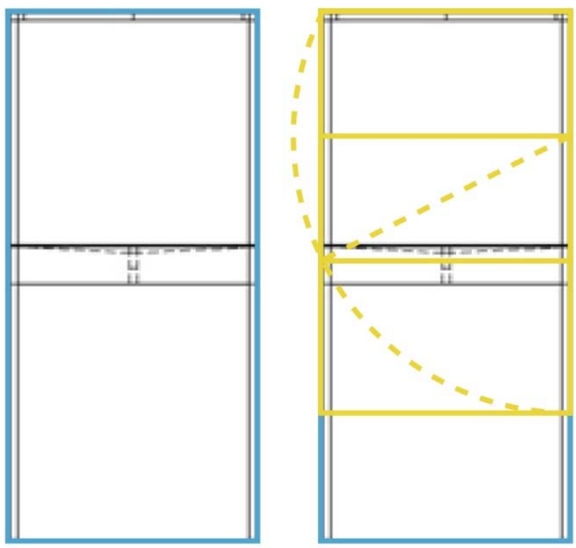
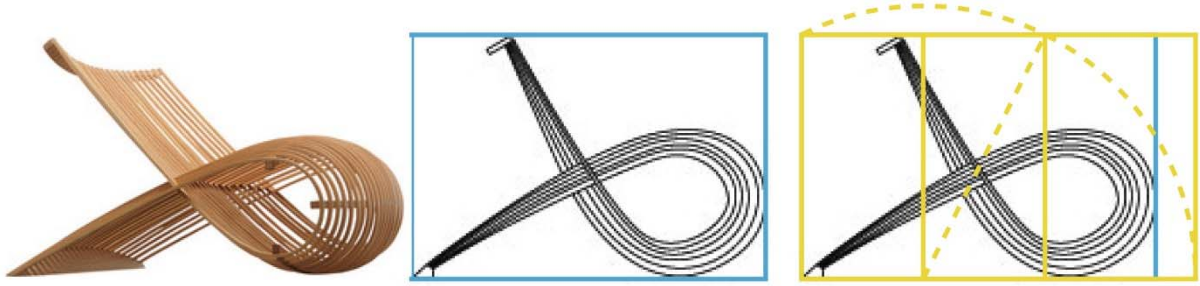
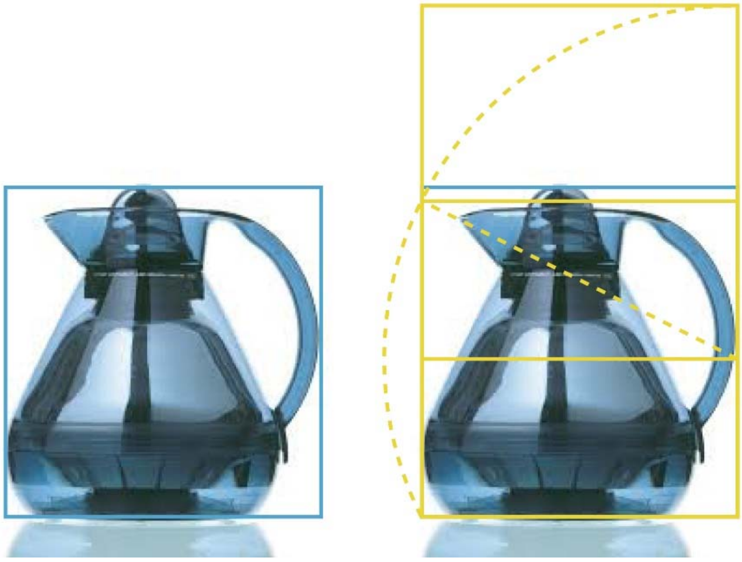
25	Ará Lamp	Flos/ 1988~	Phillippe Starck	1988	2.2
					
Downloaded from: http://www.regencyshop.com/p261/Ara-Style-Desk-Lamp/product_info.html, accessed date: 22/07/2013					
26	Ply-Chair Open Back	Vitra/ 1989~	Jasper Morrison	1988	2.131
 					
Downloaded from: http://collections.vam.ac.uk/item/O72604/ply-chair-chair-morrison-jasper/, http://www.philippmies.de/works/ply.html, accessed date: 22/07/2013					

27	Wood Chair	Capellini/ 1992~	Marc Newson	1988	1.471
					
Downloaded from: http://cappellini.it/en/products/sofas-and-armchairs/wooden-chair, accessed date: 22/07/2013					
28	Miss Blanch (chair)	Ishimaru/ 1988~	Shiro Kuramata	1988	1.482
					
Downloaded from: http://www.design-museum.de/en/collection/100-masterpieces/detailseiten/miss-blanche-kuramata.html, http://www.miniaturechairman.com/54/post/2011/12/the-melerski-collection-prototype-miniature-kuramata-miss-blanche-chair.html, accessed date: 22/07/2013					

29	Basic Thermos Flask,	Alfi/ 1990~	Ross Lovegrove	1988-1990	1.066
					
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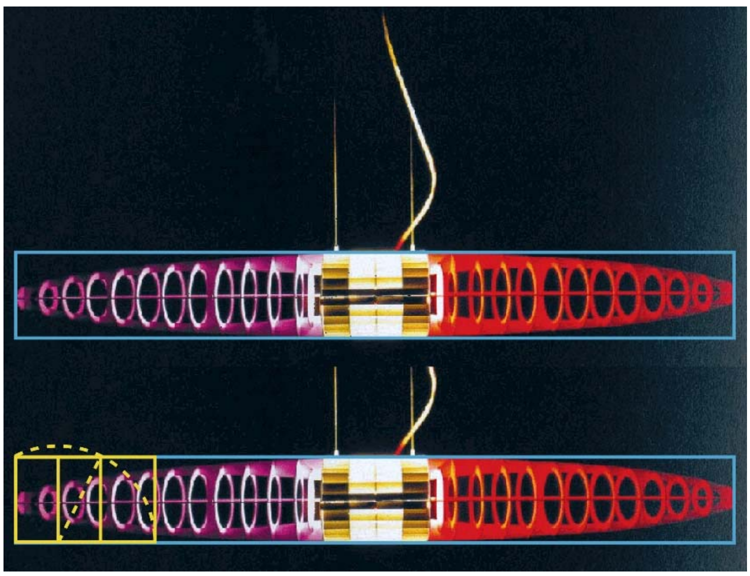
30	Titania(light)	Luce Plan/ 1989~	Alberto Meda	1989	8.75
					
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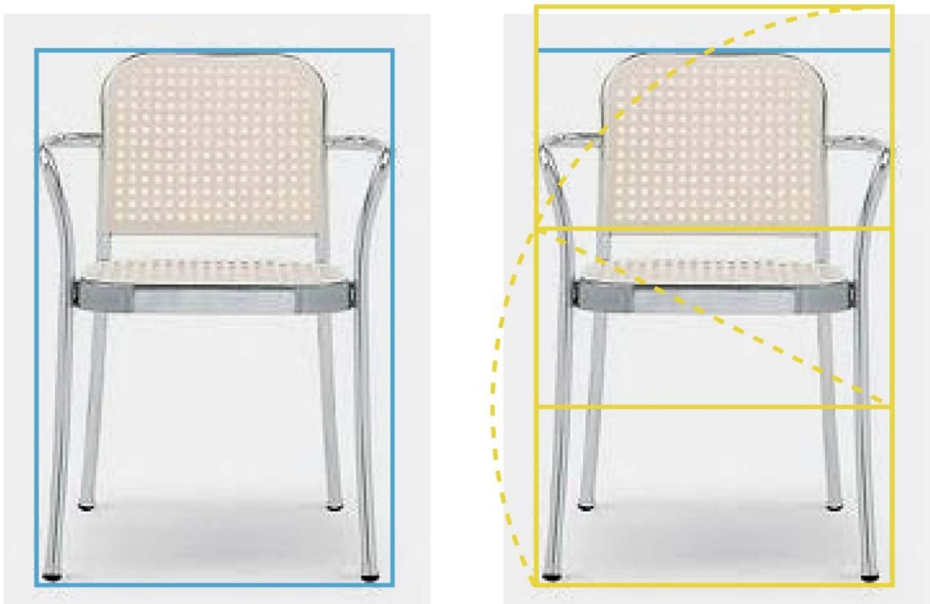
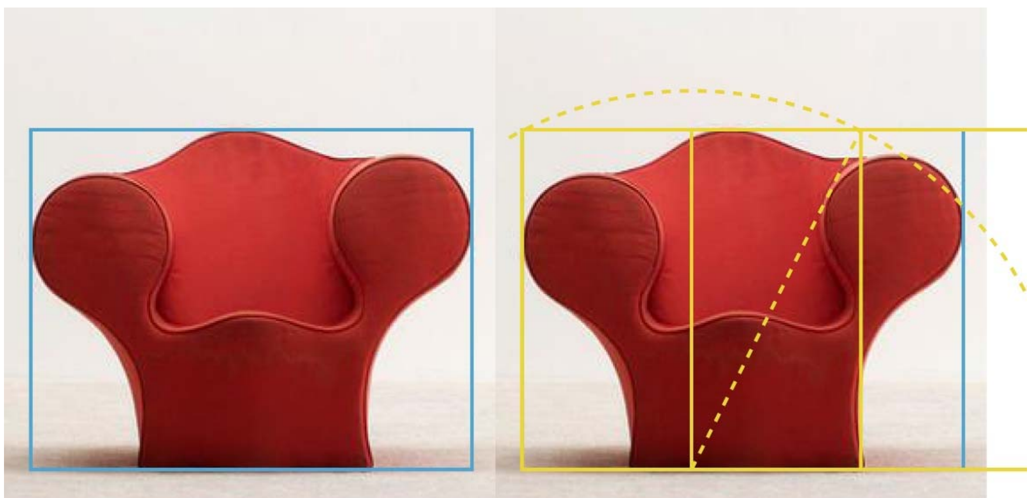
<tr><td>31</td><td>Silver Chair</td><td>De Padova 1989~</td><td>Vico Magistretti</td><td>1989</td><td>1.5</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">Downloaded from: http://www.archetypen.ch/de-padova-silver-armlehn.html, accessed date: 23/07/2013</td></tr>
<tr><td>32</td><td>Soft Big Easy</td><td>One Off/ (1989), Morso/ 1990~</td><td>Ron Arad</td><td>1989</td><td>1.308</td></tr>
<tr><td colspan="6"></td></tr>
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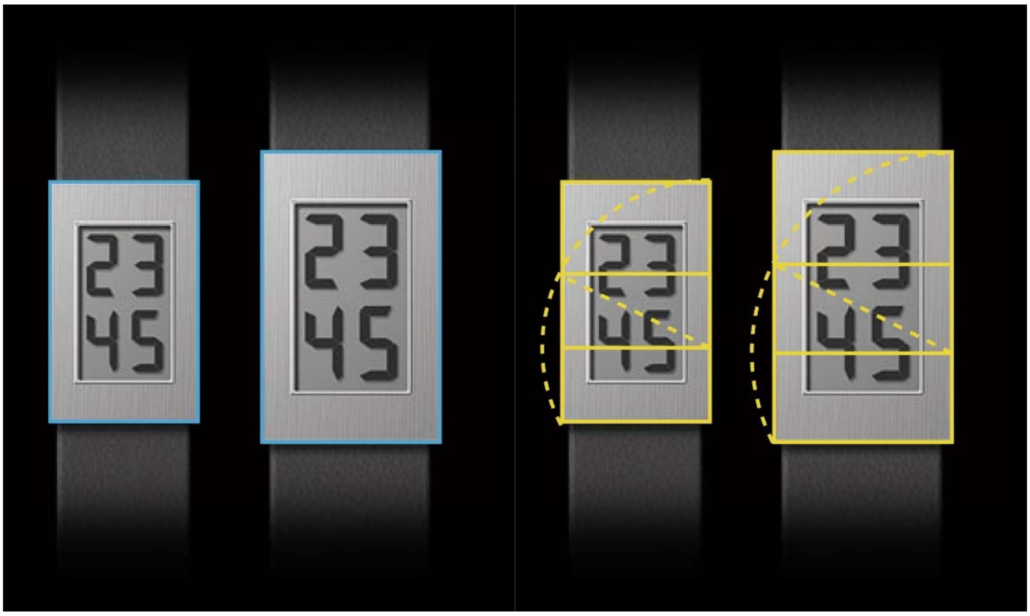
33	WATCH	Ventura Design On Time/ 1989-1999	Flemming Bo Hansen	1989	1.618
					
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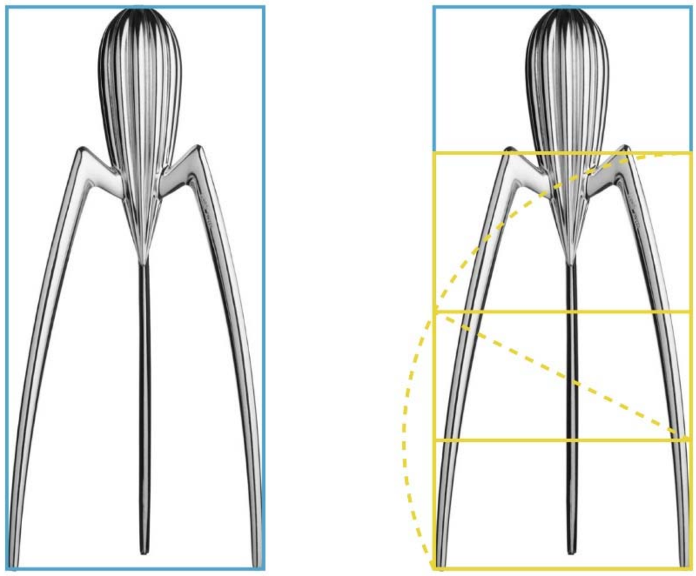
34	Ellice	Danese/ 1990~	Marco Ferreri	1990	9.25
					
Downloaded from: http://www.panik-design.com/acatalog/Danese-Milano---Ellice-Bookmaker.html, accessed date: 23/07/2013					

35	Juicy Salif	Alessi/ 1990~	Phillippe Starck	1990	2.071



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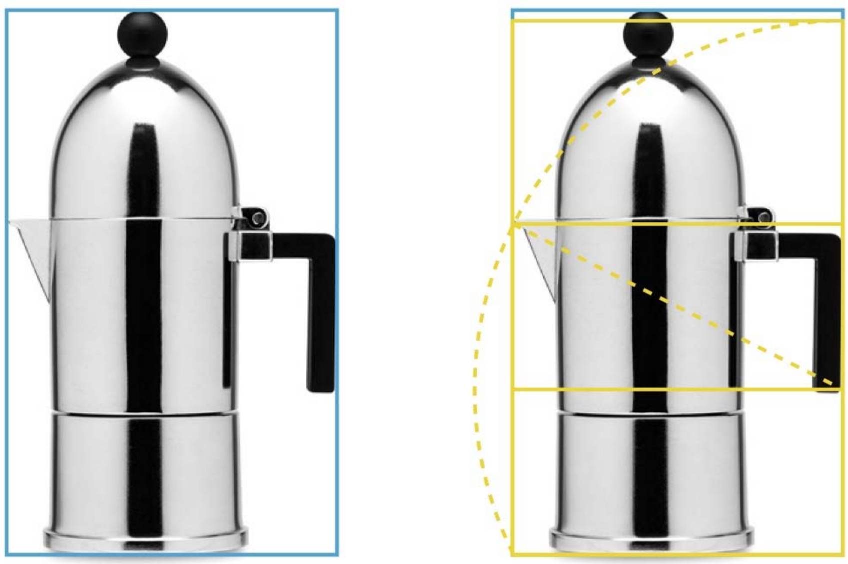
36	La Cupola	Alessi/ 1990~	Aldo Rossi	1990	1.683



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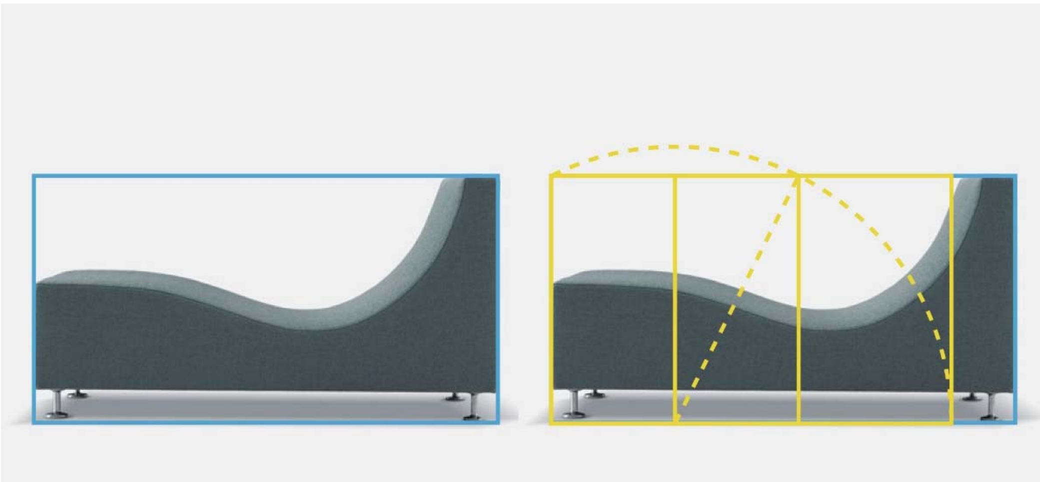
37	Olympus Mju	Olympus/ 1991~	Akinori Mitsuse	1991	1.777
					
Downloaded from: http://www.olympus-global.com/en/corc/history/camera/popup/m_mju.html, accessed date: 23/07/2013					
38	Three Sofa de Luxe (TSA3)	Cappellini/ 1992~	Jasper Morrison	1991	1.875
					
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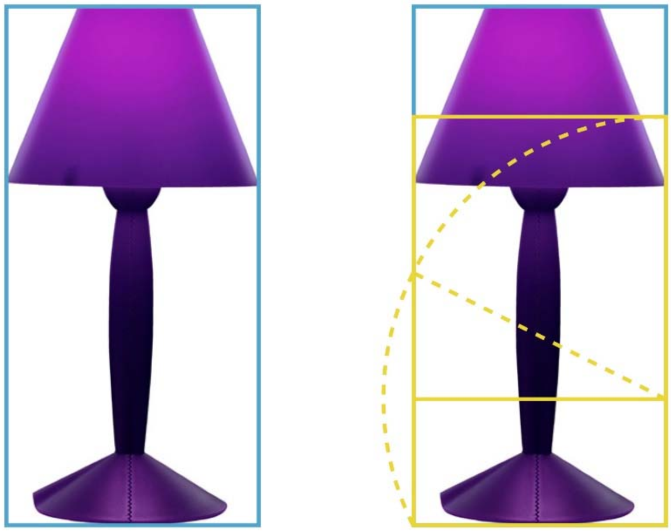
39	Miss Sissi Table Lamp	Flos/ 1991~	Phillippe starck	1991	1.989
					
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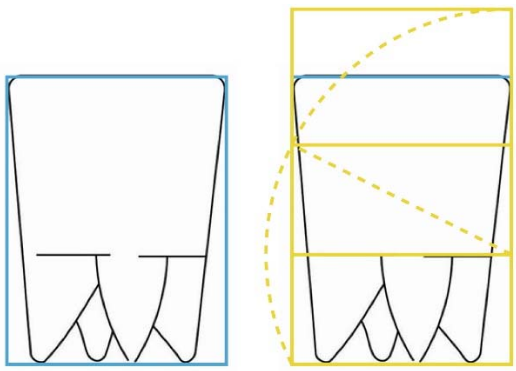
40	Bubu stool	XO/ 1991~	Phillippe starck	1991	1.303
 					
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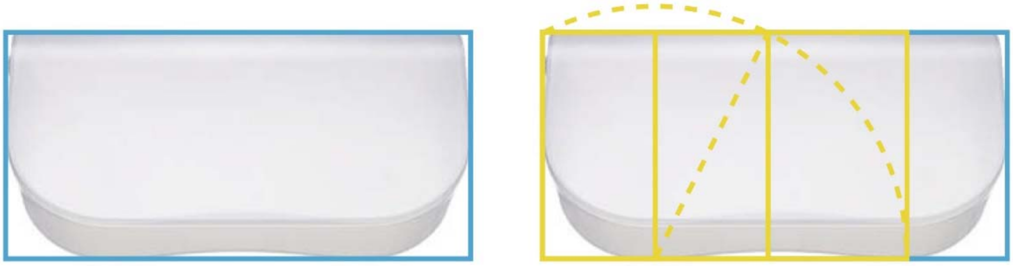
41	Flores Box	Danese/ 1992~	Enzo Mari	1992	2.06



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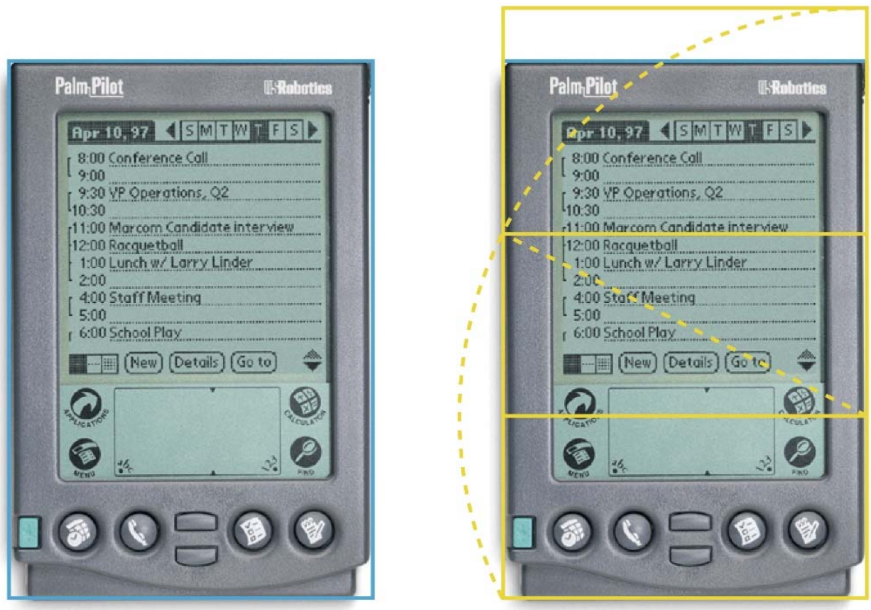
42	PalmPilo	PalmOne/ 1996~	Jeff Hawkins	1992-94	1.5



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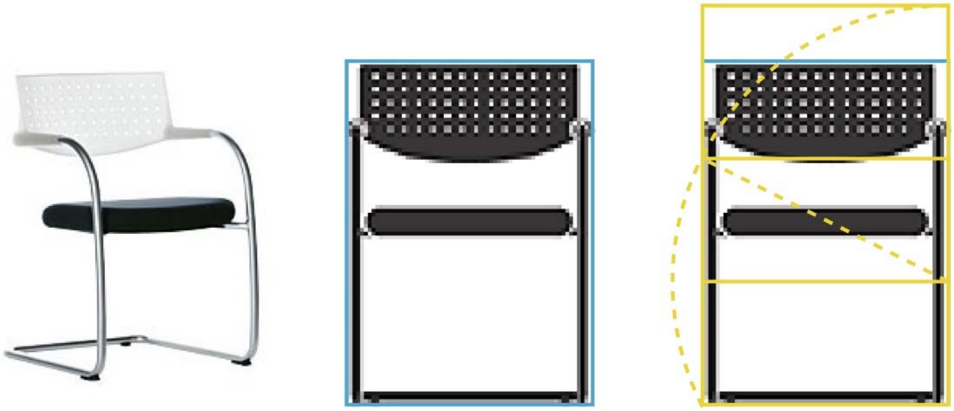
43	Visavis	Vitra/ 1992~	Antonio Citterio	1992	1.454



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44	IBM ThinkPad	IBM/ 1992~	Richard Sapper	1992	1.428

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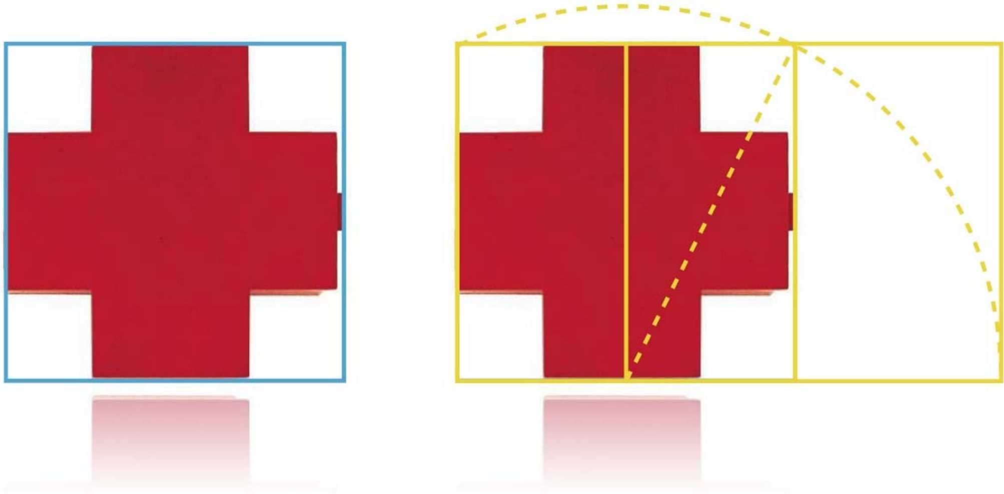
45	Red Cross Cabinet	Cappellini/ 1992~	Thomas Eriksson	1992	1
					
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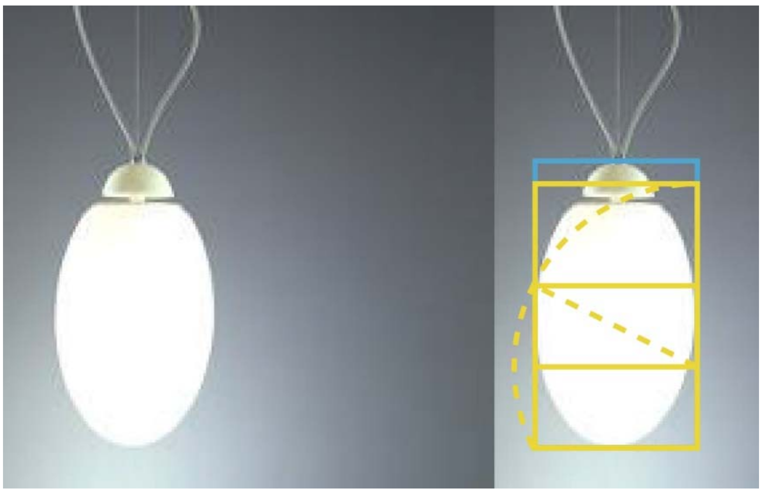
46	Brera	Flos/ 1992~	Achille Catiglioni	1992	1.864
					
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47	Monster M900	Ducati/ 1993~	Miguel Galluzzi	1992	2.032
					
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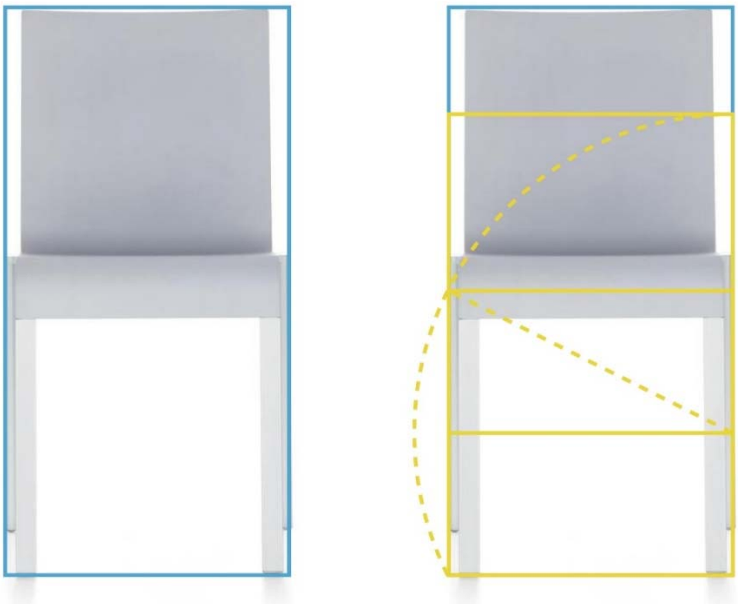
48	Chair N.2	Maarten van Severen/ 1992-1999, Vitra/ 1999~	Maarten van Severen	1992	2.157
					
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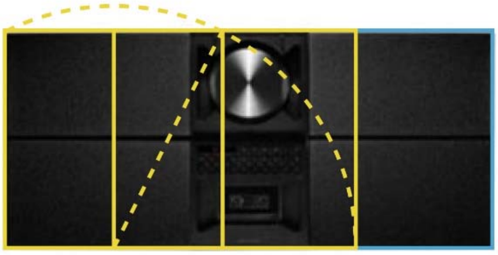
49	BeoSound Century	Bang &Olufsen/ 1993-2004	David Lewis	1993	2.027
 					
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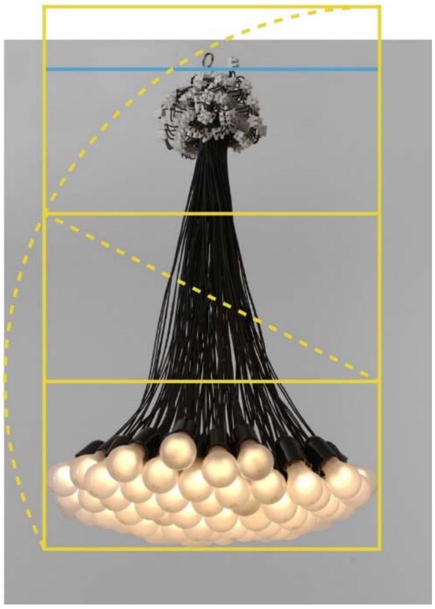
50	Chandelier 85 Lamps	Droog Design/ 1993~	Rody Graumans	1993	1.428
 					
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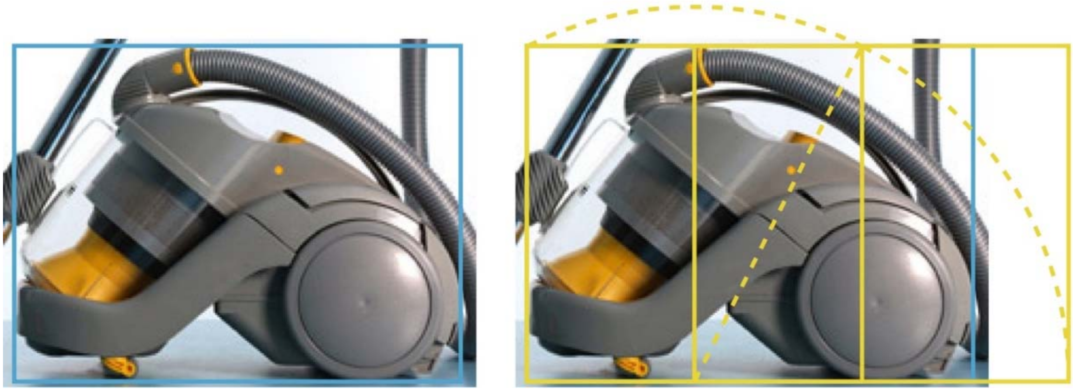
51	Dyson DC01/DC02	Dyson/ 1993-2002	James Dyson	1993	1.333



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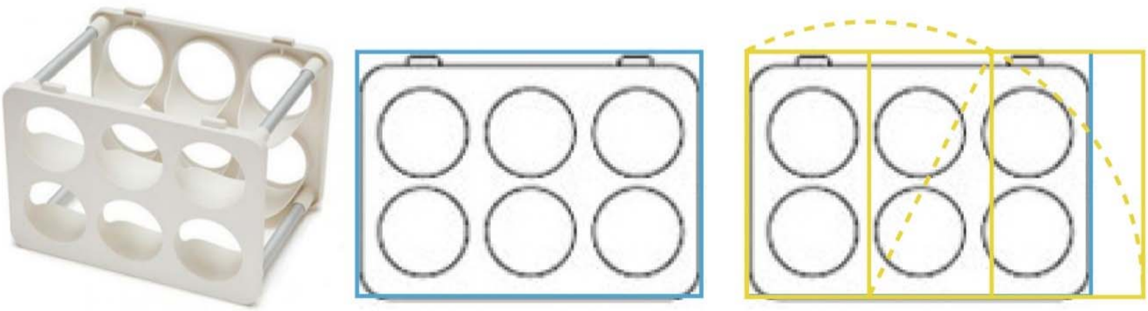
52	Bottle	Magis/ 1994~	Jasper Morrison	1994	1.44



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53	Aeron Chair	Herman Miller/ 1994~	William Stumpf	1994	1.554

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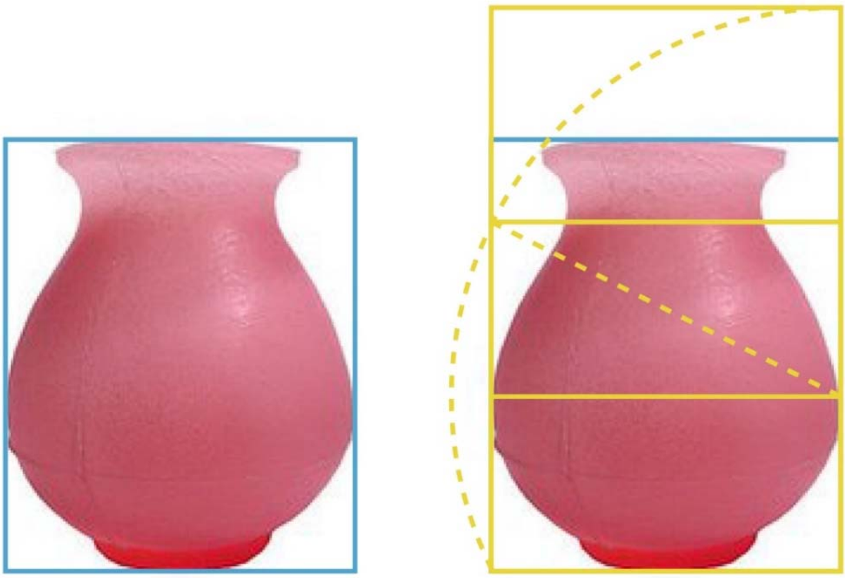
54	Soft Urn	Jongerius Lab/ 1994~	Hella Jongerius	1994	1.25



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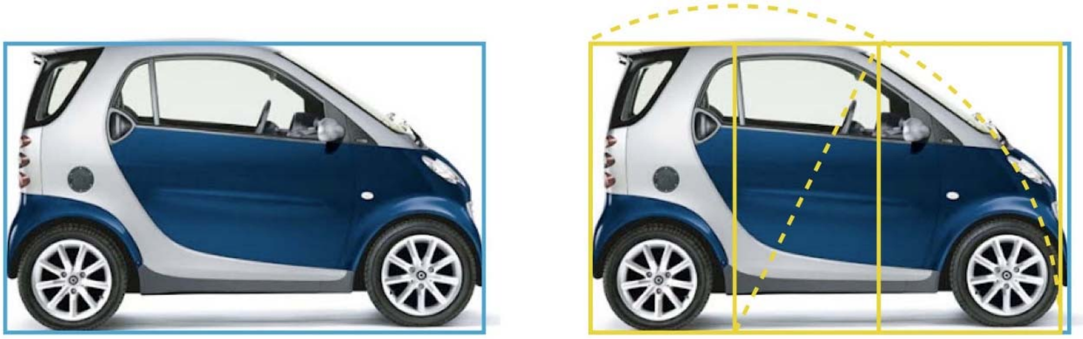
55	Smart city-coupé	Smart/ 1998~	Smart design team	1994	1.666
					
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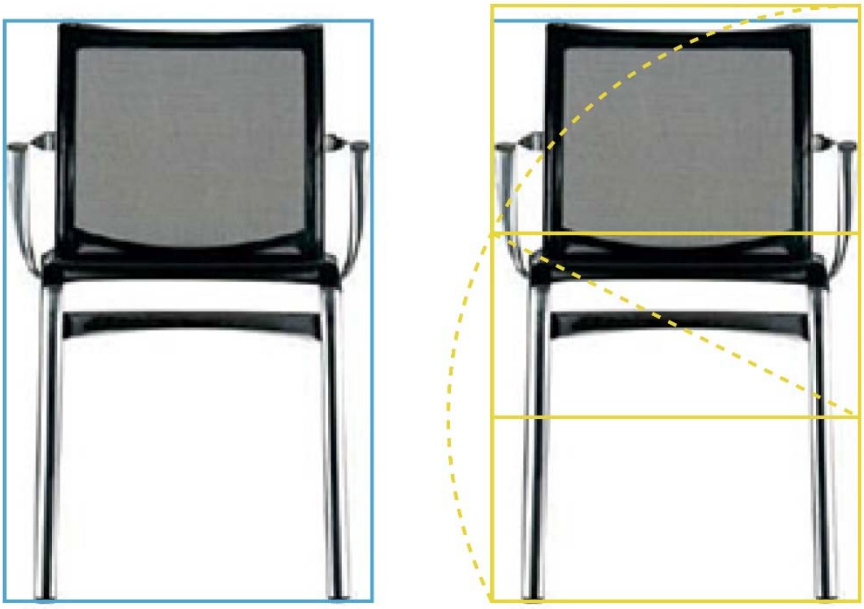
56	Bigframe	Alias /1994~	Alberto Meda	1994	1.577
					
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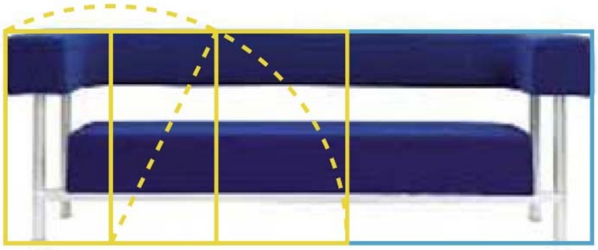
57	JI1 Sofa Bed	CBI/ 1994~	James Irvine	1994	2.898
 					
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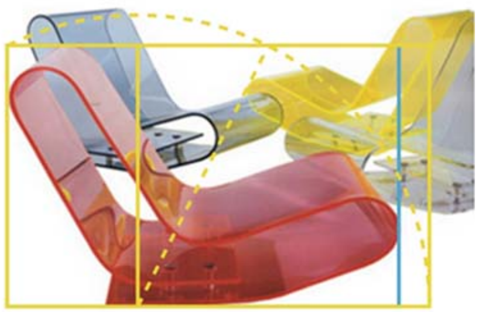
58	LC95A, Low Chair Aluminium	Maarten van Severen Meubelen/ 1996~1999, TM, division Top Mouton/ 1999~	Maarten van Severen	1993~5	1.49
 					
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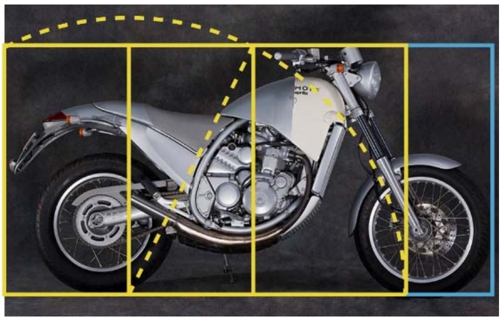
59	Aprilia Moto 6.5	Aprilia/ 1995~	Philippe Starck	1995	2.012
 					
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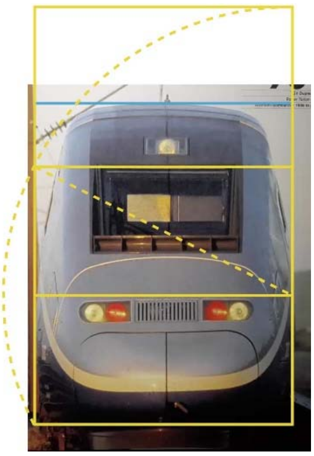
60	TGV Duplex	Alsthom, Bombardier/ 1996~	Roger Tallon	1996	1.275
 					
Source from: Phaidon design classics volume three, n. 937					

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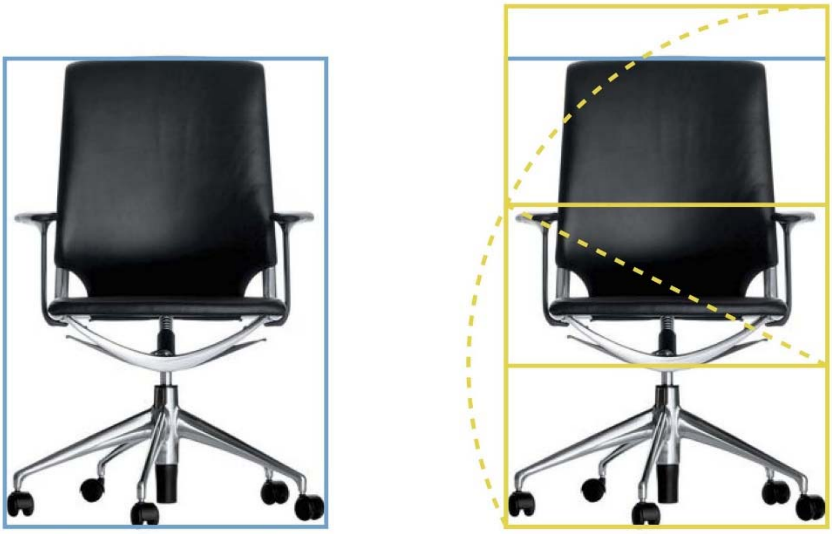
<tr><td colspan="6"></td></tr>
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<tr><td>62</td><td>B Meda Chair</td><td>Vitra/ 1996~</td><td>Alberto Meda</td><td>1996</td><td>1.437</td></tr>
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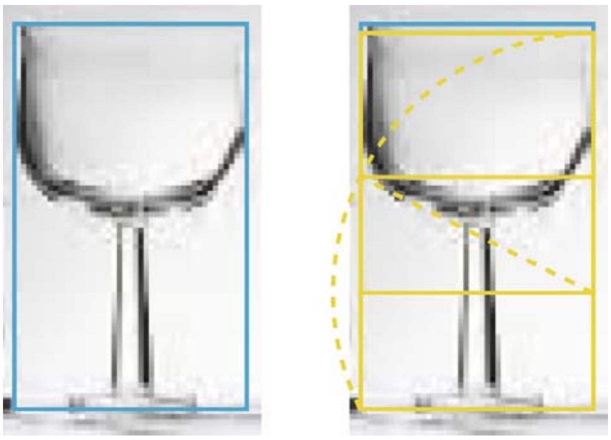
63	Washing-up Bowl	Normann Copenhagen/ 2002~	Ole Jensen	1996	2
					
Downloaded from: http://www.trademotorcycles.com.au/features/1410/aprilia-moto-65-bike-detectives/, http://www.awhiteroom.com/normann/normann-washing-up-bowl.asp, accessed date: 28/07/2013					
64	Ginerva glass	Alessi/ 1996-2001, 2003~	Ettore Sottsass	1996	1.68
					
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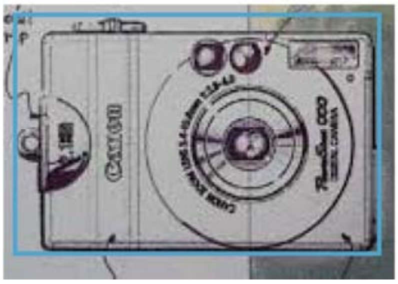
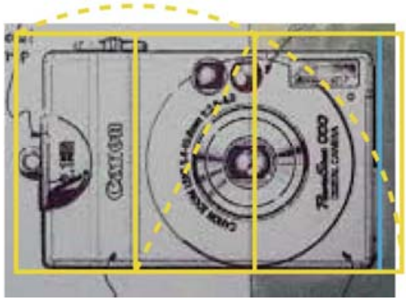
65	Canon Ixus	Canon/ 1996~	Yasushi Shiotani	1996	1.5
  					
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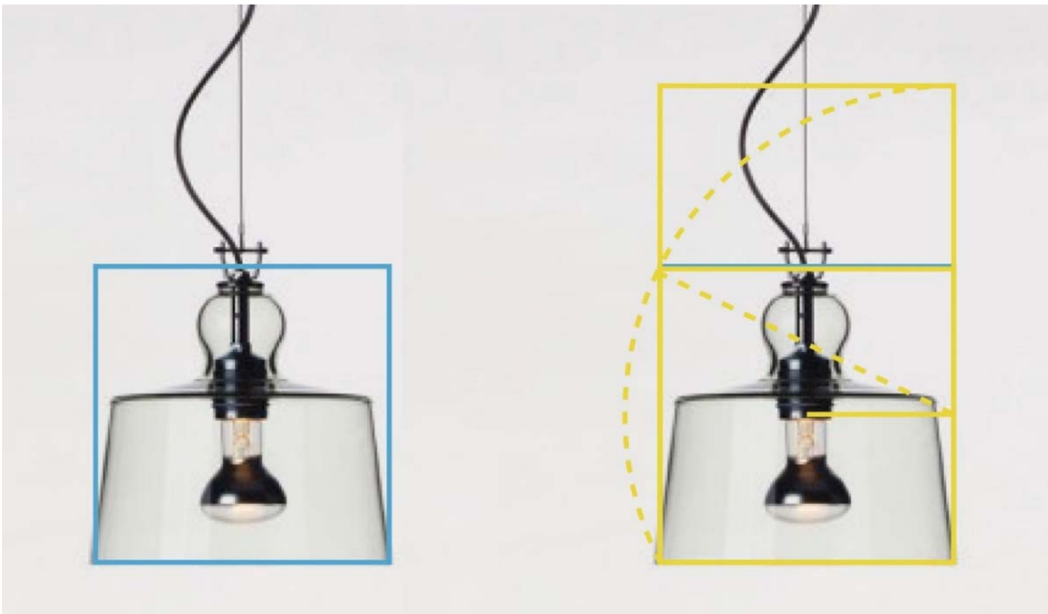
66	Acquatinta	Produzione Privata/ 1996~	Michele De Lucchi & Alberto Nason	1996	1.074
					
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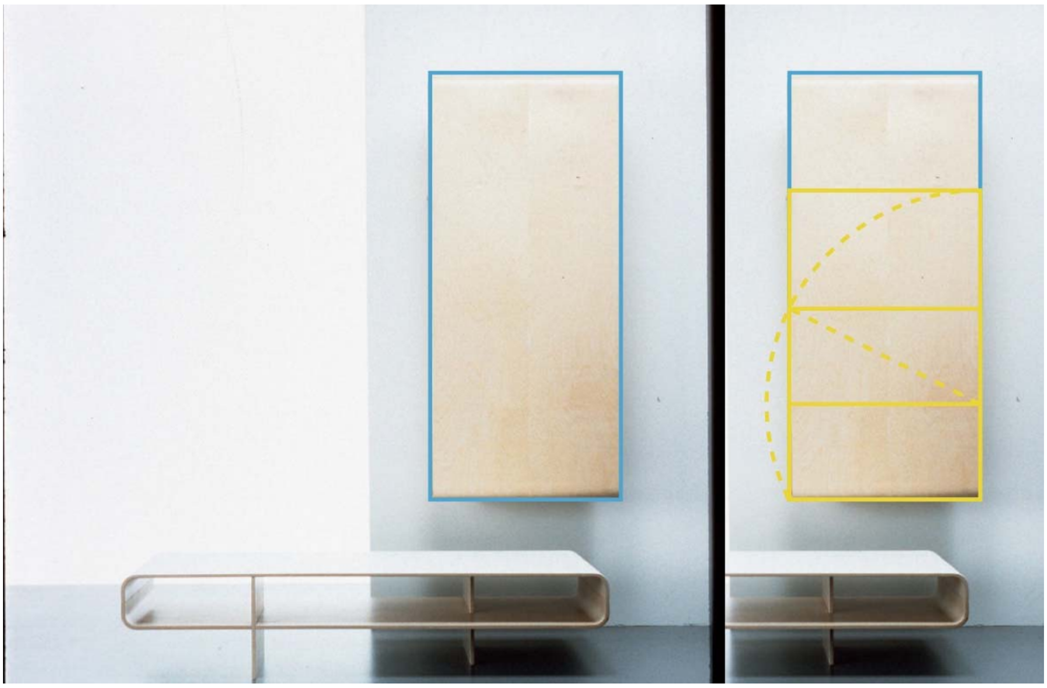
67	Loop Coffee Table	Isokon Plus/ 1996~	Barber Osgerby	1996	2.25



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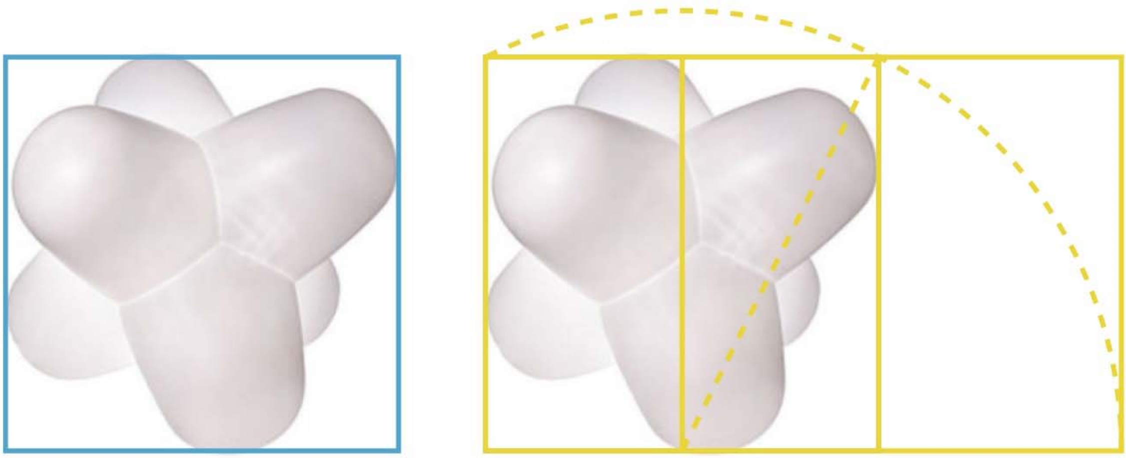
68	Jack Light	Eurolaunge/ 1996~	Tom Dixon	1996	1



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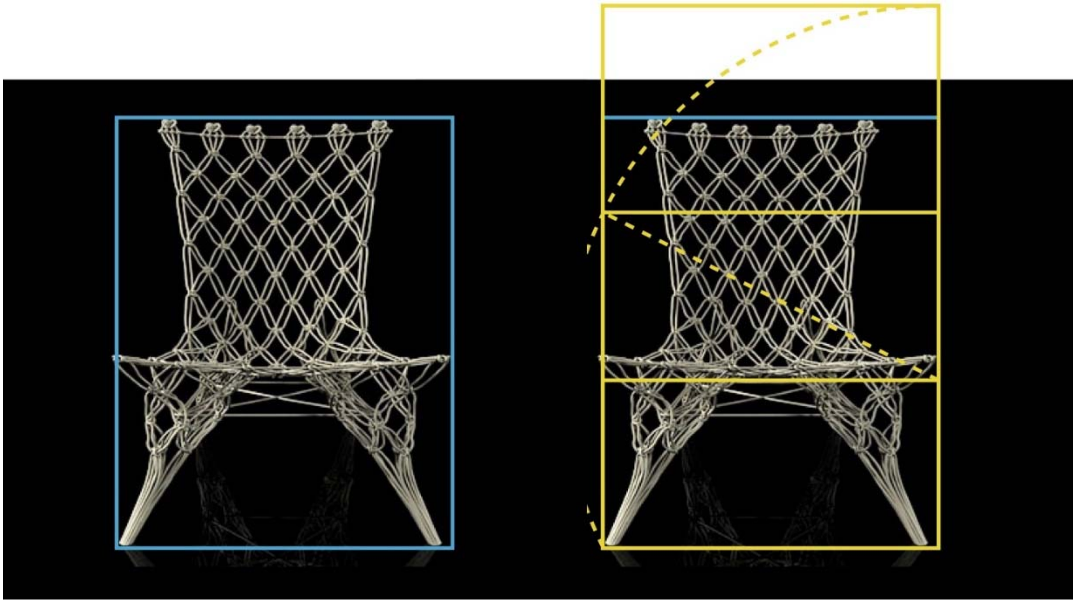
69	Knotted chair	Cappellini/ 1996~	Marcel Wanders	1996	1.285



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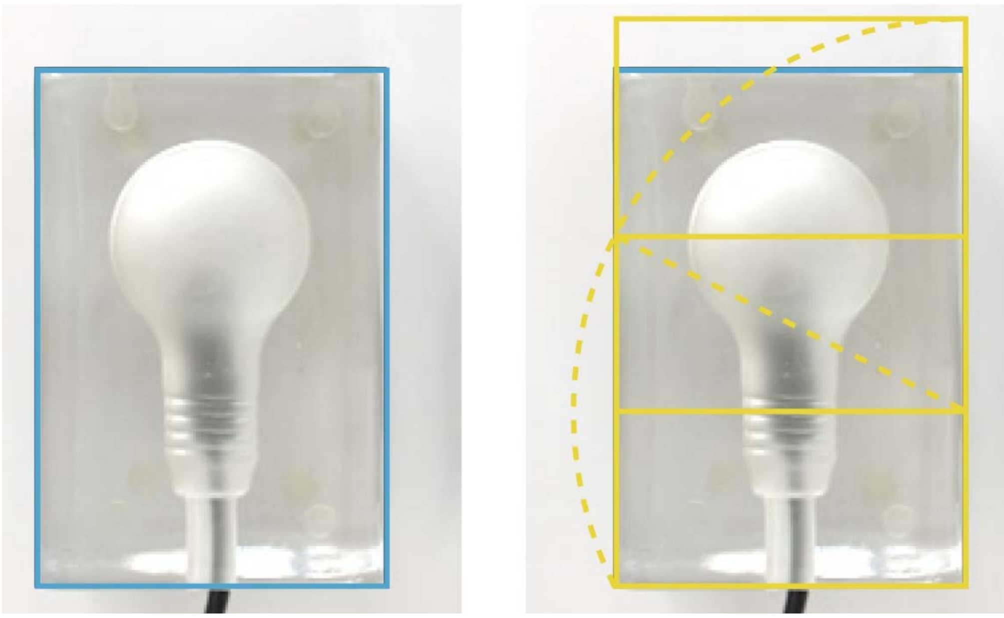
70	The Block Lamp	Desgin House Stockholm/ 1998~	Harri Koskinen	1996	1.458



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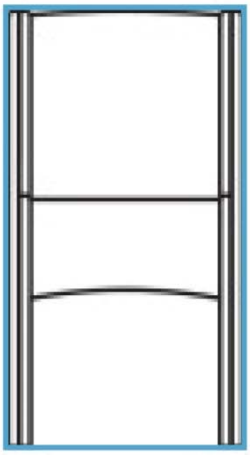
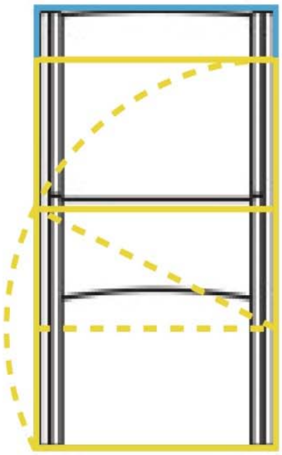
71	Fantastic Plastic Elastic	Kartell/ 1997~	Ron Arad	1997	1.837
  					
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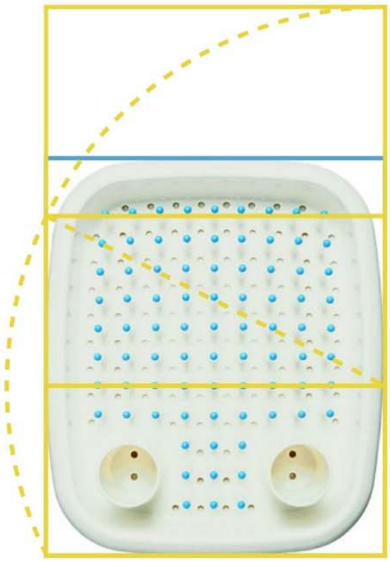
72	Dish Doctor	Magis/ 1998~	Marc Newson	1997	1.172
  					
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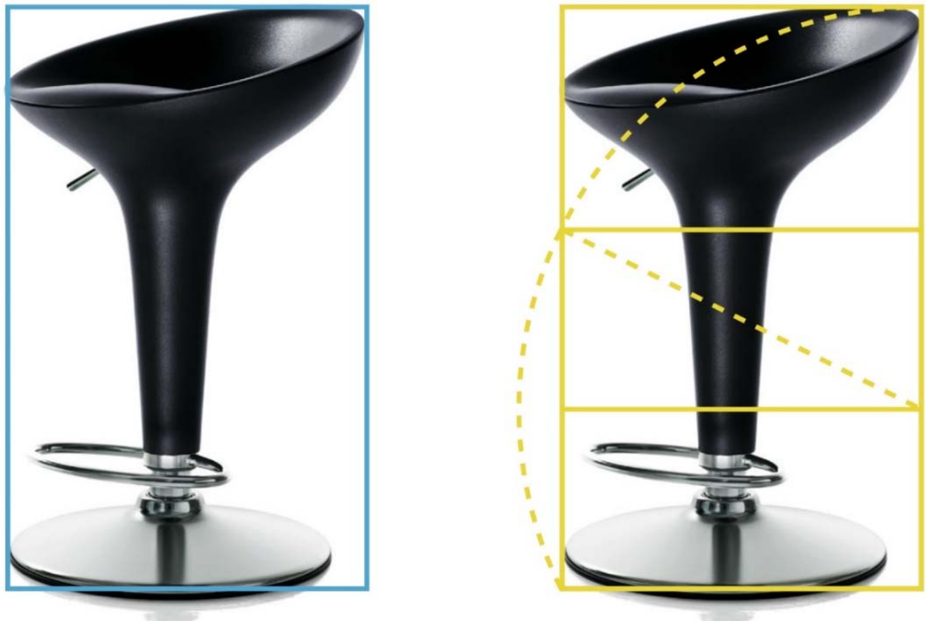
73	Bombo Stool	Magis/ 1997~	Stefano Giovannoni	1997	1.681



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74	Tom Vac	Vitra /1999~	Ron Arad	1997	1.25

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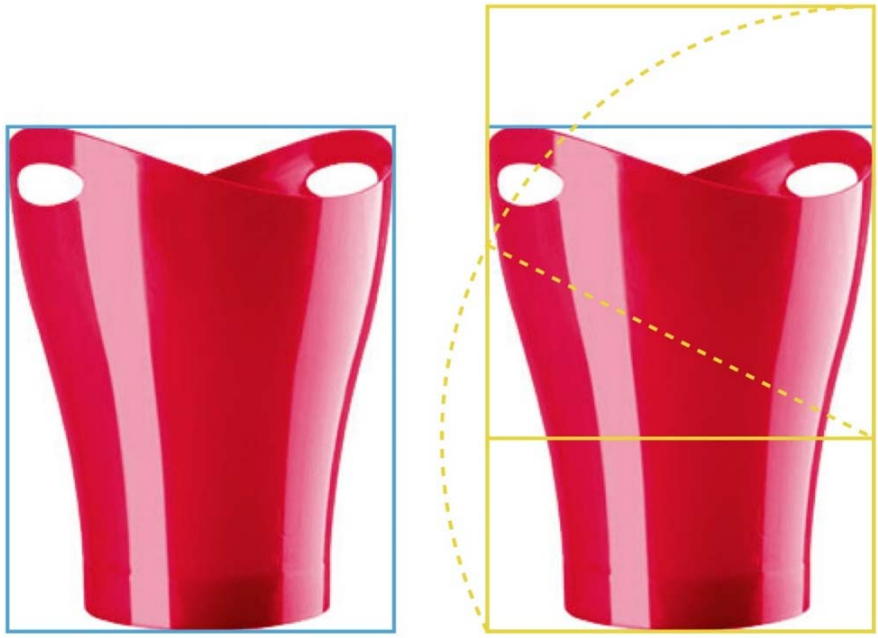
75	Garbino	Umbra/ 1997~	Karim Rashid	1997	1.3
					
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76	Wait	Authentics/ 1999~	Matthew Hilton	1997	1.63
					
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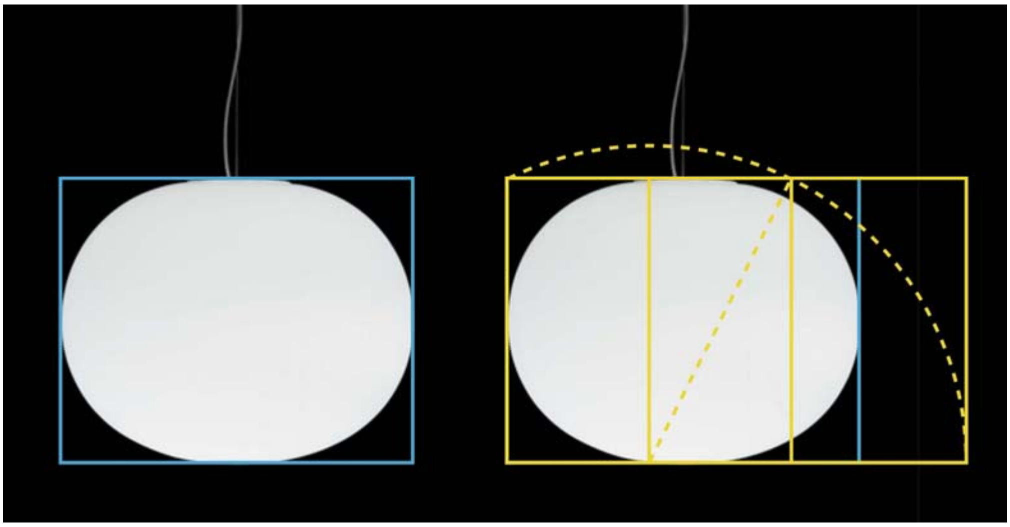
77	Gio-Ball	Flos /1998~	Jasper Morrison	1998	1.268



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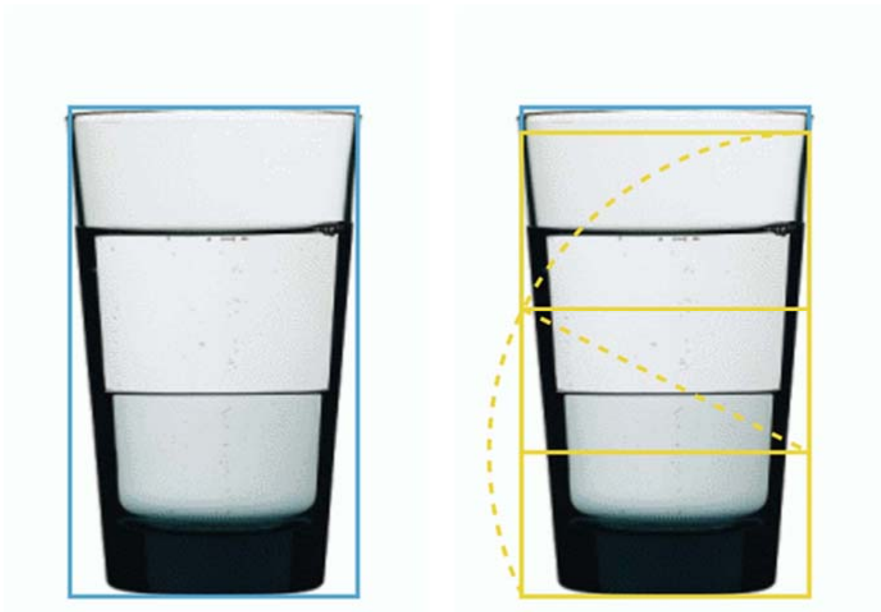
78	Relations Glasses	iittala/ 1999-	Konstantin Grcic	1999	1.709



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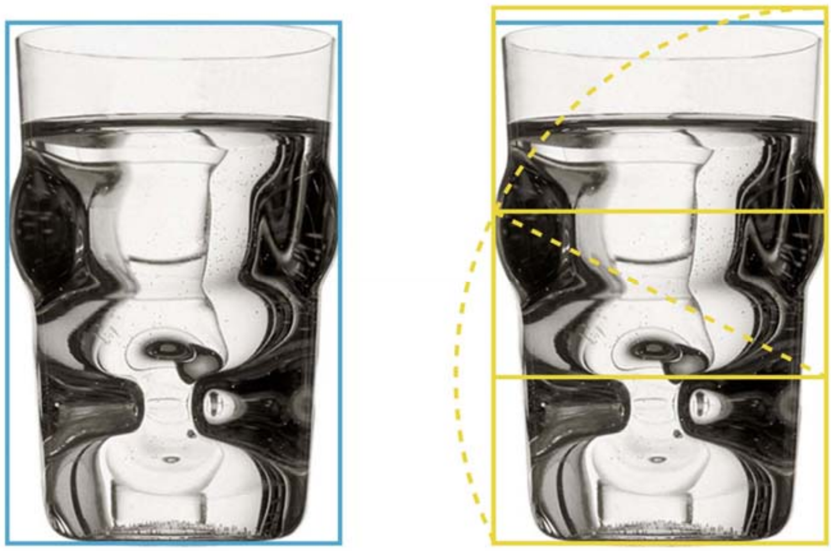
79	Optic Glass	Droog Design/ 2004~	Arnout Visser	1998	1.5
					
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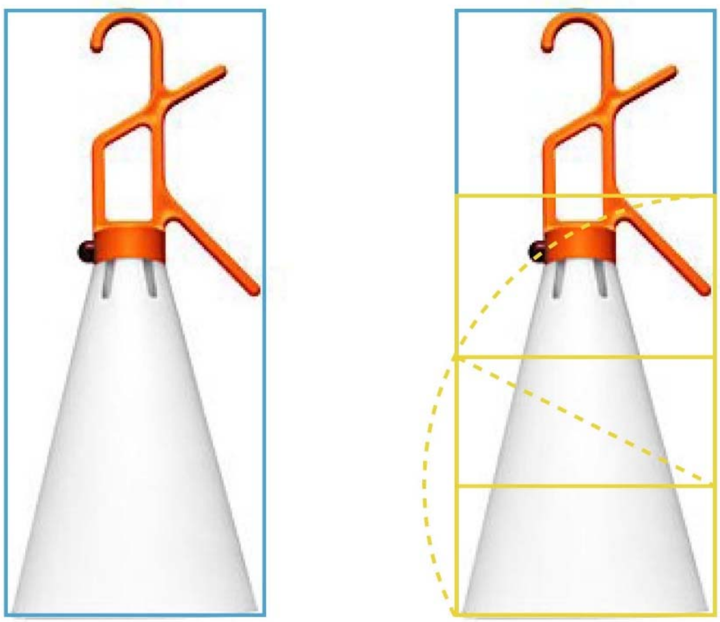
80	May Day Lamp	Flos /2000~	Konstantin Grcic	1998	2.467
					
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81	Ypsilon	Vitra/ 1998~	Mario Bellini	1998	1.705
 					
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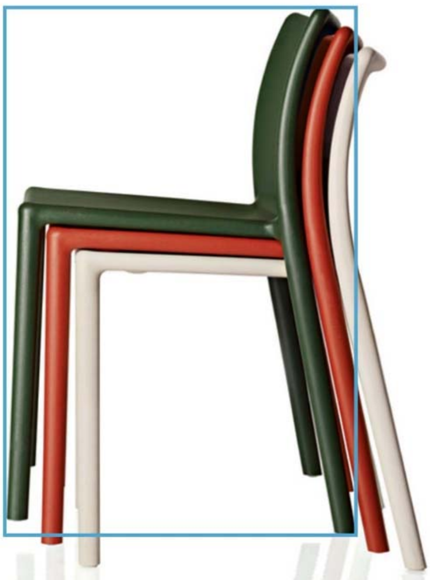
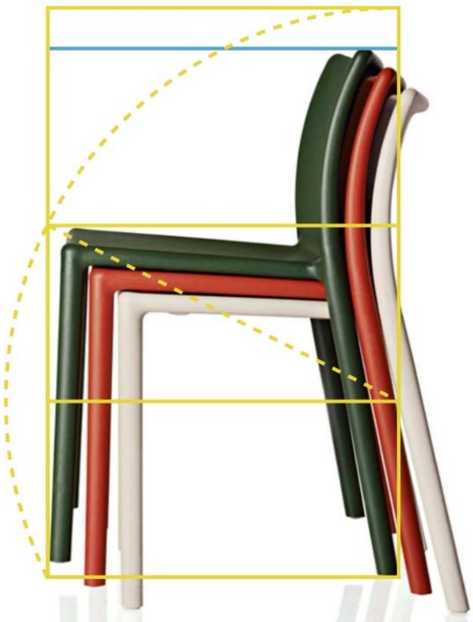
82	Air-Chair	Magis/ 2000~	Jasper Morrison	1999	1.52
 					
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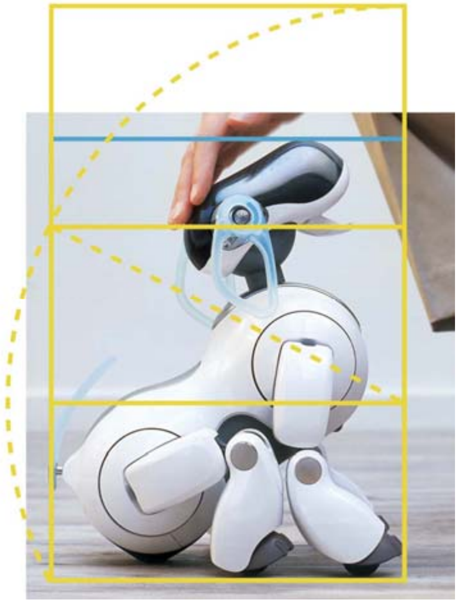
83	Aibo Robot	Sony/ 1999~	Hajime Sorayama (1947~) Sony Design Team	1999	1.285
 					
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84	Low Pad	Cappellini/ 1999~	Jasper Morrison	1999	1.217
 					
Downloaded from: http://www.aram.co.uk/low-pad-chair.html, accessed date: 30/07/2013					

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<tr><td>85</td><td>LEM</td><td>Lapalma/ 2000~</td><td>Shin Azumi</td><td>2000</td><td>1.66</td></tr>
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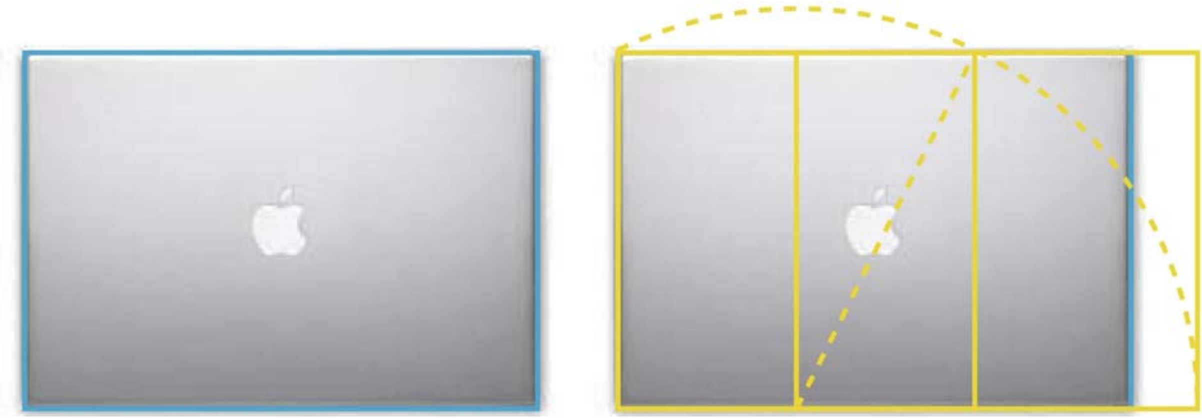
<tr><td colspan="6"></td></tr>
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87	iPod	Apple computer/ 2001~	Jonathan Ive	2001	1.673

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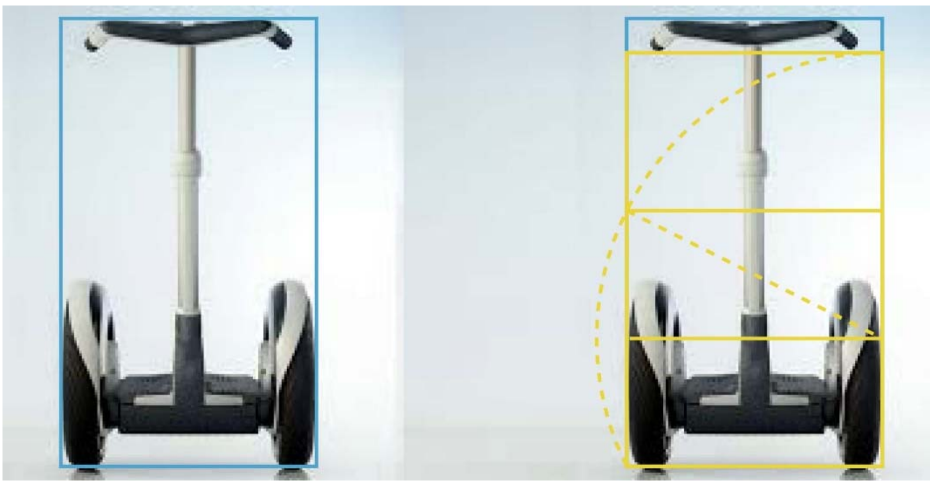
88	Segway Human Transporter	Segway/ 2002~	Segway design team	2001	1.76



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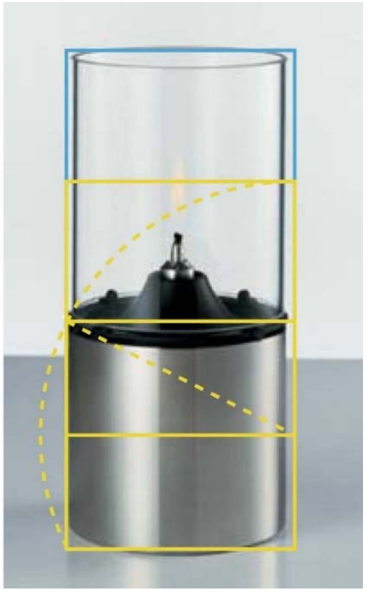
89	Oil Lamp	Stelton/ 2001~	Erik Magnussen	2001	2.176
 					
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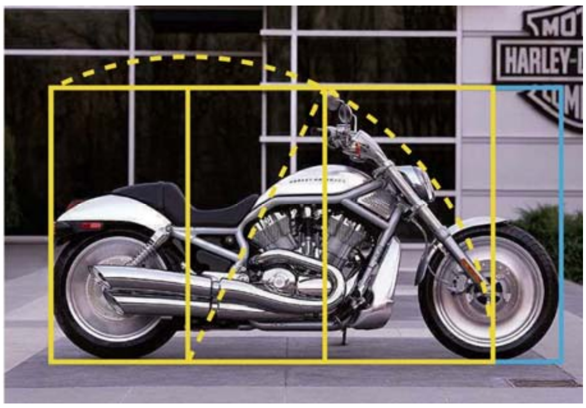
90	V-Rod	Harley-Davidson/ 2001~	Willie G Davidson	2001	1.942
 					
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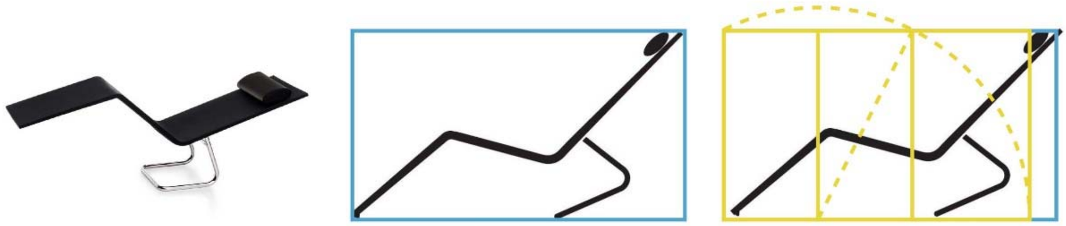
91	MVS Chaise	Vitra/ 2002~	Maarten van Severen	2002	1.776



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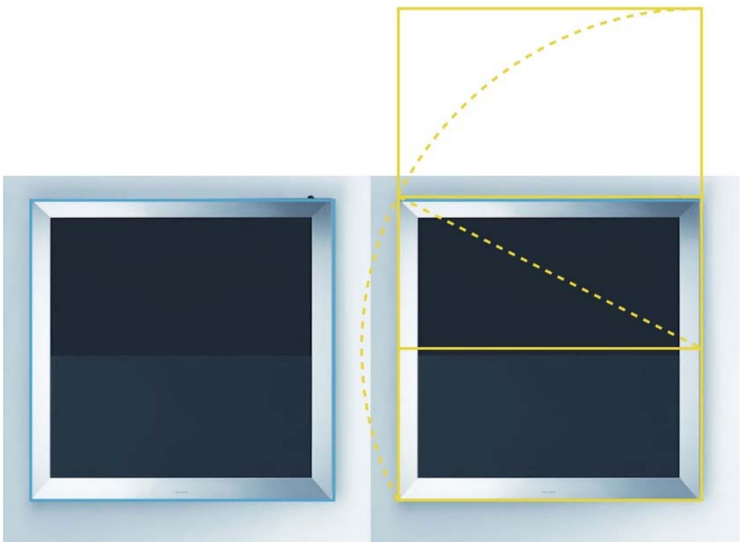
92	BeoVision 5	Bang & Olufson/ 2002~	David Lewis	2002	1.061



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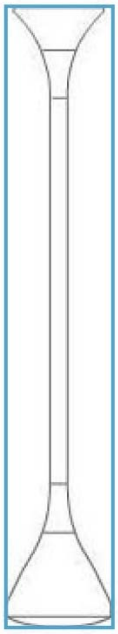
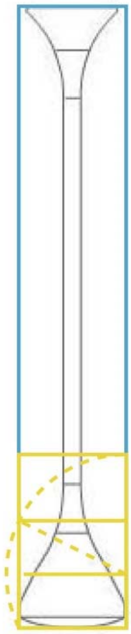
93	Pipe Sospensione	Artemide/ 2002~	Herzog & de Meuron	2002	6.571
  					
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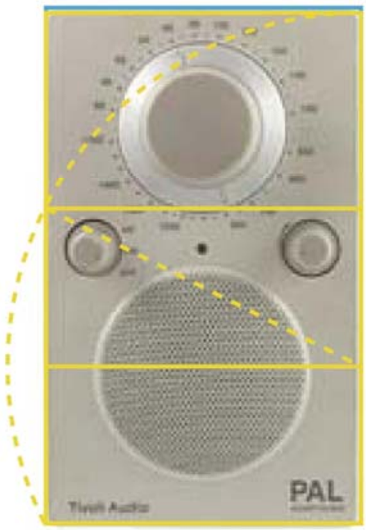
94	PAL	Tivoli Audio/ 2002~	Henry Kloss	2002	1.694
 					
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95	Beolab 5	Bang & Olufson/ 2003~	David Lewis	2003	1.979
 					
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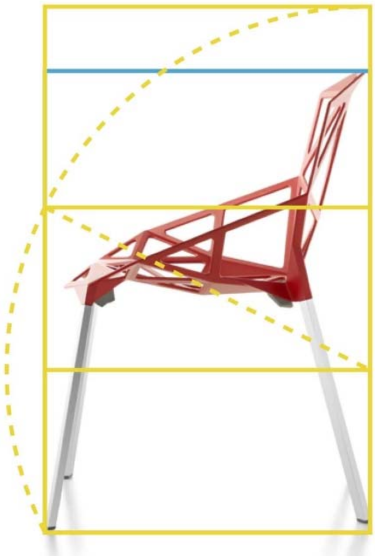
96	Chair one	Magis/ 2004~	Konstantin Grcic	2003	1.444
 					
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97	Brunch Set (Kettle)	Rowenta/ 2004~	Jasper Morrison	2003	1.281
					
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98	Brunch set (coffee maker)	Rowenta/ 2004~	Jasper Morrison	2003	1.101
					
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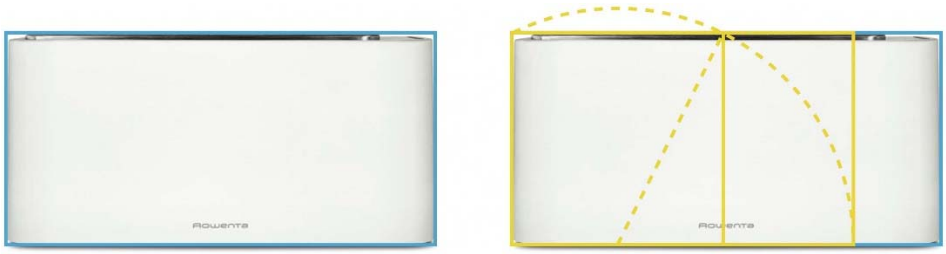
99	Brunch set(toster)	Rowenta/ 2004~	Jasper Morrison	2003	2.021



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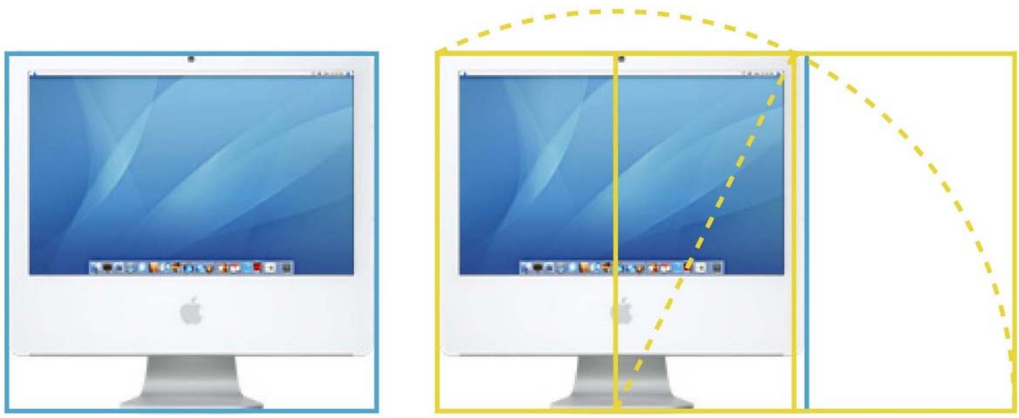
100	iMac G5	Apple computer/ 2004~	Apple design team	2004	1.013



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Appendix III The details of 100 Bestselling designs

<table>
<tr><th></th><th>Product</th><th>Company</th><th>Ratio</th></tr>
<tr><td>1</td><td>iPod touch 16GB 4th Generation - White</td><td>Apple</td><td>1.884</td></tr>
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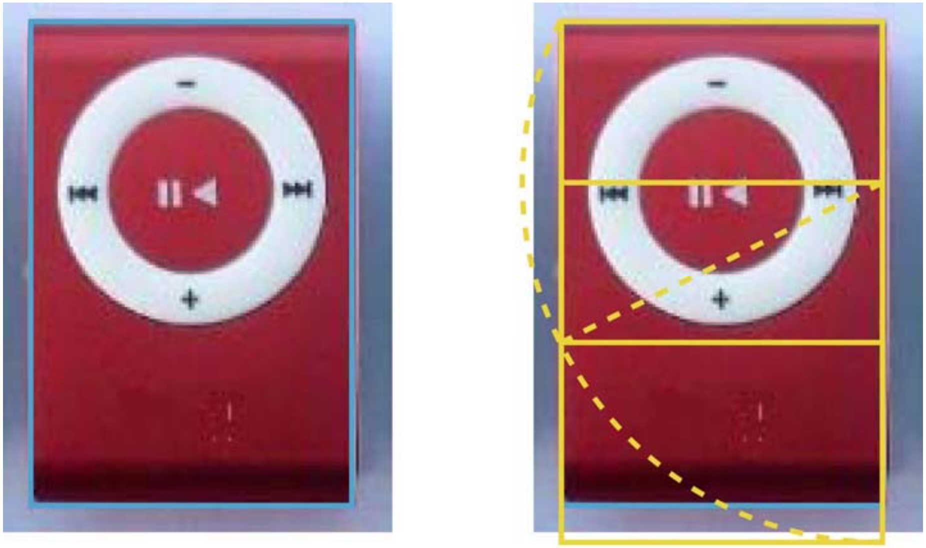
<tr><td colspan="4">Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-MP3-Digital-Audio-Players/zgbs/electronics/573372/ref=zg_bs_nav_ce_2_560884, accessed date: 23/03/2013</td></tr>
<tr><td>2</td><td>iPod touch 16GB 4th Generation - Black</td><td>Apple</td><td>1.884</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-MP3-Digital-Audio-Players/zgbs/electronics/573372/ref=zg_bs_nav_ce_2_560884, accessed date: 23/03/2013</td></tr>
</table>

3	Mini Fashion Clip Metal MP3 Music Player with Earphone & USB Cable , Support 1 - 32GB SD Card (Mixed Colour)	Amulfi	1.5



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4	Sansa Clip+ 8GB MP3 Player	SanDisk	1.571

Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-MP3-Digital-Audio-Players/zgbs/electronics/573372/ref=zg_bs_nav_ce_2_560884, accessed date: 23/03/2013

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<tr><td>5</td><td>iPod Nano 16GB 7th Generation - Slate</td><td>Apple</td><td>1.9</td></tr>
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<tr><td>6</td><td>Galaxy S 8GB Wi-Fi MP3 Player with 4.2 inch Display - White</td><td>Samsung</td><td>1.877</td></tr>
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</td></tr>
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<table>
<tr><td>7</td><td>iPod classic 160GB - Black - 6th Generation</td><td>Apple</td><td>1.674</td></tr>
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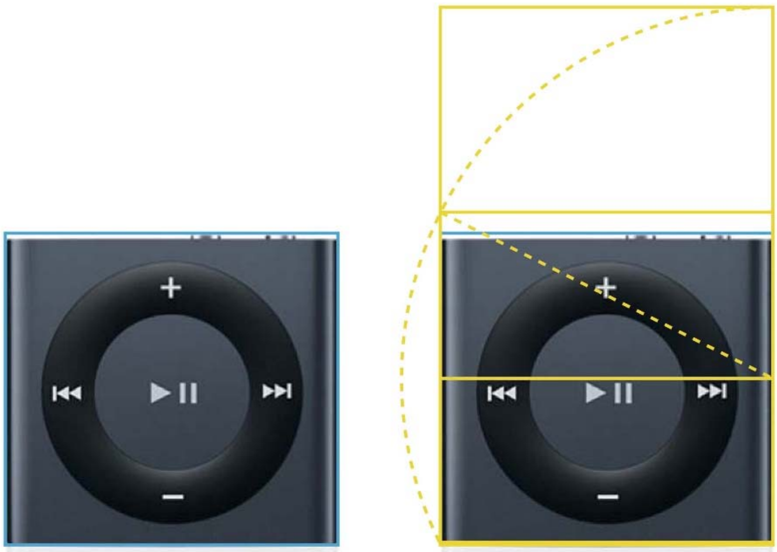
<tr><td>8</td><td>iPod shuffle 2GB - Slate</td><td>Apple</td><td>1.089</td></tr>
<tr><td colspan="4"></td></tr>
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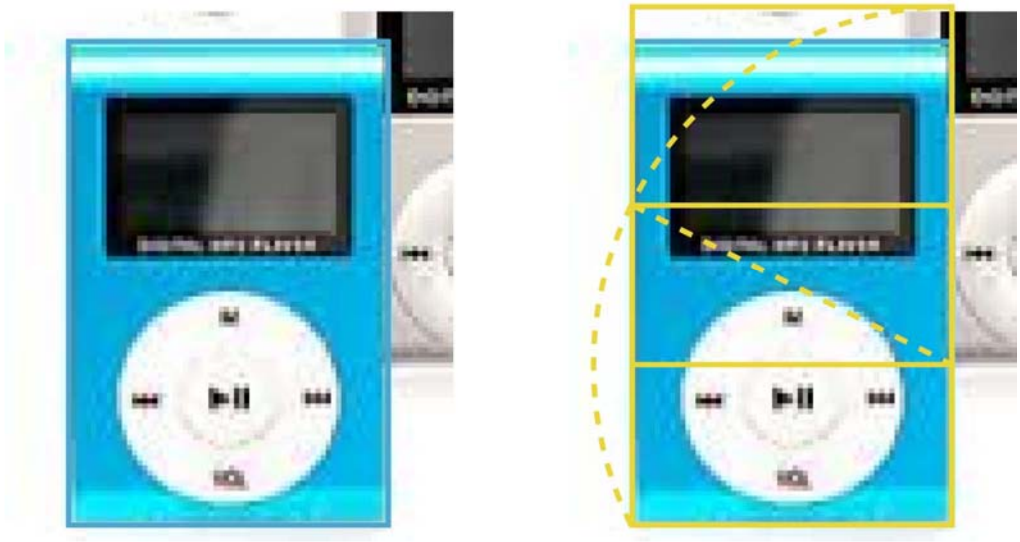
9	LCD CLIP 4GB MP3 FLASH MEMORY PLAYER - Black	Brilliant	1.6
			
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10	iPod touch 32GB 5th Generation - Blue	Apple	2.103
			
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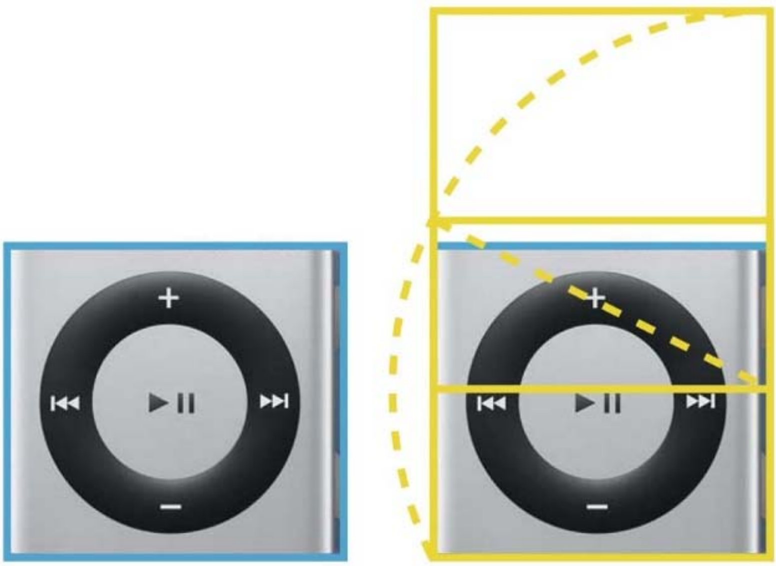
<tr><td>11</td><td>iPod shuffle 2GB - Silver</td><td>Apple</td><td>1.089</td></tr>
<tr><td colspan="4"></td></tr>
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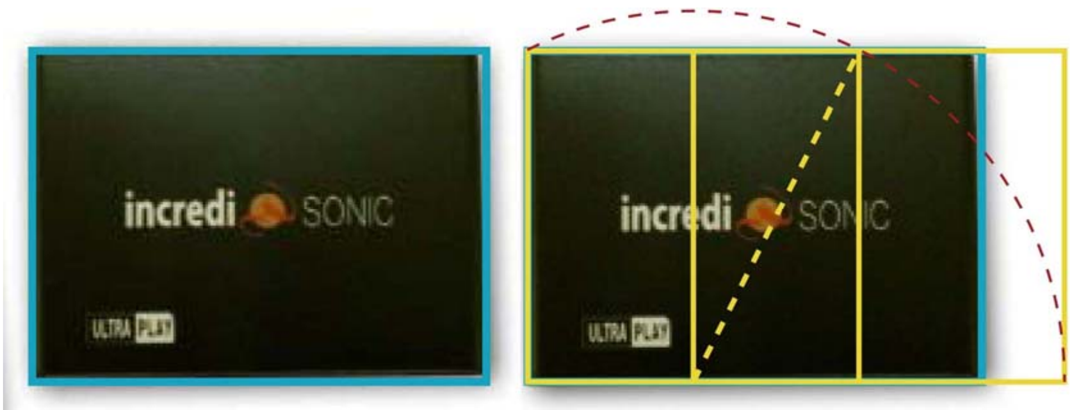
<tr><td>12</td><td>Ultra Play IMP150 - HD TV Digital Mini Media Player</td><td>IncrediSonic</td><td>1.49</td></tr>
<tr><td colspan="4">
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13	iPod Nano 16GB 7th Generation - Blue	Apple	1.936

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14	iPod touch 32GB 5th Generation - Black	Apple	2.098

Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 23/03/2013

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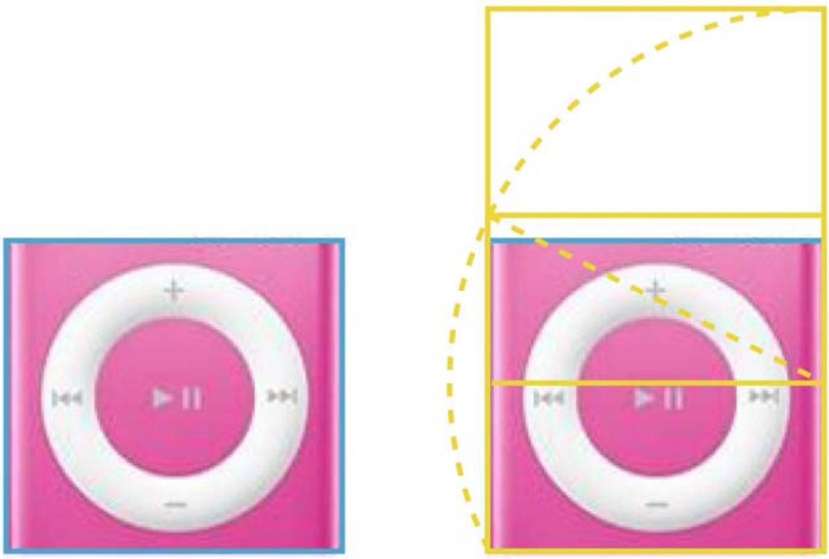
<tr><td>16</td><td>iPod shuffle 2GB - Pink</td><td>Apple</td><td>1.089</td></tr>
<tr><td colspan="4"></td></tr>
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17	iPod classic 160GB - Silver - 6th Generation	Apple	1.674
			
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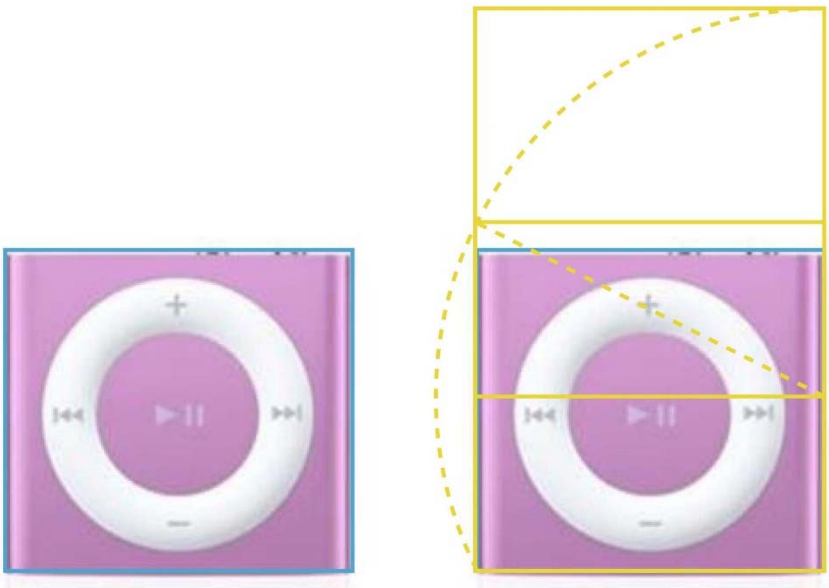
18	iPod shuffle 2GB - Purple	Apple	1.089
			
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19	iPod touch 8GB - Black - 4th Generation 2010	Apple	1.884
 			
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20	iPod Nano 16GB 7th Generation - Silver	Apple	1.931
 			
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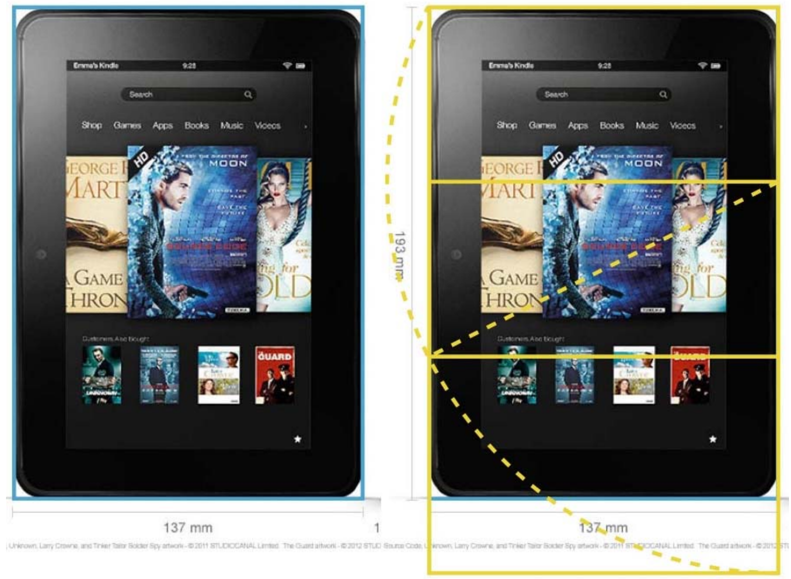
21	Fire HD Tablet 16 GB	Kindle	1.408
			
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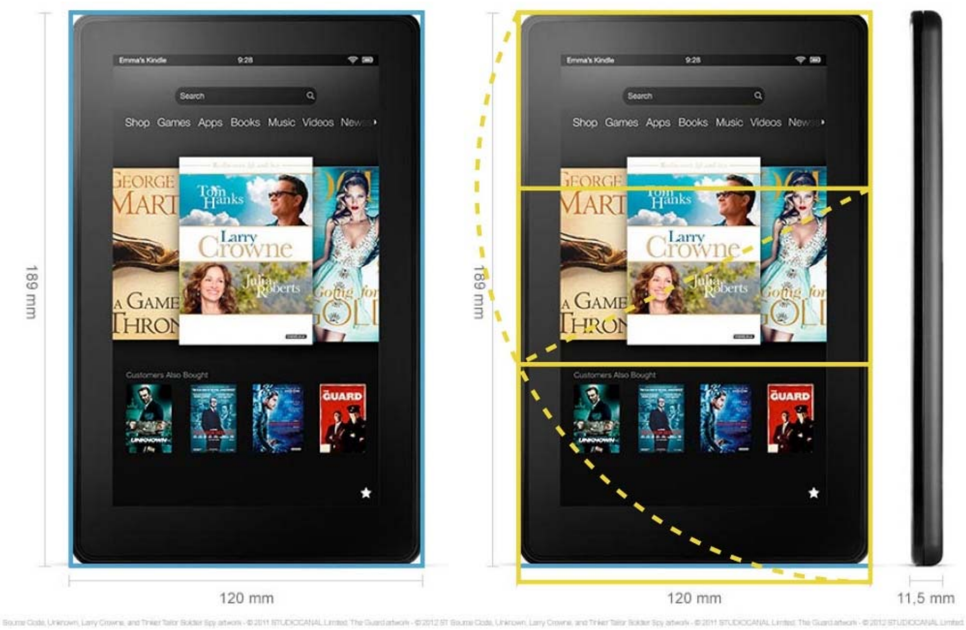
22	Fire Tablet 8GB	Kindle	1.575
			
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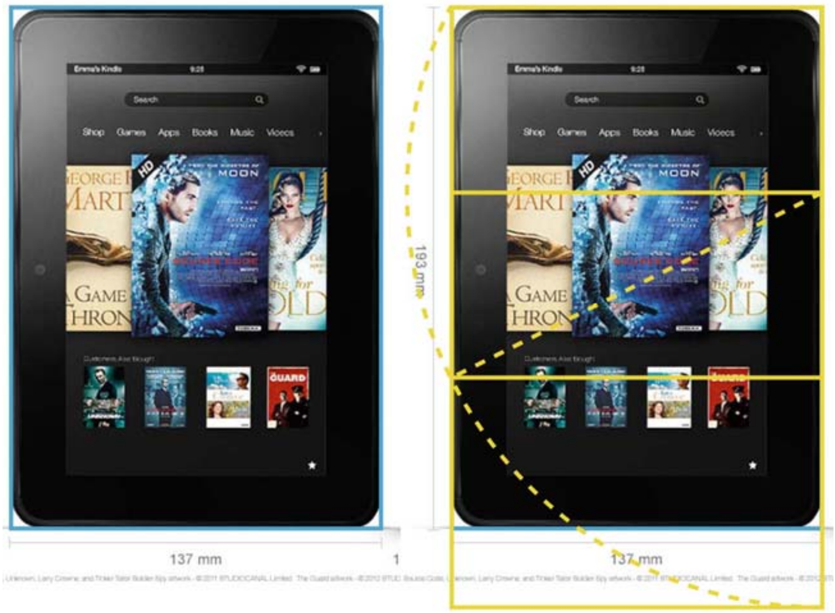
23	Fire HD Tablet 32 GB	Kindle	1.408



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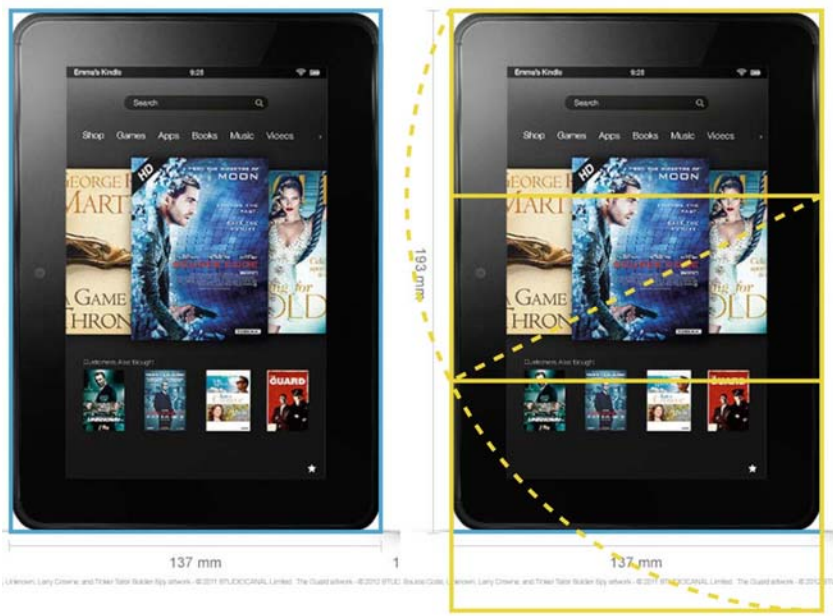
24	Fire HD Tablet 16 GB	Kindle	1.408



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25	iPad 2 Wi-Fi - Tablet - 16 GB	Apple	1.295
 			
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26	A13 pink	LélikTec	1.5
 			
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27	iPad mini6 Black Matt	Apple	1.279
			
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28	A13 white	LélikTec	1.5
			
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29	A13- Blue	LélikTec	1.5
 			
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30	Galaxy Tab 2 10.1 inch Tablet - Silver	Samsung	1.468
 			
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31	iPad Mini 16GB Wi-Fi (White)	Apple	1.287
 			
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32	Galaxy Tab 2 7 inch Tablet - Silver	Samsung	1.59
 			
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33	iPad with Retina display - 4th generation - WiFi - 32 GB - Black	Apple	1.298
 			
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34	Fire HD 8.9" Tablet 32 GB	Kindle	1.466
 			
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35	Galaxy Tab2 10.1 inch Tablet - White	Samsung	1.468
			
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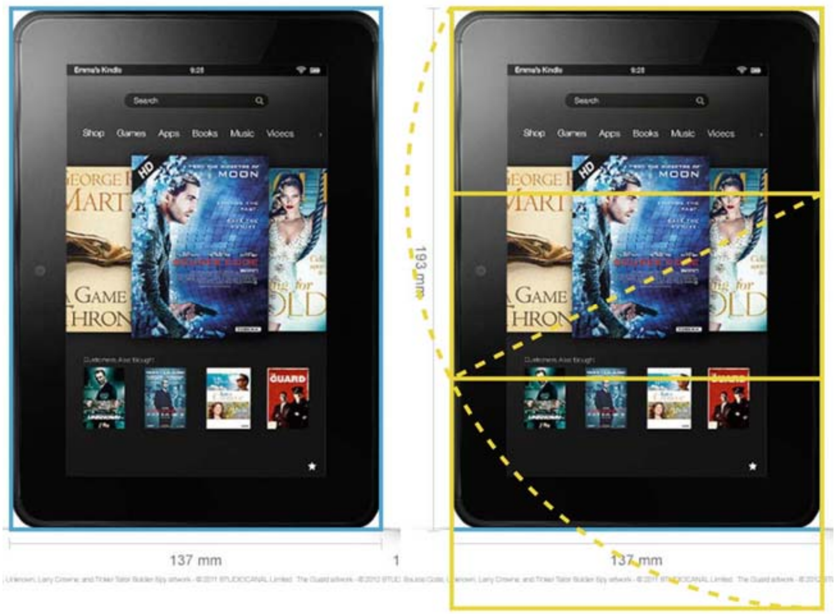
36	Fire HD Tablet 7inch 32 GB	Kindle	1.408
			
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37	Galaxy Note 10.1 inch Tablet - White	Samsung	1.455
 			
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38	Galaxy Tab2 10.1 inch Tablet - White (16GB)	Samsung	1.468
 			
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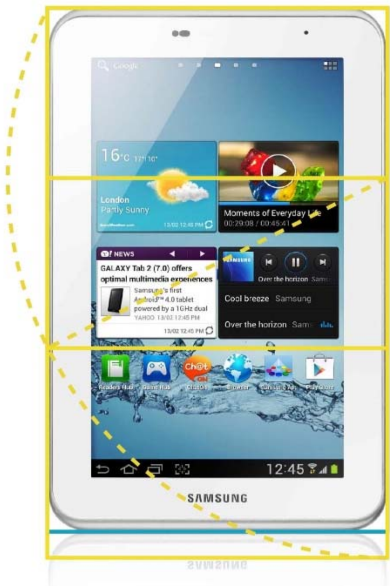
39	Galaxy Tab 2 7 inch Tablet - White (8GB)	Samsung	1.509
 			
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40	Fire HD 8.9" Tablet 16 GB	Kindle	1.466
 			
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41	Chromebook Wifi (Launched Oct 2012) Laptop	Samsung	1.022

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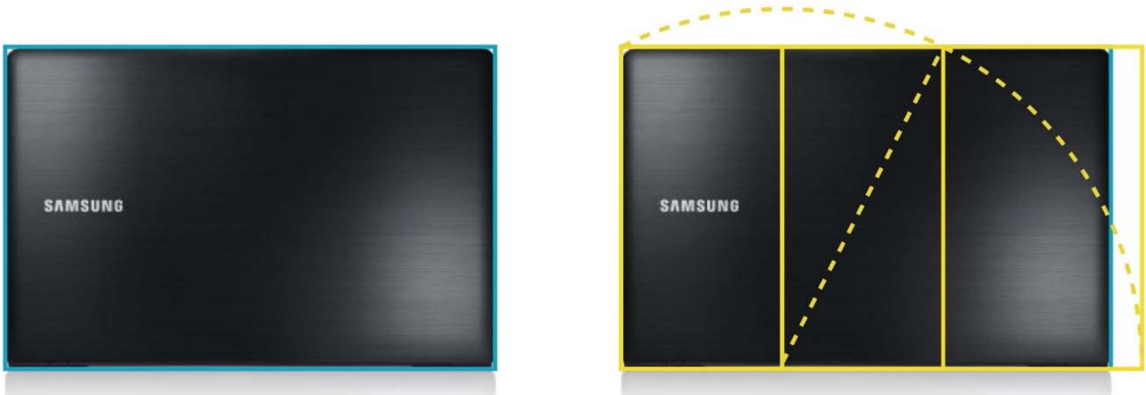
42	350E7C 17.3-inch Laptop (Black)	Samsung	1.522



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43	Aspire E1 15.6-inch Laptop (Black/Silver)	Acer	1.509
			
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44	C7 Chromebook (Gloss Grey)-(11.6 inch	Acer	1.56
			
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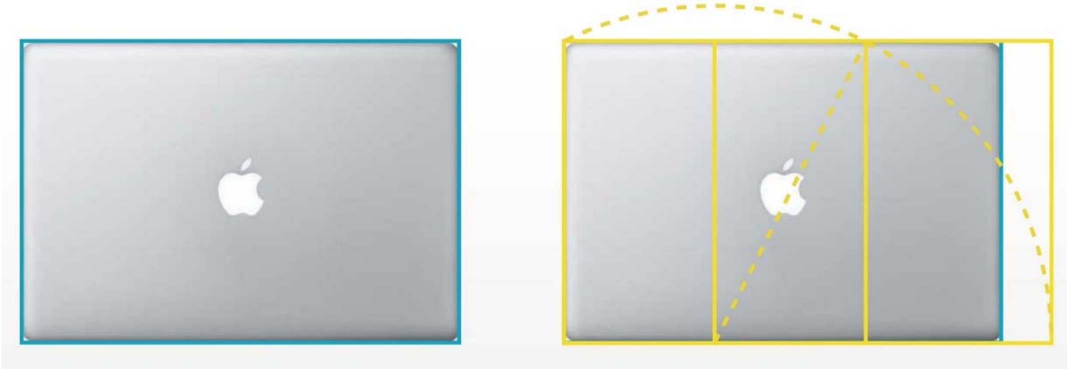
45	13-inch MacBook Pro	Apple	1.431
			
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46	S200E 11.6-inch VivoBook Touchscreen Laptop	Asus	1.515
			
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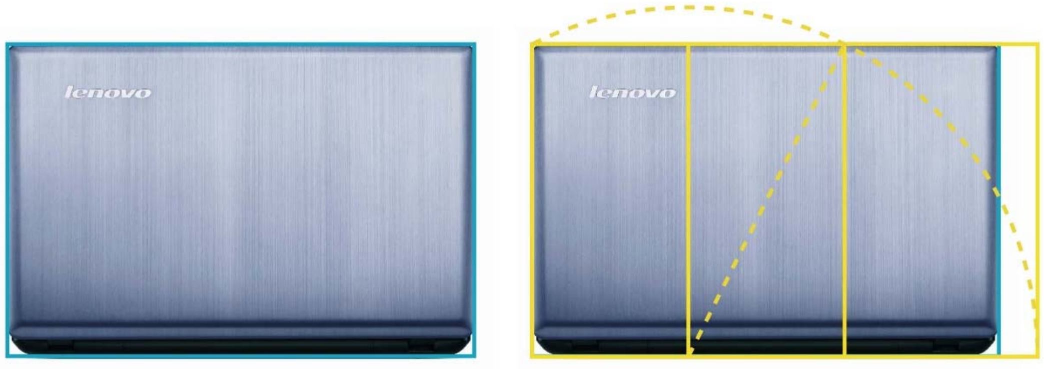
47	Ideapad Z580 15.6 inch laptop - Gunmetal	Lenovo	1.641
			
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48	Aspire E1 15.6-inch Laptop (Black/Silver	Acer	1.509
			
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49	K55A 15.6-inch Laptop (Aluminum)	Asus	1.406
			
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50	Satellite C870 - 198 17.3-inch Notebook	Toshiba	1.215
			
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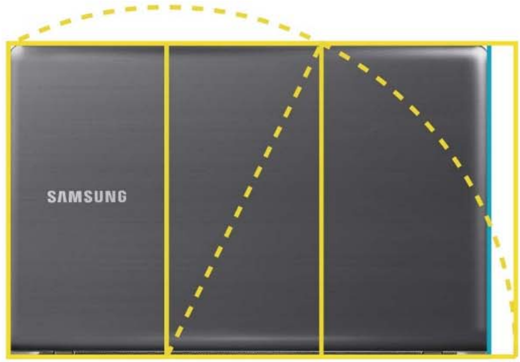
51	355V5C 15.6-inch Laptop (Silver)	Samsung	1.534
 			
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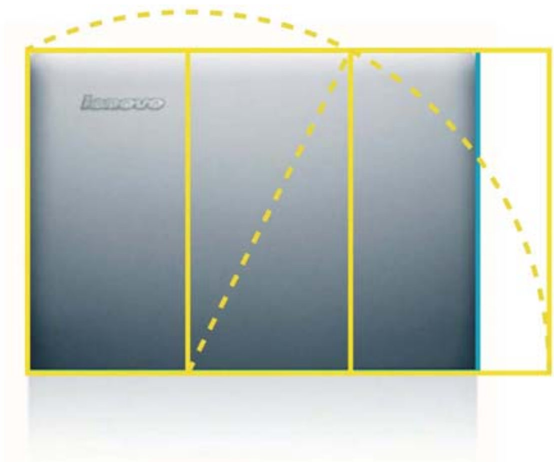
52	Ideapad S300 13.3-inch Laptop (Grey)	Lenovo	1.546
 			
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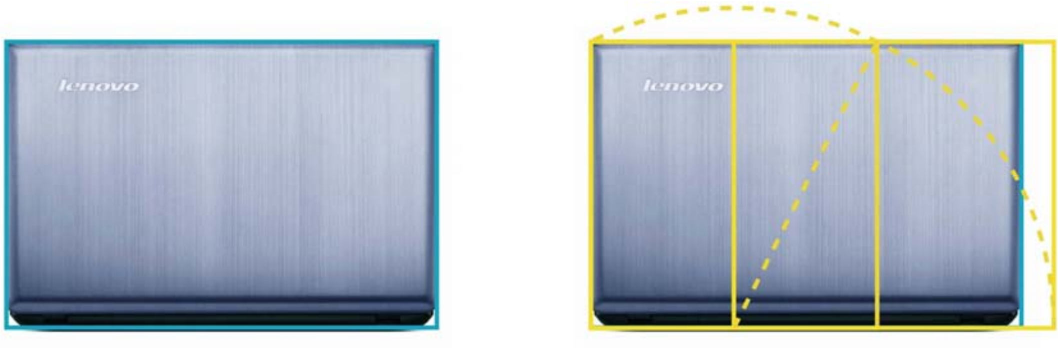
53	Ideapad Z580 15.6-inch Laptop (Gunmetal)	Lenovo	1.504
			
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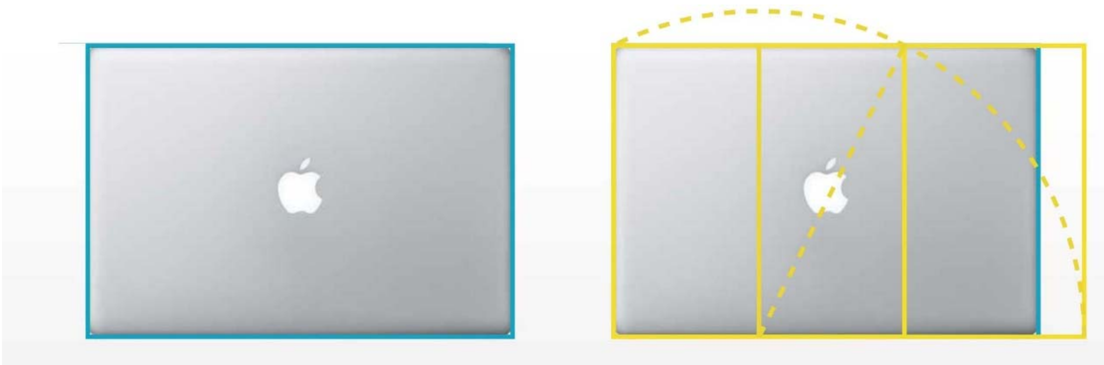
54	13-inch MacBook Pro	Apple	1.451
			
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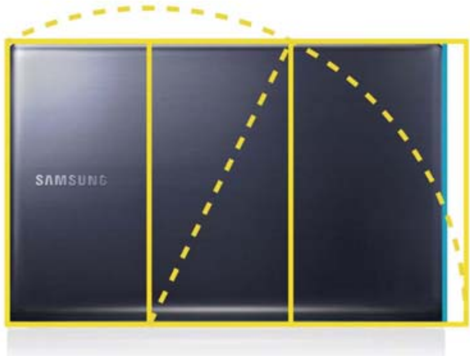
55	350V5C 15.6-inch Laptop (Silver)	Samsung	1.534
 			
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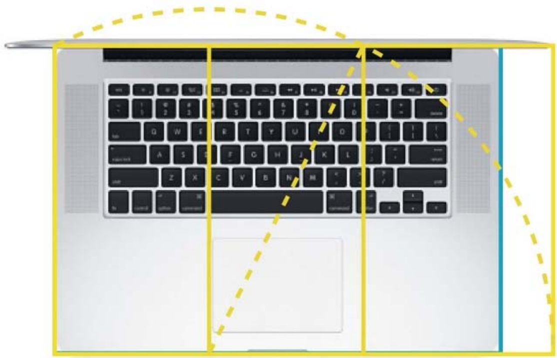
56	ME664B/A 15-inch MacBook Pro with Retina Display	Apple	1.372
 			
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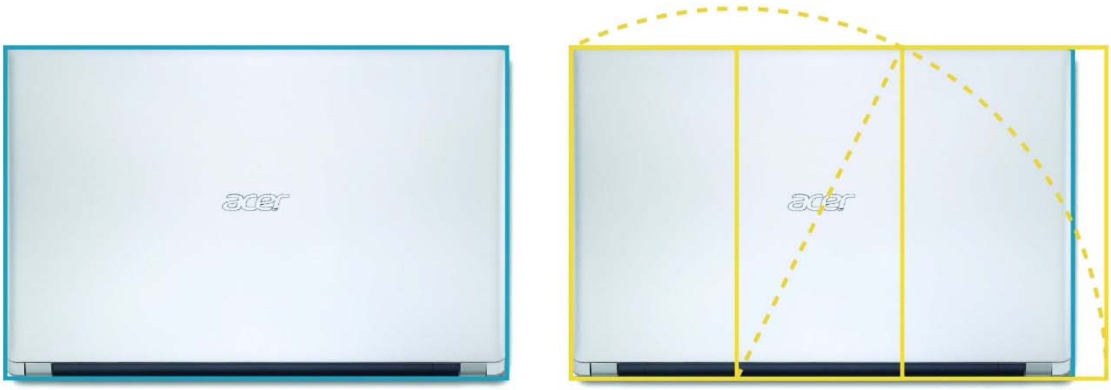
<tr><td colspan="4"></td></tr>
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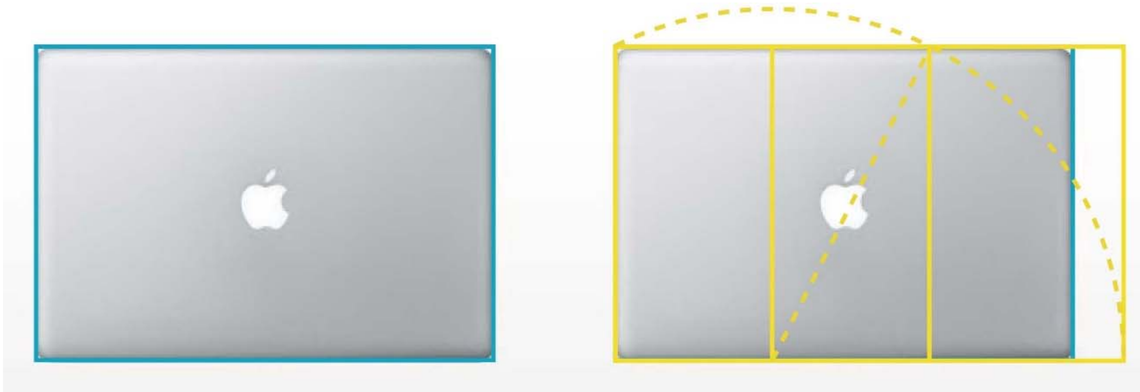
<tr><td colspan="4"></td></tr>
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61	DV300F SMART Compact Digital Camera - Black	Samsung	1.684
			
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62	COOLPIX S3300 Compact Digital Camera - Black	Nikon	1.64
			
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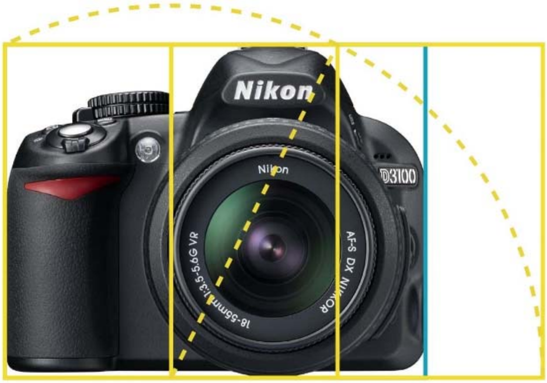
63	D3100 Digital SLR Camera	Nikon	1.288



64	FinePix S4500 Digital Camera	Fujifilm	1.18

65	SZ-31MR Digital Compact Camera - Black	Olympus	1.547
 			
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66	D3200 Digital SLR Camera with 18-55mm VR Lens Kit - Black	Nikon	1.302
 			
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67	NX1000 Digital Compact System Camera White	Samsung	1.824
 			
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68	Cyber-shot DSC-HX20V Super-Advanced High Zoom Camera	Sony	1.722
 			
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69	WB150 Compact Digital Camera - White	Samsung	1.777

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70	IXUS 125 HS Digital Camera - Silver	Canon	1.635

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71	DMC-TZ30EB-K Compact Camera - Black	Panasonic	1.78

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72	FinePix HS30EXR Digital Camera	Fujifilm	1.039

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73	EOS 1100D Digital SLR Camera	Canon	1.302
 			
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74	EOS 600D Digital SLR Camera	Canon	1.33
 			
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75	DMC-SZ1EB-K Compact Digital Camera - Black	Panasonic	1.666
 			
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76	Galaxy Camera - White	Samsung	1.817
 			
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77	PowerShot SX50 HS Digital Camera	Canon	1.411

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78	WB150 Compact Digital Camera - Black	Samsung	1.777

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79	COOLPIX P510 Compact Digital Camera - Gunmetal	Nikon	1.445

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80	COOLPIX L27 Compact Digital Camera - Black	Nikon	1.454

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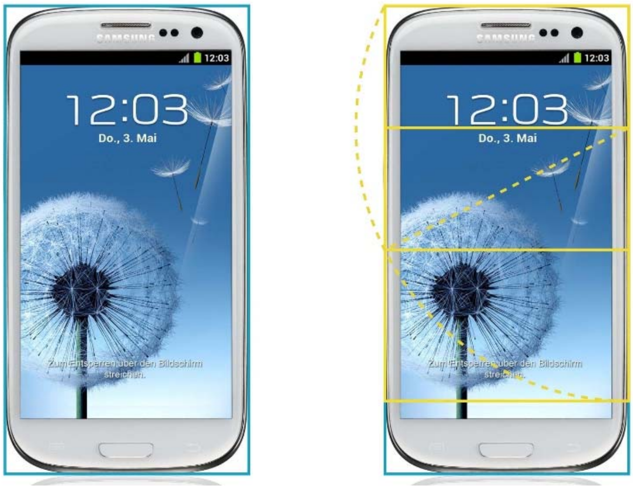
83	Galaxy SIII UK Sim Free Unlocked Smartphone -16GB-white	Samsung	1.934



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84	Galaxy SIII Mini UK Sim Free Smartphone - Blue	Samsung	1.929

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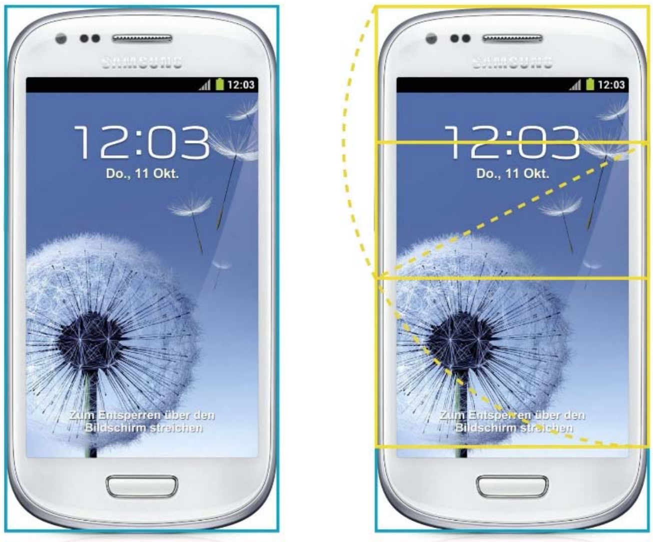
<tr><td colspan="4">
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87	One 32GB UK SIM Free Smartphone - Silver	HTC	2.014

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88	Lumia 800 Sim Free Windows Smartphone - Matte Cyan Blue	Nokia	1.903

Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 24/03/2013

89	Google Nexus 4 8GB Smartphone Black Sim Free	LG	1.942
	 		
	Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 24/03/2013		
90	S5830 Galaxy Ace Sim Free Smartphone	Samsung	1.876
	 		
	Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 24/03/2013		

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<tr><td>92</td><td>iPhone 5 SIM FREE</td><td>Apple</td><td>2.112</td></tr>
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93	Lumia 800 Sim Free Windows Smartphone - Matte Cyan Black	Nokia	1.903
 			
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94	I9100 Galaxy S II 16 GB	Samsung	1.893
 			
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97	Galaxy Note 2 16GB Sim Free Smartphone - Ceramic White	Samsung	1.864
			
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98	iPhone 3GS 16GB SIM-Free - Black	Apple	1.854
			
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99	iPhone 4 16GB SIM-Free - Black	Apple	1.671

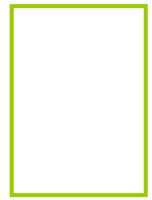
Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 24/03/2013

100	Curve 9320 Smartphone - Black	BlackBerry	1.816

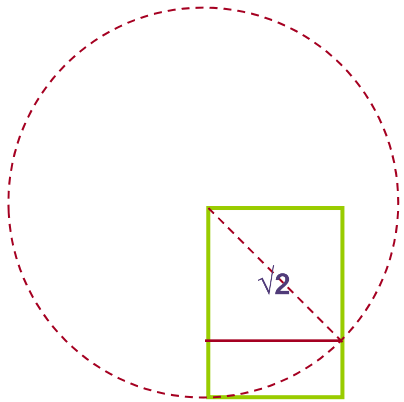
Downloaded from: http://www.amazon.co.uk/Bestsellers-Electronics-Mobile-Phones-Smartphones/zgbs/electronics/356496011/ref=zg_bs_nav_ce_3_1340509031, accessed date: 24/03/2013

A Basic step–by–step guide to geometric analysis

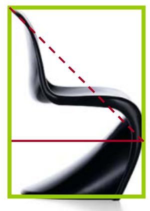
1. Obtain the original dimensions of the work to be analyzed
2. Draw a “frame” around the work that is at a tangent to, or touches, the work to be done. Usually, this frame is rectangular. Once this is done a ratio can be calculated. It is important to note that any measuring system will work. Whether in inches, centimetres, the ratio always comes out the same. Simply divide the lesser measure to the greater.

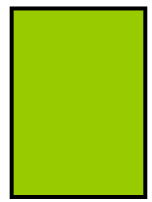


3. Draw the two diagonals, which will give you the centre point.
4. From the centre, bisect the four angles of the two diagonals. In a square, these angles are 45° but in a rectangle, these four angles can vary in size, depending on the ratio of the rectangle. These bisected lines will give the vertical and horizontal mid–lines of the rectangle, parallel to the sides.



5. Draw the eight half–diagonal lines. These lines work with the diagonals of that thirds, fourths and other fractional parts of the rectangular surface can be found.
6. If desired, do the constructions for the other fractional parts of the rectangle. These will include fifths, sixths, eighths, tenths, etc. For example, if fifths, are found, three of them will yield 3/5 = 60%. This is very close to the golden section, which is .618033…= 61.8033% of the height or width.





7. Another suggestion in the analysis is to apply the golden section(s) to the work.

Golden Section Rectangle

Quite simply.
In figure 1 draw a square.

In figure 2 divide it into two.

In figure 3 draw diagonal from the midpoint A of one of the sides to an opposite corner B.

In figure 4 this diagonal becomes the radius of an arc that extends beyond the square to C.

In figure 5 the smaller rectangle and the square become a golden section rectangle.

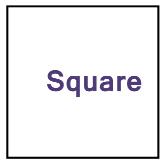


Figure 1

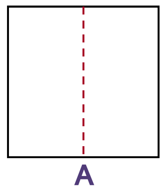


Figure 2

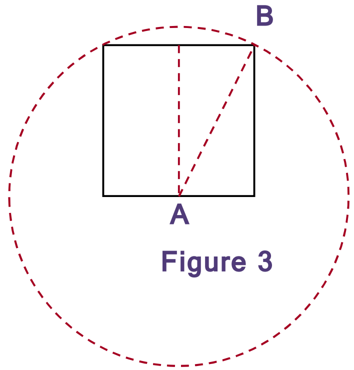


Figure 3

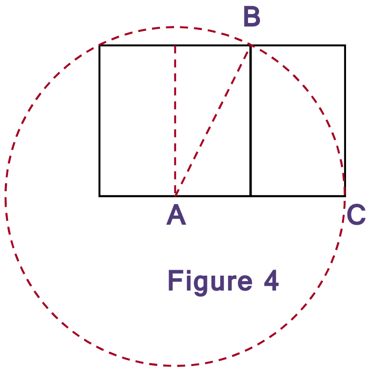


Figure 4

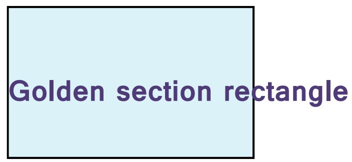


Figure 5

Golden Section Spiral Construction

Quite simply.

1. Draw a golden section rectangle.

2. In Figure 2 draw a diagonal line from A to B of the golden section rectangle.

3. In Figure 3 draw a diagonal line from C to D.

4. Draw a parallel line from E to F. we have created a small square 1.

5. Draw a parallel line from G to H. Now we have created Square 2.

6. Draw a parallel line from I to J. Now you have created the third Square.

7. Draw a parallel line form K to L. Now you have created the fourth square.

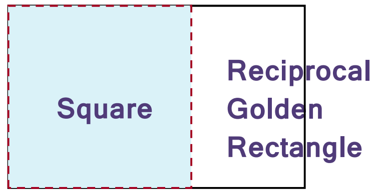


Fig 1

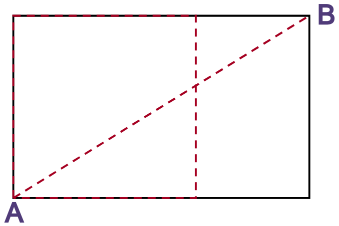


Fig 2

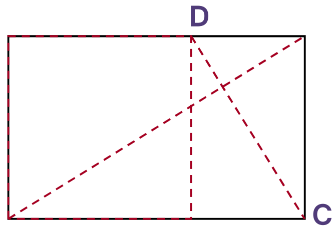


Fig 3

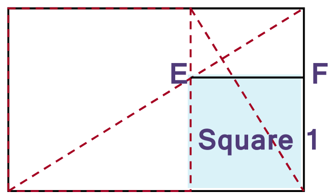


Fig 4

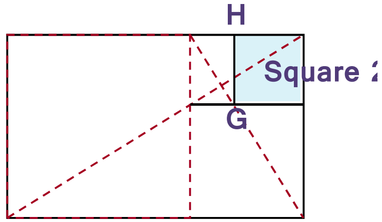


Fig 5

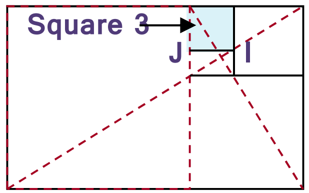


Fig 6

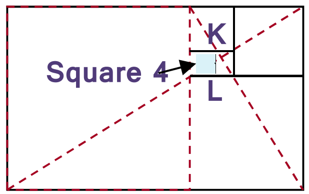


Fig 7

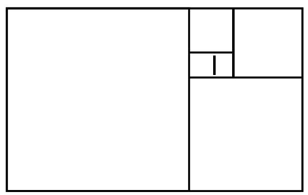


Fig 8

Golden Section Spiral Construction

Quite simply.

1. In figure 8 draw an arc from A to B.

2. In figure 9 draw an arc from B to C

3. In figure 10 draw an arc from C to D.

4. In figure 11 draw an arc from D to E.

5. In figure 12 draw an arc from E to F.

6. In figure 13 you create a golden spiral.

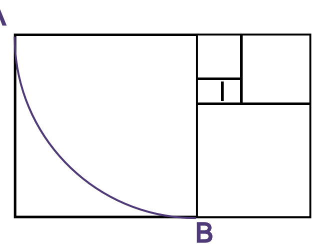


Fig 8

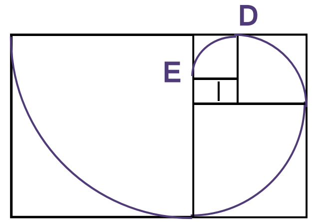


Fig 11

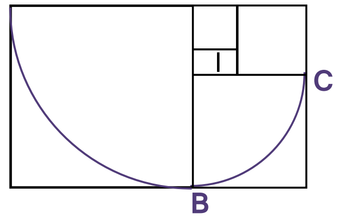


Fig 9

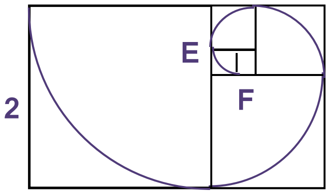


Fig 12

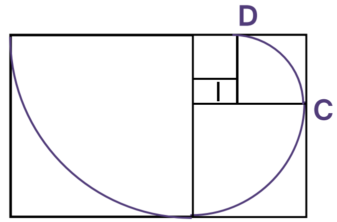


Fig 10

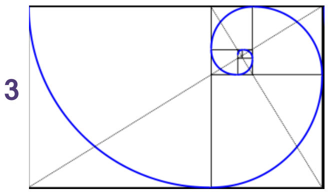


Fig 13

Golden Section Ellipse

Quite simply.

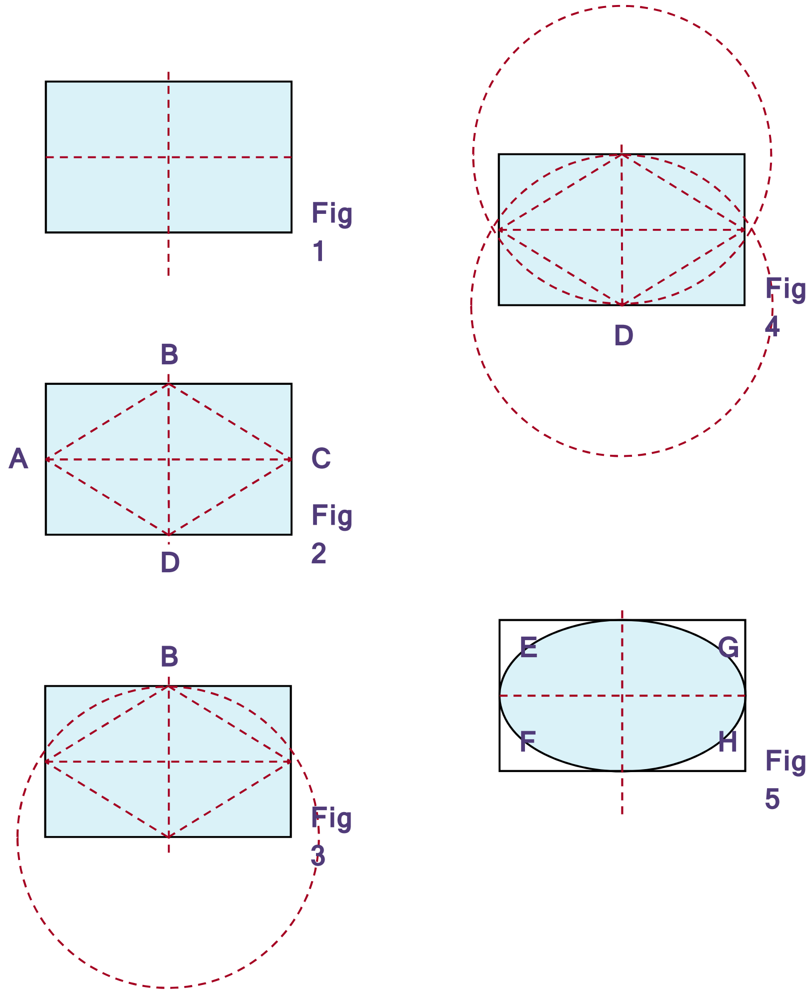
1. Draw a golden section rectangle.

2. In Figure 2 divide the golden rectangle into 4. Draw a diagonal line from A to B. B to C, C to D and D to A

3. In Figure 3 Draw a semi circle through point B.

4. In Figure 4 Draw a semi circle through point D.

5. Draw an arc freehand in order to connect ellipse line E and F, G and H.



The Root 2 Rectangle Construction

Quite simply.
In Fig 1 draw a square.

In Fig 2 Draw a diagonal within the square. Use the diagonal as an arc that touches the square base line. Enclose a rectangle around the new figure. This is a root 2 rectangle.

In Fig 3 another method of constructing a root 2 rectangle is by beginning with a circle. Inscribe a square in the circle.

In Figure 4 extend the two square sides of square so that they touch the circle. The resulting rectangle is a root 2 rectangle.

Fig 1

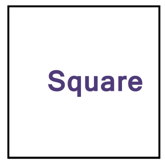


Fig 3

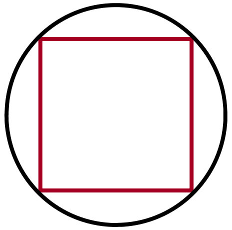


Fig 2

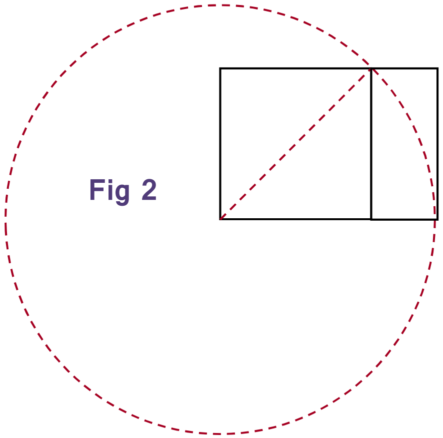
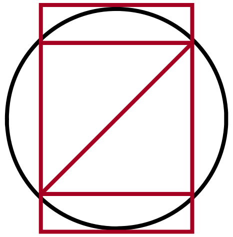
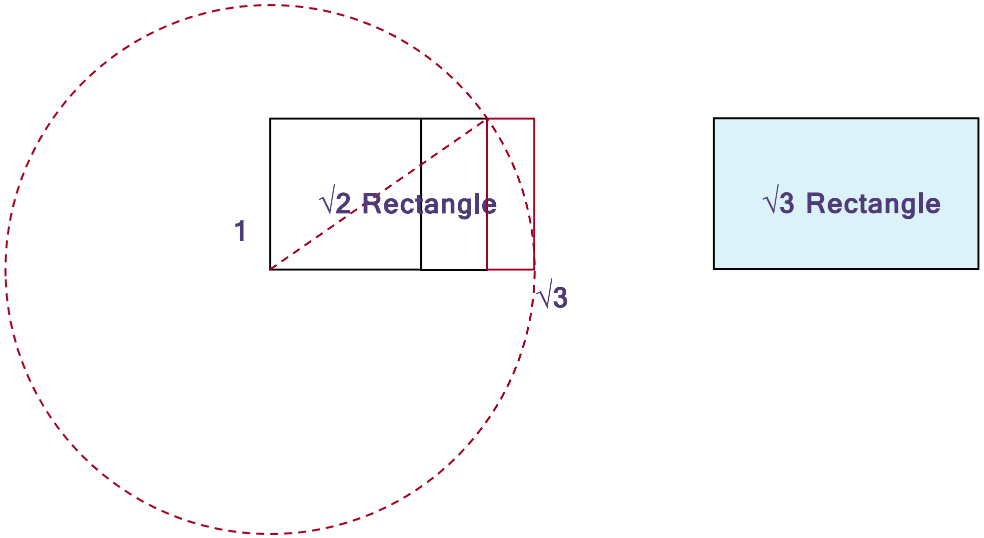


Fig 4

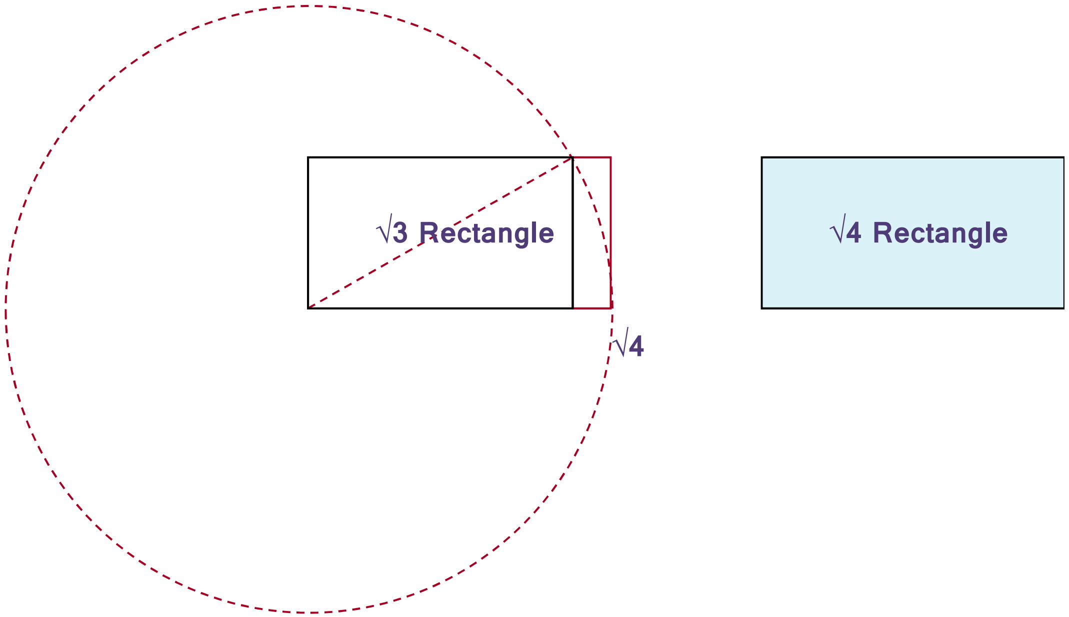


The Root 3 and 4 Rectangle Construction

Root 3 rectangle construction
Begin with root 2 rectangle
Draw a diagonal within the root 2 rectangle.
Use the diagonal as an arc that touches the square base line.
Enclose a rectangle around the new figure. This is root 3 rectangle.



Root 4 rectangle construction
Begin with root 3 rectangle.
Draw a diagonal within the root 3 rectangle.
Use the diagonal as an arc that touches the square base line.
Enclose a rectangle around the new figure. This is root 4 rectangle



The Root 5 Rectangle Construction

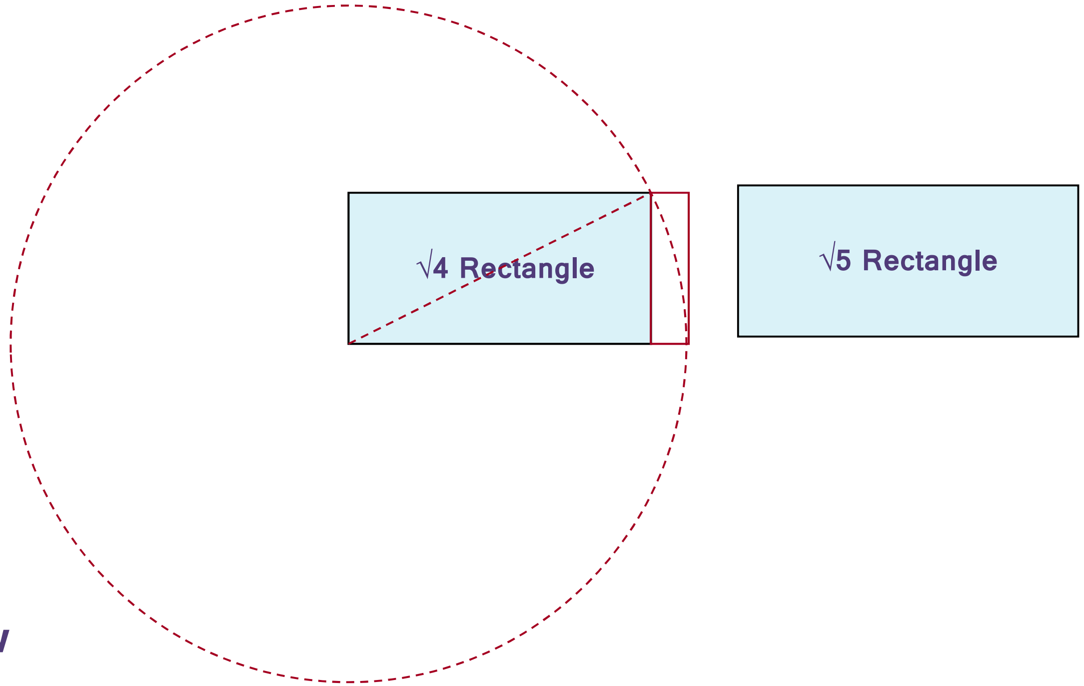
Root 5 rectangle construction :

Begin with root 4 rectangle

Draw a diagonal within the root 4 rectangle.

Use the diagonal as an arc that touches the square base line

Enclose a rectangle around the new figure. This is root 5 rectangle.



Exercise 1: Geometric analysis

Exercise 2: Geometric analysis

Exercise 3: Geometric analysis

Geometry Workshop

Questionnaire 1

Surname: Name:

Age:________________________ Sex: F / M

Degree: BSc in _________________ or BA in _______________________

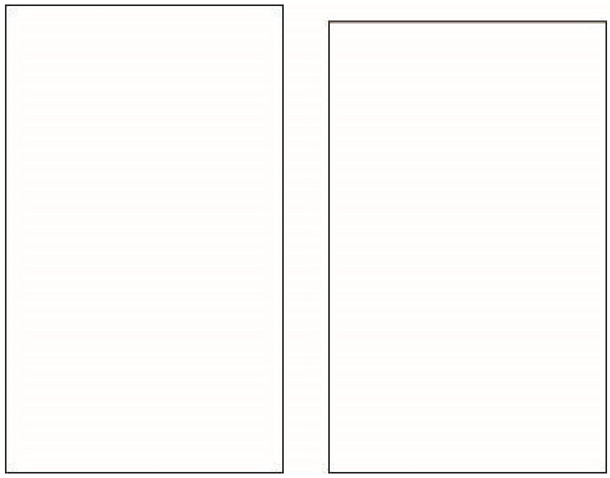
1. Have you heard of any of thee concepts? The ‘golden section’, the ‘golden ratio’, the ‘golden mean’, the ‘golden number’ or the ‘divine proportion’ (these are all the same meaning) (Yes / No)

2. What is a specific numerical ratio or proportion of the ‘golden section’? Please write down its value?__________________________

3. Reorganize the rectangles in order starting with your favourite to your least favourite:

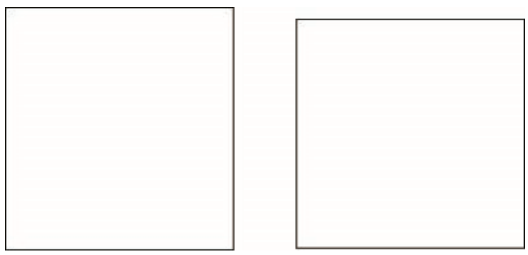
A B C D E F

4. Choose a favourite rectangle



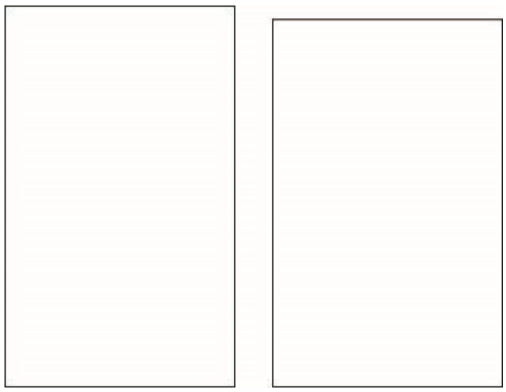
A B

5. Choose a favourite rectangle



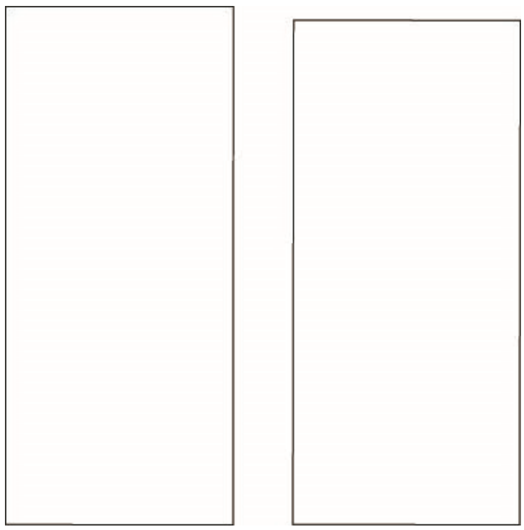
A B

6. Choose a favourite rectangle



A B

7. Choose a favourite rectangle



A B

Questionnaire 1

Surname: Name:

Age:________________________ Sex: F / M

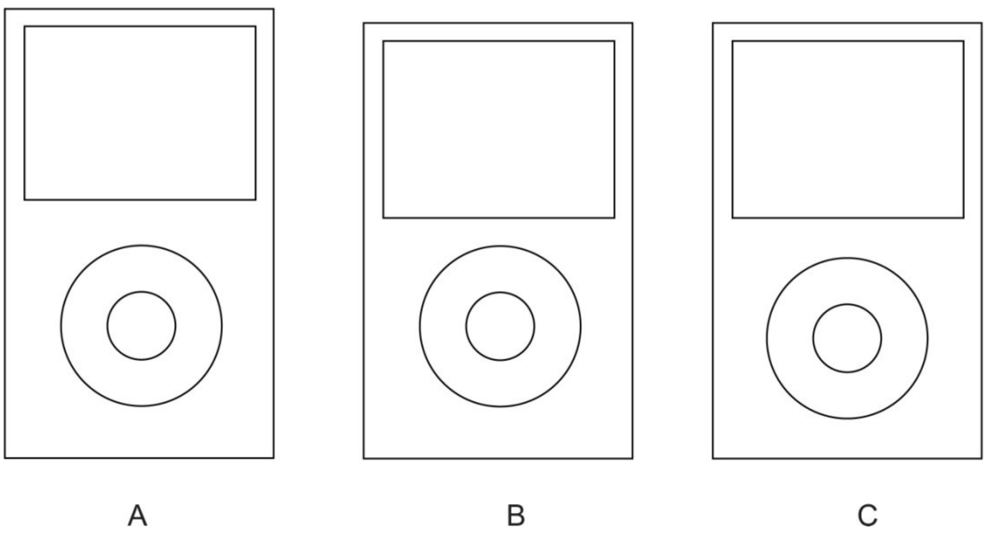
Degree: BSc in ________________ or BA in _______________________

Occupation: Experience: years

1. Have you heard of any of thee concepts? The ‘golden section’, the ‘golden ratio’, the ‘golden mean’, the ‘golden number’ or the ‘divine proportion’ (these are all the same meaning) (Yes / No)

2. What is a specific numerical ratio or proportion of the ‘golden section’? Please write down its value?__________________________

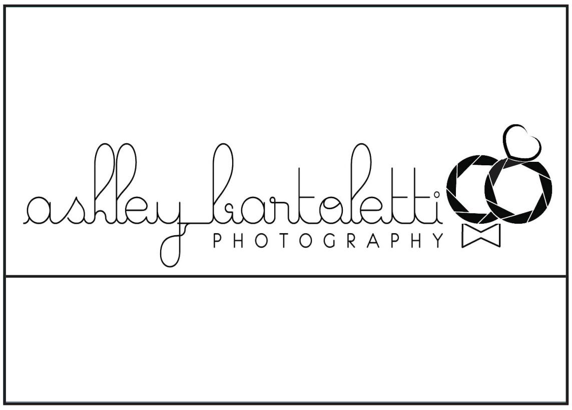
3. Choose favourite between designs ‘A’, ‘B’ or ‘C’



George Diamantidis - Most favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

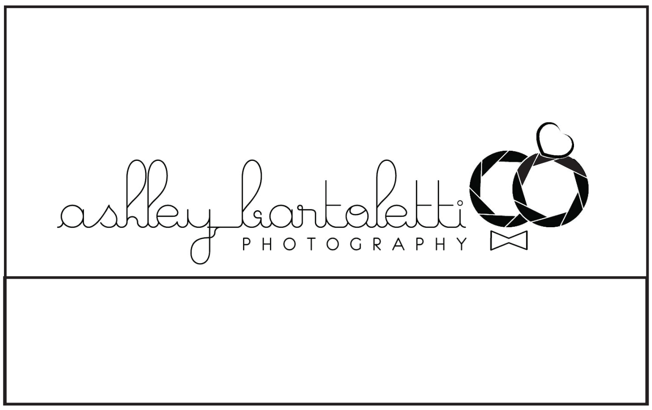
A



B

C

D



George Diamantidis - Most Favourite 2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

A

B

C

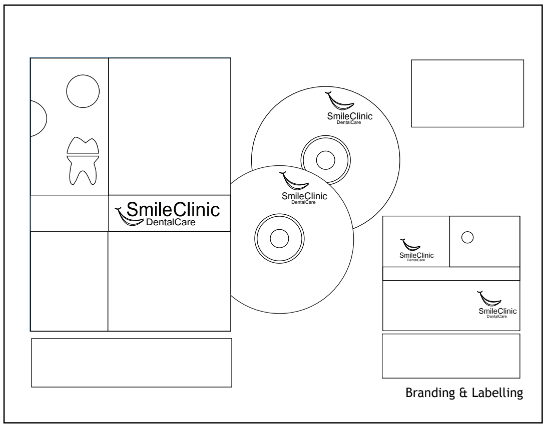
D

E

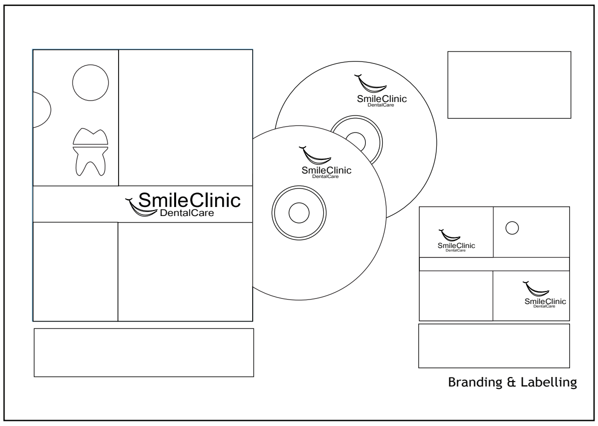
George Diamantidis - Most Favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

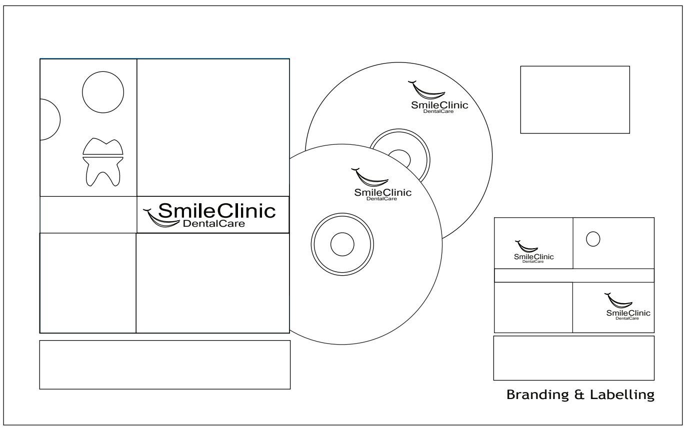
A



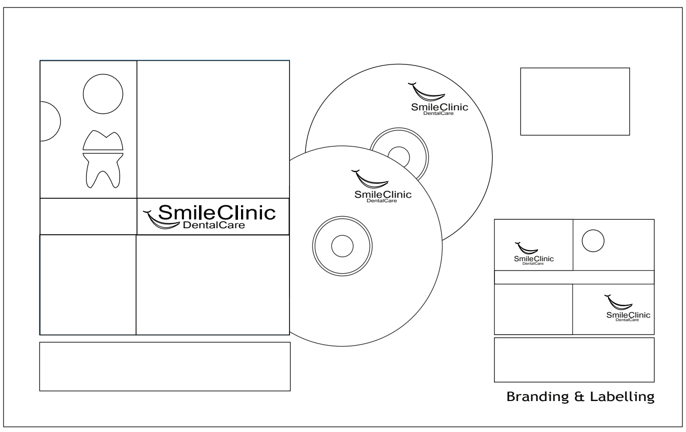
B



C



D

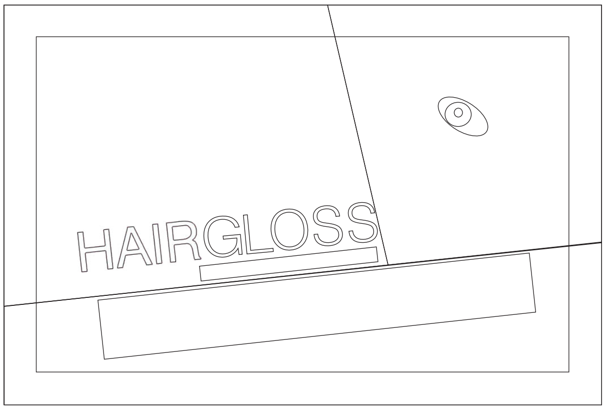


George Diamantidis - Least Favourite 1

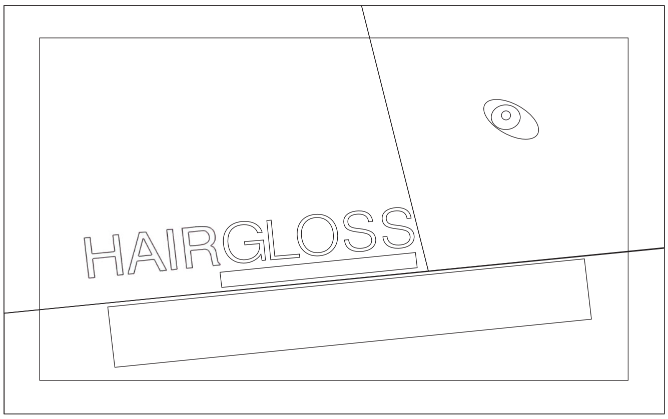
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

A

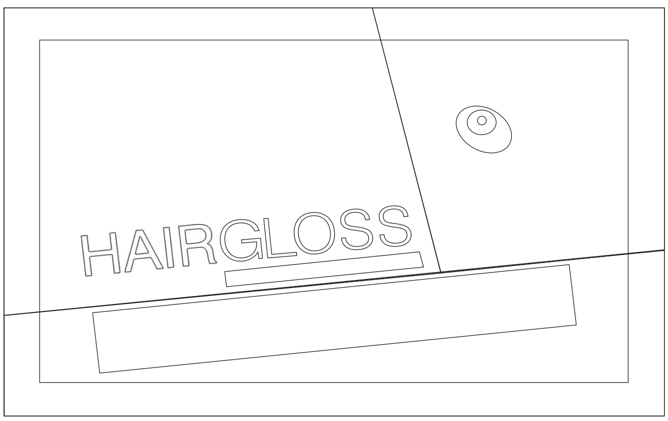
B



C



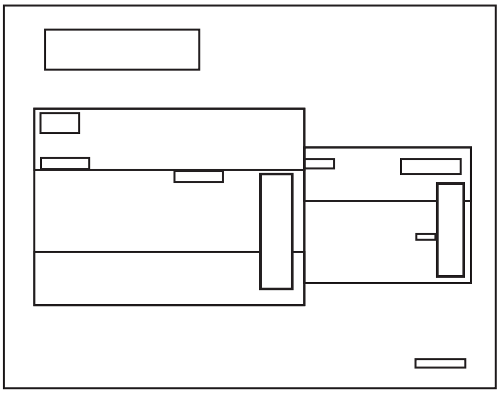
D



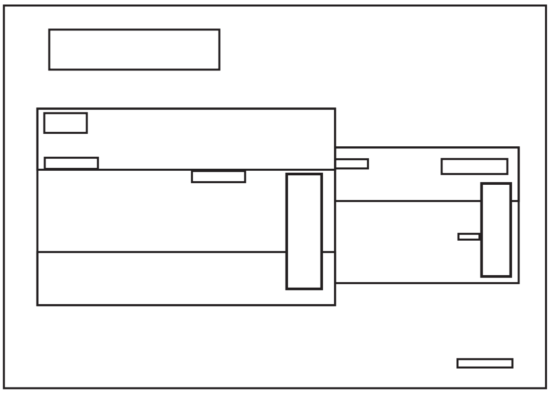
George Diamantidis - Least Favourite 2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

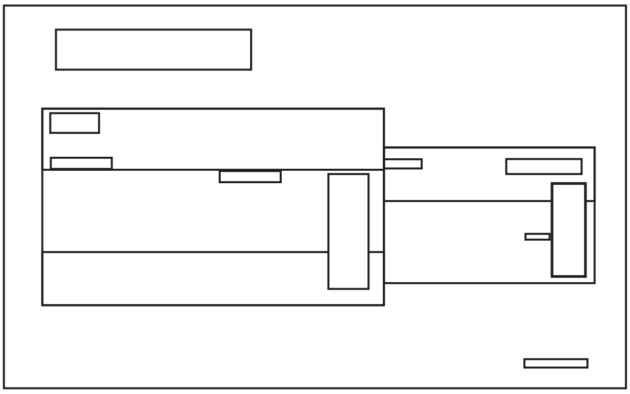
A



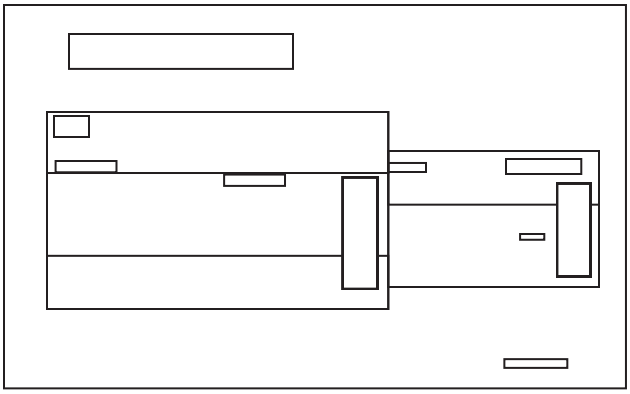
B



C



D



George Diamantidis -Least Favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

A

B

C

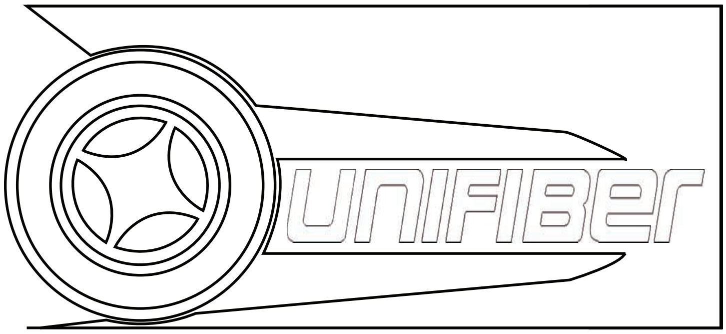
D

E

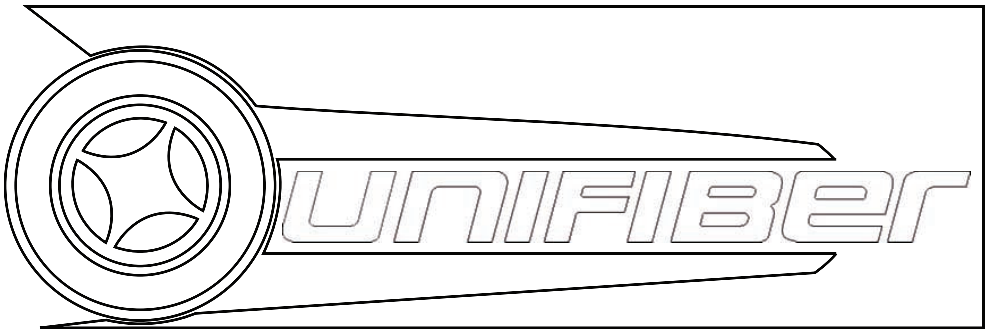
Paul Davey- Most favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

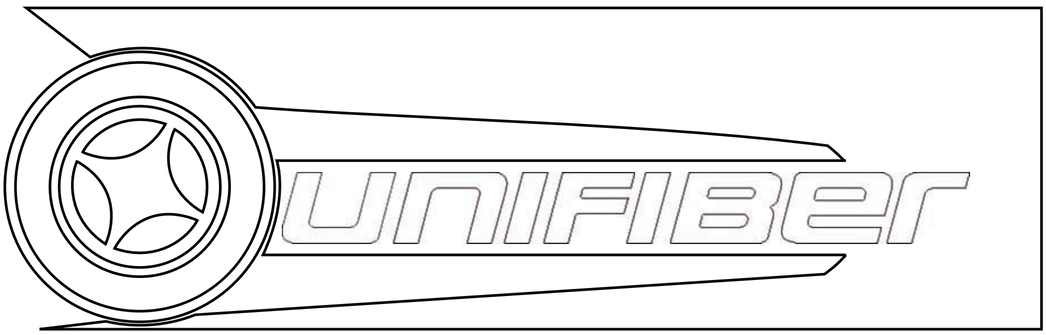
A



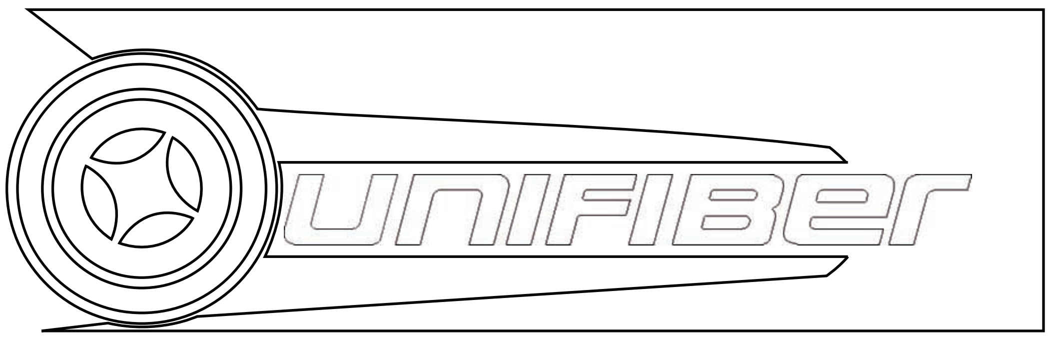
B



C

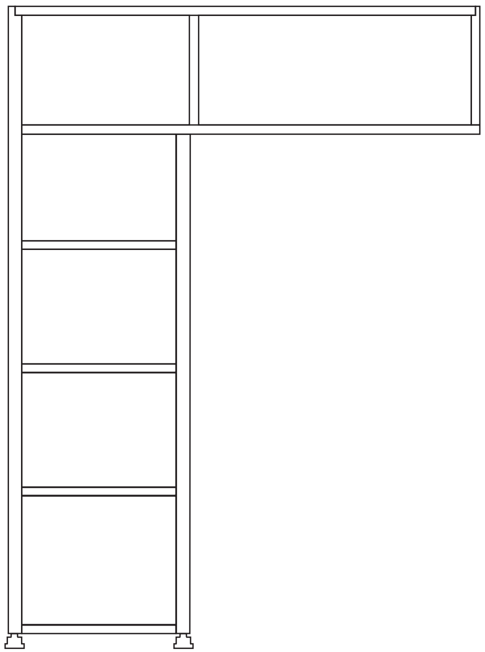


D

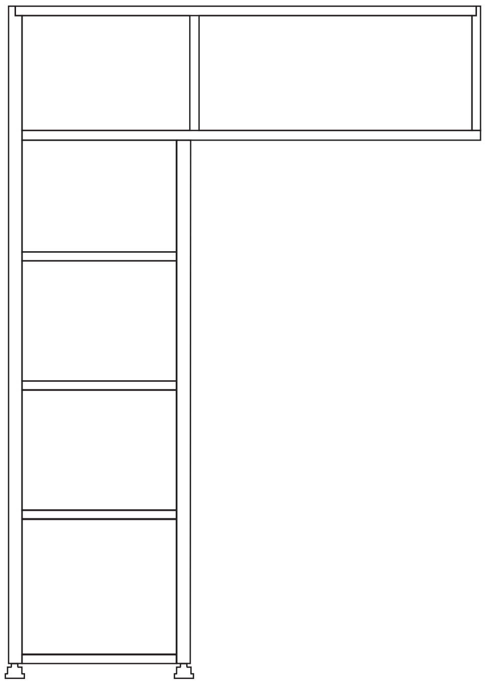


Paul Davey - Most favourite 2

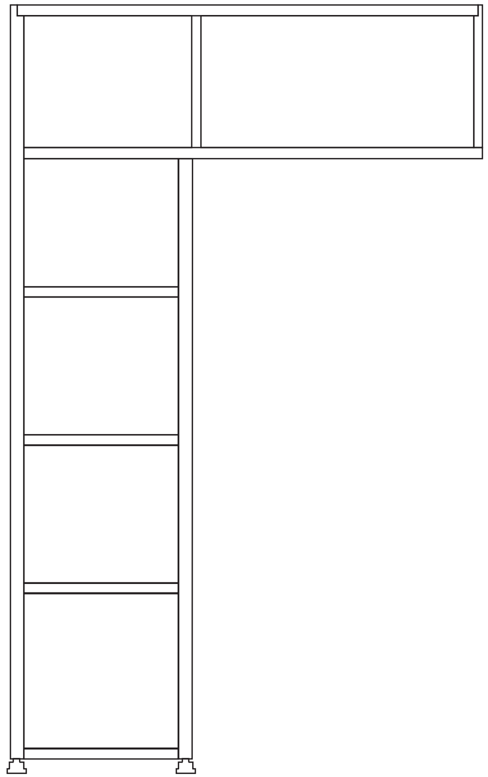
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



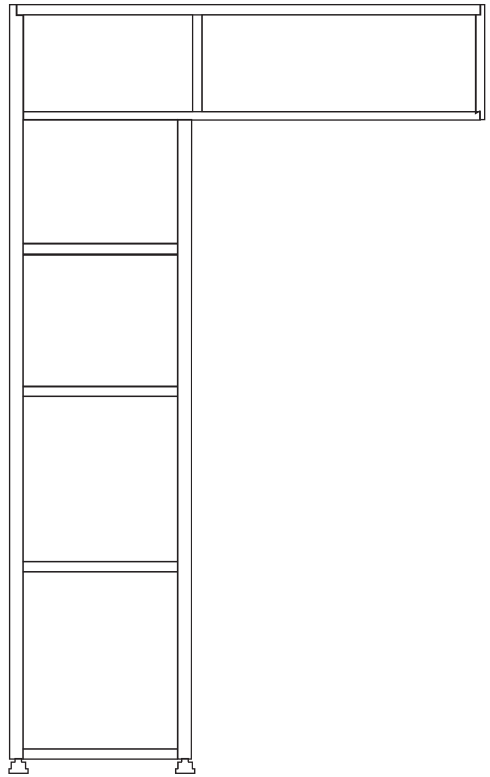
A



B



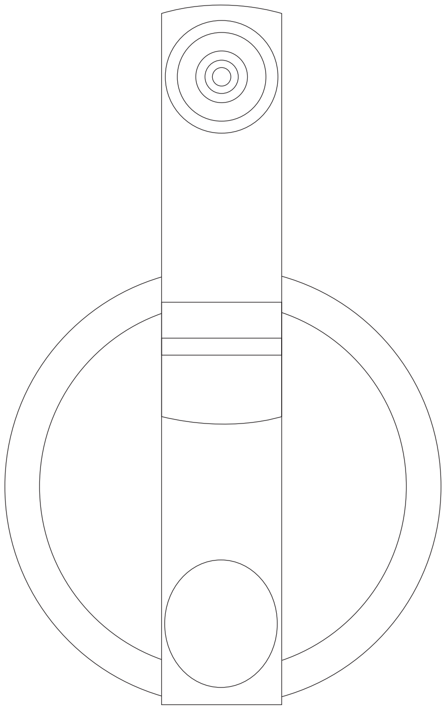
C



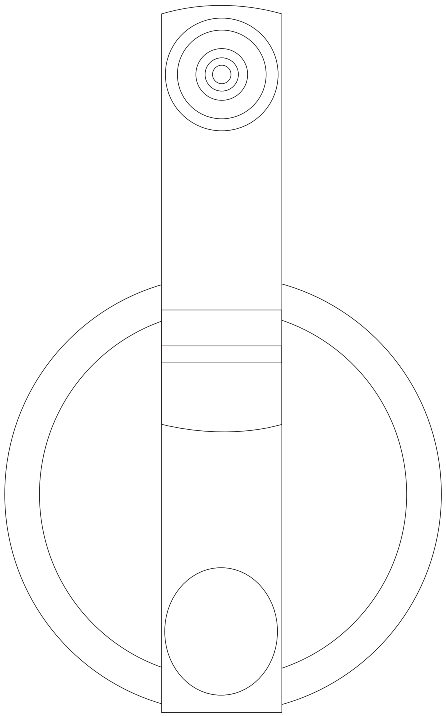
D

Paul Davey- Most favourite 3

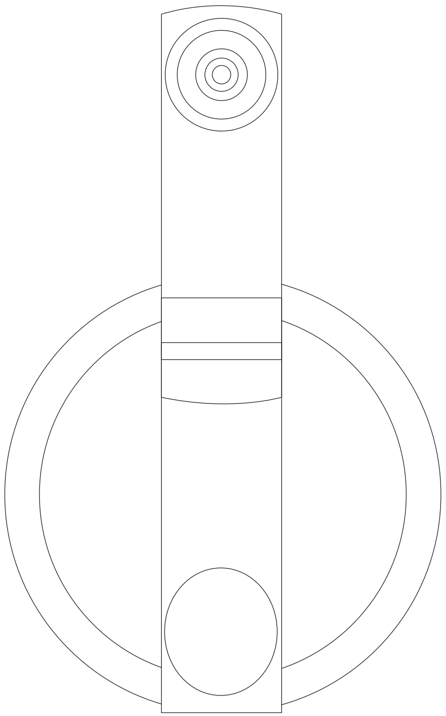
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



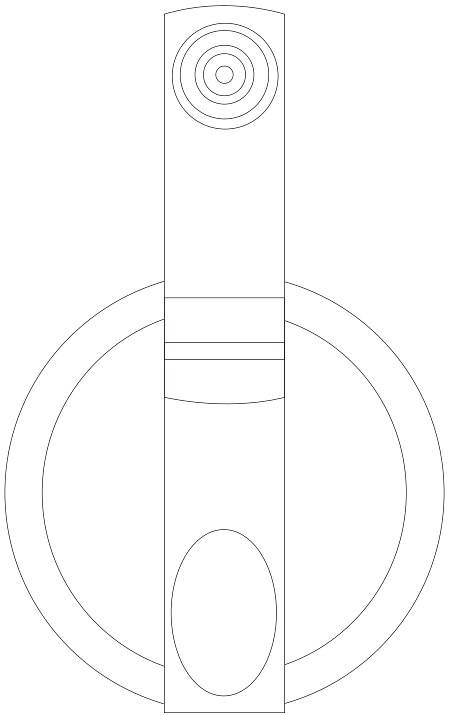
A



B



C

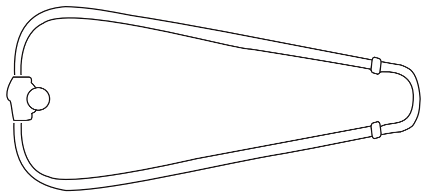


D

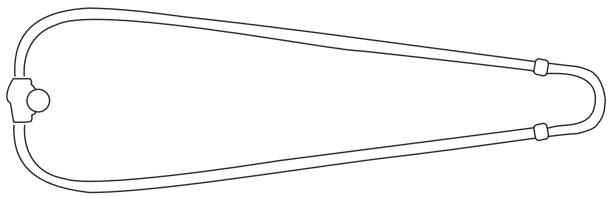
Paul Davey- Least favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

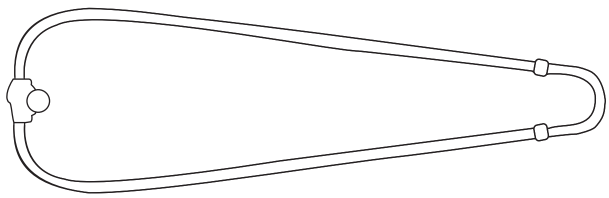
A



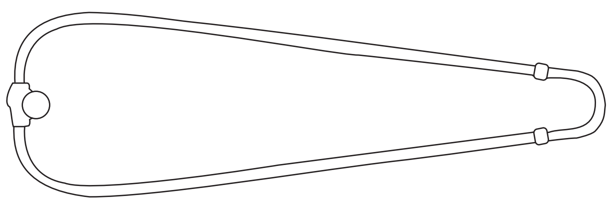
B



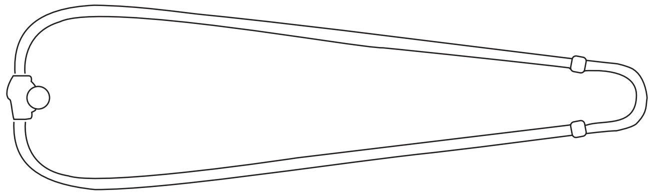
C



D

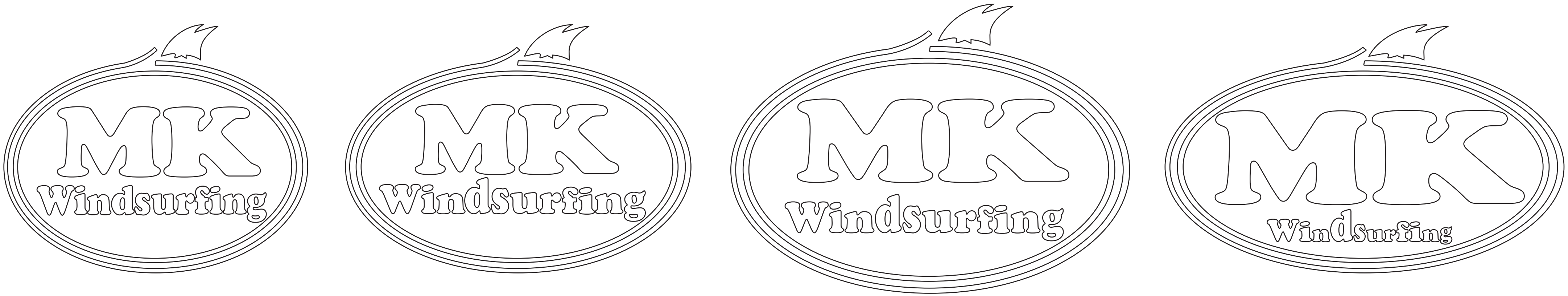


E



Paul Davey - Least favourite 2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

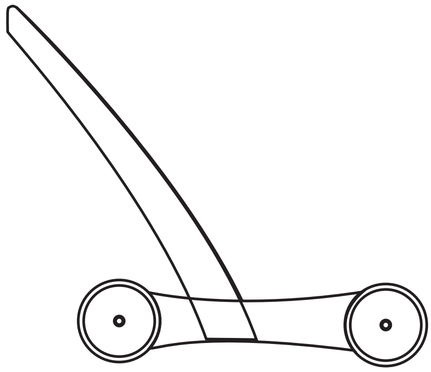


A B C D

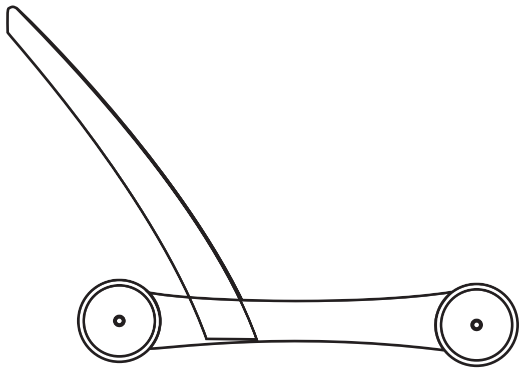
Paul Davey - Least favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

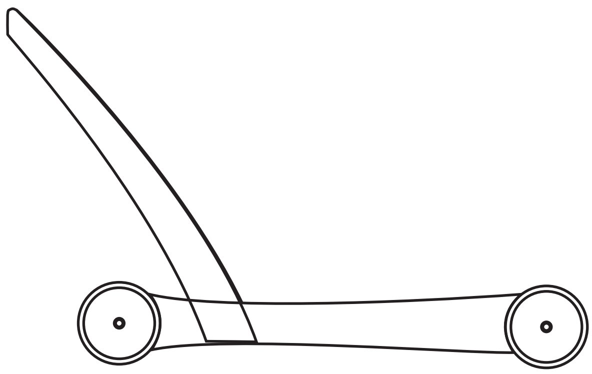
A



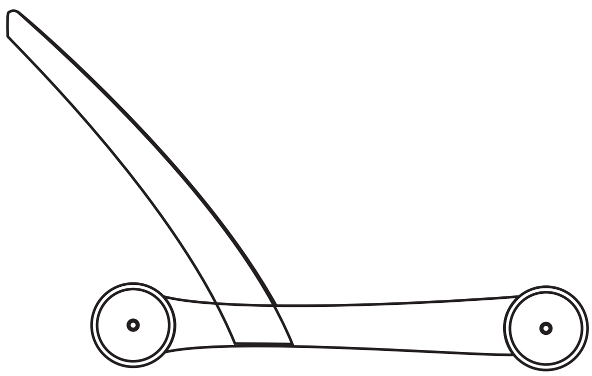
B



C

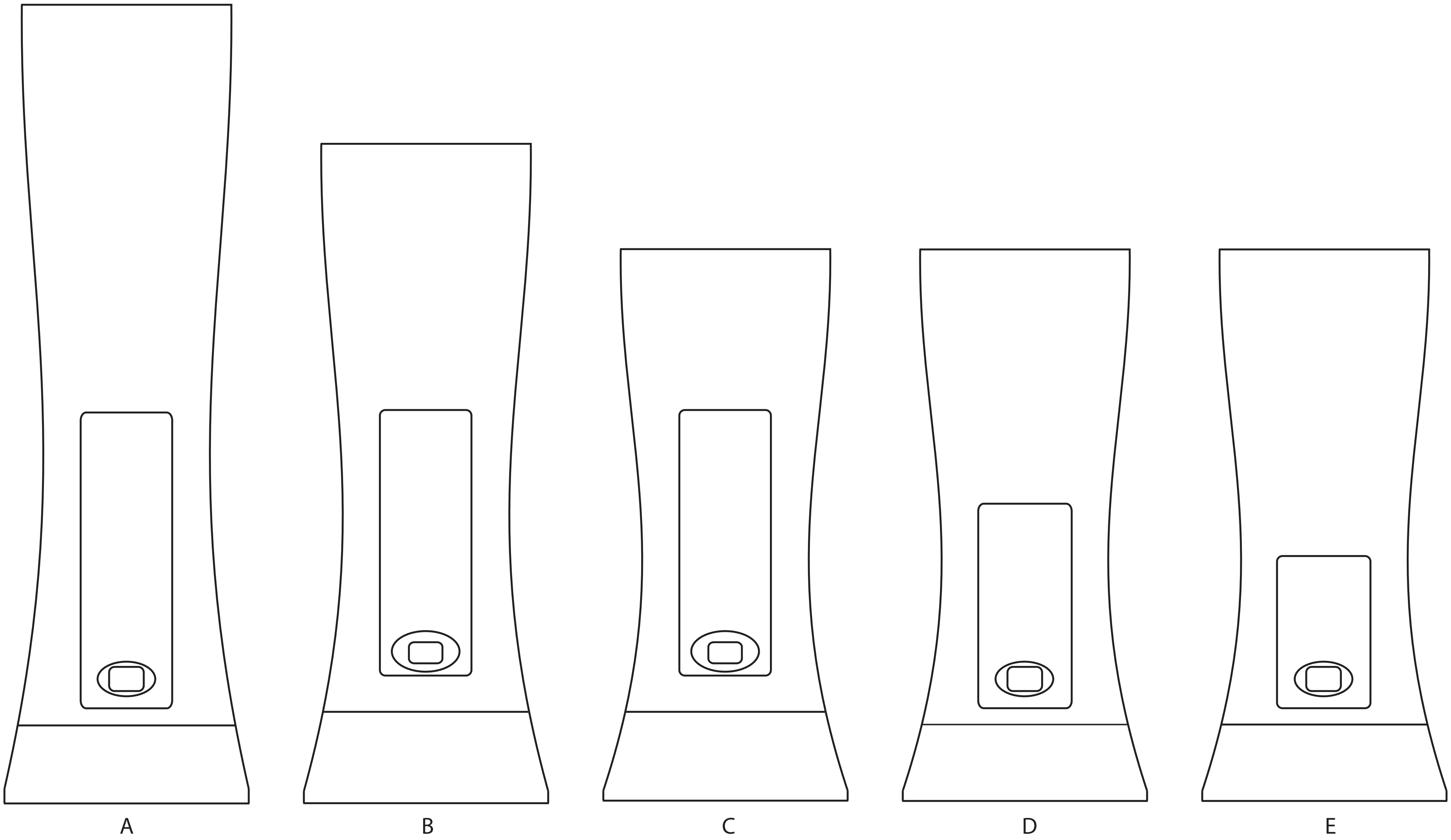


D



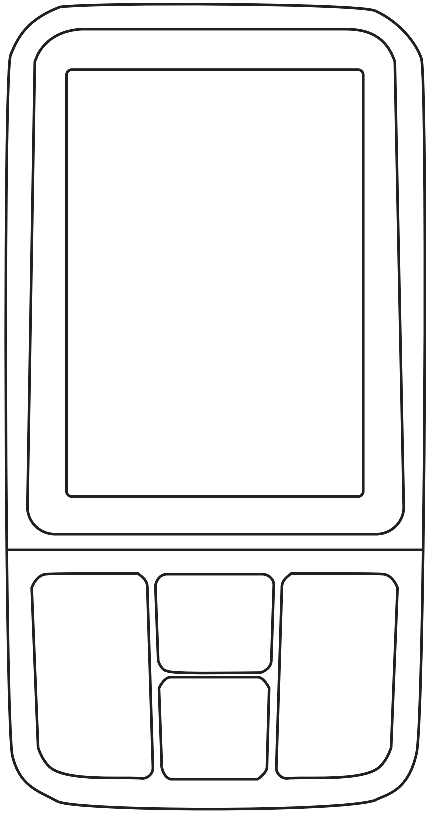
Max Lilley- Most favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

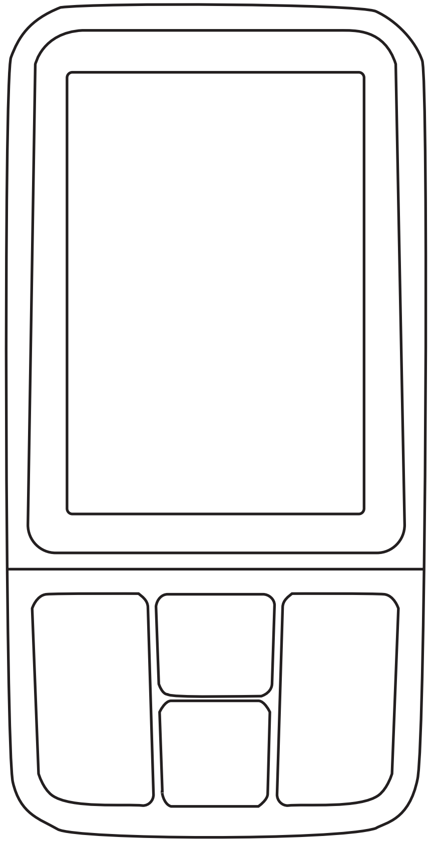


Max Lilley- Most favourite 2

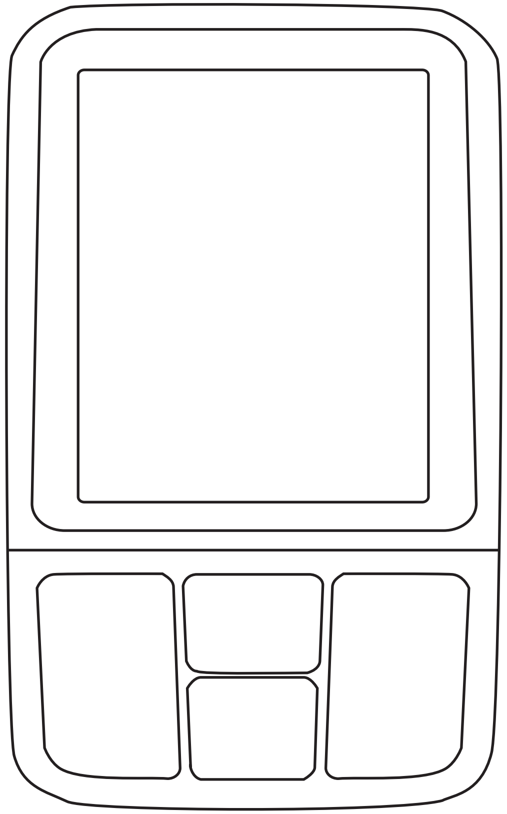
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



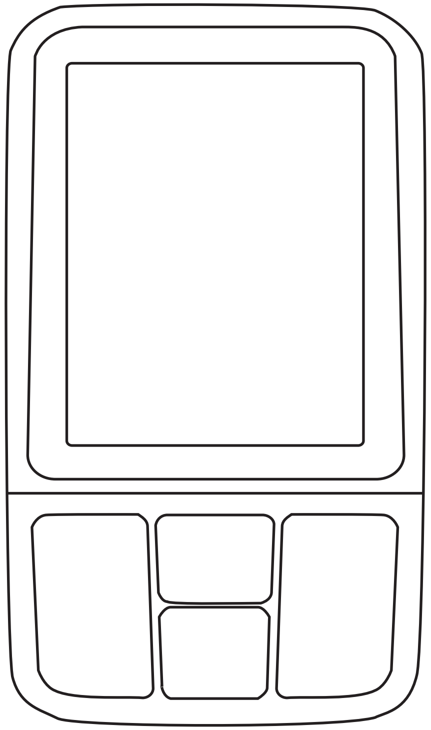
A



B



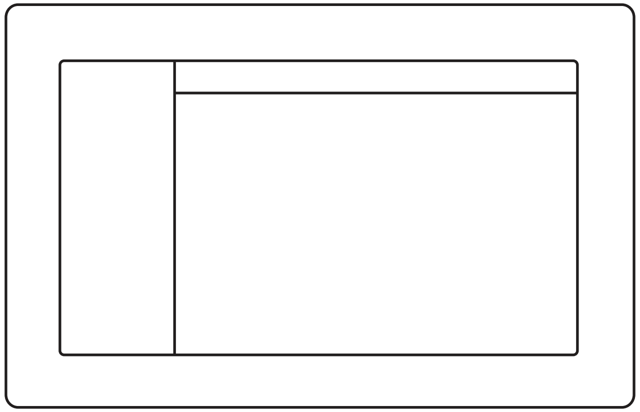
C



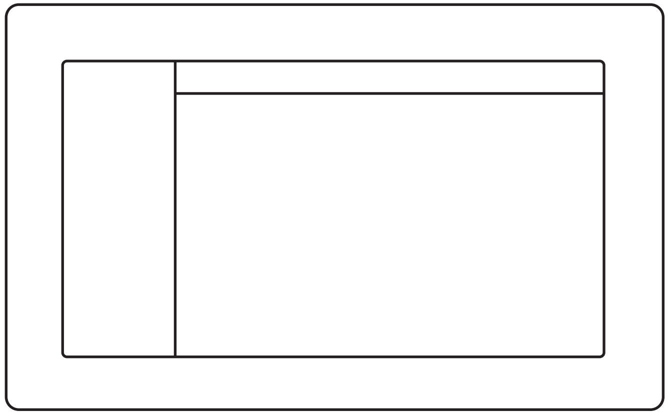
D

Max Lilley- Most favourite 3

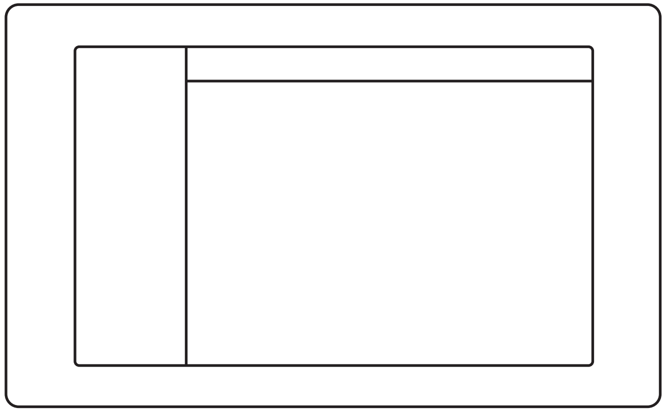
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



A



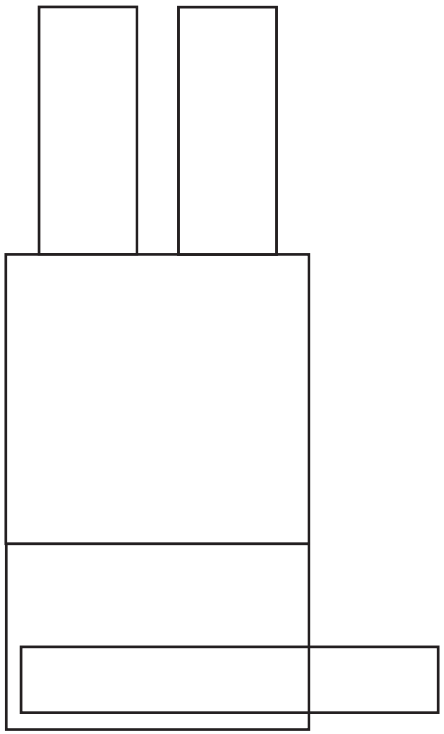
B



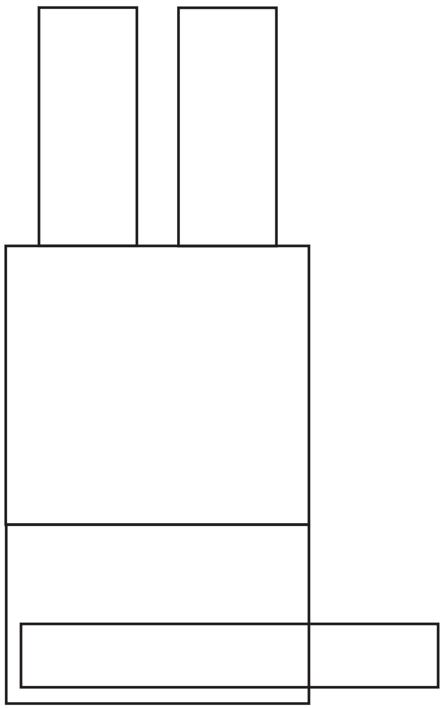
C

Max Lilley -Least favourite 1

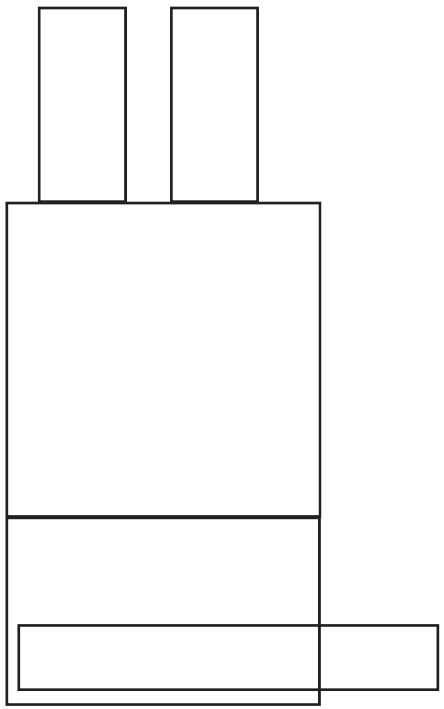
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



A



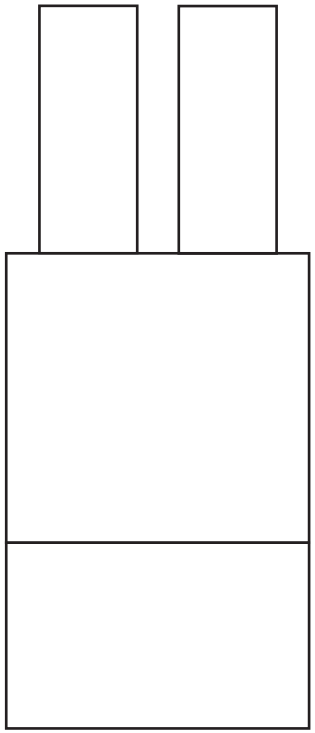
B



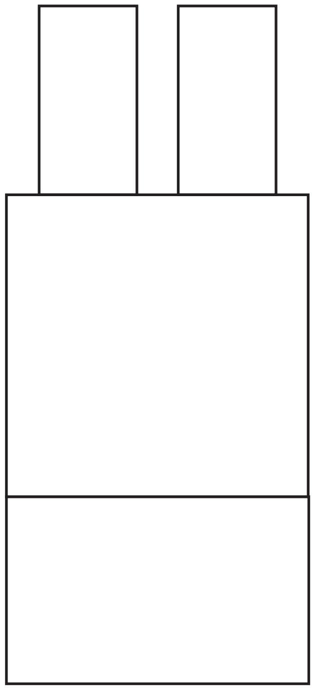
C

Max Lilley -Least favourite 2

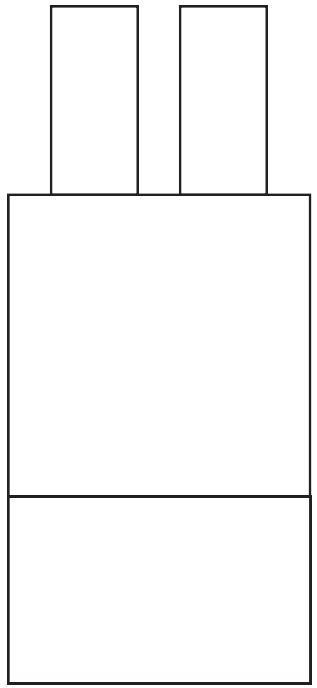
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



A



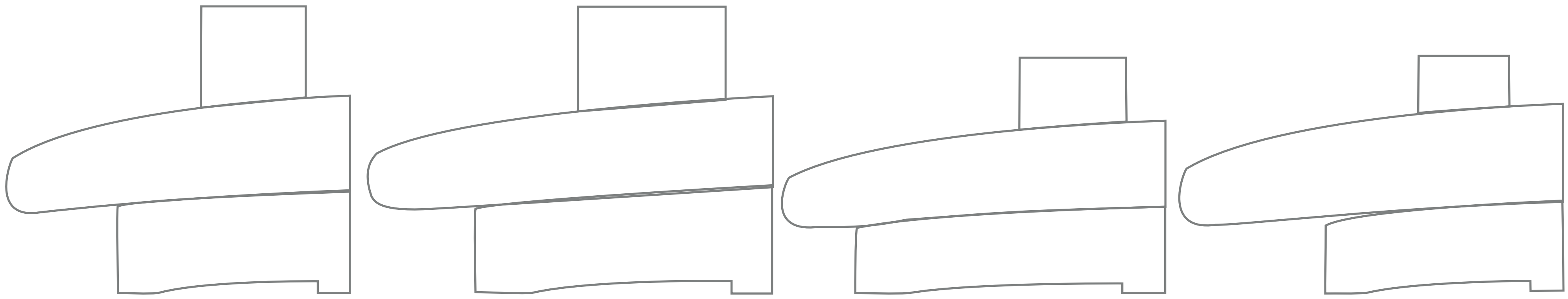
B



C

Max Lilley - Least favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

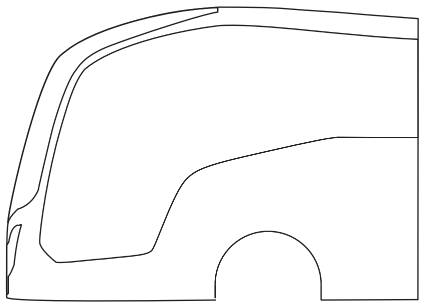


A B C D

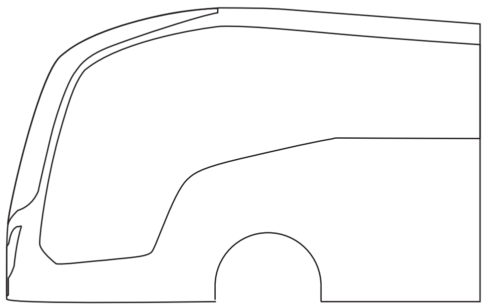
Owen Evans - Most Favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

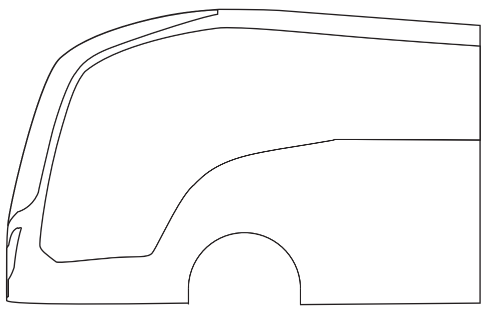
A



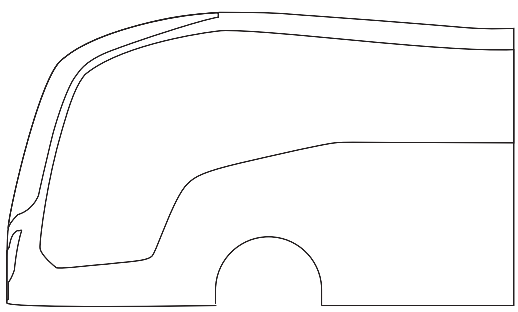
B



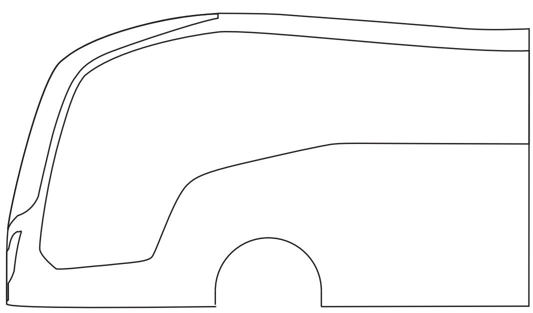
C



D



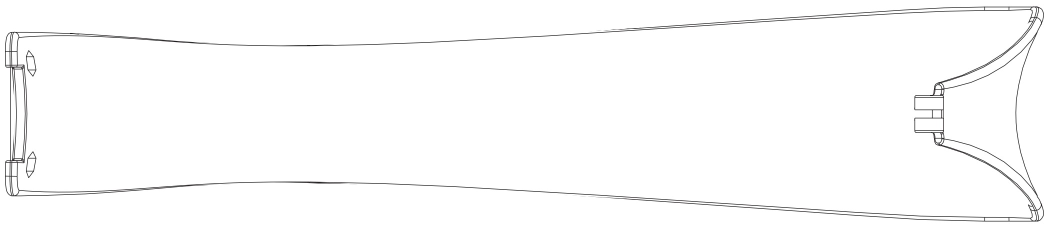
E



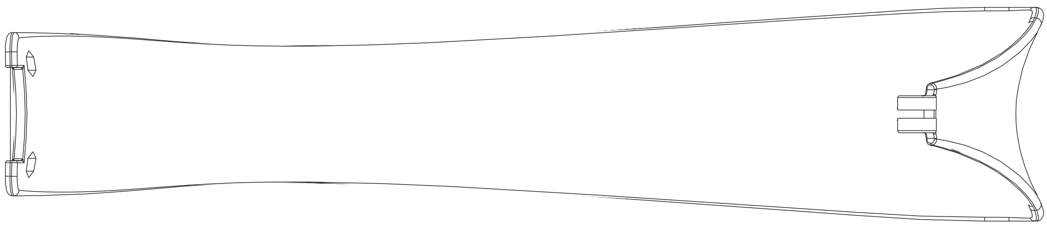
Owen Evans - Most Favourite Design 2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

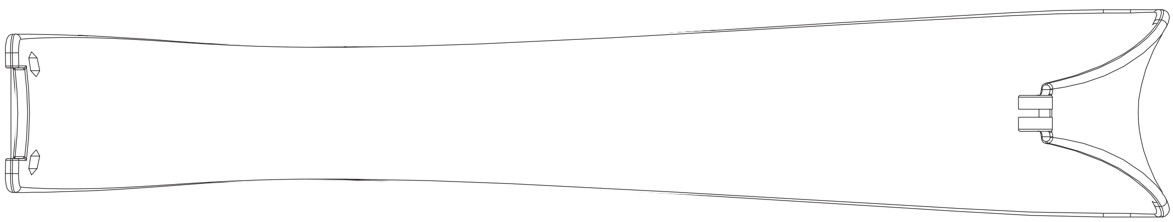
A



B



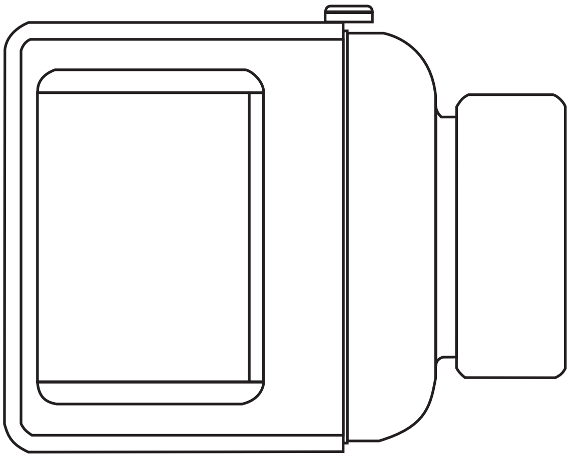
C



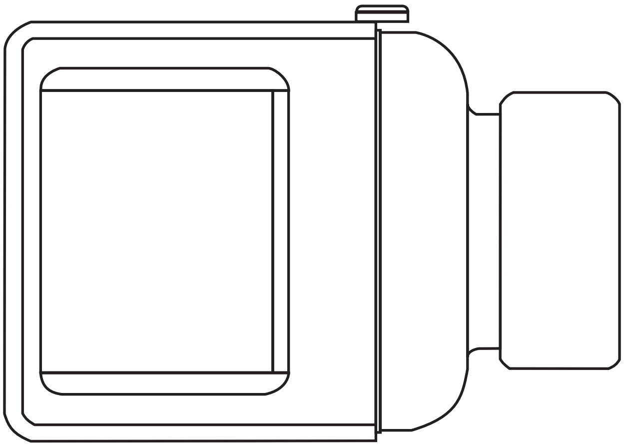
Owen Evans - Most Favourite Design 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

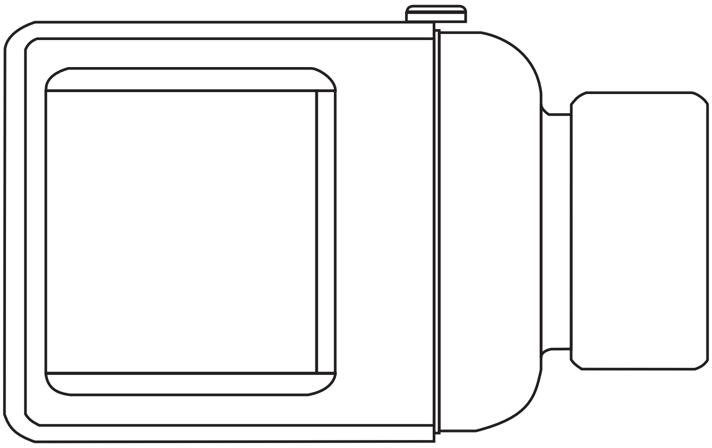
A



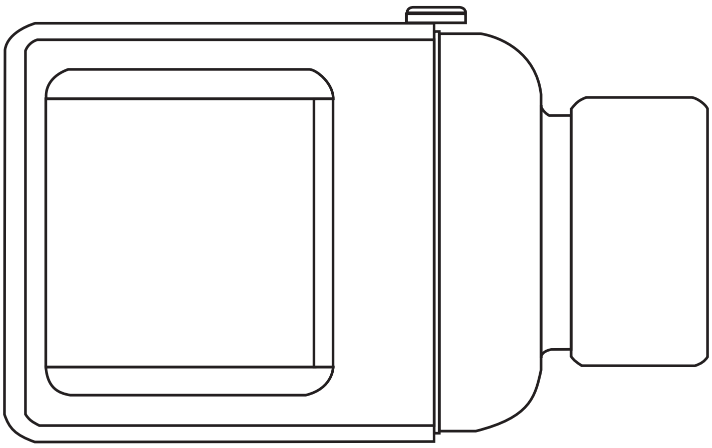
B



C



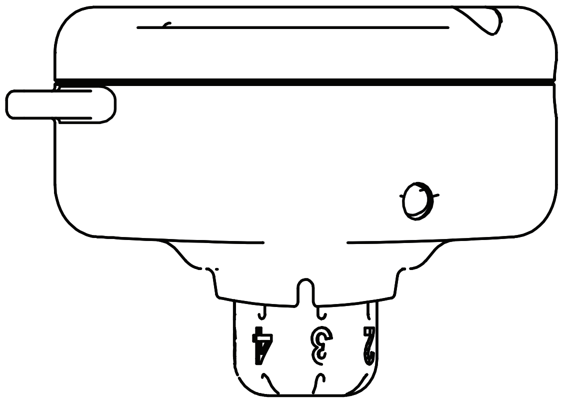
D



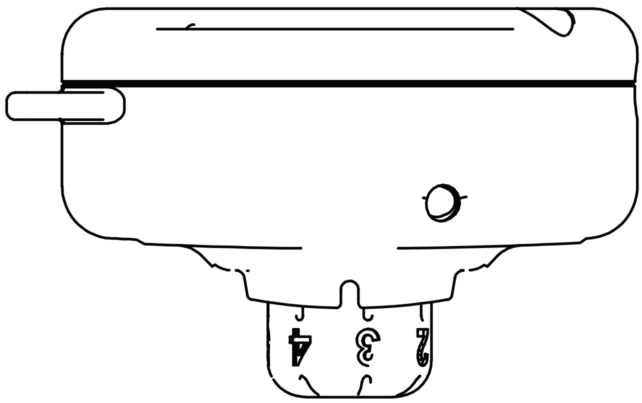
Owen Evans- Least Favorite design1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

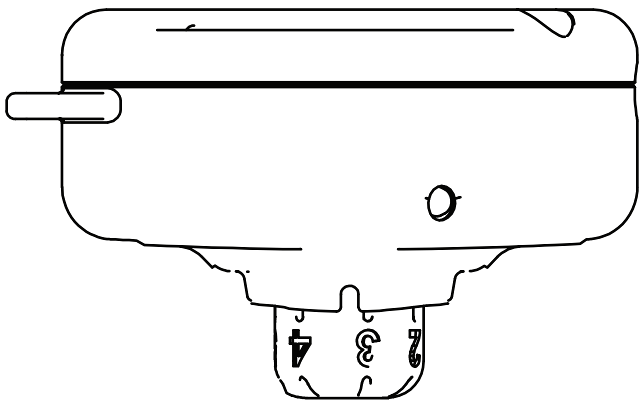
A



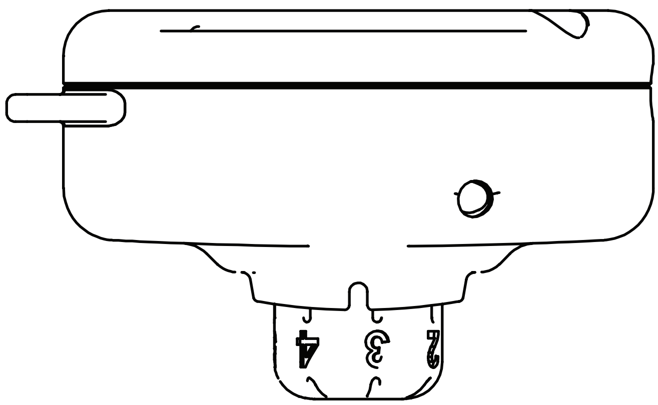
B



C



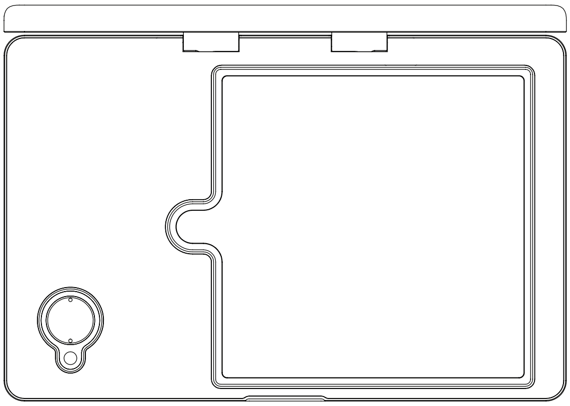
D



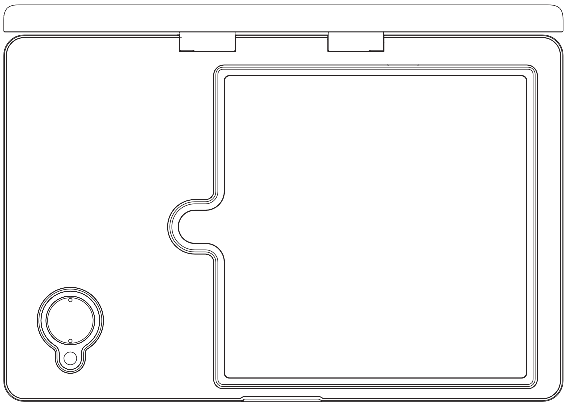
Owen Evans- Least Favorite design2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

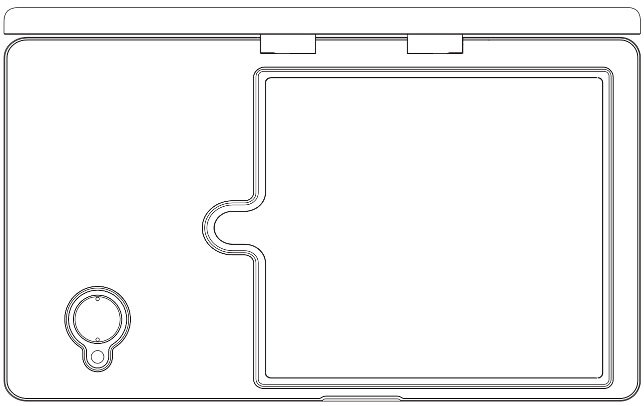
A



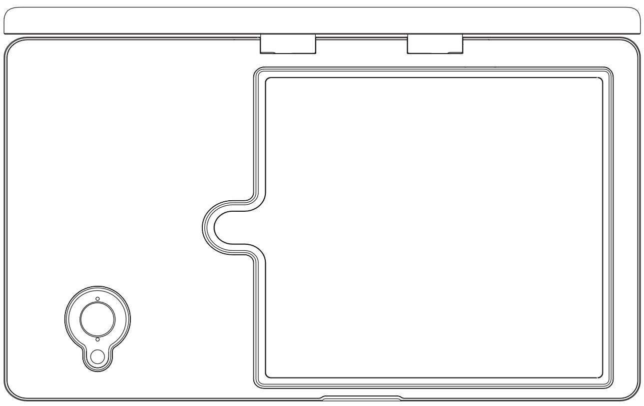
B



C



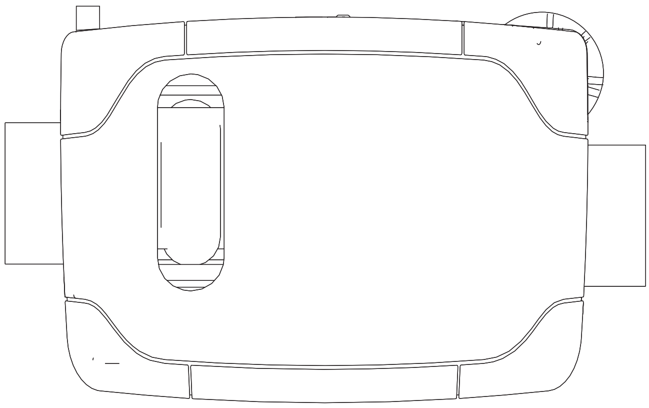
D



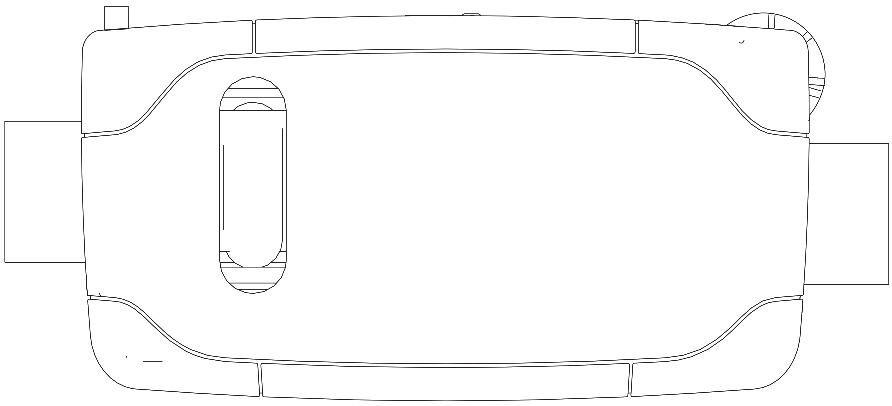
Owen Evans - Least Favorite Design 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

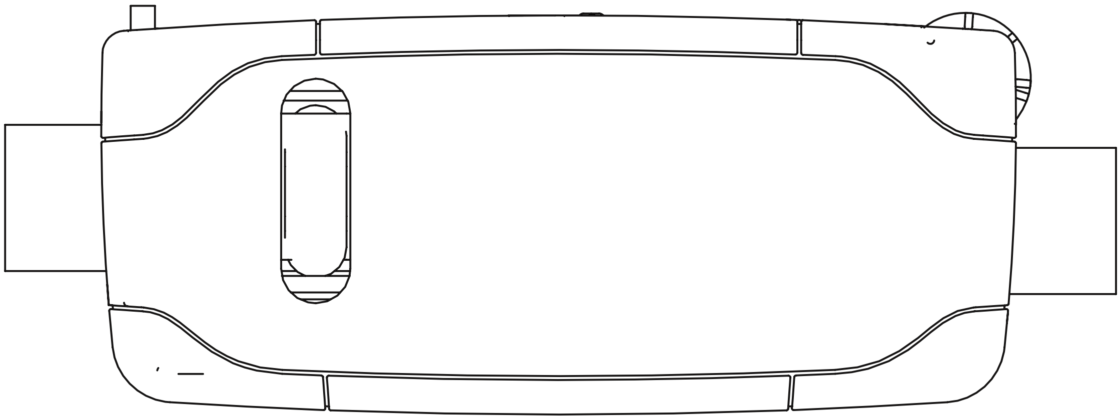
A



B

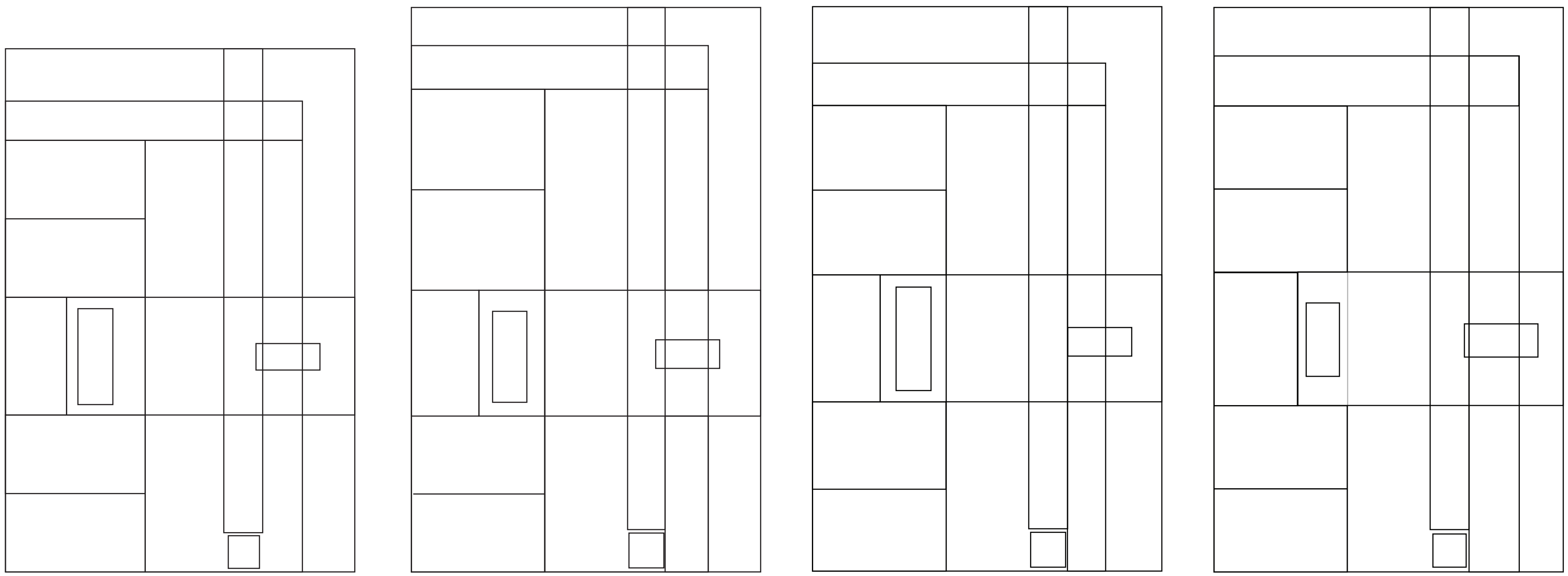


C



Claire Potter- Most favourite 1

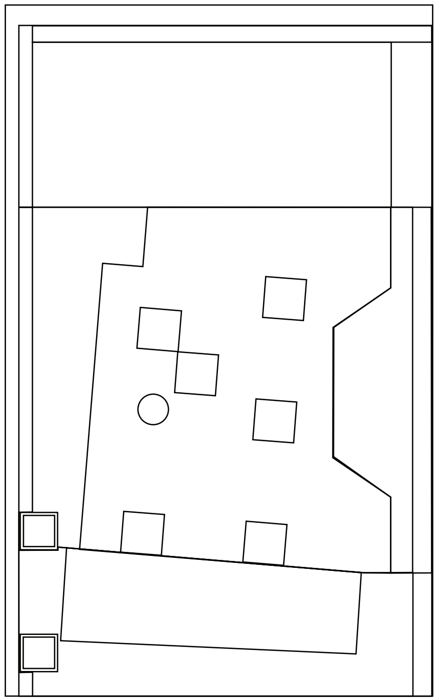
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



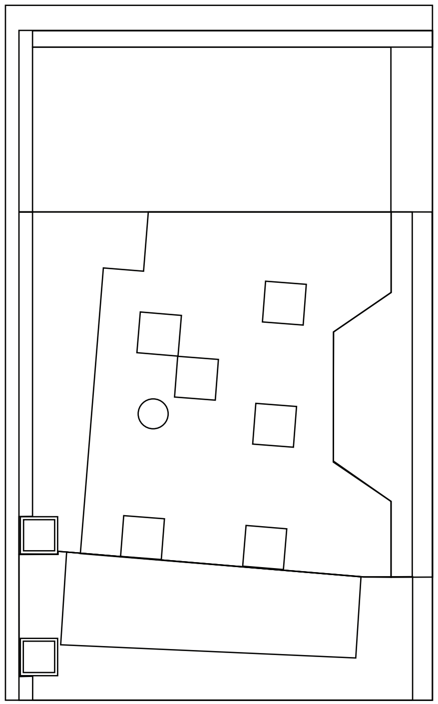
A B C D

Claire Potter - Most favourite 2

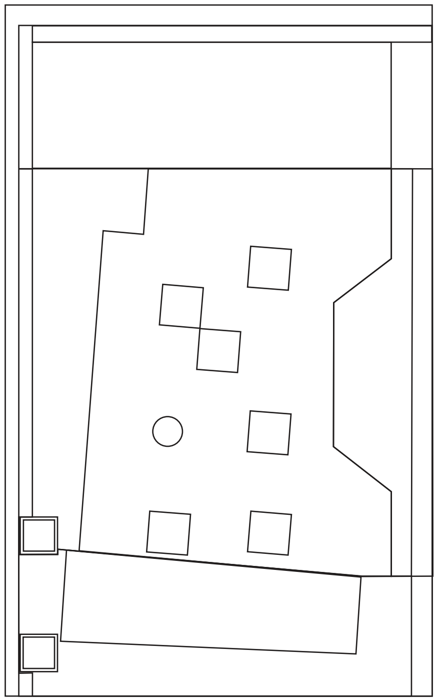
Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



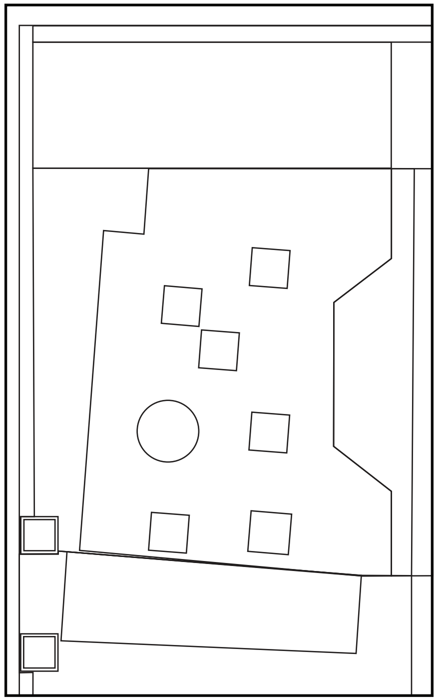
A



B



C

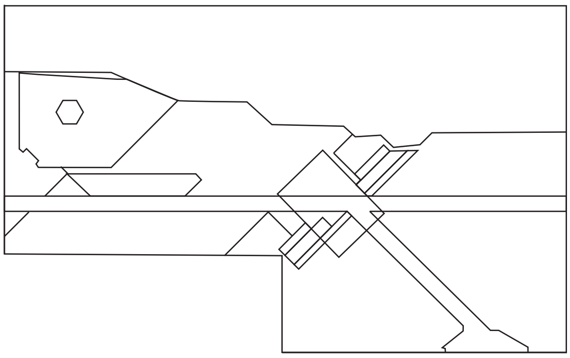


D

Claire Potter- Most favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

A



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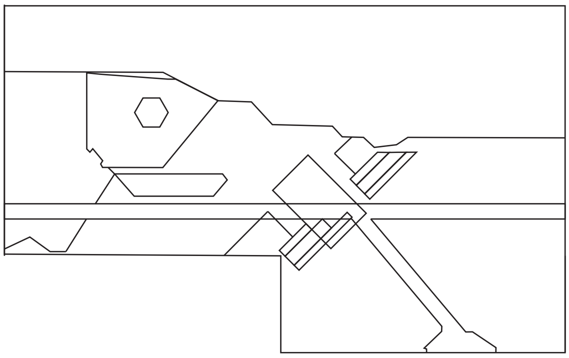

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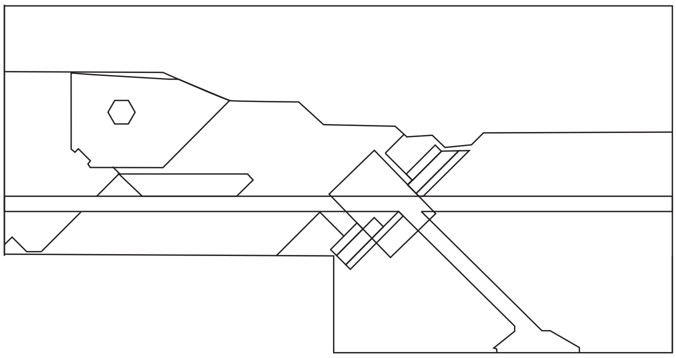

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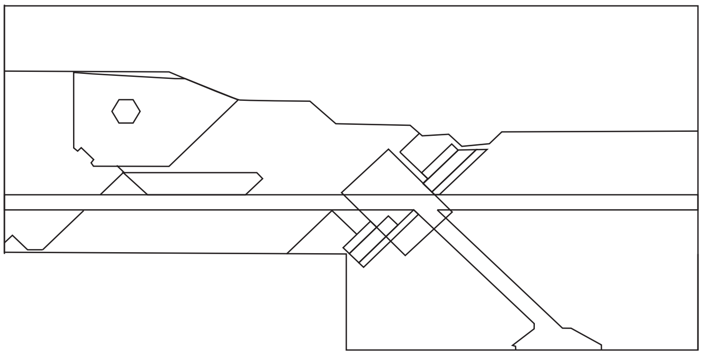
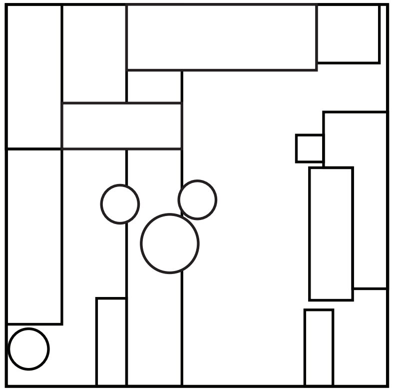
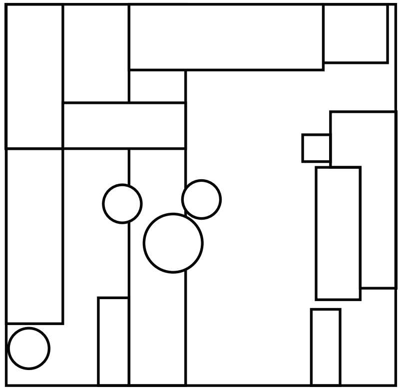


Claire- least favourite 1

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



A



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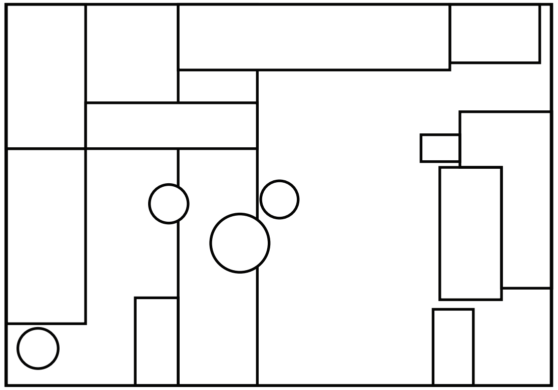

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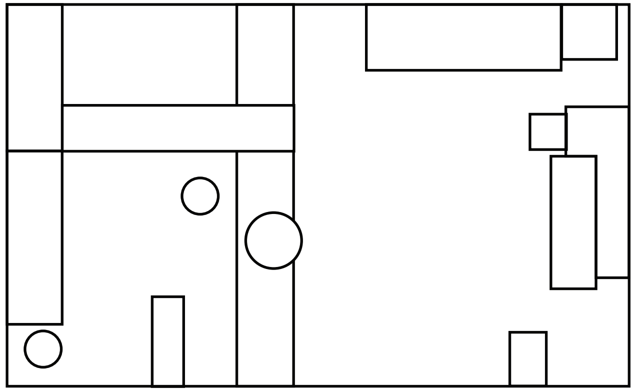
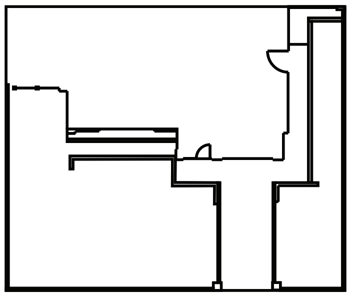


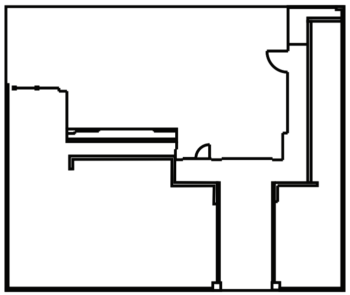
D

Claire- Least favourite 2

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:



A



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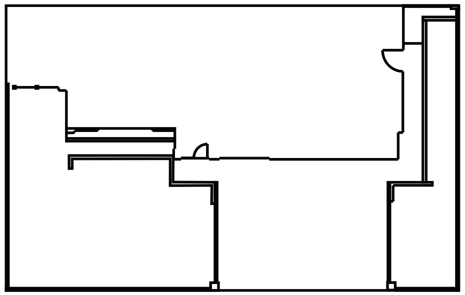

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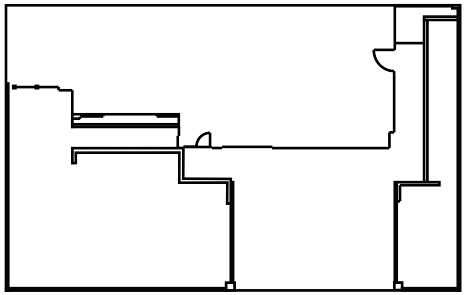

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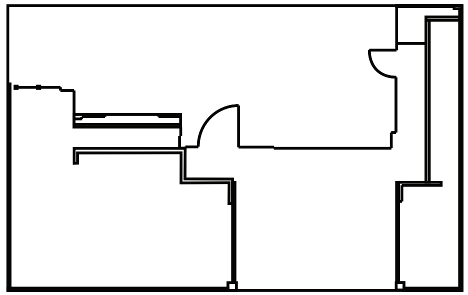
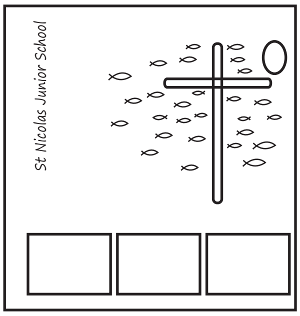


E

Claire Potter- Least favourite 3

Reorganize the designs in order starting with your favourite to your least favourite and explain why you like about:

A



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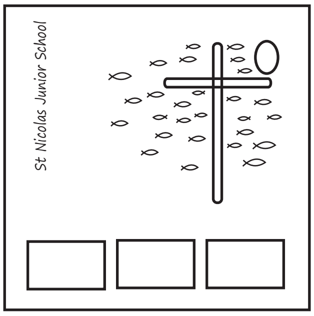

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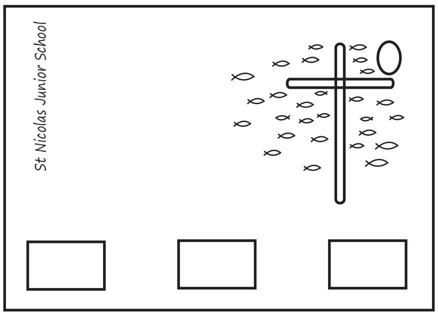

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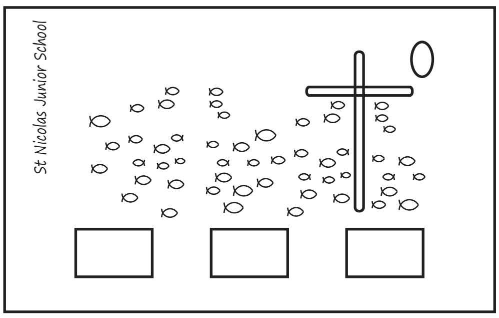

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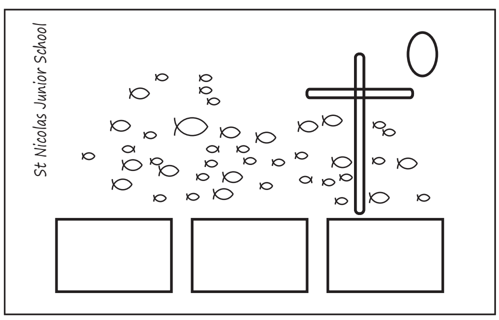

US

University of Sussex

CONSENT FORM FOR PROJECT PARTICIPANTS

PROJECT TITLE: THE APPLICATION OF PRACTICAL GEOMETRY AND THE GOLDEN RATIO IN PRODUCT DESIGN

I agree to take part in the above University of Sussex research project. I have had the project explained to me and I have read and understood the Information Sheet, which I may keep for records. I understand that agreeing to take part means that I am willing to:

- Be interviewed by the researcher
- Allow the interview to be audio taped
- Allow the researcher to use transcrip
- Allow the researcher to analyse my designs

I understand that any information I provide is confidential, and that no information that I disclose will lead to the identification of any individual in the reports on the project, either by the researcher or by any other party.

I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalised or disadvantaged in any way.
I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the Data Protection Act 1998.

Name: George Diamantidis

Signature

Date: 12/04/2015

US
University of Sussex

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Name: [illegible]

Signature [illegible]

Date: 01/12/14

University of Sussex

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Name: Paul Davey.

Signature: P. M. Davey.

Date: 28/12/2014.

University of Sussex

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Name: OWEN EVANS

Signature

Date: 9 DEC 14.

University of Sussex

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Name: CLAIRE POTTER

Signature

Date: 02/12/14

APPLYING GEOMETRIC RELATIONSHIP IN PRODUCT DESIGN

Hyo Jin Koh[1]
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ABSTRACT

Geometry and the golden ratio in art, architecture and design are frequently used as a way to perceive aesthetically pleasing structures rather than as a principle to further develop visual coherence and as a basis for rational decisions in the design process. The aim of this paper is to demonstrate how geometric relationships can be applied to the product design process. It will also investigate how geometric relationships can provide effective design rules which can be practical and directly applicable in design. Geometry workshops were carried out in the Creativity Zone at the University of Brighton and in the Design Studio at the University of Sussex between 2011 and 2012. During the workshops three hypotheses have been tested on product design students to investigate how design practitioners perceive geometry and how the golden ratio in designs may be utilised to recognise harmonious geometry.

Keywords: geometry, the golden ratio, design principles, harmonic proportion, theory and practice

1 INTRODUCTION

Geometry is one of oldest sciences and a branch of mathematics which has been used since ancient Greece and Egypt. In particular the implication of the golden section, 'phi' in art architecture and design were known as a guideline of aesthetic beauty. Artists, architects and designers, such as, Leonardo da vinci, Le Corbusier, A.M. Cassandre, designers such as, Dieta Rams and Jonathan Ive have carefully and rationally embedded geometry in their works. All of which have been regarded as masterpieces or well known and respected good examples of designs in design history. However, learning and applying geometry in product design at BSc degree level is still a new area which needs to be explored to develop this tool as a basic principle for design practitioners. This paper shows how geometry could be a useful skill to improve design practitioner's visual coherence and advanced awareness of aesthetic forms and styling.

2 GEOMETRY IN ART AND DESIGN

Researchers in aesthetics and psychologists have investigated geometric forms as stimulus objects in order to understand the aesthetic feelings about the objects. The first researcher who studied the aesthetic preference of the golden section rectangle was the famous German psychologist Gustav Fechner, in 1876. His subjects chose from the most–preferred to least-preferred among ten rectangles of varying proportions from 1:1, 5:6, 4:5, 3:4, 7:10, 2:3, Φ, 13:23, 1:2, to 2:5. He gathered a total of 347 responses and his experiment shows that 35 % of people preferred the golden section rectangle and that no subject chose the golden section rectangle as their least favoured choice. The least preferred rectangle chosen by the subjects was the 2:5 with 35.7%. Other researchers repeated the experiment, such as Witmar (1894), Lao (1908) and Thorndike (1917) and all outcomes remained similar to the original. Not all studies done would agree that people are attracted to the golden section rectangle. For example, Berlyne's work (1970) suggests that cultural factors could be influential toward the chosen preference of different sized rectangles or squares. This was the result of his experiment which showed evidence that Japanese high school girls preferred squares rather than the golden section rectangle. Fischler (1981) claimed there was no sufficient documentation to support the theory that an artist used the golden ratio as the theoretical basis of his work. David and Jahnke's research (1991) would also suggest there is not enough solid data gathered to be a decisive factor in terms of aesthetic preference for the individual choice. They concluded that their experiments "provide no basis for the golden section as an aesthetic ideal"[2]. Whilst both these studies produced results that seem to place less emphasis on the golden ratio as a design concept the results are by no means conclusive in any way. Fischler, and David and Jahnke in their own words both mention a lack of sufficient data when attempting to write a conclusion to their research. This does not constitute conclusive proof of anything. There are as many, if not more, examples of the reverse actually being the case. Others, such as Jay Hambidge -who analyzed Greek vases based on his theory of 'Dynamic symmetry'- discovered that the root rectangles (√2, √3, √4 and √5) and the golden section rectangle were used for Greek vase design. He suggested that ancient Greek artists and designers were consciously experimenting with geometry and frequently used the golden ratio and the root rectangles all of which are deeply embedded in ancient Greek design. Whilst not all of le Corbusier's works exhibited the use of geometry and the golden ratio deliberately, many of his works such as Chaise Lounge (1929), Façade of the Arsenal of the Piraes (1931) and Villa Savoye (1931) were his examples of applying the golden ratio. More recently Kimberly Elam in her book 'Geometry of Design' describes how geometry can be a useful tool for analyzing designs. A number of graphic designs and product designs were carefully analysed by applying geometry and the golden ratio.

Figure 1. L'intransigeant poster [3]

For example, A.M Cassandre' L'intransigeant Poster in 1925 (see figure 1), illustrates how artistic creativity had been expressed under consciously planned geometric composition, proportion and harmonious subdivisions. All this may suggest that this geometric process in product design could help students to improve their visual coherence and harmonise design forms. The visual format of the original poster shows a square inside of a root two rectangle with the face and neck organized inside of the square.

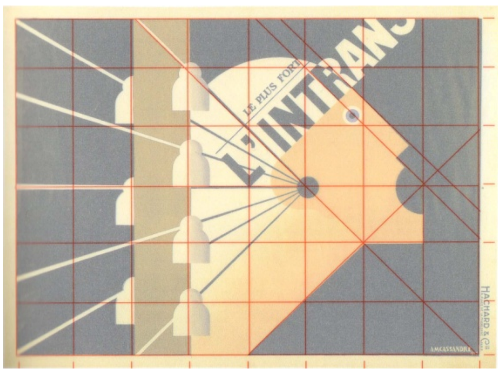

Figure 2. Geometric analysis of L'intransigeant poster [3]

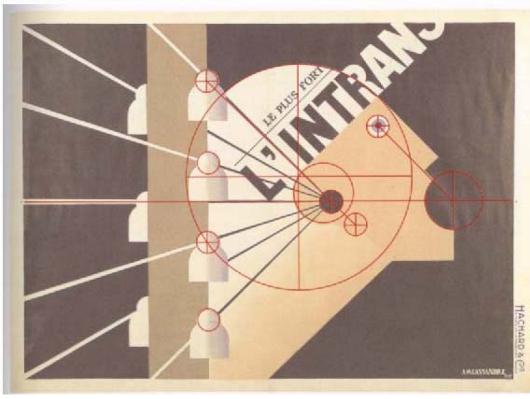

Figure 3. Geometric analysis of L'intransigeant poster [3]

To illustrate how every element of Cassandre's designs used geometric harmony figure 2 shows subdivisions of the poster within 48 small squares and diagonals of the square in side of the root 2 rectangle. The 'L' displays at the centre of the poster while the angle of the text, 'L'INTERANS' and the neck lines are carefully designed to be paralleled within dynamic motion. In particular figure 3 shows how Cassandre utilized the more aesthetically pleasing notion of the circle to attract viewers attention. All of the circles in figure 3 are directly proportionate to each other for example the head circle is 4 times the ear circle etc. [3].

3 APPLYING GEOMETRIC ANALYSIS IN PRODUCT DESIGN

Geometry workshops were carried out in the Creativity Zone at the University of Brighton and in the Design Studio at the University of Sussex between 2011 and 2012 two times (2 hours each). The workshop was designed to introduce a group of 35 second and third year BSc Product Design students (1/3rd female and 2/3rd male) to analyse their own designs using geometry and the golden ratio. The geometry workshop explored ways to expand creativity through a series of exercises, including learning how to use and apply the golden ratio and geometric analysis. This workshop aimed to show students how to be able to apply geometry to their own designs naturally in order to develop visual coherence through geometry practices and to help design practitioners to communicate effectively - where necessary - to support design decisions with rational explanation. Ultimately each design practitioner will be able to find their own way towards using geometry as a design tool for stimulating their artistic skills, creativity and sensitivity. The workshop process had three steps: 1) questionnaire, 2) learning geometry and applying geometry to analyse designs and 3) reviewing assignments and discussion regarding the pros and cons of implementing geometry into their own design and how would design practitioners perceive geometry and geometric analysis as effective design rules?

3.1 Questionnaire

Question 1 – asked students whether they were familiar with the 'golden section', the 'golden ratio', the 'golden mean', the 'golden number' or the 'divine proportion' (these all refer to the same concept).
Question 2 – asked students what the specific numerical ratio or proportion of the 'golden section' is.
Question 3 – was a test asking students to choose a favourite from 'A' to 'F'. 'C' was the only option which conforms to the Golden Ratio. None of the students were aware of which of rectangle was the golden section rectangle (see figure 4).

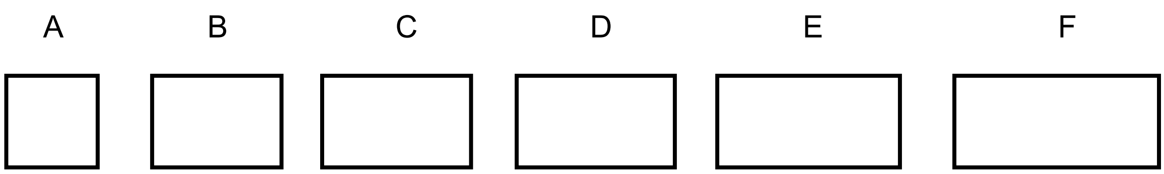

Figure 4. Question 3

Question 4 – students were asked to choose their favourite rectangle between ‘A’ or ‘B’. Rectangle ‘A’ is the same ratio as the iPod classic (1.67) and ‘B’ is a rectangle constructed from rectangle ‘A’ which has been modified to conform to golden ratio proportions (1.618) (see figure 5).

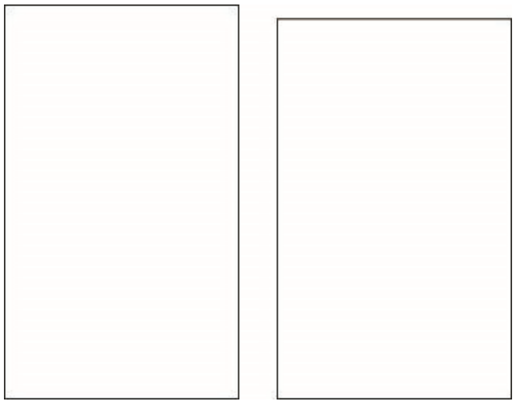
A B

Figure 5. Question 4

3.2 Findings

35 students completed the questionnaire regarding geometry and the golden ratio. Although the majority (31) of students were familiar with the concept of the golden ratio, only four students knew the value of the golden ratio, ‘1.618’ and four students had not heard about it whatsoever. It appears - from data collected in question 3 that the golden section rectangle is most attractive to viewers and the second favourite choice is root two rectangle. The result of question 4 shows that the number of students attracted to the Golden Section rectangle (‘B’) was 31 of 35, 88.5% of the class. A significantly higher number of students chose the Golden Section rectangle and a mere 11.5% chose the rectangle that does not conform to Golden Ratio principles. This is an important result as one would have expected a much more equal division of choice considering there was no pronounced difference between the sizes of both rectangle options.

3.3 Learning geometry and applying geometric analysis to your design

The students learned how to construct frequently used measures in geometry, such as √2, √3, √4 and √5 rectangles and the golden section rectangle as well as the golden spiral. After learning the basic geometry, students attempted to apply what they had learned in order to analyse design examples. Three exercises were given to students in order to practice geometric analysis. During the workshops three hypotheses were also tested regarding applying geometry analysis to design.

Hypothesis 1; ‘*Is an intuitive understanding of what constitutes good design linked to a fundamental relationship of geometry?*’, Hypothesis 2; ‘*Does a formal knowledge of geometric rules and visual coherence improve design skills?*’, Hypothesis 3; ‘*Does bad design result when the geometric rules are ignored*?’ Hypotheses 1 was used to examine how their perception is linked to geometry and in particular the golden ratio. Also, if design practitioners show a higher level of visual coherence in their designs, do they use geometry and the golden ratio more effectively? And then, how should design practitioners effectively learn and use geometry and the golden ratio in order to analyse designs and also to develop their visual coherence? Hypothesis 2 investigated how design practitioners perceive this geometric exercise in terms of finding their own personal style and to find out if knowledge of geometric proportion has been helpful to them as designers. For Hypothesis 3, students were asked to try not to use geometry in design in order to experiment with their conception and perception and see how they have progressed. This final hypothesis is to analyse whether geometry is useful to them and how intuitively they apply geometric principles without intending to do so. Thus the students completed four experimental assignments which were designed to test the hypotheses.

Assignment 1 – to apply geometric analysis to your design and find out what your intuitive geometric ratio is.

Assignment 2 – to refine your original design through applying the golden ratio.

Assignment 3 – to avoid geometric knowledge gained while redesigning your original design.

Assignment 4 – to display all three designs from assignment 1-3 and chose a favourite design and explain the reason for that choice.

4 RESULT

24 completed the assignments. 16 students chose their refined original design to conform to the golden ratio as their favourite design and one student chose his favourite design which conforms to root 5 ratio although his original design ratio, 1:1.987 was close to root 4 (see table 1). Only 7 students chose their original designs as their favourite and their design ratios were close to root rectangle ratios and phi group ratios (see the yellow marked ratios in table 2). Although in assignment 2 they did not necessarily express a marked preference for their 'golden ratio' modified designs, 5 of the 7 students chose the golden section rectangle as their favourite in question 3 and 4 of the questionnaire.

Table 1. Favourite design choice

Designs	Favourite design choice
Original design	7 (29.1%)
Refined original design to conform to the golden ratio	16 (66.6%)
Redesign original design while avoiding geometric principles	0 (0%)
Refined design to conform to root 5	1 (4.16%)

The original design ratios of the students' designs show that their intuitive design ratios almost entirely conform to the golden ratio and other common geometric numerical quantities (see table 2). Thus in total 70 % of the students preferred their refined design which conformed to the golden ratio and root 5 ratio. None of the students chose the design from assignment 3 which had no geometrical knowledge applied as their favourite design overall. The results of the hypotheses in fact correlate with the findings from question 3 and 4 of the questionnaire and patently manifest a high number of students inclined to the golden section rectangle. In addition, after having learned about the golden ratio etc, when they were then asked to redesign their original design without using what they had learned about geometry they struggled with the task. It is interesting that once they had designed using geometric principles they found it difficult to work without it. It appears that their intuitive perception of geometry has increasingly emerged and has become a design consideration.

Table 2. Original design ratios

Ratios	1:1	1:1.2	1:1.3	1:1.4	1:1.5	1:1.6	1:1.7	1:1.8	1:1.9	1:2	1:2.1	1:2.2
Frequently used geometric ratios	1:1	1:1.272 (=√Φ)		1:1.414 (=√2)		1:1.618 (=Φ)	1:1.732 (=√3)			1:2 (=√4)		2:2.236 (=√5)
Original design ratios of the students	1:1.03 1:1.008 1:1.96	1:1.2 1:1.23 1:1.231		1:1.404 1:1.414 1:1.44 1:1.454	1:1.58	1:1.612 1:1.625 1:1.631 1:1.661	1:1.72 1:1.74 1:1.79	1:1.805 1:1.83	1:1.918 1:1.987	1:2.09	1:2.18	

Three student comments below are typical and exhibit their feelings regarding applying geometry in product design.

"It is beneficial to have an understanding of geometry in design as it may help the proportion and ratio of your design that previously did not look right before. It is practical and it will take practice to apply it to my own work." - Tala Jarallah, Product Design Year 2, University of Sussex.

"It is very interesting to see that behind a beautiful design there is geometry, ratios, shapes. Sometimes it is hard to believe that someone actually planned this geometry into mysterious design…I think it can be very beneficial when you are carrying out a design and something does not feel right you can actually try to apply geometry to your design and "fix" what was wrong with it" - Demosthenis Katsouris, Product Design Year 2, University of Sussex.

“Aesthetically it can be good but I am interested to see if geometry and the golden ratio still make the function better” - Catlyn Adams, Product Design Year 3, University of Brighton.

Since being introduced to the idea of using geometry as a design consideration according to student feedback they would all consider applying geometry to their design as a way to refine their work. Learning geometry and successfully applying it to the design process takes time and requires practice. At the end of the geometry workshop the students have more idea how to compare their design styles and forms through geometric analysis. Thus geometry provides a method of analyzing designs and develops an ability to express design concepts rationally when needed. A possibly more effective approach to help design practitioners would be to set specific tasks which involve engaging with and observing geometry in nature and their surroundings.

5 CONCLUSION

The geometry workshops have demonstrated how to apply geometry and the golden ratio into product design as a design tool for analysing or refining designs. The results of the questionnaire and the hypotheses appear to show that the golden ratio is chosen to be one of the favourite design ratios by design practitioners. Also the original design ratios of the design practitioners are close to common geometric ratios which explain how every designer has their own intuitive geometric organization i.e. whether they are actually aware of it or not, they produce designs that conform to geometric principles. However, “in design and architecture it is far less intuitive and far more often a result of knowledge that is thoughtfully applied.”[3] The point of learning about geometry and how it relates to design is not to use it as a substitute for the creative process, but rather as a means of obtaining a deeper understanding of it. Without the initial spark of imagination and creativity geometry on its own will not make a good design. One of the aims of this workshop was to explore and analyze students intuitive sense of geometry. Then to discover ways to apply geometry to designs in order to produce an end result of a coherently designed product. It is clear that only a few workshop sessions may help design practitioners to obtain tangible benefits from learning how to apply geometric analysis to their designs. In the short term, it would be a useful approach to review their designs to improve them in terms of proportion and composition. For the longer term using geometry would lead to gaining true benefits when it comes to developing creativity and imagination.

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