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Emotive Implications of Rendering in Conceptual Design

by

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This thesis
is dedicated to
my parents and brother for their endless love, encouragement and support

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Abstract

Emotions play an important role in human cognition and affect reasoning, judgment, decision-making, and other cognitive processes. However, there has been little scientific research into the role emotions play in designing. Rendering enables the visualisation of conceptual models by providing graphical presentation of design concepts. Such a presentation can convey not only object information but also emotive information and can evoke human emotive responses. The work presented in this thesis addresses five main elements: *emotive implications*; *adoption of Interacting Cognitive System* (ICS) *to designer perception*; *adoption of Kansei Engineering as the analytical tool for the research*; *testing a spectrum of existing rendering techniques developed to date*; and *testing of perception with academics, students and design practitioners from industry.*

This thesis presents a novel study of the emotive effectiveness of different rendering styles that cover a spectrum of existing photorealistic rendering (PR) and non-photorealistic rendering (NPR) styles in conceptual design. The study involved a sample of sixty-one respondents, which included academics, fourth year and fifth year undergraduate and postgraduate students. The main contribution of knowledge is in the form of insights into the emotive implications of different rendering styles in conceptual design. The insights can act as a guide for designers to base their decisions in using the respective rendering style/emotive implication paradigms when creating designs that elicit desired responses. The overall idea of gaining the insights is to support the designer in creating and influencing the emotional impact of a new design.

The results of the study highlight fourteen emotive implications of computer graphic images, the four underlying constructs that describe the fourteen emotive implications, i.e. ***affective***, ***cognitive***, ***functional*** and ***motivational***, and the patterns of relationships between the rendering styles and emotive implications. The results show that different kinds of rendering styles have definite and significant effects. For instance, PR styles are most effective for conveying ***affective*** and ***motivational*** content; and NPR styles are most effective for conveying ***affective***, ***cognitive*** and ***functional*** content. A survey-based study involving thirty-three design practitioners from industry was used for the validation of the research results.

The thesis finishes by presenting the strengths and weaknesses of the research outcome, the techniques employed and the research methodology utilised to facilitate the work presented in this thesis. Finally, based on the current research findings, future works have been identified, including extension of the research within actual design practice and further investigation of an alternative rendering approach for presenting vague information that is often found in the conceptual design stage.

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Abbreviations, Symbols and Nomenclatures

Unless stated explicitly, the following abbreviations, symbols and nomenclatures are used in this thesis.

Abbreviation	Meaning
APA	American Psychological Association
CAD	Computer Aided Design
DMEM	Design, Manufacture and Engineering Management
HCI	Human Computer Interaction
HCS	Human Computer Symbiosis
HMD	Head Mounted Display
IDA	Intelligent Design Assistant
ICS	Interacting Cognitive System
NPR	Non-photorealistic rendering
PR	Photorealistic rendering
SPSS	Statistical Package for the Social Sciences

Symbol	Meaning
M	Mean
SD	Standard Deviation
N	Sample
p	Probability
r	Pearson correlation coefficient
Z	Test statistic
μ	Assumed mean
$\overline{X}$	Sample mean
H0	Null hypothesis
H1	Alternate hypothesis
$\geq$	Greater than or equal to
Σ	Sum of

Nomenclature	Meaning
Highlight	The lightest tonal or colour values in an image, describing any point or area where the maximum amount of light is reflected from a surface.
Image	An image is a 'reproduction or imitation' or the optical counterpart of an object. In other words, it is the visual representation of a scene.
Lighting	The term is used to designate the interaction between material and light sources, as well as their interaction with the geometry of the object to be rendered.
Material	Material is the substance or matter from which something is or can be made, or also substance or matter for creating an image.
Mesh	A grid-like polygonal subdivision of the surface of a geometric model. In short, it a series of polygons grouped to form a surface.
Object or model	A collection of geometric entities is referred either as an object or a model.
Picture	A picture is 'a design or representation', or a description so vivid or graphic as to suggest a mental image or give an accurate idea of something.
Polygon	In the context of 3D modelling, a polygon is a multi-sided object composed of edges, vertices, and faces.
Presentation	A presentation is defined as the visualisation of a product, for example, in a graphical or textual form.
Representation	A representation describes an aspect about a product (i.e. the product shape) in a computer processable form (i.e. the geometry model).
Respondent	A person who replies to something, especially the one supplying information for a survey or questionnaire.
Scene	A scene is a collection of models comprising everything that is included in the environment to be rendered. A scene can also include material descriptions, lighting and viewing specifications.
Texture	A tactile impression of a surface as rough, sandy, smooth as conveyed by the hatching used.
Rough	A rapid and loosely worked sketch showing the basic form of an illustration or design.

1. Introduction

Cognition is the mental action or process of acquiring knowledge and understanding through thought, experience and the senses [1]. Cognition has been investigated for decades in domains of psychology, computer science and engineering design, which resulted in a number of cognitive theories and cognitive models [2-7]. Researchers in design have started to relate their work to a number of areas of research in cognitive psychology and cognitive science [8, 9].

Design is an important, all pervading domain of human activity [10]. Even if not often stated explicitly, the tendency in much cognitive design research is to consider design as a specific 'cognitive activity'. *Cognitive activity refers to the way in which people realise their task at a cognitive level* [10]. Simon proposed a definition for design in his book *Sciences of the Artificial* [11] as:

> "Design...means synthesis. It means conceiving of objects, of processes, of ideas for accomplishing goals, and showing how these objects, processes, or ideas can be realised. Design is the complement of analysis – for analysis means understanding of the properties and implications of an object, process, or idea that has already been conceived". (Simon, 1999, p.246)

Cognitive design studies[1] have been developed since the 1960s [10], with focus on cognitive aspects of design, that is, the actual cognitive activity (for example, design thinking, design reasoning, design intuition, learning in design and how designers design) implemented by designers during their work on design projects. Typical approaches to such studies include: direct observation of the results of designing; protocol studies of individual and collaborating designers designing; and surveys of designers' perceptions [12]. The results of such studies provide insights into the behaviour of designers as they are designing. These insights can form the basis of the development of computational support tools for designers.

The work presented in this thesis adopts a cognitive viewpoint of design by focussing on the cognitive activities implemented by designers in conceptual design. During engineering conceptual design, a designer's geometric design can gradually evolve from a vague geometric concept, in the form of paper-based sketches, towards a computer image of the

[1] The studies of design focusing on its cognitive aspects are termed 'cognitive design studies' [10], where cognitive aspects refers to designers' cognitive processes and structures (knowledge and representations).

design in a Computer Aided Design (CAD) system [13]. Computational conceptual design can be considered as a loop between the cognitive human-computer activities that include: *communication* of the designer with the computer (e.g. using sketch input devices), *modelling* (generation of the computer model), *rendering* (graphical presentation of information), *visualisation and interpretation* of the displayed image on computer, *comparison* and *iteration* (see Figure 2-5 in Chapter 2). However, when computer-based systems are used to support conceptual design, sometimes there is a significant difference between a design as displayed by the computer and the designer's mental model of the design concept, which is a hindrance to human computer symbiosis (HCS). The difference is because of the variety of mediums involved, for instance paper and computer, and the loss of representations translating between these mediums. This difference hinders the computer supported design at the early conceptual stages, and can lead to misinterpretations, and, in many cases, possible criticism and avoidance of the computer system. Thus, in order to enhance HCS in conceptual design there is a requirement to:

- Facilitate computer generated presentations that are closer to the mental models of the design concepts.
- Support the emotive information of the design concepts.
- Minimise the loss of information during the design-loop.

Emotions play an important role in human cognition and affect reasoning, judgment, decision-making and other cognitive processes. In decision-making[2], the emotional consequences of how choices are framed may affect which choices are preferred [15]. There is indeed considerable evidence[3] that emotion affects cognition in a variety of ways. Although some main theories of cognition do not take into account emotion [2, 18, 19], for instance theories of vision such as 'bottom-up' and 'top-down', there are theories such as *Interacting Cognitive Systems* (ICS) [20] that account emotions as an integral part of the human cognitive system.

Of late, the emotions of artefact users are being considered by certain designers, with the aim to design new artefacts that these users would experience as pleasant or desirable [21-24]. Affective Computing, Affective Design, Affective Engineering, Design and Emotion, and *Kansei Engineering* are phrases gaining ground in the study and use of relationships between artefacts and users' subjective responses to them. The research on the role of emotion in the

[2] See [14] for more information on the role of emotion in decision-making.

[3] See [14, 16, 17] for more information on emotion and cognition-emotion interaction.

domain of design cognition is just in its early stages [10], especially in computer graphics. Computer images are characterised by both visual aspects and emotional meaning of a displayed design. Comparison of the appearance of real world and rendered images is a topic that has a relatively long history [25-27]. Researchers have conducted studies to investigate the fidelity of computer generated renderings with respect to the real world [28-30]. However, the focus of these studies has been on the visual aspects such as reflectance and illumination perception per se, than on the emotional meaning carried by the rendered images and the emotions elicited by the rendered images. In this thesis, the notion of 'emotive implications' is introduced and from the research of the work it is suggested that *emotive implications of images are the implicational information of images that imply or stimulate designers' emotive responses.* Psychologically, rendered designs can maintain different affordances[4] and influence perception and interaction. It is important to be able to investigate the emotive implications of rendered images by assessing the users' emotive responses, the insights from the results can provide starting points for creating a new design. As such, this type of work presents an innovative aspect to conceptual design and development by understanding how images rendered by different styles provoke emotions and influencing the emotional impact of a new design.

Inspiration for this research stems from the fact that current research has concentrated more on technical innovation of sketch input devices (online/offline), improving modelling capabilities (e.g. [13, 33-39]), collaborative sketch based design support (e.g. [40-43]), sketch recognition approaches (e.g. [44-51]) and enhancing realistic rendering techniques (e.g. [52]). In conceptual design, where creativity[5] is prevalent, there is lack of a systematic study of the best way to present concept designs using rendering so that the design as displayed by the computer matches the designers' mental model of the design concept. Such systematic study will lead to an increased understanding of how to present designs in a way that more fully supports human creativity during computational conceptual design. Thus, the work presented in this thesis aims to investigate, through a novel study, the emotive implications of different rendering styles[6] and, thereby, provide insights of the best way to

[4] The word 'affordance' was coined by Gibson [5, 31] in the study of visual perception. It depicts a fundamental aspect of human cognition, that much information needed for perception and action is in the environment as invariants which can be picked up directly [32]. According to Gibson, affordances are relationships. They are the properties of the world that exist naturally and need not have to be visible, known or desirable.

[5] Creativity is the quality of humans to conceive new ideas and artefacts [53].

[6] In this thesis, rendering 'styles' are taken to reflect those that are used to present the objects in an image (for instance, pen-and-ink, shaded drawing, line drawing and cartoon styles); and rendering 'techniques' refer to the technical generation of those 'styles' to produce computer graphic images.

present concept designs. As such, the work aims to provide a basis to overcome the inadequacies of existing works on rendering and address the requirements to enhance HCS in conceptual design. The insights from the study results can provide implications and future directions for the development of computational support tools to create designs that match designer intent and expectations in conceptual design. For example, a computer supported system can be equipped with the inference rules of the emotions elicited by different rendering styles, so that it could create designs that are reflective of the designers' mental model when the designers interact with it.

The work presented in this thesis addresses five main elements: emotive implications, adoption of ICS to designer perception, adoption of Kansei Engineering as the analytical tool for the research, testing a spectrum of existing rendering techniques developed to date, and testing of perception with academics, students and design practitioners from industry.

In this thesis, due to the complexity of investigation of effectiveness of the number of existing rendering styles, the scope is bounded to investigate emotive implications of these rendering styles in conceptual design, which is supported by and derived from the analysis of data gathered from academics and students. However, the validation of the results needs experienced design practitioners from industry. Due to the time restrictions of the design practitioners, it was decided to limit the validation of results relating to NPR line styles only and hence increase the likelihood of their participation.

1.1 Aim and objectives

The overall aim of the work presented in this thesis is to provide insights into the emotive implications of different rendering styles in conceptual design. In order to achieve this aim, the following objectives have been identified as needing to be met:

- Establish the design problem in conceptual design and the focus of the research based on the review of computer supported sketch systems.
- Review the existing rendering techniques to understand their features and their role during the design process, especially in conceptual design, and derive the key aspects for the generation of computer graphic images.
- Review cognitive theories to understand the cognitive principles underpinning the visualisation and interpretation of the generated computer graphic images and derive the key aspects for visualisation and interpretation.

- Recognise the inadequacies of existing works related to rendering. The works are critically reviewed with respect to the derived key aspects for rendering.
- Define the research problem. The research problem is formalised considering the inadequacies of existing works with respect to the key aspects for rendering.
- Conduct a systematic study, overcoming the inadequacies of existing studies, to investigate the emotive implications of different rendering styles, which involves:
    - Evaluate the characteristics and features of rendering in conceptual design, including: the nature of rendering, the nature of different rendering techniques and the limitations with current CAD systems. The insights gained could be then used during the identification of the emotive implications of images and the evaluation of the effectiveness of different rendering styles.
    - Perform pilot studies to gain insights into the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles.
    - Identify the emotive implications of computer graphic images. The identified emotive implications could be then used as a basis for assessing the emotive effectiveness of different rendering styles.
    - Evaluate the effectiveness of different rendering styles in conveying emotive implications, based academics' and students' perception and emotive responses to different rendering styles. The results could then provide insights into the emotive implications of different rendering styles
- Validate the results with a cross-section of design practitioners from industry.
- Analyse the strengths and weaknesses of the research outcome, research techniques and research methodology undertaken.
- Identify the avenues of future research based on the current research findings.

1.2 Research methodology

An adaptation of the research methodology developed in the CAD Centre, University of Strathclyde, by Duffy and O'Donnel [54] was utilised to undertake the research presented in this thesis. This methodology was chosen as the foundation for conducting the research presented in this thesis for a number of reasons, including:

- It was founded on the requirement to conduct effective research into the Intelligent Design Assistant (IDA) philosophy [55] to attain HCS (see Section 2.3.1 in Chapter

2). The IDA philosophy refers to the principle focus of the CAD Centre, where this research was undertaken. The ultimate aim of the research presented in this thesis is to be able to develop a more mature IDA system that supports conceptual design by being able to develop computer tools to attain HCS.

- Its successful application to a number of previous research studies [56-60] in the engineering design field has verified the methodology as a valid and appropriate approach on which to facilitate research in this area.

The research presented in this thesis was conducted in accordance with the methodology illustrated in Figure 1-1. This figure source came from Lim's thesis [56] that adopted it from [54, 60, 61].

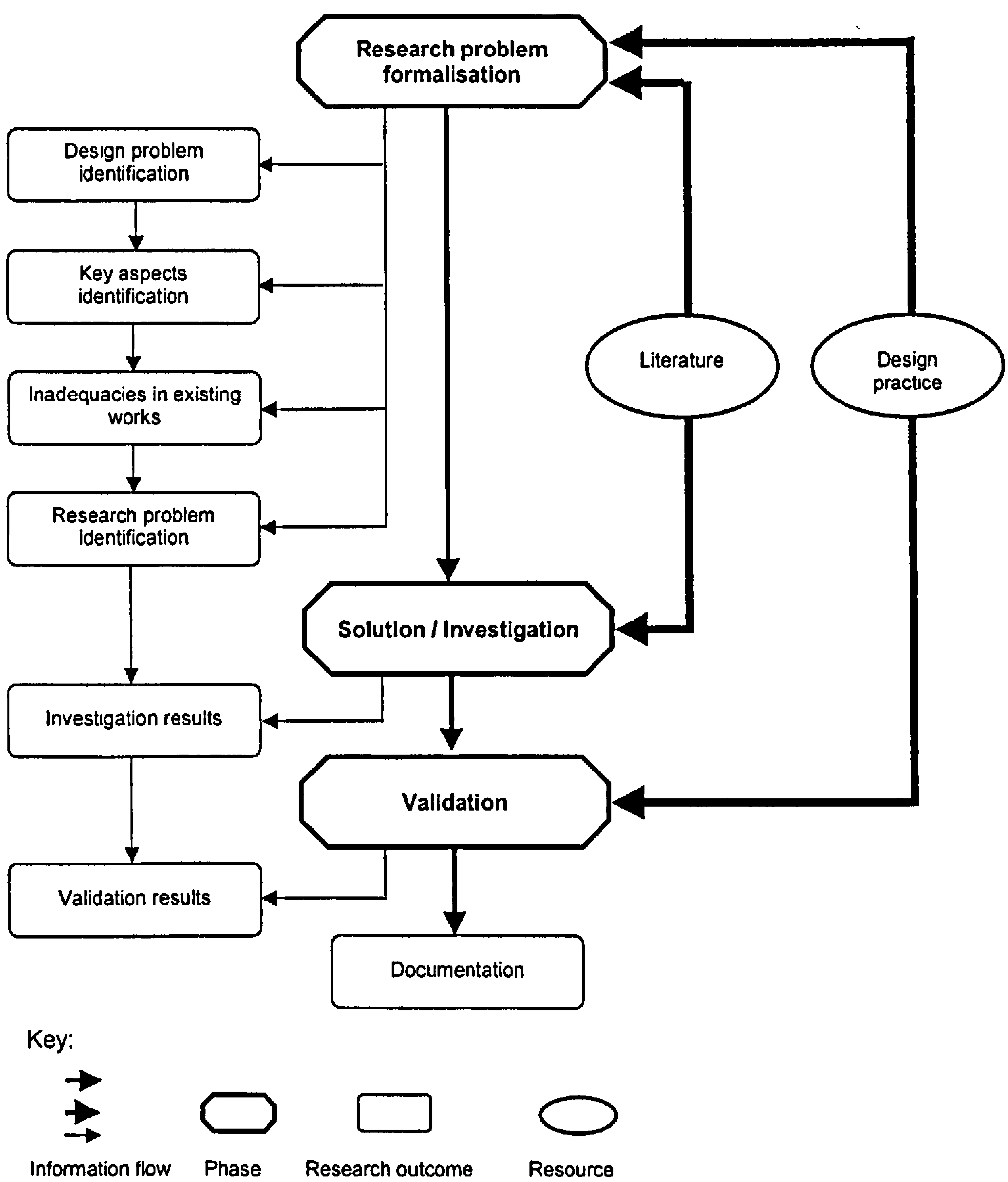


Figure 1-1: Research methodology (adapted from [54])

With regard to Figure 1-1, *Research problem formalisation*, *Solution/Investigation* and *Validation* are contemplated to be the main phases in conducting the research. *Design problem identification*, *key aspects identification*, *inadequacies of existing works*, *research problem identification*, *investigation results*, *validation results* and *documentation* are the main outcomes of the research. The outcomes from a later phase are procured based on the outcomes from the earlier phases.

With regard to the overall approach presented in Figure 1-1, from design practice and pertinent literature, a design problem is identified. Based on the design problem, the research problem formalisation considers literature based research to identify key aspects and to identify the inadequacies of existing works based on these defined key aspects. Thereby, an investigation based on the research problem is conducted by overcoming the inadequacies of existing works. Literature is considered from the identification of the design problem to the solution of the research problem. The resulting findings are validated based on design practice. Finally, the research is reported.

Some of the following explanations of the phases are adopted from Lim's thesis [56] that adopted the same method with Manfaat [57]:

- ***Literature***: Literature serves as a basis for most of the other elements of the methodology. For example, to define the design problem and research focus, a literature review of the computer supported sketch systems in conceptual design was carried out. Further, literature review of rendering techniques was carried out to identify the key aspects and inadequacies of existing works in rendering.
- ***Design practice***: Design practice was considered and involved so that the end result would prove useful to the industry. Some key elements to identify the design problem are investigated from design practice and literature. Further, design practice was used to validate the findings resulting from the study presented in this thesis.
- ***Research problem***: In this thesis, the research problem refers to the challenge concerned with overcoming the inadequacies of existing works with respect to the key aspects. The research problem was formalised based on the highlighted deficiencies of the existing works.
- ***Solution/Investigation***: The solution/investigation is aimed at solving the research problem and overcoming the inadequacies of existing studies. In the work presented in this thesis, an investigation, involving surveys of academics' and students'

perceptions, was carried out to produce novel results concerning the emotive implications of different rendering styles. The results of such studies provide insights into the emotive implications of different rendering styles. These insights can form the basis of the development of computational support tools for designers.

- ***Validation***: Validation of the solution/investigation results, i.e. assessing how well the research results are consistent and the generality of the results. In order to enable the validation of the research results obtained from the study with academics and students, the investigation was carried out with a cross-section of design practitioners from industry.
- ***Documentation***: The result of the research is documented primarily in this thesis, and further in some published [62, 63] and unpublished reports [64-66].

1.3 Thesis structure

The remainder of the thesis is structured into three parts, as follows (see also Figure 1-2).

PART – 1: Research problem formalisation (Chapters 2, 3, 4 and 5)

Chapter 2 presents a review of computer supported sketch systems in conceptual design with the purpose to identify the design problem in conceptual design and establish the focus of the research.

Chapter 3 presents a literature review of different rendering techniques for the generation of computer graphic images.

Chapter 4 discloses a cognitive framework of human information processing between the visualisation of a generated computer graphics image and its interpretation. The notion of 'emotive implications' of computer graphic images is introduced and their potential is delineated.

Chapter 5 critically reviews existing works related to rendering in order to identify their inadequacies. Key aspects are identified from Chapters 2, 3 and 4 to serve as the basis for the critical review. Areas for further research are identified based on the highlighted deficiencies of existing works. The research problem is then formalised.

PART – 2: Solution / Investigation (Chapters 6, 7, 8)

Chapter 6 presents an exploratory study on different characteristics and features of rendering in conceptual design.

Chapter 7 presents the pilot study conducted as part of the work presented in this thesis and outlines the Kansei Engineering methodology, which in turn identified emotive implications of computer graphic images.

Chapter 8 presents the main study in the research for the identification of the most effective rendering styles for conveying the identified emotive implications. Kansei Engineering, which has never been used before in the computer graphics community, is used as a means for evaluating the degree of emotive effectiveness of different rendering styles. In this chapter, the existing photorealistic rendering (PR) and non-photorealistic rendering (NPR) styles are evaluated and the results are presented in the form of *impact* and *correlations* of these rendering styles.

PART– 3: Validation and discussion (Chapters 9, 10, 11)

Chapter 9 presents a study involving design practitioners from industry to investigate the validity of the prior findings.

Chapter 10 reviews the main findings from Chapters 6 to 9 in order to summarise and consolidate the key insights.

Chapter 11 discusses the strengths and weaknesses of the research outcome, the techniques used and the research methodology undertaken for the work presented in this thesis. In addition, future works are identified.

Finally, Chapter 12 concludes the thesis by summarising the work and outlining the main findings and outcomes of the work presented in this thesis.

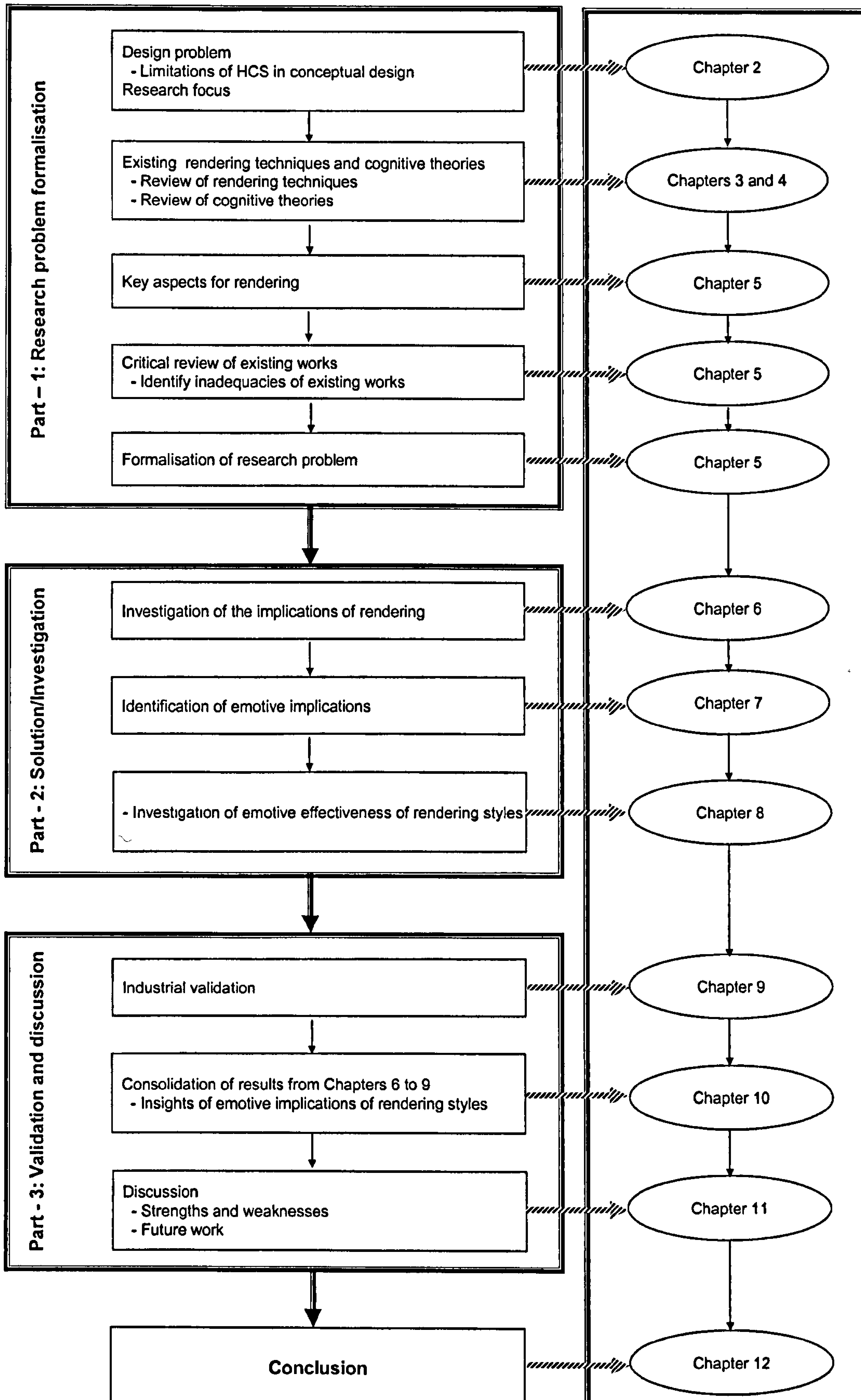


Figure 1-2: Thesis structure

PART 1 - RESEARCH PROBLEM FORMALISATION

2. Computer aided sketching

The aim of this chapter is to present a review of existing computer-based systems that support sketching activity in conceptual design. The objectives of the review are to (1) identify the design problem and (2) establish *rendering* and *visualisation and interpretation* as the research focus (discussed in Chapters 3 and 4 respectively).

Before reviewing computer based sketch-support systems, it is appropriate to give an overview of sketching in conceptual design. Thereby in Section 2.1, a general introduction to design sketching and the need of computer aid for sketching in conceptual design is given. Section 2.2 presents a review of existing computer-based systems that support the sketching activity during conceptual design. In Section 2.3, the vision of human computer symbiosis (HCS) for creating an intelligent partnership between humans and computers in conceptual design is introduced and factors that characterise the design problems are identified. In Section 2.4, *rendering* and *visualisation and interpretation* are recognised as the focus for the research presented in this thesis. The requirements to enhance human computer symbiosis (HCS) in conceptual design are identified in Section 2.5. Finally, Section 2.6 summarises the chapter.

2.1 Conceptual design sketching

Conceptual design often incorporates 'ill-structured representations' that are ambiguous, fluid, imprecise, intermediate and vague in nature [8]. The term 'sketch' belongs to these representations. Hence, almost by definition of an ill-structured representation, a sketch has inherent vagueness [8]. A sketch can be considered as:

- A rough, or unfinished drawing or painting, often made to assist in making a more finished picture [1].
- A brief account without many details conveying a general idea of something, a rough draft or general outline [1].
- An informal, private drawing that designers use as a medium for graphic thinking in the exploratory stages of their work [67].

Figure 2-1 shows some typical sketches used in conceptual design. Ferguson [68] classified design sketches into three types namely, (i) *thinking sketch*: used to focus and guide non-verbal thinking, (ii) *talking sketch*: produced through discussion between designers from a technical background as a means of clarifying complex tasks and (iii) *perspective sketch*: used to direct a draftsman in the construction of a final drawing.

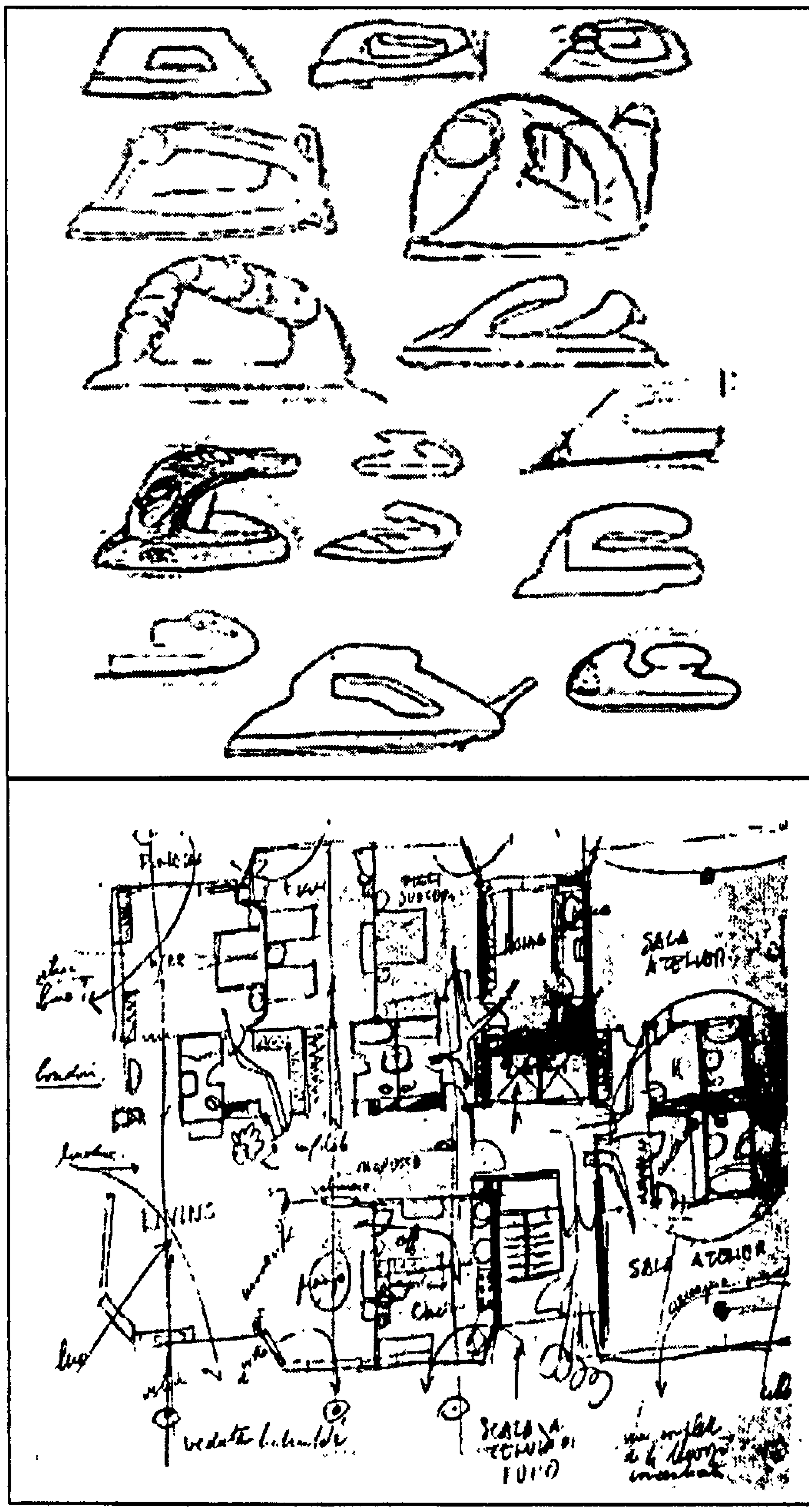


Figure 2-1: Sketches in conceptual design (from [56, 69, 70])

A sketch is inexact in nature, thus avoiding the need to provide unnecessary details at conceptual design. The abstract and ambiguous[7] nature of a sketch makes it suitable for the underdeveloped state of the design at the conceptual stage. Sketches have the characteristics

[7] Ambiguous: The general definition [1] is as follows:
1: a double meaning that is either deliberate or caused by inexactness of expression.
2: an expression able to be interpreted in more than one-way.

of being vague: where information and ideas are often approximate and incomplete and subject to radical changes at all levels [13]. They carry with them a 'minimum commitment' approach, where the designer either lacks information to make a given decision or simply chooses to postpone it [69]. Also, there exists a convenience of exploration of alternatives, where the designer 'branches off' at arbitrary points in order to examine alternative solution approaches [13].

Sketching activity

Sketching is a broad term that can mean different things. From a design perspective, sketching is initially a highly abstract activity that evolves a concept into a more concrete geometric representation as a design develops towards a definitive design solution [71]. In the words of Tovey et al [72], it is a process that allows the designer to give an external definition to an imagined or half-imagined form. This externalisation, therefore, acts as a language for handling multiple possibilities for potential design solutions. Whereas, Schon [73] refers to sketching as 'reflection-in-action', which refers to the ability to allow contemplation and discovery of ideas. The features of sketching activity, summarised from the literature [46, 67, 71, 74-76], can be considered as:

- Allowing *easy manipulation* of ideas at various levels of abstraction.
- *Archiving* the geometric and topologic form of a design without the need to provide unnecessary details. In short, they help the design idea take shape easily.
- *Communicating* ideas between designers as well as between designers and clients.
- Contributing to the *evolution* of designers' ideas, because of the flexible nature of the information being considered.
- *Discovering* new interpretations and opening avenues to new perspectives for solutions.
- Enabling to *visualise* ideas even if the drawn figures are ambiguous, this speeds the drawing of a sketch whilst avoiding fixing a particular idea.
- Facilitating *creativity*, because of the abstract nature of the information being considered, low degree of commitment to generated ideas and coarseness of detail in conceptual design.
- Providing chances to *re-interpret* sketches by simultaneously attending to previously described sketched elements that have not been attended together before. In this way, the designers can *discover* hidden features, configurations and relationships.
- Serving as an analysis tool and to simulate the design.

Indeed, in teaching, design sketching is regarded as a means to promote 'free' exploration of as many raw ideas as possible [75].

Owing to the above mentioned features, often designers have adopted sketching as an invaluable part of the design process since it is possible to include sketches of solutions, layout drawings, names of materials, and illustrations [77, 78]. Hwang and Ullman [79] commented that 67% of the marks made on paper during conceptual design were sketches. Furthermore, McGown et al [80] in a series of experiments showed that the sketching activity has peaks and troughs in the design process. The highest peak being near the beginning of the design process, the conceptual design. During this stage of the design process, sketching is considered to be a key activity for designers from various fields [71], which is illustrated in Figure 2-2.

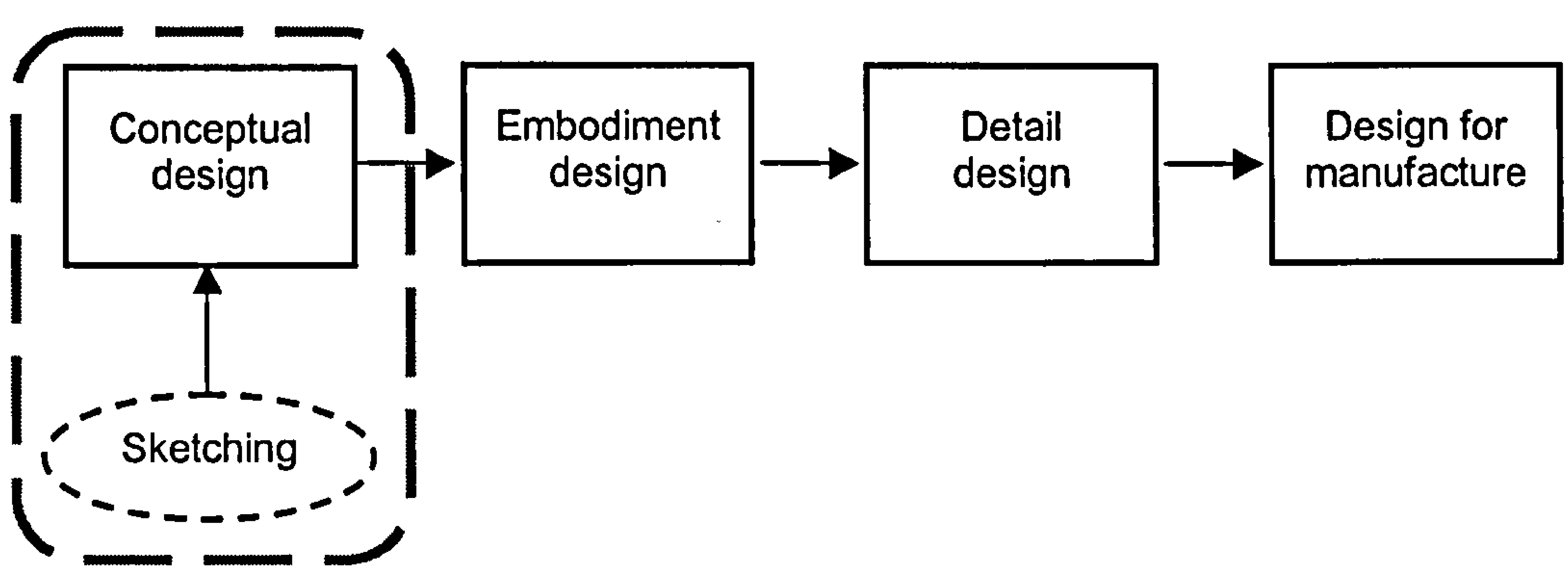


Figure 2-2: Sketching support in the design process [56]

Need of computer aid to support sketching

The aim of this section is to describe the need of computer aid for sketching in conceptual design. Although many CAD programs are available, most conceptual and creative work is still done using traditional media such as paper and pencil [81]. Pencil on paper is more flexible and easy to use compared to conventional CAD programs. Paper-based sketches allow a designer to capture the design at the moment of its conception and design details before they are forgotten. A designer does not require special expertise to draw a sketch on paper and ideas can be quickly explored from different angles. Designers prefer to use paper and pencil because it allows imprecision, supports ambiguity and incremental formalisation of ideas and rapid exploration of alternatives [13, 82]. However, some of the limitations of paper-based sketches include[83, 84]:

- Cannot re-use an original sketch in other concepts: This implies that the designer should produce another sketch to express a new or extended concept.

- Deletion: They do not allow for deleting elements from a compound object easily and need to start afresh if any changes are to be done.
- Difficult to store, organise, search and reuse when on paper.
- Modification: They are hard to modify as the design evolves. The designer must redraw the common features that the design retains.
- Translation: Some of the elements used in paper-based sketches are difficult to translate to a computer. In the process of translation, some of the inherent information in the sketches is lost.
- Version history: The paper-based sketches may be annotated by a designer but cannot be easily searched in the future to find out why and how a particular design decision was made.

The above limitations of paper-based sketches underpin the usage of computer supported tools that are capable of interpreting design sketches and supporting evolution of ideas right from the conceptual design stage. With computer aid for sketching, it is possible to use sketches as starting point for the computer-aided detailed design. Beyond tools for making and editing sketches, the computing environments for conceptual design support some interesting activities, such as generate alternatives based on the sketched figures and provide simulations, critiques and annotations. The following section presents the review of computer-based systems that support the sketching activity during conceptual design.

2.2 Scope of the review

Many researchers have tried to solve the problems associated with sketching during conceptual design that can be found in many design support systems. Since Sutherland's Sketchpad [51], which was the first computer based drawing system, numerous systems were developed. Several researchers reviewed relevant research on computational tools that aim to support sketching [56, 81, 85]. They generally use the word 'sketch' to advocate the idea of drawing with a pen or having an easy to use interface. Interesting ideas such as using constraints in a drawing environment, sketch interpretation and virtual reality technology have been explored in these systems building effort. Based on existing reviews, these efforts have been classified into three areas, ***geometric modelling***, ***virtual reality*** and ***collaborative support*** based systems. This review discusses and assesses some systems within these three areas, illustrating their features and functions. Table 2-1 indicates the review areas, sub-areas, general features, functions and representative works of the systems in these areas.

Table 2-1: Review areas, sub-areas, features, functions and representative works

Review area	Sub-area	Features	Functions	Representative works
Geometric modelling	Precise input and output	The drawings are presented as clean and rectified objects.	Online Sketch recognition Gestural recognition Editing	Sketchpad [51], Sketchpad III [50], SKETCH [82], SketchIT [86].
	Sketchy input and precise output	Supports sketchy, rough drawings as input and convert them into precise objects.	2D/3D sketching Sketch recognition Automatic line tidy Editing Online/Offline Sketch recognition Rapid prototyping Generation of virtual 3D worlds	HUNCH [70], Kato et al [47], Spur and Jansen [87], ARCREC [88], Sketch-Solid [33], Easel [46, 89] Grimstead and Martin [34], Lipson [90], Fluid Sketches [91], Lamb and Bandopadhay's system [35], Viking [92], IDes [93], Grimstead and Martin et al [34] Varley et al [94-96], Akeo's system [97], Quick-Sketch [36], Digital Clay [98], PENCIL [99], FFDS [100], Electronic Cocktail Napkin [44], Sketch-N-Make [101, 102], Marti et al [48], X-Sketch [49], Sketch-VRML [103], VR Sketchpad [104], Harold [105].
	Sketchy input and output	Supports sketchy input and sketchy output, where output refers to the ability to capture vague information, maintain sketchy presentations and generate alternative representations.	2D/3D sketching Online/Offline Sketch recognition Automatic line tidy Image processing Vague modelling Rendering	GEMCON [37], ISOSKETCHER [13], IMAGI [38], PerSketch [106], Transculent patches [107], SILK [84, 108, 109], Right-Tool-Right-Time system [81], SKETCH [82], Teddv [110], Moderato [111], Sketch VRML [103], Harold [105], Alex [39].
Virtual Reality	Immersive/ Non-immersive	Supports design activity in the virtual environments.	3D sketching 3D environment Spatial walkthrough Creation and manipulation Rendering	HoloSketch [112, 113], VRAD [114], DDDOOLZ [115-117], COVIRDS [118], 3DIVS [119], Zheng et al [120], Fiorento et al [121], Franz et al [122], Diehl et al [123].
Collaborative support	Synchronous/ Asynchronous	Supports the concurrent and co-operative interaction of several designers working together on a design project, possibly across several physical locations.	2D/3D sketching 3D environment Annotation Group discussion Manipulation, editing and viewing Sketch recognition Spatial walkthrough Automatic surface creation	Videoborard [124], Clearboard [125, 126], Liveboard [127], Shared 3D Viewer; Laviola et al; AGENTCAD; NetDraw [40, 128-130], Immersive Redliner; SketchBox [131-135], Vitual design studio[136, 137], CALVIN [138], NetSketch [40], Fan et al [42], Stork el at [41], SketchAR [139], mX-SKetch [43].

2.2.1 Geometric modelling

This group of 'sketch' based systems refers to the work that focuses on creation (primarily using sketch recognition) and presentation of the objects that are determined during conceptual design. The ***geometric modelling*** based systems can be classified into the following three sub-areas, according to the type of input and output:

(a) Systems that support precise input and output.

(b) Systems that support sketchy input and precise output.

(c) Systems that support sketchy input and output.

(a) *Systems that support precise input and output*

In this group, the drawings are presented as clean and rectified objects [81]. That is, no sketchy lines, either as input or output, are involved. The typical examples belonging to this category are Sketchpad [51], Sketchpad III [50], SKETCH [82] and SketchIT [86]. With Sketchpad and Sketchpad III, designers draw using a light pen to digitise primitive objects such as points, lines and circular arcs in two-dimensions (2D) and three-dimensions (3D) respectively; with SKETCH, designers input a 3D model by drawing three straight line gestures; and with SketchIT, designers select objects from a tool palette and place them in a mechanical drawing.

This type of input is more advantageous to a software developer than to a designer. This is because, by requiring the designer to provide formal/structured input the software developer avoids the problems of accommodating imprecision, vagueness and uncertainty. However, the limitations include: freehand sketchy input remains largely unexploited as a means of interacting with the CAD system and the systems do not accommodate the inherent nature of design concepts in conceptual design, such as imprecision, vagueness and uncertainty.

(b) *Systems that support sketchy input and precise output*

This group of systems recognise sketchy, rough drawings and convert them into precise objects. Taggart's system HUNCH [70] was one of the early attempts at using information from a sketch to transform it into a precise design. For example, HUNCH converts sketchy lines into intended straight lines and sketchy curves into pointed corners. Various other systems, thereafter, have been proposed to solve the problem of sketch recognition.

The system developed by Kato et al [47] recognises and tidies 2D primitives such as lines, circles, flow-chart symbols and some Chinese characters. Spur and Jansen [87] presented a system for automatic recognition of hand drawn contours. ARCREC [88] recognises freehand sketches and tidies linear segments, circular arcs, and corners. Sketch-Solid [33] turns sketchy lines on an isometric grid into 3D objects. Easel [46, 89] describes the rough sketch in terms of its basic primitives and replaces it with its exact geometric version. Grimstead and Martin [34] described a method of constructing boundary representation (B-rep) solid model from a single hidden line removed sketch view of a 3D object. Lipson [90] described a freehand interactive sketcher where the raw sketch is analysed and the basic geometric entities (lines, elliptic arcs and corners) are classified and smoothed. Fluid Sketches [91] tightly couples sketch recognition and morphing to ideal geometric shapes to create a continuous and immediate form of feedback. Lamb and Bandopadhay's system [35] interpret a 3D object from a rough 2D sketch by sequential reconstruction of adjacent faces. Viking [92] is a system for designing precise dimensioned solid objects using interactive sketch interpretation. IDes [93] allow the creation of 3D models. Grimstead and Martin [34] described a method for constructing B-rep solid model from a single hidden-line removed sketch view of a 3D object. A similar system for constructing B-rep models from 2D sketch of a single homogeneous polyhedral object was described by Varley et al [94-96]. Akeo's system [97] uses cross-section lines of an idea sketch of an object to reproduce automatically a 3D wire frame model of the object. Quick-Sketch [36] converts a 2D or 3D sketching of an object into a solid model. Digital Clay [98] derives 3D digital models from 2D freehand sketches using Hoffmann-Clowes labelling scheme. PENCIL [99] creates 3D objects such as hexahedron, sphere, cone, extrusion, swept body, revolved body, lofted body and their assemblies by recognising sketch outlines as formal rigid shapes first.

FFDS (Fuzzy Freehand Drawing System) [100] interprets the vague, imprecise and uncertain information resulting from sketched input and generates the smooth and precise geometric primitives that the user intended to draw using fuzzy logic. Qin et al [140] described a fuzzy logic based system for interpretation of 3D geometry from sketched input and interactive input. With Electronic Cocktail Napkin [44] designers draw using a pen with varying degrees of precision, ambiguity and abstraction. It involves a recogniser for freehand sketches and an end-user programmable visual language parser for configurations. It uses an internal representation for uncertainty and ambiguity as well as a means to resolve ambiguity and uncertainty from contextual information [85, 141]. By providing facilities for recognition, the Electronic Cocktail Napkin enables designers to gradually move from unstructured sketches towards more formal and structured CAD representations.

Moreover, some research works [101, 102] aimed at allowing paper based freehand sketches generated during the early, conceptual design stage to be transformed into 3D physical prototypes. Some of the research works concentrated on interpreting freehand scanned sketches and extracting 3D shape models (e.g. [48, 49]). Whereas, some other works aimed at generating virtual 3D worlds using the user's 2D sketch. Interacting with 3D worlds by sketching is an emerging area of research [85]. Typical examples of such works are Sketch-VRML [103], VR Sketchpad [104] and Harold [105].

It can be seen that the reviewed systems in this group convert sketchy lines to 2D straight lines and geometric objects, 3D forms, solid models, physical prototypes, or to virtual 3D worlds. These models in turn can be used as front ends to sophisticated modelling, rendering or animation environments, with these systems serving as a hand-sketching tool in the preliminary design phase [36].

The following includes the limitations of this group of systems. Most of these systems in an attempt to interpret the sketchy, rough drawing input, remove its inherent vagueness. That is, the sketchy input is converted into formal and structured CAD representations by making the inherent approximate information and relationships exact. This may lead to loss of considerable information in original concepts and the actual design intent. The emphasis has been on precise modelling of the objects than approximate modelling. In spite of some systems (e.g. FFDS, Electronic Cocktail Napkin) trying to interpret and maintain the vague, imprecise and uncertain information in the sketched input, the resulting presentation is, often, in the form of one formal and structured CAD representation. Formal/structured presentations do not help designers with their reasoning [81]. The designers' interpretation of the presented object could change based on the different design purposes, yet most systems in this group present one standardised description for an object. The computer system should be able to recognise the vague, imprecise and uncertain information in a sketch and present a computational representation that carries not just one class heritance but multiple classes for different purposes [81, 142]. This is because the vague, imprecise and uncertain information in a sketch could convey different meanings.

(c) ***Systems that support sketchy input and output***

This group refers to the work that recognises sketchy input and output. Within the scope of this review, sketchy output refers to the ability to capture vague information, generate alternative representations and maintain sketchy presentations.

GEMCON [37] supports the representation of a vague geometric configuration by refining the vague intentions of a designer, and produces spatial relationships. However, it requires precise, concrete and complete specification of the defining elements of a geometric model. On the other hand, ISOSKETCHER [13] offers designers an environment supporting a minimum commitment method, in which the designer is not compelled to make any commitment as to size, location or spatial relationships until desired. IMAGI [38] creates a vague geometric model and various alternatives associated with the vague shape information from the freehand sketches. PerSketch [106] presents an image processing approach to support extracting visual images from freehand sketches as they would be perceived by people. It creates multiple readings of possible shapes (as perceived by people) and allows the user to select portions of a freehand drawing. Alex [39] presented a new approach to transform existing 2D sketches directly into a new kind of sketch-like 3D model and a novel sketching technique that removes the distinction between 2D and 3D altogether. In that, a sparse set of 2D sketches provide a novel visualisation of 3D form, with enough information present to suggest 3D shape, but enough missing that the designer can 'read into' the form, seeing multiple possibilities. This unspecified information enables to think of new ideas.

Transculent patches [107] maintains handwriting and sketchy objects and supports moving irregular sketched shapes. SILK (Sketching Interfaces Like Krazy) [84, 108, 109] interprets freehand sketches as interface objects and allows the user to interact with the objects. SILK preserves the important properties of pencil and paper: a rough drawing can be produced quickly and the medium is flexible. The Right-Tool-Right-Time system [81] supports the recognition of sketched input, maintains the sketchy presentation and allows manipulation of freehand sketches by allowing designers to name drawing symbols according to their personal drawing style and preference.

SKETCH [82], though discussed under the first group of systems, supports some of the features that come under this group. Following the input of a 3D model by gestures, the user approximates the complex shapes with aggregates of simpler primitives. SKETCH renders these approximate models with non-photorealistic rendering techniques to give a sketchy presentation and enable designers to focus on the essence of the problem rather than on unimportant details. Similar to SKETCH, Teddy [110] is designed for construction of approximate models using pen-and-ink rendering. Moderato [111] allows designers to sketch digital lines and polygons in 3D space. The lines are rendered in a number of ways to mimic, for example, pencil lines or airbrush lines, to make evocative marks in a sketch. Similarly the 3D virtual worlds that are created using the user's 2D sketch (e.g. Sketch VRML [103], Harold [105]) are rendered so that they maintain a hand-drawn appearance as the user navigates through it.

2.2.2 Virtual reality

This group of systems refer to the work that focuses on creation of the objects that are determined during conceptual design using virtual reality technology with sketching as the primary tool.

This technology is inherently spatial by nature and it enables interactive manipulation of the design. Sutherland [143] demonstrated the basic idea of virtual reality as a prototype head-mounted stereo display. By 1990 several research and development groups were actively working on developing this technology [144]. Virtual reality can be immersive or non-immersive, based on the level of immersion required. Immersive virtual reality [145] implies when the user's field of view is completely surrounded by a computer generated, 3D environment. To create the psychological illusion of being immersed in a computer generated environment, rather than viewing outside through a screen, usually immersive display and tracking equipment is employed. Examples of such equipment are head mounted display (HMD), head trackers or by using a large screen system such as video projector, data gloves and data suits [146]. Non-immersive virtual reality (Desktop virtual reality) [147] usually refers to the use of a conventional computer monitor, as the output device onto which the 3D environment is rendered. The designers view and interact with entities in a 3D environment using stereo-display monitor, stereo glasses, 2D mouse, although 3D devices such as data gloves or 3D trackers can be used. Additional features such as audio, haptic and sensory interfaces further enhance immersive or non-immersive systems [147].

HoloSketch [112, 113] enables quick 3D sketching using head tracked stereo shutter glasses, 6D hand input device and desktop CRT (cathode ray tube) display configuration. The virtual objects are created with high accuracy and more rapidly than traditional 3D drawing systems. Once created the presentations could be viewed with stereo HMD, stereo LCD (liquid crystal display) projection display and non-stereo CRT displays thus giving added flexibility. VRAD (Virtual Reality Aided Design) [114] system enables 3D architectural sketching using virtual reality techniques. The system uses voxel[8] models that allow sufficient fuzziness in the conception phase and are accurate enough to proide information for rendering on a VR output device, which lacks in CSG (constructive solid geometry) models. DDDOOLZ [115-117] is similar to VRAD. It is a 3D voxel sketch tool aimed to explore the use of virtual reality technology, to offer a sketch like environment in virtual reality, in early stage design. COVIRDS (COnceptual VIRtual Design System) [118] creates concept shape design using bimodal voice and hand-tracking based user interface. The methodology adopted was to stimulate the way in which designers use a combination of voice commands and hand position to indicate the shape and size of the parts. In this way the system enables the creation of 3D models on computer by using natural interaction mechanisms. 3DIVS (3-Dimensioonal Immersive Virtual Sketching) [119] enables the creation and manipulation of 3D models in a semi-immersive design space using shutter glasses with integrated head tracking for stereoscopic viewing and gloves with a stylus device for interaction. Zheng et al [120] used CyberGlove as an input device to use gestures to conduct various geometric shape operations instead of depending on keyboard and 2D mouse. Systems described by Fiorento et al [121] and Franz et al [122] employ virtual reality techniques to obtain 3D virtual line-based models from the virtual sketching strokes. Diehl et al [123] developed two systems, Phantom based 3D-sketching system and Gesture based 3D sketching systems, for generating exact CAD product models from 3D raw sketches using virtual reality techniques.

2.2.3 Collaborative support

Unlike the ***geometric modelling*** and ***virtual reality*** based systems that support only the creation of models, this group of systems focuses on collaborative sketch based support. This technology facilitates the concurrent and co-operative interaction of several designers working together on a design project, possibly across several physical locations. In essence, the focus is on the use of sketching for conceptual design by distributed design teams [42].

Designers generally group together to engage in the goal-oriented activity of designing an artefact. They work co-operatively to perform tasks requiring more than one person. Inherent in such co-operative work is the communication and co-operation between

[8] Voxel (VOlume piXEL) is the smallest distinguishable box-shaped part of a three-dimensional image [148].

designers in geographically distributed environments. Communication modes such as telephone, express mail or fax are used to communicate with colleagues around the world. Electronic media such as email and file transfer are used to send drawing files or spreadsheets to the collaborators at different locations. However, such communication modes create management problems. The time difference between remote locations and version control mechanisms for shared work raise problems. It is therefore desirable to have a co-operative CAD environment or a virtual space for all parties involved within the design to visit, review and make changes at their convenience. This need gave rise to the idea behind the currently developing computer supported cooperative work (CSCW). CSCW is the use of computers to support and enhance work activities of groups [42, 149, 150]. It allows geographically distributed users to interact either synchronously or asynchronously or in both ways with a design database.

Initial work in this area includes Videoborard [124], Clearboard [125, 126] and Liveboard [127] that allows remote participants to draw on a shared 2D drawing space for collaborative design. On the other hand, some systems (e.g. [40, 128-130]) support collaborative discussion of 3D models. They provide tools for shared camera views, manipulating, viewing 3D models, annotating, textual interaction, to point at and refer to a drawing in a shared virtual space to allow participants to discuss details of the product. Some research work [131-135] aims at 3D collaborative annotation systems based on sketching. These systems enable the participants in a design process to view a 3D model and annotate it with text comments (post-it notes) or by drawing directly on the 3D model. The collection of annotations can be reviewed by anyone browsing the 3D model and provide alternative designs for comment. Usually sketch recognisers are incorporated to interpret the pen marks made on model surfaces. Maher et al [136, 137] have developed and experimented with designers using computer mediated collaborative environments, which they refer to as a virtual design studio. Virtual design studio is an emerging area of research. The major feature of virtual design studio is the development of the design within the collaborative, multi-user environment. Virtual design studio can range from a simple email for project communication to a collaborative virtual environment. CALVIN [138] is a networked collaborative environment for designing indoor architectural spaces and requires the use of virtual reality equipment, as also remarked in [42]. However the aforementioned systems do not support 3D modelling or the creation of models.

NetSketch [40] supports collaborative conceptual 3D modelling by proving tools for creating, manipulating and viewing 3D models in a shared virtual space. The works of Fan et al [42] and Stork el at [41] developed a sketched based interface for collaborative conceptual design that combines sketch elements, direct manipulation of 3D objects and non-photorealistic rendering to result in a 2D sketch-to-3D modelling system. As stated by Diehl et al [123], SketchAR [139] is a collaborative immersive modelling system that supports 3D modelling not only in virtual reality but also in augmented reality. It uses input and output devices such as tracked pen together with a tablet, HMD, head trackers and as well as lookthrough glasses. Additionally, SketchAR supports collaborative scenarios where multiple users model different parts of a virtual model and also supports annotations to document the changes in certain areas of a model and make them visible for participants in a design review session. Farrugia et al [43] aimed at paper-based collaborative design by developing a portable, sketch-based 3D modelling tool (mX-SKetch) allowing designers to rapidly obtain and share 3D CAD models on cameraphones directly from paper-based sketches. In essence, their system enables users to remotely obtain visual representations of 3D geometric models from freehand sketches by combining the portability of paper with that of cameraphones [151].

Table 2-2: Summary of sketch support systems

Main area	Geometric modelling			Virtual reality	Collaborative support
Sub-area	Precise input and output	Sketchy input and precise output	Sketchy input and output	Immersive/ Non-immersive	Synchronous/ Asynchronous
Strengths	Clean and rectified objects. No ambiguity in interpretation.	Support freehand sketchy input. Interpret sketchy drawings and transform into structured design. Convert sketchy lines to 2D straight lines and geometric objects, 3D forms, solid models, physical prototypes, or to virtual 3D worlds. Interprets the vague, imprecise and uncertain information resulting from sketched input. Replaces with exact geometric version or formal and structured CAD representations.	Support freehand sketchy input. Support the recognition of sketched input. Capture vague information, maintain sketchy presentations and generate alternative representations. Use rendering for presentation of information.	Design activity occurs in the virtual environments. More intuitive 3D interface than traditional CAD systems. Enable interactive manipulation of the design. Organise design information spatially. Overcome the drawbacks of current CAD systems that require the designer to specify shape and dimensions to create CAD models at the concept development stage.	Communication of designers in a geographically distributed environment. Support annotation.
	These models in turn can be used as front ends to sophisticated modelling, rendering or animation or virtual reality environments.				
Weaknesses	Does not support freehand sketchy input. Does not accommodate imprecision, vagueness and uncertainty.	To interpret the sketchy input, the inherent vagueness is refined. Loss of considerable information in original concepts and the actual design intent. Does not keep original sketch after refinement. Systems in this group offer one standardised description for an object. The resulting presentation is in the form of one formal and structured CAD representation.	Emphases more on sketch recognition than on presentation. Very few systems handle vague spatial relationships and vague shape types. Few systems that support freehand sketchy input and output. Very few systems used rendering techniques for presentation of information.	Realistic immersive images of design fail to take advantage of vague information involved in the conceptual design stage.	Very few support creation of models.

2.2.4 Summary

The strengths and weaknesses of the reviewed areas are summarised in Table 2-2. ***Geometric modelling*** based systems create CAD models using formal or sketchy input in conceptual design. ***Virtual reality*** based systems overcome the drawbacks of current CAD systems that require the designer to specify shape and dimensions to create CAD models at the concept development stage. Such systems use a variety of input devices (such as gloves, HMD, 3D navigation devices and visual/haptic displays) to provide a 3D interface for design and interaction. Alternative input methods such as voice and gesture are also supported. ***Collaboration support*** based systems represent a departure from the usual perception of CAD applications as single user tools. In such systems, a new generation of applications address the needs of designers beyond the creation of models.

From the review of the three groups of ***geometric modelling*** based systems, it can be noted that there are few systems that support freehand sketchy input and output. The emphasis is more on sketch recognition than on the sketchy presentation of the information. This could be due to limitations in their modelling capabilities and, thereby, more emphasis on problem solving than on capturing design intent. Rendering is inadequate for sketchy presentations, instead the rendering capabilities have been explored for the presentation of immersive and non-immersive virtual environment. Seeing ***virtual reality*** based systems only in terms of creating realistic immersive images of designs fails to take advantage of the inherent vague information of the design sketches involved. Limiting ***collaboration support*** based systems to general-purpose videoconferencing and a shared white board ignore the cognitive human-computer activities involved in conceptual design.

In essence, the examination of the computer-based sketch systems has shown that the emphasis has been on the input. Output has focused on realistic rendering and none on the designers' perception of the rendered model to meet the cognitive needs of the designer. There has been a growing interest in improving all aspects of the interaction, such as input and output, between humans and computers. However, it is desirable that the computer takes into account the human aspects (i.e. the very nature of the humans such as their perception, recognition and understanding) to exploit new technologies and insights in service of better design applications [152]. The examination has highlighted the need for an improvement in the computer's ability to collaborate with the designer, which in turn forms the background to the human computer symbiosis[9] vision adopted in this thesis.

2.3 Human Computer Symbiosis (HCS)

Licklider [153] described a vision for Human Computer Interaction (HCI), which he called 'man computer symbiosis', that was later referred to as Human Computer Symbiosis (HCS). HCS is an expected development in co-operative interaction between humans and computers. Licklider's vision of HCS challenges how humans and computers should interact and communicate. The present certain styles of HCI are being accustomed to using windows, icons, menu and pointer (WIMP) metaphors, humans giving instructions and are responsible for all planning and initiation, and the computers responding to the explicit instructions by conveying status information. He predicted the development of computer software that would allow people to think in interaction with a computer in the same way as one would think with a colleague whose competence supplements one's thinking. He opined that computers should enable humans to co-operate in making decisions and controlling complex situations without dependence on predetermined situations. A true symbiotic interaction requires at least the following three elements [154]:

1. Division of Labour: A complementary and effective division of labour between humans and computers. Computers can do things effectively that are impossible for humans (such as memory storage, version history, data manipulations, computations, repetitive and routine works, analysis) and humans are capable of doing things that are impossible for computers (such as visual perception, interpretation, strategic thinking, ability to learn and make decisions). Thereby, a true symbiotic interaction should co-operate the strengths of humans and computers.
2. Representing the user: Users have a mental model of the design concepts/tasks. An explicit representation in the computer of the user's concepts, beliefs or intentions or emotions results in a true symbiotic interaction.
3. Non-verbal communication: Communication via natural means. For examples, gestures convey intentions, beliefs and desires.

[9] Symbiosis can be defined as a mutually beneficial relationship between different entities or people or groups [1]. In design and context of this research, symbiosis refers to representing the respective strengths of humans and computers within the creative conceptual design.

Similar to Licklider's vision, Mann and Coons [155] identified the possibility of using computers as 'partners in the creative process[10]' to facilitate the hypothesis exploration process and consequently produce an escalation of 'scientific creativity'[156]. They stated [155]:

> *'It is clear that what is needed if the computer is to be of greater use in the creative process, is a more intimate and continuous interchange between man and machine. This interchange must be of such a nature that all forms of thought that are congenial to man, whether verbal, symbolic, numerical, or even graphical are also understood by the machine and are acted upon by the machine in ways that are appropriate to man's purpose'.*

Closely following Mann and Coons' vision that considers the computer to be a designer's assistant, Duffy stated the following about the 'team effort' between humans and computers in computer aided design [157]:

> *'Computer Aided Design involves a combination of attributes of man and computer, and may be considered as a team effort between the two. These two contributors have their own special strengths that should be used to the full during the design process. Humans ability to create, make decisions, deduce, reason, judge- in essence features of their intelligence- are crucial components in the success of the design, so is the computers ability to carry out fast reliable processing, with large memory storage, investigate and explore for better solutions'.*

To achieve Lickliders' or Mann and Coons' vision requires a fundamental understanding of the respective creative process as well as being able to develop computer tools to attain HCS [156]. In essence, it is required to have a careful examination of the abilities of the human and the computer, followed by a fuller presentation of the roles to be played by the designer and the system [157]. Whitfield et al [156] listed the respective strengths of humans and computers within the decision-making process (see Table 2-3), which was originally cited by Cummings [158]. In the context of development of decision support systems, Cummings [158] opined that it is important to recognise the critical role that humans play in complex decision tasks and allocate decision-making functions between humans and computers accordingly.

[10] Creative process is the process of learning how to accomplish the desired result [155].

Table 2-3: Strengths of humans and computers in decision-making [156, 158]

Humans are better at:	Computers are better at:
Perceiving patterns	Responding quickly to control tasks
Improvising and using flexible procedures	Repetitive and routine works
Recalling relevant facts at appropriate time	Reasoning deductively
Reasoning inductively	Handling many complex tasks simultaneously
Exercising judgement	

2.3.1 The Intelligent Design Assistant (IDA) philosophy

A characterisation of Mann and Coons' design assistance philosophy is that of the Intelligent Design Assistant (IDA) [55]. Figure 2-3 illustrates some key complementary roles that a designer and an IDA are proposed to play within the scenario of intelligent CAD.

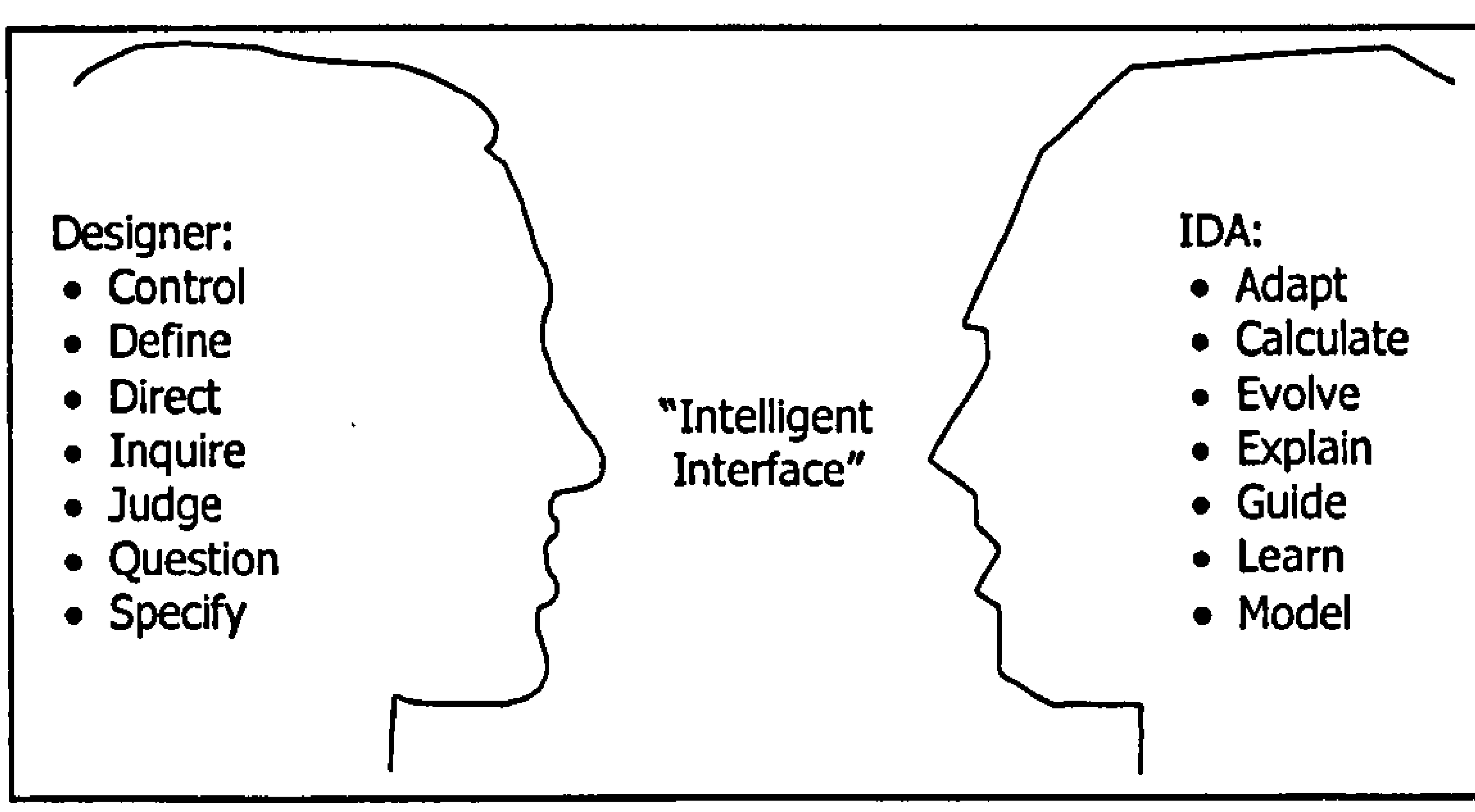


Figure 2-3: An intelligent design assistant (IDA) [157]

Whitfield et al [156] described the roles of a designer and IDA in the intelligent CAD scenario as follows:

> '*Designers are initiators of a discourse; they retain authority and control over the progress of the interaction with the IDA, and have the ultimate responsibility for the correctness of results. They are able to express the nature of the problem, to describe concepts to be explored, and to justify their judgements. In addition, they hypothesise, refer to past experience, and apply a range of modelling tools. In contrast, the IDA is the active partner to the designer. It is a source of design expertise and past experience that complements a designer's memory. It is able to develop an understanding of a problem and description of concepts, assess the feasibility of concepts, identify the implications of concept changes, suggest possible*

solution paths, and can assume much of the burden of mundane and repetitive analysis tasks'.

Various implementations of aspects of the IDA vision have been produced (e.g. [37, 56, 60, 159, 160]) that represent different combinations of interactions between the designer and the IDA. These implementations have in general had specific applications for the focus of interaction between the designer and the IDA [156]. In essence, the implementations demonstrate that the computer provided assistance within specific design problems.

In this thesis the design assistant philosophy is adopted whilst considering both Licklider and Mann and Coons' vision of how to leverage the potential of both designer and computer within this partnership. The ultimate objective of the research presented in this thesis is creating an interactive and intelligent partnership between a designer and computer for the creative activities involved in conceptual design. To achieve the adopted philosophy requires an understanding of the creative process in conceptual design as well as being able to develop computer tools to attain HCS. Although the development of computer tools fits within the scope of further research (see Section 11.4), firstly the creative process in conceptual design and the role of the designer and computer is delineated here. This in turn can serve as a foundation for the development of computer tools, to provide assistance within specific design problems during the creative activities in conceptual design, in future.

2.3.2 Conceptual design process

As a starting point of understanding the creative process, first the conceptualisation process in general is investigated and is followed by the specific activities of the designer and computer in conceptual design.

Conceptualisation process

The conceptualisation process can be considered as a loop formed by steps for creation/modification and evaluation of concepts [161]. Kuczogi et al [161] described the loop by the following three partial models in the case of computer supported conceptualisation (see Figure 2-4):

- mental model[11] of the concept: This is the internal representation of the designer's ideas, intentions, feelings, or emotions.
- computer model of the concept: The model generated in the computer.
- designer's view about the computer model: This is the mental model of the generated computer model.

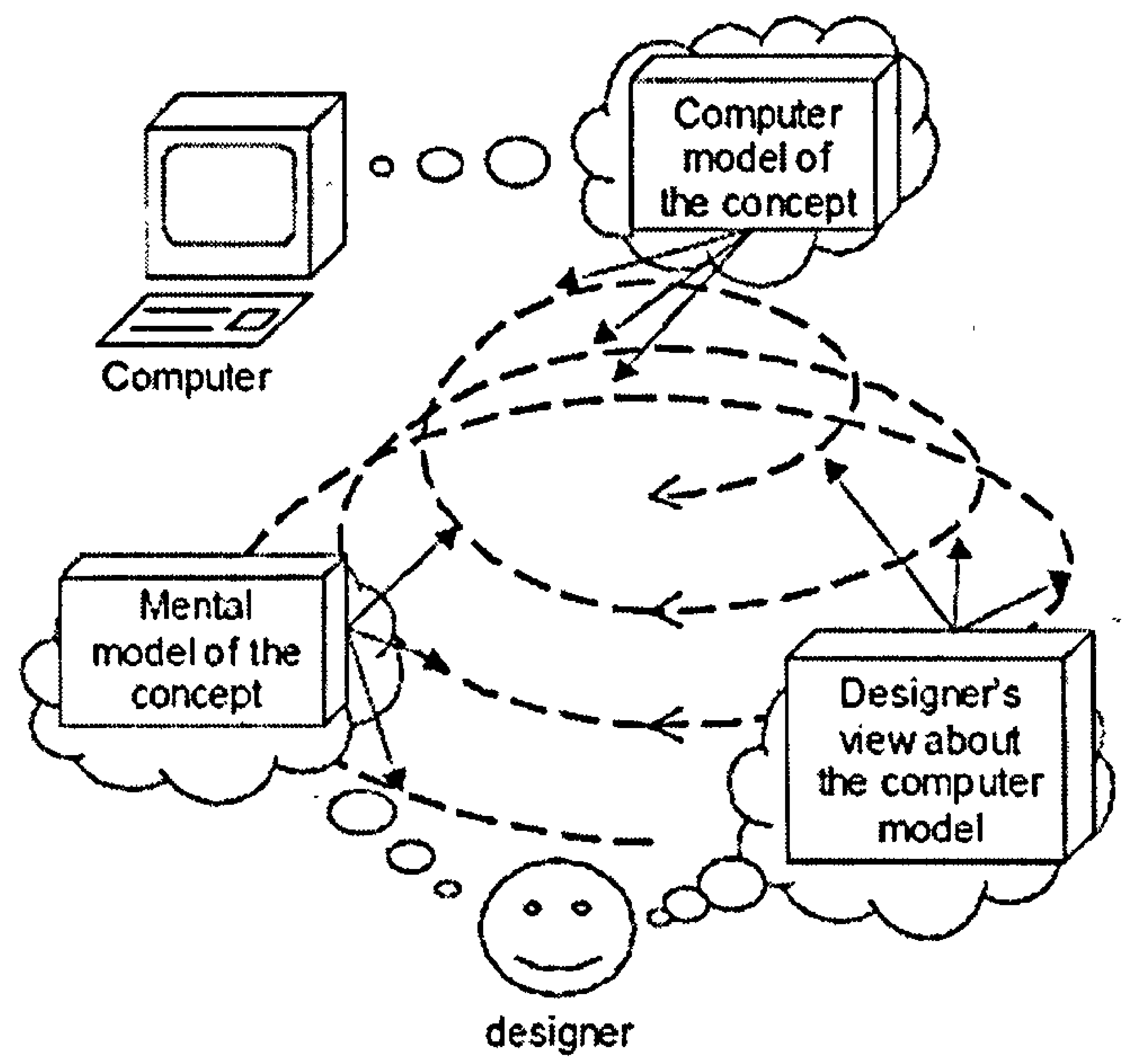


Figure 2-4: Evolution of models in conceptualisation process [161]

The evolution of concepts and models could be represented as a spiral. Where the diameter of the spiral shows how close the three models are to each other semantically [161]. During the conceptualisation process, each model usually changes, as the design evolves, and gets closer to the other. The process is considered to be finished when the computer model matches the design concept such that the designer is satisfied with it.

[11] Mental models: These are internal representations of the world's structure, used to accomplish cognitive tasks [162]. Mental models are deeply held internal images of how the world works. They represent a person's view of the world, including implicit and explicit understandings. They also provide the context to view and interpret new material. They represent more than a collection of ideas, memories or experiences. Mental models have powerful influence on what we do because they affect what we see because they help us to make sense of the world we see. From the above understanding, mental models, in the context of this thesis, are defined as internal representations of a designer's ideas, concepts or intentions, to achieve a cognitive task. Images are a distinct sort of mental representation. Johnson-Laird [163] opined a relation between images and mental models. Images correspond to views of models: as a result either of perception or imagination, they represent perceptible features of the corresponding real-world objects. Images represent objects [163]. That is the structural relations between the parts in an image correspond to the perceptible relations between the parts of the objects represented.

Activities in computer supported conceptual design process

During conceptual design, a designer's geometric design can gradually evolve from its original vague geometric concept, in the form of sketches, towards a more detailed design and eventually to the specification of the final artefact [13]. At the end of this process, these sketches are often transferred into or directly developed in existing CAD systems to define a model for refining, detailing, analysing, and passing to downstream processes. In this process, the computer supported conceptual design can be considered as a loop between the following activities of the designer and the computer (see Figure 2-5):

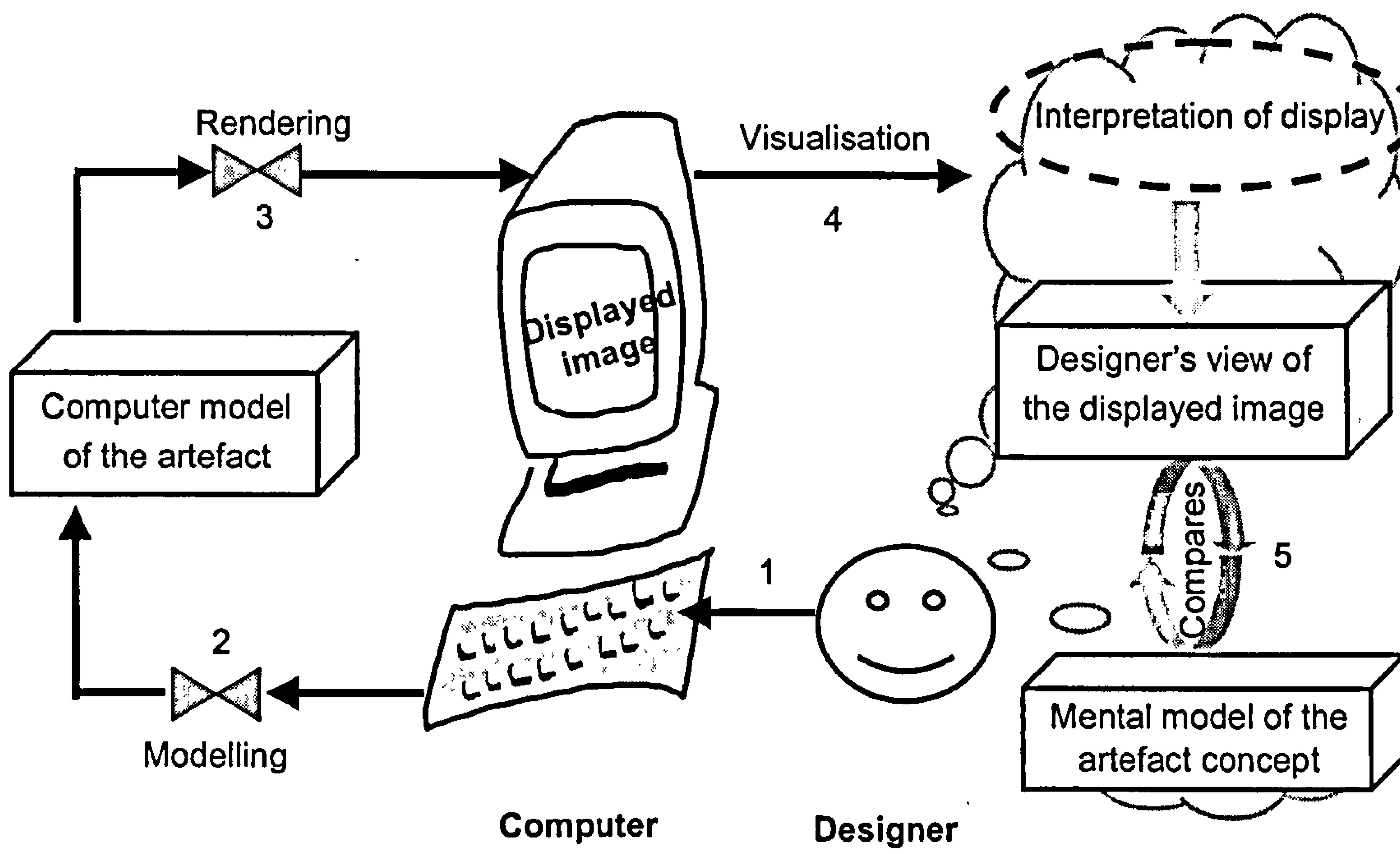


Figure 2-5: Human computer symbiosis in conceptual design

Step 1 *Communication* of the designer with the computer: The designer's mental model is used to initialise a computer model in a CAD system using input devices. Online methods such a pen and stylus (e.g. [45-47]) or a light pen on a screen (e.g. [50, 51]) or offline methods using scanned sketches (e.g. [48, 49]) or virtual reality devices (e.g. [112, 113]) are often used for sketch input.

Step 2 *Modelling*: The initial stage for generation of a computer model is usually *modelling*, which consists of production of an abstract description of the sketched concept in 2D or 3D. Figure 2-6, which shows an example of the modelling process, explains the typical stages of interpreting a sketched input to generate a computer model. For example, systems such as Sketch-Solid [33], Grimstead and Martin's system [34], Lamb and Bandopadhay's system [35], Quick-Sketch [36], Electronic Cocktail

Napkin [44] and PENCIL [99] amongst many others generate a model using the abstract description from the sketched input.

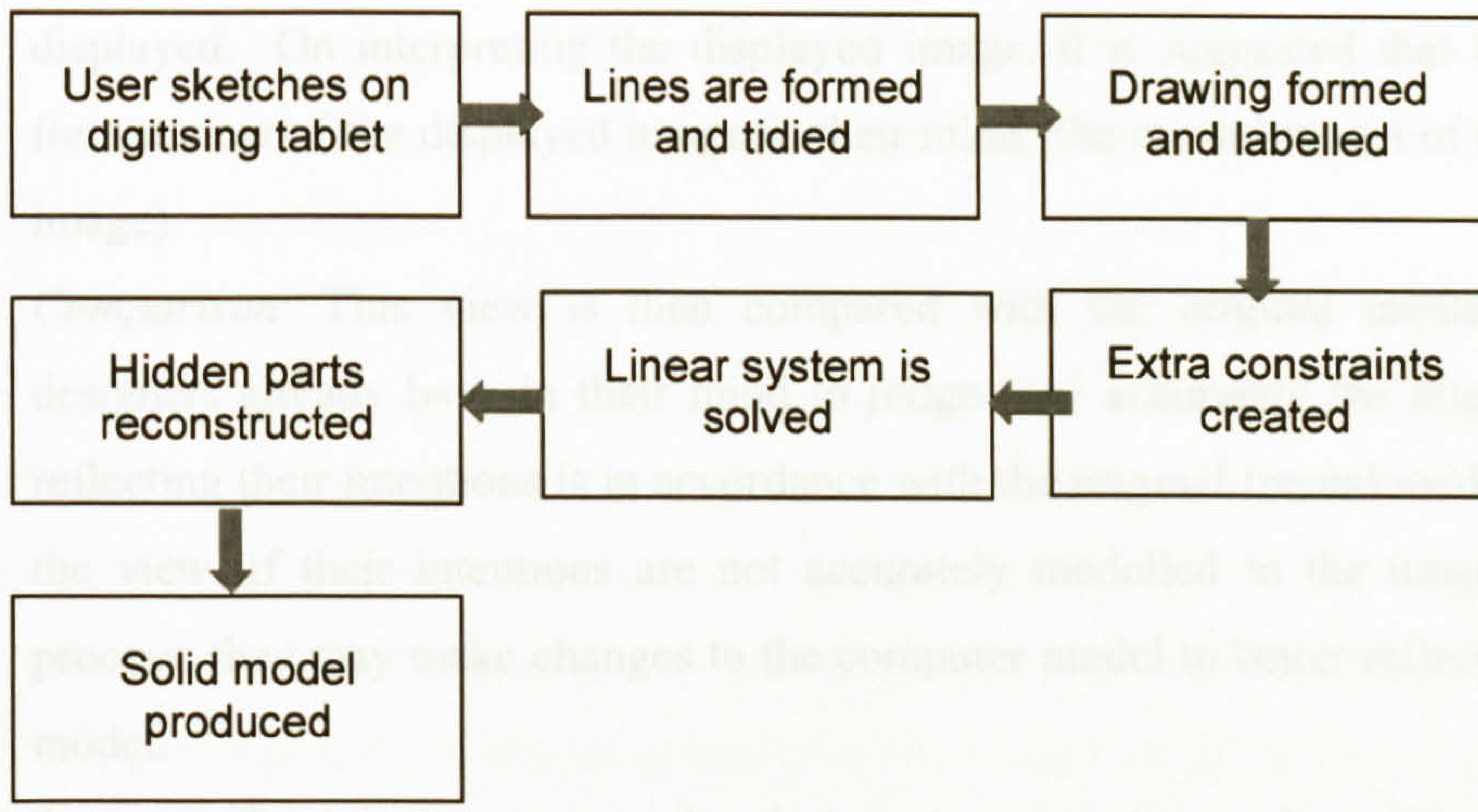
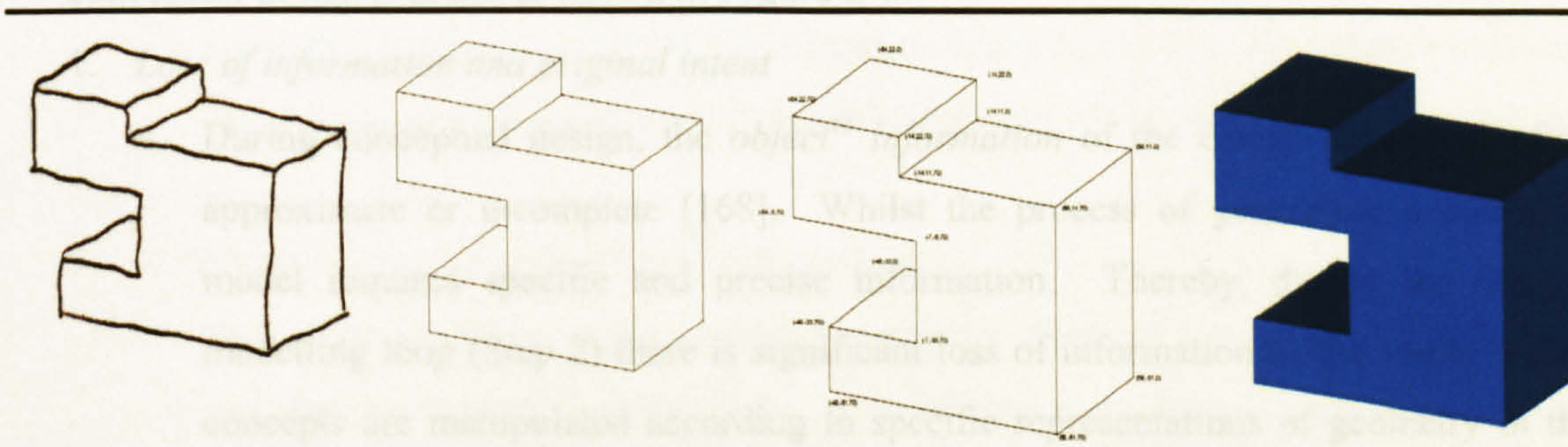


Figure 2-6: Example of a modelling process [34]

Step 3 *Rendering* uses the description produced by *modelling* (Step 2) for presenting visual information. In essence, rendering is the conversion of an object-based description obtained from *modelling* into a graphical image for display [164] (see Figure 2-7). It involves such things as shading, hidden lines and surface removal, textures, colour, light, animations and other realistic features. That is, the objects can be displayed in wireframe form, or lighting and surface-rendering techniques can be applied to shade visible surfaces of the modelled object [164] (e.g. SKETCH [82], Teddy [110] and Moderato [111]).



Designer sketches objects	Drawing is latched and tidied	Boundaries and vertices labelled, 3d coordinated assigned	Solid model displayed using rendering

Figure 2-7: Example of a computer model generated and rendered (from [85])

Step 4 *Visualisation*[12] *and interpretation* of the displayed image: The displayed image is visualised and interpreted by designers. This involves interactions of cognitive processes in the human mind to form an understanding of the visual information displayed. On interpreting the displayed image, it is suggested that the designers form a view of the displayed image in their mind (the mental model of the displayed image).

Step 5 *Comparison*: This view is then compared with the original mental model the designers already have in their mind to judge how accurately the displayed image reflecting their intentions is in accordance with the original mental model. Based on the view, if their intentions are not accurately modelled in the image generation process, they may make changes to the computer model to better reflect their mental model.

Step 6 *Iteration*: During this process the designer's original mental model of the design concept changes as the design progresses due to an evolving understanding during the process of creation/modification and evaluation of concepts [167]. Steps 1 to 5 are followed, until the designer is satisfied with the resulting generated image in the computer. In essence, as shown in Figure 2-4, the process is considered finished when the design displayed by the computer image matches the design concept such that the designer is satisfied with it.

2.3.3 Problems during HCS in conceptual design process

The following are contemplated to be some of the problems during the computer supported conceptual design process, as shown in Figure 2-5:

1. *Loss of information and original intent*
   - During conceptual design, the *object*[13] *information* of the design concept is often approximate or incomplete [168]. Whilst the process of generating a computer model requires specific and precise information. Thereby, during the design-modelling loop (Step 2) there is significant loss of information as the vague design concepts are manipulated according to specific representations of geometry in the computer. Thus, the refinement of the design concepts in conceptual design in a CAD system involves the loss of vague information and the original design intent [56].

[12] Visualisation is the act or process of interpreting in visual terms or of putting in visual form [165, 166].

[13] Object is the representation that concerns shape, size, location and orientation in an artefact.

- Realistic rendering (Step 3) requires a precise geometric model to convert into a graphical image for display. Thereby, the CAD systems require the vague design concepts to be defined into precise models whilst allowing rendering. This involves loss of information and design intent as such rendering conveys precision and a sense of exactness and do not reflect the true nature of the design concepts in conceptual design.
- During *visualisation and interpretation* (Step 4), there is loss of information and design intent, when there is a significant difference between a design displayed by the computer and the designer's mental model of the design concept.

2. *Mismatch between mental and computer models*
   - One of the obstacles to symbiotic interaction is the mismatch between designers and computers in their modes of operation. The mental model is often vague, abstract, and incomplete. Whereas, the representations of geometry in a CAD system is precise and specific. Hence, there is a mismatch between the designer's mental model of the design concept and the design displayed by the computer.
3. *Generation of inappropriate images*
   - When the images reflecting the designer's intentions are not in accordance with their mental model, or when the designer's intentions are not accurately modelled in the model generation process, result in generation of inappropriate images.
4. *Misinterpretation, non-convergent design steps and rejection of the computer tool*
   - When computer based systems are used to support creative design, there is significant difference between a design displayed by the computer, and the designer's mental model of the design concept. This difference hinders the computer supported design in conceptual design, and can lead to misinterpretations, non-convergent design steps and possible rejection of the potential of the computer tool.
5. *Insufficient support for the emotive information*
   - One of the problems in the symbiotic interaction between humans and computers is insufficient support for the emotive information in design concepts. Design concepts are characterised by both object information and emotive information. Such emotive information is difficult to express and is based on the emotions of the designer that could be characterised by the level of e.g. presence, excitement, comfort, recognition and detection. However, when the computer-based systems are used to support creative design, they primarily take into account modelling of object

information in a sketch, using sketch recognition approaches. Consequently, the designer's intentions are not accurately modelled in the model generation process.

2.4 Research focus

There have been important steps taken in computer supported design systems to make input more intuitive by providing, for example, sketching input (online/offline) to generate computer models and improving the capacity of modelling (Step 1 and Step 2 in Figure 2-5). Section 2.2 provides an extensive summary of this prior work. However, there has been no systematic study of the best way to present concept models so that the designers' perception of the design displayed by the computer matches their mental model of the design concept. As seen in Figure 2-5, rendering acts as a mediator between the computer world (data of the computer model) and the perception of the displayed computer graphics image (output as seen by the designer). Consequently, given the significant challenge and potential in this area, the focus of the research presented in this thesis (see Figure 2-8) was on *rendering* (Step 3) and *visualisation and interpretation* (Step 4), for symbiotic interaction between designers and computers.

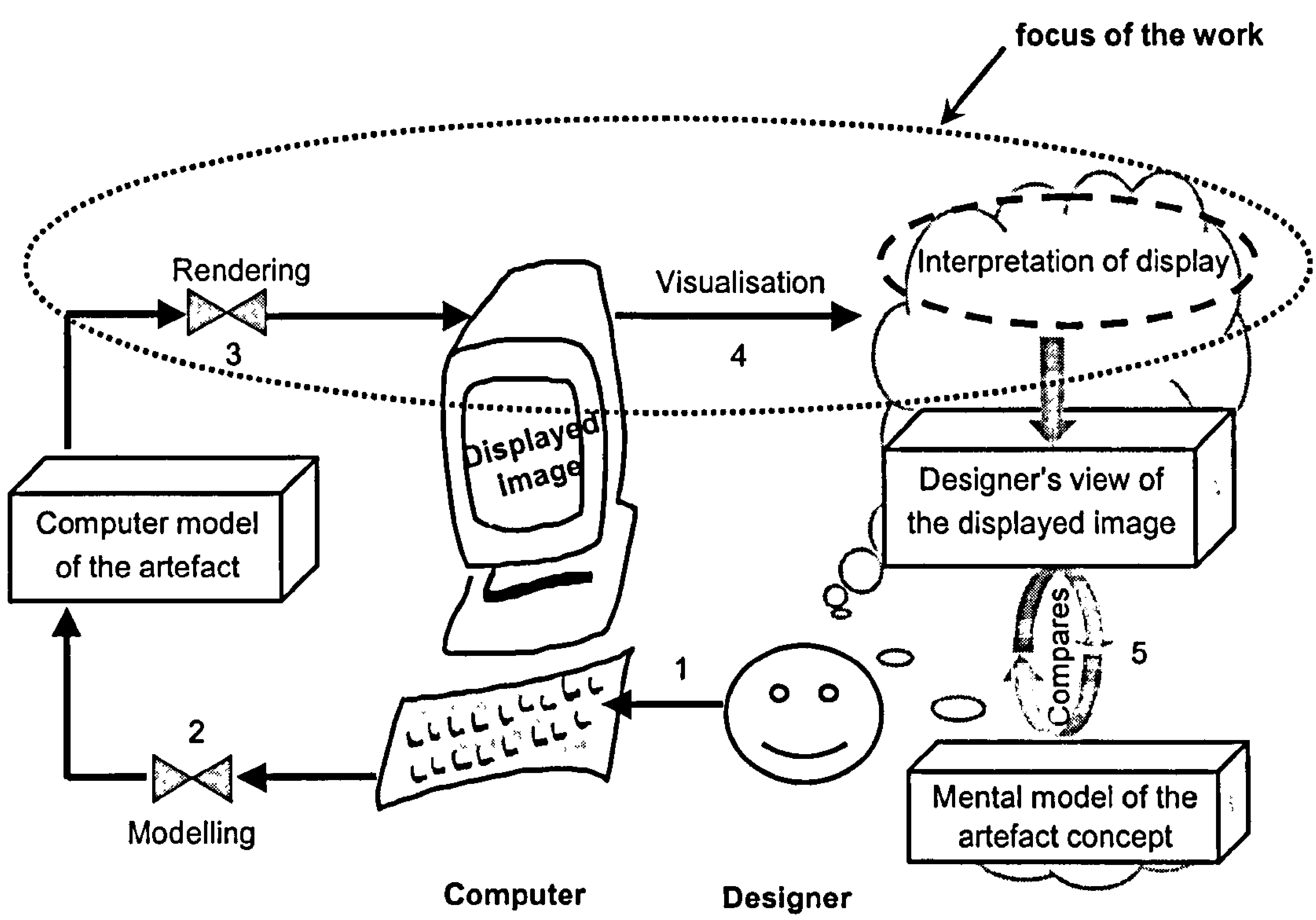


Figure 2-8: Research focus

2.5 Requirements to enhance HCS in conceptual design

In the preceding section, it was pointed out that the focus of the research presented in this thesis was on *rendering* (Step 3) and *visualisation and interpretation* (Step 4), for symbiotic interaction between designers and computers (see Figure 2-8). Therefore, in order to enhance HCS, by overcoming the problems during the conceptual design process (see Section 2.3.3), based on the principles of *rendering* and *visualisation and interpretation,* there is a requirement to:

(i) Facilitate computer generated presentations that are closer to the mental models of the design concepts to minimise the gap between the design displayed by the computer and the designer's mental model of the design concept. Thereby, minimising misinterpretations, possible criticism and avoidance of the computer tool.

(ii) Support the emotive information of the design concepts. This is because sometimes in conceptual design, a designer may express emotive information through the qualities of objects to stimulate emotive responses to the viewers.

(iii) Minimise the loss of information and original design intent, especially during refinement of vague information in a CAD system and during *visualisation and interpretation.* Thereby, minimising the gap between the design displayed by the computer and the designer's mental model of the design concept.

Based on the research focus, the following two aspects are addressed for developing symbiotic interaction between designers and computers:

1. *Sketch rendering*

   The existing systems that support sketching during conceptual design have been reviewed in Section 2.2. The strengths and weaknesses of each group with respect to sketching are summarised in Table 2-2. From the review it was deduced that there was less emphasis on the freehand computer generated sketching output. The main purpose of these systems was either on creating models, using sketch recognition and virtual reality technology, or on collaborative support. Furthermore, existing research on modelling has concentrated on refining vague information from a rough sketch, possibly because recognising and understanding a sketch is often regarded as a key difficulty in computer support for sketching. Rendering (Step 3 in Figure 2-8) provides graphical presentation of an image. It has been inadequate for sketchy presentations of the design. Psychologically, sketch-rendered designs maintain different affordances, wherein sketched images appear preliminary, unfinished, and therefore variable to both the designer and the client to communicate design ideas [169, 170].

2. *Cognitive Science*

   The essence of visualisation (Step 4 in Figure 2-8) is to utilise human cognitive skills in interpreting information and discovering new insights in the generated computer graphic images. To form an interpretation of the generated computer graphic images, it is necessary to re-appraise how information is represented and understand the cognitive principles. In this sense, cognitive science attempts to understand the capabilities and operation of the human mind in terms of its ability to process information [171]. Researchers in design have started to relate their work to a number of areas of research in cognitive psychology and cognitive science. There is a considerable amount of research in sketching activities in literature in cognitive psychology and cognitive science [172-174]. Purcell and Gero [9] provided an extensive summary of this prior work. They reviewed the role of sketching to three of these areas such as working memory, imagery interpretation and mental synthesis. Radcliffe et al [175] proposed a cognitive model in which the role of sketching in the design process has been illustrated. Similarly cognitive science can be related in the context of rendering to contribute to the visual interpretation of the images displayed. It can also be utilised to realise the potential of rendered images in influencing the perception of the designers. To achieve effective symbiotic interaction there is need for the computers to take into account the emotive information in the design concepts. Cognitive science can be considered to realise how emotions can be recognised and expressed through human computer interaction based on the principles of rendering.

2.6 Chapter summary

The chapter has presented a review of existing computer-based systems that support sketching activity in conceptual design. The sketch support systems were divided into three areas: ***geometric modelling***, ***virtual reality*** and ***collaborative support*** based systems. Examination of the literature on sketch support systems has highlighted the need for an improvement in the computer's ability to collaborate with the designer, which in turn formed the background to HCS vision adopted in this thesis. An overview of symbiotic interaction between humans and computers in conceptual design is presented in Section 2.3.2. This facilitated the understanding of the (i) cognitive human-computer activities in conceptual design (see Figure 2-5), which include: *communication* of the designer with the computer (using sketch input devices), *modelling*, *rendering*, *visualisation* and *interpretation* of the displayed image, *comparison* and *iteration*, and (ii) problems during HCS in conceptual design.

In Section 2.4, *rendering* (Step 3) and *visualisation and interpretation* (Step 4) were established as the research focus for the work presented in this thesis (see Figure 2-8). Thereby, Chapters 3 and 4 are organised according to Steps 3 and 4. That is, Chapter 3 presents a review of different *rendering* techniques for the generation of computer graphic images (Step 3) and Chapter 4 presents a cognitive framework of human information processing between the *visualisation* of a generated computer graphics image and its *interpretation* (Step 4). In addition, a set of requirements to enhance HCS was established in Section 2.5.

3. Sketch rendering

In Chapter 2, the focus of the research was stated and justified as being aimed at *rendering* and *visualisation and interpretation* (Step 3 and Step 4 in Figure 2-8).

While Chapter 4 addresses *visualisation and interpretation* of the generated computer graphics image (Step 4 in Figure 2-8), the focus of this chapter is to present a review of *rendering* techniques for the generation of computer graphic images in conceptual design (Step 3 in Figure 2-8). The objectives of the review are to (1) establish the key aspects for the generation of computer graphic images (discussed in Chapter 5), where the key aspects provide a basis for a critique of existing rendering systems in Chapter 5, (2) establish the basis of different characteristics and features of rendering for investigation (discussed in Chapter 6), and (3) establish the basis of different rendering techniques for evaluation (discussed in Chapter 8).

Before reviewing rendering techniques, it is appropriate to give a general introduction to rendering and the different kinds of realism conveyed. Thereby, rendering is outlined in Section 3.1 and the notion of 'soft-functional' realism of images is introduced in Section 3.2. In Section 3.3, the existing rendering techniques and their features are summarised. A new concept, 'Vague rendering', is introduced in Section 3.4. Finally, the chapter is summarised in Section 3.5.

3.1 Rendering and realism

In computer graphics, rendering refers to the process by which a virtual scene is converted into an image for viewing [176]. In this definition, a scene refers to a collection of models comprising everything that is included in the environment to be rendered (for instance, material descriptions, lighting); and an image refers to the visual representation of a scene [177]. It enables the visualisation of images that was not previously possible using traditional modelling techniques.

Hand drawn and computer renderings are different types of rendering in the design process. Many architects would argue that the traditional method of hand rendering gives the drawing a human touch, whereas the computer rendering tends to look somewhat artificial. However, with computer rendering the drawings can be changed, stored, duplicated and modified as the design evolves with relatively little effort and timely manner compared to hand drawn renderings. In addition, the designers can revert to the original image if not satisfied with the changes made.

Zwicker et al [178] surmised that the computer rendering process is divided into four steps, namely scene description, discretisation, representation and rendering. They classified rendering methods into two paradigms, namely geometry-based and image-based. Image-based modelling and rendering have received much attention as an alternative to traditional geometry-based rendering [179]. In this paradigm, instead of geometric primitives, a collection of sample images is used to render novel ideas. Table 3-1 presents the properties of geometry-based and image-based rendering by specifying a characteristic property corresponding to each of the four steps. Most of the rendering techniques make use of properties associated with either of the two paradigms. It has been noted that for either paradigm, conventional systems perform only the image synthesis stage in real time, which is indicated by the grey shading in the table. The discretisation, which transforms the initial scene description to the internal representation that will be fed into the rendering procedure, is usually done in a separate pre-processing step.

Table 3-1: Properties of rendering paradigms [178]

	Geometry-based	Image-based
Scene description	Description in terms of geometry, surface properties, lighting conditions.	Description in terms of the plenoptic functions.
Discretisation	Sampling (tessellation[14]) optimised with regard to geometric properties.	Sampling optimised with regard to screen resolution.
Representation	Set of primitives (polygons, light sources)	Set of n-dimensional samples
Image Synthesis	Conventional Rendering	Reconstruction

Depicting realism[15] has been the focus of research in the computer graphics community resulting in significant advances in modelling, rendering and display algorithms. The different methods of depiction provide different kinds of realism in which certain properties

[14] Tesselation: In geometry-based rendering, the term tesselation is commonly used, which means that the surfaces are discretised into triangular meshes [178].

[15] Realism is the quality or fact of representing a person, thing or situation accurately or in a way that is true to life [1].

of a scene are accurately represented and others are approximated, abstracted or omitted [177, 180]. Often the evaluation of computer graphic images is based on the realism in images, where selected properties of a scene are presented to the viewer with varying degrees of realism. In essence, the presented image can be realistic in some aspects and not in others. Different applications require different kinds of realism. Each kind of realism uses different criteria to determine if the image is realistic and thereby place different demands on the image generation process.

Hagen [180] focused on the geometric aspects of scenes in computer graphic images to depict realism. Chiu and Shirley [181] categorised two kinds of realism, namely: ***perceptual realism*** and ***visceral realism***. Similarly Ferwerda [177] categorised three varieties of realism, such as ***physical realism***, ***photorealism*** and ***functional realism***.

Perceptual realism: An image is perceptually realistic if a viewer of the image forms a mental image similar to that formed by the virtual viewer[16]. For example, parts of a scene too dark to be visible to the viewer should also be too dark in the image. The process of producing an exact match of the internal image involves: a physically accurate renderer to compute the light that would enter the eye of the virtual viewer and the display device would then send the exact light into the eyes of the viewer. Since both viewers receive the same light, they will perceive the same image. Applications such as safety engineering, architectural simulation, or set design require perceptual realism. Although modelling perceptual realism has not been achieved to the full extent, some perceptual models have been developed that produce weaker forms of perceptual realism [181-187]. This is because of the limitations with the present display devices to produce an exact match of the internal mental image. The display devices have a limited dynamic range, such as colour range, and do not provide full field-of-view.

Visceral realism: A viscerally realistic image creates a deep, intuitive sense in the viewer that the objects in the image actually exist, even if they are improbable. For visceral realism, complexity in forms such as material, geometry and texture is more important than physical accuracy. The images need to be rich in detail for the viewers to believe that what they are experiencing is real. These images are necessary for training simulators, entertainment industry or artistic applications. However, visceral realism is difficult to be achieved

[16] According to Chiu and Shirley [181] the term *viewer* refers to the real person viewing the displayed computer graphics image, and the term *virtual viewer* refers to the imaginary person from whose viewpoint the image was generated.

because of the limitations in its image generation. There are limitations with modelling issues such as adding complexity to the images.

Physical realism: A physically realistic image provides the same visual simulation as the scene. The process of generating such images involves: the modeller should contain descriptions of shapes, materials and illumination properties of the scene; the renderer should be able to simulate the spectral and intensive properties of the light energy from a viewer's viewpoint; and finally the display device should be able to reproduce the rendered light energies. The physically accurate images can be used in a wide range of design and engineering applications domains illumination engineering, material science and manufacturing [52, 177, 188]. Despite generating physically accurate images has been the most popular goal of computer graphics community, there are a number of limitations. Firstly, the existing display devices cannot reproduce the rendered light energies, secondly generation of physically realistic images is computationally expensive, and finally, physical realism is too rich in detail just for creating images for human observers.

Photorealism: A visually based definition for photorealism is that the image has to be photometrically realistic. Wherein, photometry is the measure of the eye's response to the light energy. Hence, a photorealistic image produces the same visual response as the scene. These images can be used in a wide range of design and engineering applications. However the disadvantage includes such realism leaves little flexibility for interpretation and to visualise different options. More details on photorealism can be found in Section 3.3.1.

Functional realism: The functional definition for realism is the fidelity of the information the image provides. Information means the knowledge about the meaningful properties and relations of objects in a scene, which allows making visual judgements and performing useful visual tasks. Hence, a functionally realistic image provides the same visual information as the scene. Application of these images is in entertainment or computer game industry and also in flight simulators. Functional realism admits a wide range of rendering styles from physically based simulations through photorealism, to abstract approaches such as non-photorealistic rendering [189-191]. It has been observed that potentially many different rendering styles produce images that provide functional realism than physical realism or photorealism to human observers [177, 180].

Summary

A summary of the different kinds of realism, their features, limitations and applications is presented in Table 3-2, in chronological order. The grey area in the table indicates the notion of 'soft-functional' realism introduced in this thesis to the list of realisms already existing. It is used to indicate that the work described in the thesis is on 'soft-functional' realism, which refers to the emotions and feelings of the designer, in computer graphic images.

Table 3-2: Different kinds of realism in computer graphic images

Realism	Features	Limitations	Applications
Perceptual	Viewer of the image forms a mental image similar to that formed by the virtual viewer. Physical accuracy of light.	With displays devices: - To produce exact match of the internal mental image. - To provide dynamic range, such as colour range. - To provide full field-of-view.	Safety engineering Architectural simulation
Visceral	Creates an intuitive sense in the viewer that the image actually exists. Accuracy of material, geometry and form.	- With modelling issues such as adding complexity to images. - Introduces unintentional channel of information, which leads the viewers to infer unwanted details.	Training simulators Entertainment industry Artistic applications
Physical	Provide same visual simulation as the scene. Renderers stimulate the spectral and intensive properties of light energy.	- Display devices cannot reproduce the rendered light energies. -Computationally expensive.	Quantitative analysis for design and engineering domains Illumination engineering Material science and manufacturing
Photorealism	Produce the same visual response as the scene. Create an image that is indistinguishable from a photograph.	-Time taking. - High computational requirements.	Quantitative design analysis in design and engineering problems
Functional	Provide same information about the properties and relations of objects as the scene.	-	Entertainment or computer game industry
Soft-functional	Focuses on less tangible issues such as emotions, feelings and experiences of the designer with the images.	-	Product development industries (e.g. automotive, construction, costume, packaging) Computer game industry

3.2 Soft-functional realism

So far physical, photometric or functional appropriateness have been the focus for the generation of computer graphic images. There are less tangible issues such as emotional bonding of designers with the images generated, cultural perceptions and social value systems. These intangible issues provide insights to help expand knowledge and understanding of the designers' needs beyond the physical, photometric or functional. Such issues can be termed as 'soft-functional', which is a specific form of functionality that deals with intangible and emotional aspects [192].

In product development, the need of less tangible issues for a product success was identified and designers started to focus on consumer products that are characterised by both functional and soft-functional values [192]. Such soft functionalities are difficult to express objectively and are based on the emotions of the designer that could be characterised by the level of e.g. presence, excitement, comfort, recognition and detection.

Applications focusing on emotions are mainly in product development industries ranging from automotive, construction machinery, house construction, costume, and cosmetics to packaging and very few in computer game or entertainment industry (e.g. [170]). In these applications, the emotions of the users are considered for developing a new product or for the methodological improvement of existing products. In computer graphics, there has been insufficient support for the soft-functional aspects to depict realism.

Given the potential of soft-functional realism, in computer graphics, such realism could be introduced as a type of realism and incorporated during the generation of images. Since such soft functionalities are difficult to express objectively, they could be expressed by rendering styles through psychological means. For instance, the demands on the image generation process for achieving this type of realism could be based, similar to product development, on the emotions or feelings of the designer (viewer) that could be characterised by the level of e.g. presence, excitement, comfort, recognition and detection.

3.3 Existing techniques

The literature reviewed in this section is concerned with the existing rendering techniques for the generation of computer graphic images, photorealistic rendering (PR) and non-photorealistic rendering (NPR). The word 'photo' is derived from the Greek word '*phos*' meaning light or produced by light and 'realistic' means depicting or emphasising what is real and actual, rather than abstract or ideal [176]. The term non-photorealistic has been adopted by the computer graphics community to denote forms of rendering that are not inherently photorealistic [176]. This review discusses the existing techniques and their sub-categories (see Table 3-3), with respect to their features, the conventions used to represent such techniques and the representative works.

Table 3-3: Existing techniques, sub-categories and their representative works

PR		NPR			
Ray trace	Radiosity	Cartoon shading	Painterly	Pen-and-ink illustration	Technical illustration
RADIANCE [52], Cook [193], Cohen [194, 195], Segal [196], Whitted [197], FLY [198], CREATE [199, 200].		Lake et al [201], Thoma [202], Decaudin [203], CharToon [204], Hsu and Lee [205].	Piranesi [206], Teece [207], Hertzmann [208], Hanharan and Haeberli [209, 210], Collomosse and Hall [211], Smith [212], Cockshott et al [213], Pham [214].	Sketch-renderer [215], Winkenbach and Salesin [216], Salisbury et al [217, 218], Saito and Takahashi [190], Streit et al [219], Strassmann [220], Curtis [221], Hsu et al [222], Markosian et al [223], LineStyles [224], Hertzmann and Zorin [225], Rossl and Kobbelt [226], DeCarlo and Santella [227].	Gooch et al [189, 228-230], Dooley and Cohen [231], Seligmann and Feiner [232], Williams [233].

3.3.1 Photorealistic rendering (PR)

Computer graphics has concentrated more on the problem of photorealism and has been the focus of research in the computer graphics community. The general notion of a theoretically perfect rendering from a computer model is that it would be indistinguishable from a photograph of the realised object [234]. There are plenty of applications of photorealism, including special effects in films and design visualisation especially in automotive industry and architectural design. In photorealism the driving force is the modelling of physical processes and behaviour of light. Ray trace and radiosity are established techniques for producing good photorealistic and photometric images [176, 235]. In both cases the physical behaviour of light is simulated.

Before the advent of ray trace and radiosity, the first and common method is to use an empirical simulation of light-object interaction in conjunction with polygon mesh objects (Gouraud [236], Phong [237]). However, the disadvantage of this method is that the objects are considered to exist in isolation with respect to a light source and no account is taken of light interaction between objects themselves [238]. Although the reflection of the light incident on an object from a light source is simulated, the light that originates, by reflection, from any other object is ignored. Thus, the common phenomenon that depend on light reflecting from one object onto another, such as shadows and objects reflecting with each other, cannot be produced by such models. Such models are called local reflection models. On the other hand, global reflection models attempt to follow the path of light reflecting from one object onto another. Ray trace and radiosity are two types of such global illumination models [237].

Ray trace [193, 197] simulates global interaction by explicitly tracking thin rays of light as they travel through a scene from object to object. It works on the principle of tracing all the light paths through the scene including reflections and refractions [235]. It operates on points in the scene. Ray trace deals with scenes consisting of shiny, mutually reflective objects [238]. On the other hand, radiosity [194, 195] considers light reflecting in all directions from the surface of an object and calculates how light radiates from one surface to another as a function of the geometric relationship among the surfaces-their proximity and relative orientation. Radiosity is better for handling reflections and shadows. Further in contrast to ray trace, radiosity operates on finite areas called patches. It deals with diffuse or dull surfaces and is used mostly to simulate interiors of rooms [238].

Transparency[17], reflections and shadows[18] are examples of global illumination, in which they use information from other objects than the one being illuminated [164]. A transparent surface, in general, produces both reflected and transmitted light. The relative contribution of the transmitted light depends on the degree of transparency of the surface or whether any light sources or illuminated surfaces are behind the transparent surfaces [164]. Effects such as reflections and shadows contribute greatly to increasing the realism in a rendered image. The user also uses them as visual cues to determine spatial relationships. The basic ray trace algorithm [240] also provides for visible-surface detection, shadow effects, transparency and multiple light-source illuminations. Many extensions to the basic algorithm have been developed to produce photorealistic displays [164].

PR limitations

In order to achieve photorealism, there is a need to simulate, for instance the interactions of light, in more detail and greater precision [234]. Ray trace displays can be highly realistic, particularly for shiny objects, but they require considerable computation time to generate. The basic precondition to achieving such realistic displays is physically based lighting simulation, which is computationally demanding [241]. Current research in computer graphics is attending to, amongst many others, lighting, partial shadowing and effect of micro-structure materials on reflection. Each of the advances in current research requires a more refined model and a greater increase in time taken to render a scene [234]. The economics of computer rendering depends on the complexity of the model, usually estimated by a polygon count, and on the sophistication of the optical simulation. However, photorealism demands a complex model, full of detail. It involves choosing viewpoints, assigning the optical properties of surfaces, placing lights, and defining and placing structures. The process of producing a rendering from such a detailed model is time-consuming and unwieldy.

[17] The quality of a material that transmits light and can be seen through.

[18] Shadows: Shadows are important elements in creating realistic images and in providing the user with visual cues about object placement [239]. Hidden-surface methods can be used to locate areas where light sources produce shadows. By applying this method, the shadow areas are determined based on which surface sections that cannot be seen from the light source [164]. In some cases, texture mapping is used for creating fast shadows and lighting effects [196]. Mapping is the process of associating (a group of elements or qualities) with an equivalent group, according to a particular model or formula [1]. Texture mapping is to map texture patterns onto the surfaces of objects [164]. It is used for adding surface details and deals with materials that have some sort of patterning.

3.3.2 Non-photorealistic rendering (NPR)

NPR has received much attention as an alternative to traditional PR, by employing the judgement and skill of the designer. It does not have a precise definition, and is used as a blanket term for the methods that are not driven by the pursuit for realism, but more usually by human perception and processes employed by a designer [176]. In recent years, NPR has received lot of attention for both art and scientific applications. Typical applications of NPR include architectural sketches, illustrations in medical text books or technical manuals and cartoons [226]. It is used in animations and for the development of real-time techniques in the computer game industry [242]. Computer-assisted cartoon animation is widely used in television and feature films. Further NPR had been extended, in an immersive and interactive context, for virtual heritage applications (e.g. [200]) to assist the process of interpretation and help visualise multiple different hypotheses.

Often NPR creates images and illustrations that do not mimic physical reality but the style and quality of human artist renditions. Often these styles are reminiscent of painting (e.g. [243-246]) or various styles of artistic illustration (e.g. pen-and-ink [205, 216, 222], technical illustrations [190, 229, 231], cartoon type shading [247]). The strength of these styles lies in their scope to convey shape, spatial structure and artistic expression rather than the aesthetics of the design. NPR techniques can be different from traditional computer graphics in two aspects, in that they introduce a broader variety of styles and they offer original human-computer interaction. These techniques typically have some set of rendering parameters associated with them that vary the style of the resulting images. The choice of rendering parameters has a strong effect on the style of the resulting images. The users select the rendering parameters that add emphasis and clarity to the aspects of visualisation that they are interested in.

Several researchers reviewed relevant research on NPR (e.g. [176, 208, 229, 248, 249]). Depending on the type of simulated media, NPR can be categorised into the following [242]:

- Cartoon shading
- Painterly rendering
- Pen-and-ink illustrations
- Technical illustrations

Cartoon shading

Cartoon shading (also called 'hard shading' or 'toon shading') ranges among the first stylised shading techniques that have been explored in the context of computer graphics [202]. This is attributed to the fact that it is simple to implement and visually attractive. Cartoon shading creates a cartoon like rendering using material colour and shadow colour. Often in cartoon shading, the part of a material that is in shadow is shaded with a colour that is a darkened version of the main material colour. The boundary between shadowed and illuminated colours is a hard edge that follows the contours of the object or character. This technique is known as hard shading [201]. The cartoon shading techniques render in a variety of different styles by varying the base or main material colour, shadow colour and highlight colour. The choice of colours has a strong effect on the appearance or style of the cartoon. This type of shading presents lighting cues, shape and context. Lake et al [201] presented real-time methods to emulate cartoon styles and, additionally, techniques for emphasising motion of cartoon objects by introducing geometry into the cartoon scene. They integrated these rendering techniques with a character animation system and a multiresolution mesh to provide scalability. Ruttkay and Noot [204] developed an interactive system, CharToon, to design and animate 2D cartoon faces.

Painterly rendering

Perhaps the most prominent and widely used NPR systems are paint systems (e.g. [205, 212-214, 220, 243-246, 250]). Automatic, computer-generated, photograph-to-painterly rendering techniques have been available now for over a decade. A painterly effect is produced by forming a set of brush strokes upon a canvas at predetermined spatial intervals [211]. Attributes such as colour and orientation are often derived from the original image. In theory, painterly rendering is the process of turning an accurate depiction of reality (for example a photograph) into a more rich and stylised painting.

The development of paint renderers gained momentum with Haebreli's interactive paint system [209], which presented a variety of techniques to aid painting, including the use of an underlying source image to determine stroke properties during painting. Hanharan and Haeberli [210] provided a tool for painting textures directly onto 3D objects, whose idea has been implemented in several commercial products. Salisbury [246] introduced orientable stroke textures, as a part of pen-and-ink image processing system, in which the user specifies stroke types and orientations. Painting methods have been adapted for painting 3D images with depth buffers, containing material and depth information, in Piranesi system [206] and by Teece [207] to allow a user to paint a 3D scene to generate still images or animations. Hertzmann [208] presented a method for creating an image with a hand-painted appearance. He generated a variety of painting styles such as impressionist and expressionist, by combining the expressivity and beauty of natural media with the flexibility and speed of computer graphics. He presented a technique for painting an image with multiple brush sizes and long, curved brush strokes that are chosen to match the colours in the source image. Collomosse and Hall [211] presented an automatic NPR technique capable of rendering 2D images in a painterly style by using image salience and gradient information to determine the ordering and attributes of individual brush strokes. This approach overcomes the problem of loss of detail during painting.

Pen-and-ink illustrations

There are a number of advantages of illustrations [216], i.e. they can convey information better by: (i) omitting extraneous details, (ii) focusing attention on relevant features, (iii) clarifying and simplifying shapes and (iv) expressing parts that are hidden. In addition, they often consume less storage than realistic images and more easily transmitted and reproduced. Illustrations are also effective for conveying information at different levels of detail.

Tone[19], texture and outline are the conventions used in pen-and-ink illustrations [216], which are created by using pen strokes. The major properties that distinguish pen-and-ink illustrations from other art media [217] include: (i) every stroke contributes both tone and texture and (ii) strokes work collectively. In theory no single stroke is of critical importance, instead they work together to express tone and texture. A stroke can be produced by placing the nib of a pen in contact with the paper, and allowing the nib to trace out a path. The thickness of the stroke can be varied by varying the pressure on the nib [216]. Tone is typically created by defining different stroke textures for varying intensities or by creating multiple strokes or textures until the desired tone is achieved [216, 217, 219, 246]. Tone and texture can also be defined by using multiple strokes or parametric curves [219, 251] and contour lines [219]. Texture is defined by the type, thickness, orientation, placement and quantity of strokes. Outline can be created using edge detection [190, 219] and strategic placement of skeleton strokes [205, 219]. The medium of pen-and-ink is ideal for creating outlines with an incredible range of expressiveness. Outline strokes are used not only for the contours of an object but also for delineating the essentials of its interior.

[19] Tone refers the amount of visible light reflected towards the observer from a point on a surface.

Line art is one of the most common illustration styles. Line drawings can be found in many contexts, such as cartoons, technical illustrations, and architectural design. Several researchers [190, 223, 229, 252-254] have examined the type of lines to be drawn in computer generated images to maximise the amount of information conveyed. Lines communicate information more efficiently and precisely than photographs [225]. The appeal of line drawing depends on expressiveness and abstraction [255]. In addition, line drawing can prevent clutter, focus the attention on relevant part and omit superfluous data. Despite its simplicity, line drawing permits a variety of styles. The line styles can be varied by changing the medium (such as pen-and-ink, pencil) and the attributes of the strokes (such as thickness, tone and texture).

Strassmann [220] developed a method, Hairy Brushes, for drawing lines as brush strokes using an object-oriented approach. He tried to simulate the physical behaviour of a brush. Hsu et al [222] presented a vector-oriented approach, Skeletal strokes, for drawing lines with special effects, which is based on the deformation of predefined images. Winkenbach and Salesin [216] demonstrated a system for generating line drawings of polygonal and parametric surfaces. In particular, they introduced the idea of 'control-density hatching' for conveying tone, texture and shape by using traditional texture mapping techniques [251]. They used stroke textures to create depth and shape in line drawings of parametric surfaces. The hatching methods of Salisbury et al [217] are to hatch the visible surface according to texture, shading and orientation. They described an interactive system [246] for automatic conversion of gray-scale raster images to pen-and-ink textures. This involved the system automatically extracting an outline from the original gray scale 2D image (target image), with the user specifying the direction of each strokes drawn in each region and tones. Gray scale values in the target image are used to compute the tone of illustration. Strothotte et al [215] implemented a system called 'Sketch-renderer' for rendering sketches that are similar to the drawings drawn with a pencil. With the 'sketch renderer' system they provided interaction facilities to design lines and hatchings in a flexible way on two levels: the object level where line styles can be defined and attached to objects in the scene and global level where the users can change line styles interactively in the line drawing. Leister [256] developed a special ray tracing method to generate graphics similar to copper plates. Markosian et al [223] proposed an approach for improving the performance of pen-and-ink drawing in order to make it real-time. They presented a technique based on the economy of line, with the idea that information can be conveyed by very few strokes. Curtis [221] used 3D models to generate loose and artistic sketches and animations. LinesStyles [224] focused on the presentation of 3D models. This method can be applied to the output of an analytical renderer to create illustrative effects in line drawings. Hertzmann and Zorin [225] developed rendering techniques for automatic generation of line-art illustrations of smooth surfaces. Rossl and Kobbelt [226] presented an interactive system for computer-aided generation of line art drawings to illustrate 3D models that are given as triangulated surfaces. Grabli et al [255] gave a procedural approach to line drawing from 2D models.

Technical illustrations

In technical manuals, illustrated textbooks and encyclopaedias, the illustration conventions used are quite different from computer graphics methods. Such conventions fall under the umbrella term technical illustrations [228]. They do not represent reality because the level of detail of different objects in images is changed to express the importance of an object in the picture. In technical illustrations, important 3D properties of objects are accented while extraneous detail is diminished or eliminated [229]. Despite wide variety of techniques and styles found in technical illustrations, the common conventions include: black edge lines, cool-to-warm shading colours, single light sources, rare usage of shadows, matte objects are shaded with intensities far from black or white and metal objects are shaded as if anisotropic.

Several user perception studies [228, 257-259] have concluded that respondents can recognise 3D objects well, when edge lines are drawn versus shaded images. It was concluded by Christou et al [228, 259] that 'a few simple lines defining the outline of an object suffice to determine its 3D structure'. Lines enable to distinguish and differentiate different parts of an object and draw attention to details that may be lost in shading. Saito and Takahashi [190] used a variety of techniques to show geometric properties of objects, but their objects do not follow many of the technical illustration conventions. Some works concentrated on additional aspects of technical illustrations such as layout, object transparency and line style [231, 232]. Williams [228, 233] developed technical illustration techniques including some warm-to-cool tones to approximate global illumination and drawing conventions for specular objects. Sometimes illustrators might choose a white line instead of black edge line for discontinuities or silhouettes [260]. Gooch et al [189, 228-230] have developed several methods for technical illustrations, where the primary contributions are a new lighting model that mimics artistic shading and conventions for line drawing, surface shadowing and interactive rendering. The model uses both luminance and changes in hue to indicate surface orientation, reserving extreme lights and darks for edge lines and highlights. It allows shading to occur only in mid-tones so that edge lines and highlights remain visually prominent.

3.3.3 Summary

From the review it can be observed that sketching (Section 2.2) and rendering lie on opposite ends of the spectrum with respect to user interaction. The former offers (natural input) freedom to draw, given certain primitives. The latter read in a geometric model and generally produce an image whose appearance is difficult to modify, except in post-processing (output) [261, 262].

Table 3-4 provides an overview of the reviewed existing PR and NPR techniques. It has been adopted from [176] and updated to reflect the sub-categories of existing techniques, their features, the conventions used to represent such techniques and the applications of existing techniques.

Table 3-4: Overview of existing techniques and their sub-categories (adapted from [176])

	PR		NPR			
	Ray trace	Radiosity	Cartoon shading	Painterly	Pen-and-ink illustration	Technical illustration
Accuracy	Precise		Approximate			
Applications	Film industry, design visualisation in automobile industry, architectural design.		Animations, Computer game industry, Art and scientific applications, Architectural design, Illustrations in manual texts or technical manuals.			
Approach	Simulation		Stylisation			
Characteristics	Objective		Subjective			
Completeness	Complete		Incomplete			
Conventions	Transparency Reflection Shadows Texture mapping Tone mapping		Material colour Shadow colour Highlight colour	Brush strokes Brush size	Strokes Tone Texture Outline	Black edge lines Cool-to-warm shading colour Single light source Shadows rarely used
Deceptiveness	Can be deceptive or regarded as dishonest; viewers may be misled into believing that an image is real.		Honest- the observer sees an image as a depiction of a scene.			
Driving force	Modelling of physical processes and behaviour of light.		Processes of human perception.			
Features	- Traces all the light paths from object to object. - Better for handling reflections and refractions. - Deals with shiny objecs.	- Diffuse reflections from a surface by considering the radiant energy transfers between surfaces. - Better for handling reflections and shadows. - Deals with dull or diffused objects.	- Shading model in 2D cartoon. - Presents lighting cues, shape and context.	-A painterly effect created by a set of brush strokes on an image.	- Generate line art drawings. - Better for conveying information at different levels of detail, hidden parts, clarifying and simplifying shapes.	- Diminish or eliminate extraneous details.
Influences	Simulation of physical processes		Simulation of artistic processes			
Level of detail	Hard to avoid extraneous detail: too much information; constant level or full of detail.		Can adapt level of detail across an image to focus the viewer's attention.			

Comparison of existing PR and NPR techniques

Although both PR and NPR address the presentation of computer graphic images they differ in a number of issues including (but not limited to):

- Abstraction: Abstraction mechanisms available to the designers include 'level of detail' and 'focus attention' to stress the important parts of a drawing or enrich an image with additional visual information and effects [226]. PR techniques provide little abstraction, so the resulting PR images tend to be more confusing than the less detailed NPR technical illustrations. NPR techniques vary greatly in levels of abstraction. Their higher level of abstraction tends to put emphasis on the important information of an illustration.
- Opportunities and possibilities to create new styles of images: Computer graphic images created by PR techniques tend to look finished; thereby at times do not encourage opportunities and possibilities to create new styles of images. On the other hand, the appeal of NPR images lies in its expressiveness and abstraction, and the final impact of the NPR process depends on how the styles used to represent the objects in the image are interpreted [263]. In this sense it provides opportunities and possibilities to create new styles of a visual image.
- Presentation: With NPR styles, the information considered most important in the images can be emphasised by variation in drawing styles. For example, less important regions can be depicted with fading lines, while relevant parts with bold lines. Although the resulting NPR image is realistic, it differs from PR presentation in shape, colour, texture, light and shadow.
- Support in conceptual design: It is normal to experiment with several designs during conceptual design. PR images require high level of details, e.g. materials, lighting effect. In the early stages of design conception, when such high level details are not required, too much time and effort would be spent in modelling. The demand of PR for a detailed model limits this technique to the later stages of the design and also limits the opportunity of a designer to imagine better possible options of a design. Therefore, this technique is typically effective towards the end of the design and not as the tool to communicate design ideas and experiment with different designs in conceptual design. Whereas, NPR is better suited as it can convey the feeling of an unfinished look, which can encourage the design iteration process. This enables the designers to better communicate their vision and the clients to focus on the important aspects of a concept. Images that show the 'concept' of a design are more likely

enable the designers to open discussions with the clients, as opposed to PR images that may appear 'finished' and thereby could stifle constructive discussions [261].

Limitations of existing PR and NPR techniques

Most of the work in PR is to create an image that is indistinguishable from a photograph of a scene. That is, the main focus is on simulating the behaviour of light to match the appearance of a real scene. Designers often perceive the unerring photorealism of 3D rendering as a problem as they need to address high-quality imagery, which means high-complexity in terms of detail and precision during modelling and rendering [234]. A number of schemes have been investigated by researchers in this field with the intent to minimise the precision of information used during modelling and rendering [238].

Most of the work in NPR is on emulating artistic styles so as to give a hand-drawn appearance to the images. That is, the main focus is on simulating the behaviour of physical media. Examples of this trend are a rendering technique that produces images that appear to be drawn with ink and pens, pencils and paintbrushes on canvas. NPR creates visually attractive hand drawn images by integrating artistic effects into the 3D rendering pipeline. That is, all these effects are applied to the output of a renderer (post-processing) to create illustrative or human hand drawing effects in the images to emulate the design concepts in conceptual design. Examples of this trend (post-processing output from a 3D renderer) include:

- conversion of scanned images to pen-and-ink style (e.g. [246]),
- create illustrative effects in line drawings to the output of a renderer (e.g. [224]),
- deformation of predefined images to give a rough look (e.g. [222]),
- introduce imprecision in rendering by adjusting a plotter pen to wiggle when being moved to achieve similar wiggles of a human drawing hand (e.g. [262]), and
- turn an accurate description into stylised painting or painting on 3D objects to create images with hand drawn appearance (e.g. [208]).

Such NPR techniques present challenges from an algorithmic and artistic point of view to improve or emulate human renditions. However, they miss the opportunity of maintaining and presenting the actual vague information of the conceptual design concepts held within the computer.

The common feature of the reviewed geometry-based PR and NPR techniques is that they are based on a modeller in order to extract the image to be rendered. That is, they read in a geometric model (obtained from modelling) and produce an image, whose appearance is difficult to modify except by post-processing. Such PR and NPR techniques involve the loss of information and design intent and do not reflect the true nature of the design concepts in conceptual design, as the renderers require the vague design concepts to be defined into precise models. Such techniques convey a sense of precision and exactness and do not preserve vague information. Lack of an appropriate rendering technique, which can reflect vague information of the conceptual design concepts, is a significant problem in this field.

3.4 Chapter summary

This chapter has presented a review of existing rendering techniques, PR and NPR, and hence, has identified the need for a more relevant rendering that reflects the true nature of the design concepts, such as inherent vagueness, in conceptual design. In addition, the examination of different kinds of realism conveyed through computer graphic images (Section 3.1) has highlighted the insufficient support for soft-functional aspects, which are based on the emotions and feelings of the designer, to depict realism.

Sections 3.1 to 3.3 described in this chapter provide a basis (1) to establish the key aspects for the generation of computer graphic images (presented in Chapter 5), where the key aspects provide a basis for a critique of existing rendering systems in Chapter 5, (2) for the investigation of different characteristics and features of rendering in conceptual design (discussed in Chapter 6), and (3) for the evaluation of different existing PR and NPR styles (discussed in Chapter 8).

4. Visualisation and interpretation

Chapter 3 presented a review of different *rendering* techniques for the generation of computer graphic images (Step 3 in Figure 2-8). The focus of this chapter is on *visualisation and interpretation* of the generated computer graphics image (Step 4 in Figure 2-8).

The aim of this chapter is to present a cognitive framework of human information processing between the visualisation of a generated computer graphics image and its interpretation. Based on the understanding of the cognitive processing, the objectives are (1) to establish the key aspects for visualisation and interpretation (discussed in Chapter 5), where the key aspects provide a basis for a critique of existing studies in Chapter 5, and (2) to provide the basis for the identification of emotive implications of computer graphic images (discussed in Chapter 7).

In Section 4.1 a general introduction to cognition is given. The existing cognitive theories are briefly delineated in Section 4.2. In Section 4.3, a cognitive theory, Interacting Cognitive System (ICS), which is a foundation for the research presented in this thesis, is introduced. Section 4.4 presents the cognitive principles underpinning the visualisation and interpretation of the generated computer graphics image. In Section 4.5, the notion of 'emotive implications' is introduced. Finally, the chapter is summarised in Section 4.6.

4.1 Cognition

There is often confusion regarding cognition and perception, as both of them are closely related. As stated in Chapter 1, cognition is the mental action or process of acquiring knowledge and understanding through thought, experience and the senses [1]. With this definition, cognition is seen as the:

- Action of knowing: The study of cognition is the study of processes: the ways in which we become acquainted with things.
- Faculty: It has been common to divide the mind into faculties that represent the different mental activities of which we are capable.

On the other hand, perception is the ability to become aware of something through the senses. In other words, it is the process of acquiring, organising and interpreting sensory information [1]. In this definition perception is seen as:

- Awareness: That is acquiring information through the five senses (see, hear, smell, taste or feel).
- Interpretation: A mental impression or understanding caused on becoming aware of sensory information, analysing and processing.

To some degree, perception may be considered as part of cognition or that it influences cognition. The word 'cognitive', in cognitive science, refers to perceiving and knowing [264]. Thus, cognitive science can be considered as the science of the mind. It encompasses varied disciplines as anthropology, cognitive psychology, computer science, engineering design, linguistics neuroscience and philosophy. The expression of cognitive science is used to describe a broad integrated class of approaches to the study of mental activities and processes and of cognition in particular [265].

It is necessary to understand the cognitive theories that can explain how graphical information displayed in the computer is processed and interpreted by humans. One form that the understanding of human information processing takes is cognitive theory, at various levels of detail, that speculate mechanisms by which the observed phenomenon can be explained. Because of the large number of observations available, differences in methodology and different approaches to modelling, there is no single theory of cognition [171]. It is obviously not possible to give a complete overview for all the various theories that describe human perception and cognition. However, the theories that have found to be applicable from the perspective of rendering are discussed in the following section.

4.2 Existing theories

The theories of cognition fall into two broad groups such as microtheory and macrotheory [266]. Microtheory is concerned with the explanation of phenomena within some restricted scope. Macrotheory, on the other hand, attempts to provide a framework in which the operation of different microtheories can be situated and organised.

Theories of vision such as the following come under the microtheory category:

- 'Bottom-up' or data driven [267]: According to this theory, perception involves immediate feature extraction from the retinal image before any selectivity on the part of the perceiver. The information flows from a basic, 'bottom', level up towards higher, more integrated levels. The Gibsonian idea of perception [5, 268] is that the perceptual system of humans has evolved and learnt to perceive certain 'invariances' or 'affordances' within the visual scene directly, without much processing or interpretation.
- 'Top-down' or goal directed [267]: According to this theory, perception involves the use of prior knowledge and experience in the construction of a model of the world. In contrast to the 'bottom-up' theory, higher, global, abstract levels of analysis affect the operation of lower processes. *Gestalt*[20] principles of perception [269] (such as figure and ground, similarity, proximity or continuity, closure, area, symmetry, whole/parts and continuation) fall under this constructivist approach to perception. The Helmholtzian view [270] is that perception is an exploratory process in which the visual sensory information is evaluated against the viewer's expectations about the scene; it is a 'top-down' rather than a 'bottom-up' process.

The above-mentioned microtheories are low-level visual processes. This is because they are limiting the application of perceptual psychology to focus on the physical levels, thereby excluding the cognitive levels of explanation (i.e how information is processed and interpreted by humans).

Broader approaches of cognition have been developed that speculate the capabilities and operation of the mind in terms of its ability to process information. Strothotte [271], for example, gave a description of Weidenmann's scheme [272] for picture understanding that is based on the concept of mental models. Kieras and Meyer [7] developed a cognitive model, Executive-Process/Interactive Control (EPIC), for human information processing that accurately accounts for the detailed timing of human perceptual, cognitive, and motor activity. It provides a framework for constructing models of human-system interaction that are accurate and detailed enough to be useful for practical design purposes. One approach that is becoming known in the computer graphics community is the Interacting Cognitive System (ICS), which was developed by Barnard [3] and his colleagues. ICS is one particular approach to macrotheory that provides a framework in which the operation of different microtheories (such as 'bottom-up', 'top-down') can be situated and organised. It is one of

[20] *Gestalt* is the German word for 'form', 'shape', or 'whole configuration'.

the more developed theories that account for human information processing and explains a broad range of phenomenon, including task performance and aspects such as visual perception, cognition, emotion and inference.

Applications of ICS

ICS has already been used in the context of HCI and Computer Graphics to explore the usability of gestural interaction [273] and multimodal techniques [169]. It enables phenomena such as change blindness [270] and the craft principles of film editing [274] to be interpreted with a common framework, supporting extrapolation to computer graphics. Barnard and Teasdale had extended and applied ICS to the interaction of cognition and emotion [20]. One more application of this approach is in the minimal graphics area [266]. The goal for minimal graphics is based on a model of information (for instance, a geometric model of a scene) that should produce images that are simple, strive for a minimum level of complexity for a task and convey the intended amount of information to the observer. Recent work on haptics interface design adopted the ICS approach (e.g. [275]). With regard to the application of ICS in a design context, it describes properties of a cognitive activity at some level of approximation in a particular domain. It incorporates components that describe attributes both of mental processing and of knowledge used in it. It, therefore, provides an abstract, but explicit, representation of what is going on in the mind of the user. From this, it should be possible for a designer to link the psychological issues associated with design in a particular domain.

Given its comprehensibility in human information processing, the provision of a framework in which the operation of different microtheories of cognition (such as 'bottom-up', 'top-down') can be situated and organised, its broad range of applicability, and in particular its re-appraisal in the context of rendering (e.g. [169, 170]), ICS was chosen as the foundation for the research presented in this thesis.

The following sections present the cognitive framework of ICS that provides some insights into the cognitive levels of information within the visualisation process.

4.3 Interacting Cognitive System (ICS)

In contrast to a computer system, ICS considers the information processing mechanism with no 'central processor' or 'limited capacity working memory' [3]. It adopts a systematic approach in which information flows within a parallel and modular architecture of distributed cognitive resources [275], in which behaviour arises out of the co-ordinated operation of the constituent parts. In ICS, the behaviour of the constituent parts can be thought in much the same way as the behaviour of a team, where the individual members of the team are each doing something different but their conjoint activity is co-ordinated and constrained by common rules. As behaviour rises out of the co-ordinated operation of its constituent parts, a major advantage of ICS is that cognition and affect can be considered within an overall psychological context, therefore making it ideally suited for reasoning about perception.

Architecture of ICS

The basic architecture of ICS is illustrated in Figure 4-1. The theory assumes that human mental architecture is composed of nine functionally independent subsystems. Each of the subsystems specialise in storing and processing a qualitatively different type of information.

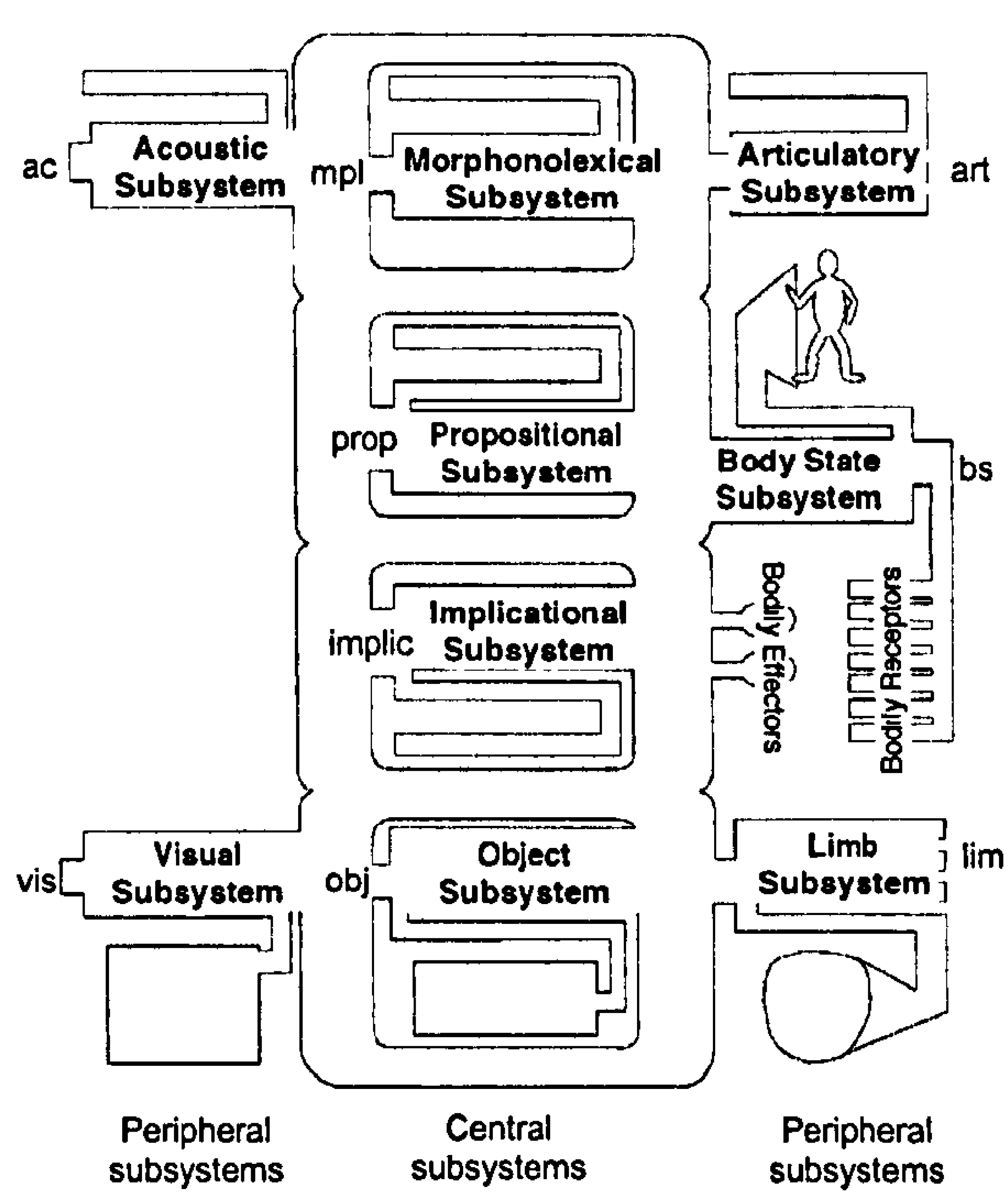


Figure 4-1: Architecture of ICS [3]

The subsystems can be classified into ***peripheral*** and ***central*** [276]. There is a key distinction between ***peripheral*** and ***central*** subsystems (see Table 4-1 for the type of information handled by each of these).

Peripheral subsystems exchange information with the world via the senses (*sensory* subsystems) or the body (*effector* subsystems). There are five ***peripheral*** subsystems.

- *Sensory* subsystems take input information derived directly from the external world by sense specific transducers. Three subsystems, acoustic (ac), visual (vis) and body state (bs), are specialised for *sensory* information.
- *Effector* subsystems take inputs from other subsystems and map their outputs in the form of motor instructions to the relevant musculatures. Two subsystems, limb (lim) and articulatory (art), are specialised for effector action.

Central subsystems (*structural* and *meaning* subsystems) exchange information only with other subsystems. These subsystems take inputs from other subsystems and produce outputs that can be used by other subsystems. Basically these subsystems interact with other susbystems. There are four central subsystems.

- *Structural* subsystems handle abstract structural descriptions. Two subsystems, morphonolexical (mpl) and object (obj), are specialised for *structural* information.
- *Meaning* subsystems handle different levels of meaning. Two subsystems, propositional (prop) and implicational (implic), process different levels of *meaning*. Propositional *meaning* can be thought of as specific, "cold" and "rational" whereas implicational *meaning* is both generic and potentially "affect-related" [3].

Table 4-1: Types of information in ICS [3]

Subsystems	Type of Information
Peripheral	
a) Sensory	
1. Acoustic (ac):	Sound frequency, timbre and pitch from the ears. Subjectively, what we 'hear in the world'.
2. Visual (vis):	Wavelength and brightness of light, hue, colour, etc from the eyes. i.e., information about colour, and shapes of objects in the image. Subjectively, what we 'see in the world' as patterns of shape and colours.
3. Body state (bs):	Stimulation (pressure, temperature, muscle), location and intensity. Subjectively, bodily sensations of pressure or pain, positions of parts of the body, as well as tastes and smells
b) Effector	
4. Limb (lim):	Force, target position and timing of skeletal musculatures. Subjectively, 'mental' physical movement.
5. Articulatory (art):	Force, target position and timing of articulatory musculatures. Subjectively, subvocal speech output.
Central	
c) Structural	
6. Morphonolexical (mpl):	Language in sound space, specifically word order and identity information; words, lexical forms.
7. Object (obj):	Objects in visual space, in particular identification of objects boundaries, the relationship of objects to other objects and attributes of objects, mental imagery, shapes etc. Subjectively, our 'visual imagery'.
d) Meaning	
8. Propositional (prop):	Relationships and identities of objects (visual or auditory) in semantic space. Subjectively specific semantic relationships (knowing that). This involves the referential knowledge, that is 'facts about the world', including properties and relationships between entities
9. Implicational (implic):	This is the most difficult form of information to describe and represents very high level of abstraction. Ideational and affective content. This information is concerned with schematic models, recognises affective content with environmental contexts. Subjectively, holistic senses of knowing (e.g. 'familiarity' or 'casual relatedness' of ideas), or of affect (e.g. apprehension, desire). These holistic senses become aware through their semantic (proportional), and structural (object/morphonolexical) refinement, or through feedbacks from their psychological consequences (body state) and effects in the world.

Working mechanism

The subsystems differ in their input and output, but have the same internal structure (see Figure 4-2) resulting in the same working mechanism. The basic working mechanism is that all the incoming information arriving in a subsystem (*input array*), is copied into an *image record* and, in parallel, is transformed (*transformation process*) for use in another subsystem [277]. The notation 'A-B', here and in the remainder of the chapter, is used to denote the process in the subsystem 'A' that transforms its input for subsystem 'B'. The input for a later subsystem is procured based on the output from the earlier subsystems.

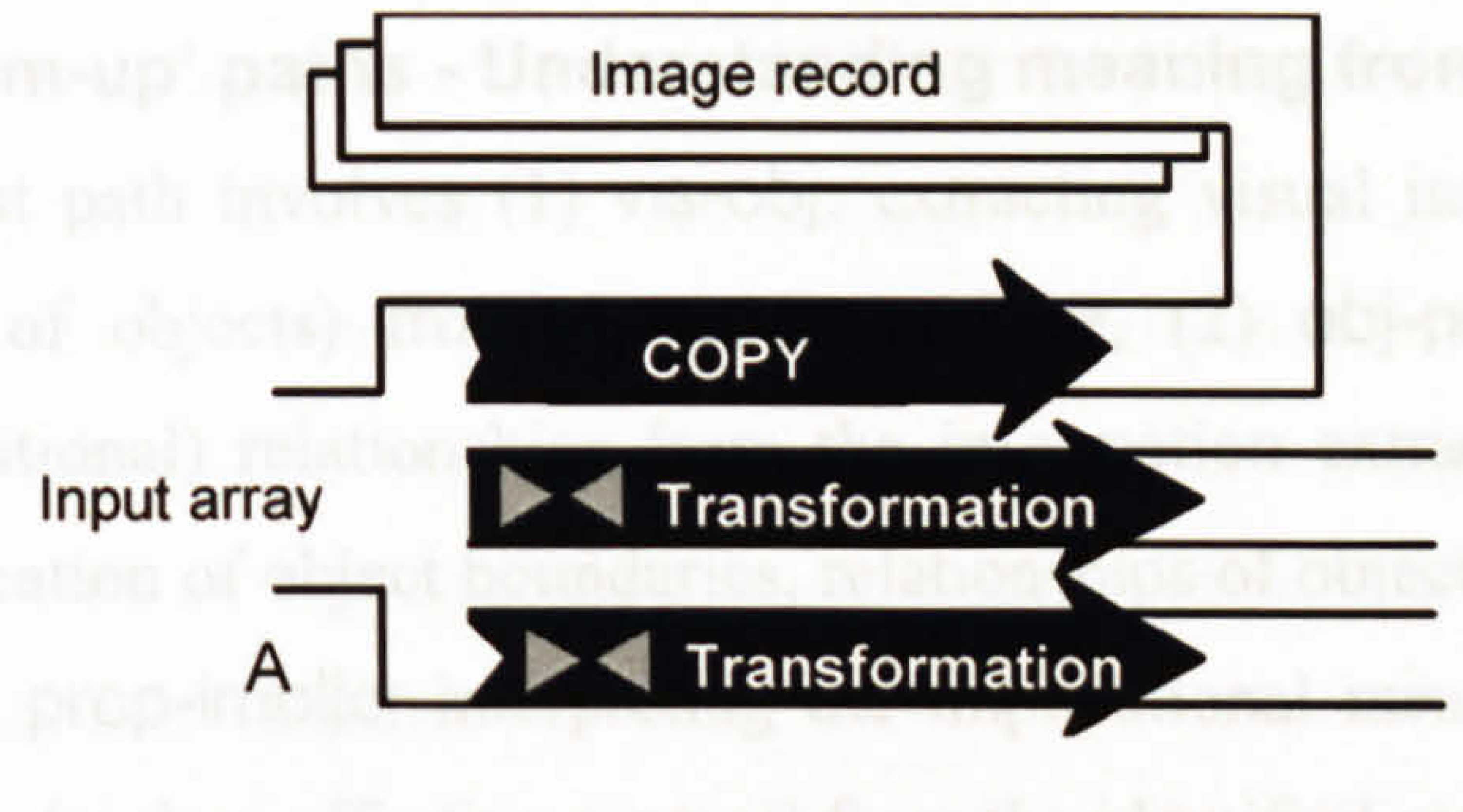


Figure 4-2: The internal structure of each subsystem [276]

A primary *copy process* in each subsystem copies all its incoming information from the *input array* to its own *image record*, which acts as a memory 'local' to the subsystem. The copying of information to memory gives rise to a sense of awareness of information. At each stage in the flow of information, the transformation processes within the subsystem may recruit this stored knowledge, derived from previous experiences, to enrich the incoming information [276]. Overall behaviour of the cognitive system is determined by the possible transformations between the subsystems and the demands of a particular task.

4.4 Cognitive processing during visualisation and interpretation

ICS may be used to reason about the flow of information through the human cognitive architecture between the visualisation of the image and its interpretation. For example, if a designer is presented with a computer generated image (such as to obtain as much information as possible about the image displayed) a characteristic flow of information, see Figure 4-3, may be predicted using ICS. In the text, each subsystem is identified by an acronym shown on the figure.

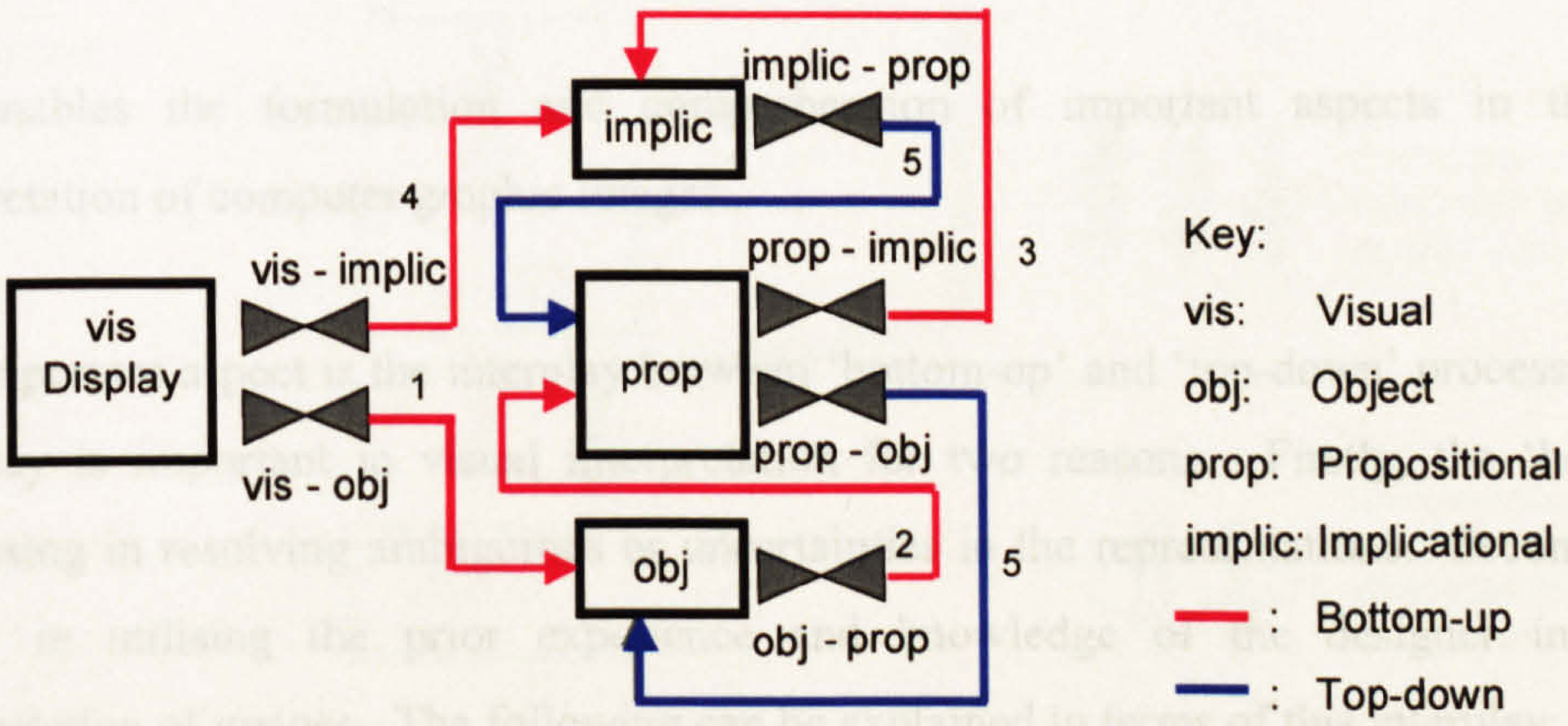


Figure 4-3: Cognitive resources during interpretation of an image (adapted from [266])

(a) 'Bottom-up' paths - Understanding meaning from visual information

The first path involves (1) vis-obj: extracting visual information (such as colour and shapes of objects) from the retinal image, (2) obj-prop: identifying the semantic (propositional) relationships from the information extracted (such as interpretation or identification of object boundaries, relationships of objects to other objects in the image) and (3) prop-implic: interpreting the implicational meaning relative to environmental contexts (such as affective content) from the identified semantic relationships.

In parallel, there is (4) vis-implic: extracting implicational meaning directly from the visual information, in addition to the interpretative and propositional route. There are certain aspects of visual field that give rise to direct implicational responses. For example, sharp objects or shapes may imply threats or hazards.

(b) 'Top-down' path - Construction of object level representation from meaning

In addition to these 'bottom-up' processes that take visual information to implicational meaning, there are 'top-down' processes (5) (implic-prop and prop-obj) that interact to construct an object level representation from meaning or understanding.

(c) Blending

Various streams of data that arrive into any subsystem (either from 'bottom-up' or 'top-down' processing or both) blend to produce a composite representation. For instance, the object representations that the visual subsystem produces (vis-obj) combine with the 'top-down' flow of representations being output by the propositional subsystems (prop-obj) to produce an integrated, object-based level of representation.

ICS enables the formulation and comprehension of important aspects in the visual interpretation of computer graphic images.

One important aspect is the interplay between 'bottom-up' and 'top-down' processing. This interplay is important in visual interpretation for two reasons. Firstly, the 'bottom-up' processing in resolving ambiguities or uncertainties in the representations. Secondly, 'top-down' in utilising the prior experience and knowledge of the designer in forming interpretation of images. The following can be explained in terms of this interplay:

- An existing mental model of what a designer expects to see ('top-down') is integrated (blended) with a consistent model of an image that the designer is actively viewing ('bottom-up') to form a rich composite interpretation of an image. This interplay influences the processes of visual interpretation, as the interpretation is not hindered by any ambiguity or uncertainty because of the designer's mental imagery (prior knowledge).

Another aspect is the role of 'top-down' processing:

- Generalising knowledge and matching patterns is a basic human trait in re-using prior experiences [278]. When prior knowledge is used, often knowledge of similar attributes is clustered (grouped) as a process of learning or as an aid to manage the complexity and re-use of prior knowledge [159, 278, 279].
- When a rendering system generates an image, the designer's 'top-down' processing ability is required to extract information from the images.

4.4.1 Cognitive levels of information

Based on the understanding of cognitive processing during visualisation and interpretation (see Figure 4-3), the relationship between *sensory*, *structural* and *meaning* subsystems is illustrated in Figure 4-4. This gives an overview of the different cognitive levels of information inherent in the generated computer graphics image.

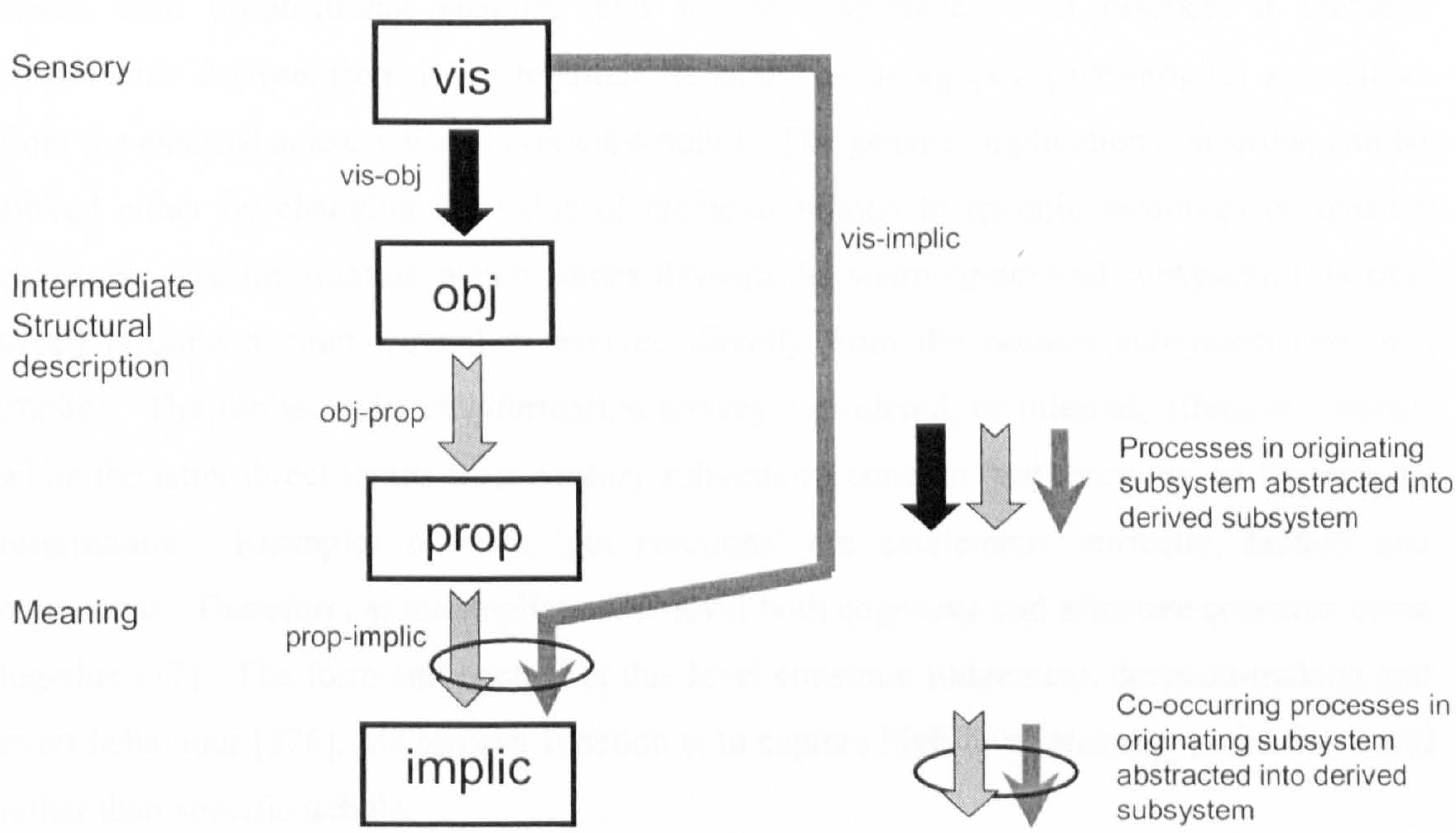


Figure 4-4: Cognitive levels of information [17]

From the incoming stream that arrives at the *sensory* subsystem (1) vis-obj: a *structural* description is derived, which is transformed into a (2) obj-prop: propositional *meaning* (by identifying semantic relationships from the information extracted), which then produces (3) prop-implic: implicational *meanings* (by interpreting the emotional meaning relative to the semantic relationships identified). In addition, from the incoming stream at *sensory* subsystem (4) vis-implic: implicational *meanings* are derived directly.

As seen in the figure, the cognitive processing from *sensory* to *meaning* subsystems indicates that the 'understanding' of an image is not just based on surface phenomena, e.g., the visual elements of the image, but rather involves deeper levels of relationship across different levels of *meaning*. *Sensory* and *structural* pertains to surface levels of cognition and *meaning* involves deeper levels of relationships across different levels. In addition, as seen in the figure, the prop *meaning* subsystem does not receive information directly from *sensory* subsystems, but mediates the flow of information between the *structural* subsystems and the higher-level *meanings* of the implic subsystem. This implies that prop subsystem constitutes low-level *meaning* compared to implic subsystem. The overall flow diagram illustrates that implic subsystem constitutes the most generic level of the ICS subsystems.

Further deliberations on implicational meaning

As seen in Figure 4-4, implicational *meaning* subsystem captures processes and co-processes across both propositional *meaning* and *sensory* experience. In essence, it includes constituents derived from the referential, semantic *meaning* (via prop-implic) as well as from the external *sensory* world (via vis-implic). The generic implicational *meaning* can be altered either by changing the value of elements related to specific *meanings* or *sensory* elements. The information which comes through the *meaning*-derived subsystem (via obj-prop) is quite distinct from that received directly from the *sensory* subsystem (via vis-implic). The former indirect information convey considered, or inferred, affective content, while the latter direct inputs from *sensory* subsystems concern 'gut reactions' to the *sensory* information. Examples of such 'gut reactions' are excitement, curiosity, fantasy and enjoyment. Therefore, at the implicational level both cognitive and affective concerns come together [17]. The form and content at this level constrain judgement, decision-making and overt behaviour [276]. Its broader function is to capture high-level *meaning* about the world rather than specific details.

4.4.2 Role and impact of implicational information

The aim of this section is to delineate the role and impact of implicational information in different contexts.

Sketch renderings of architectural design provoke an improved dialogue, compared to photorealistic renderings, between architects and clients [261]. This is because sketchiness conveys a sense of openness to change and modification. This effect is not just a matter of perception, but also involves levels of cognition connected with judgement and articulation [171]. In psychological terms, the sketch rendered image has an affective content, separate from its structural detail. Cartoonists use implicationally derived data such as sharp/threat, round/friendly paradigms in their drawings to convey emotions [266], apart from structural object information. Evidence that abstract, affect-related information is available separate from structural object information can be found in a number of experiments (e.g., [171, 280-283]). Two examples (each from an early and a recent experiment respectively) of emotive responses based on such affect-related information are summarised below:

Provins et al [282]: When asked to glance at a drawing of a radar display (Figure 4-5) and quickly identify which group (circles or triangles) of aircraft are *hostile* forces, nearly all respondents identified the triangular symbols.

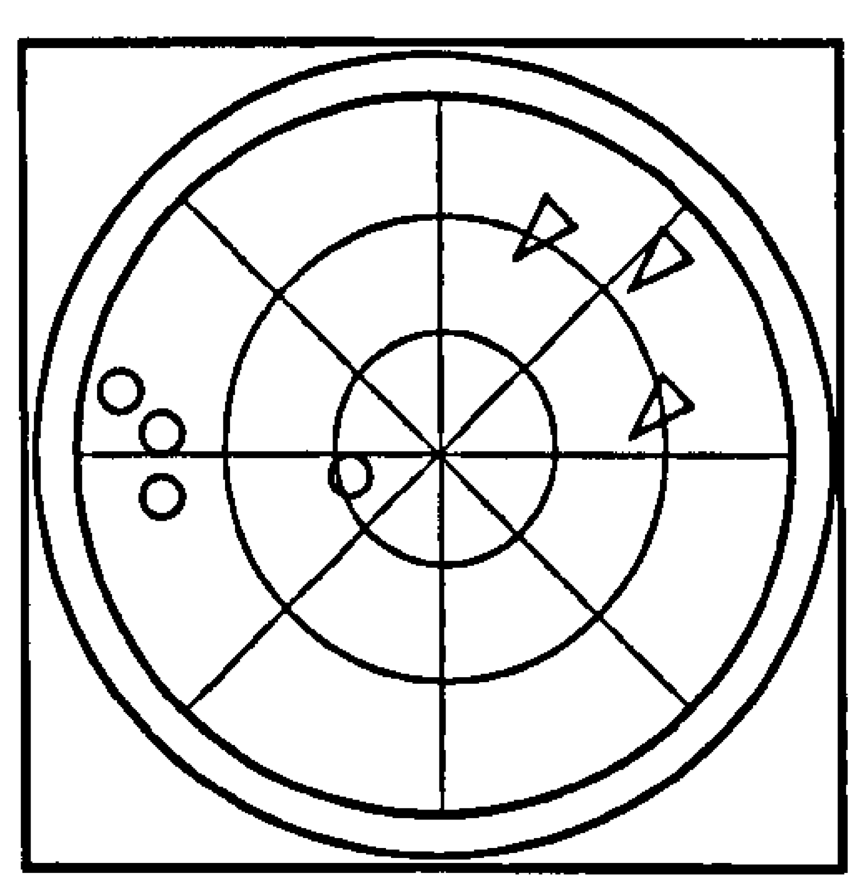


Figure 4-5: Radar display ([171], originally from [282])

Halper [283]: When asked to identify the door that contains danger (Figure 4-6), 67% respondents identified the jagged door on the extreme left, which features threat-connotative line styles, over the simple or wavy door.

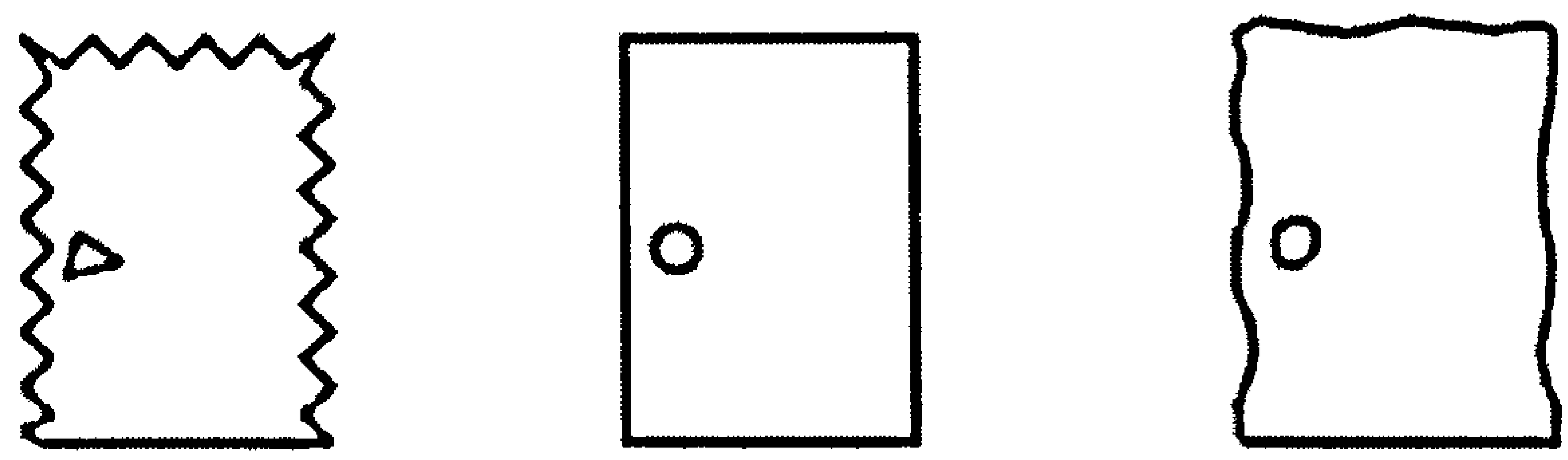


Figure 4-6: Identifying door with danger [284]

These examples illustrate that affective (emotive) information (for instance, in the above examples, *hostile* and *danger*) can be conveyed through qualities of shapes. The very nature of people justifying their assessments is characteristic of the involvement of implicational information in an image.

4.4.3 Rendering implicational information

The aim of this section is to delineate how implicational information can be mapped in a rendering system to convey the intended affect.

A feature of ICS is the relation of inverse mapping [266]. Inverse mapping involves working backwards from the cognitive architecture of ICS to yield insights into structure and functionality of a rendering system that generates the image. Such insights (i) illustrate the way designers perceive information to form interpretations, (ii) aid in deciding the type of information needed to be mapped in an image for better understanding and interpretation, and, in some instances, they may also provide subtle cues of (iii) the way designers need to perceive and (iv) the considerations that might be needed in deciding the information content of images.

For instance in ICS (see Figure 4-3), the propositional (prop) subsystem obtains information from both the object (obj) and implicational (implic) subsystems. This implies that, in general, for the propositional understanding of the displayed image (in other words, semantic or broad understanding), there are roles of both object and implicational information. The conclusion from ICS is that if both object and implicational information are mapped in an image may lead to its better understanding and interpretation.

Further explanation on inverse mapping of information is given by taking the simplest approaches to computer graphics, in which a computer model of an artefact is rendered. The information in an image for *visualisation and interpretation*, which ultimately leads to the propositional understanding of the displayed image, is derived from this computer model (see Figure 2-5). This information includes structural object information (representation that concerns shape, size, location, and orientation in an artefact) and also information about the intended affect. Evidence that abstract, affect-related, information is available separate from structural object information can be found in Figure 4-5 and Figure 4-6 (see Section 4.4.2 for further explanation).

Recent work on human animation, particularly in facial expressions, separated the basic geometry from the problem of configuring the geometry to capture expressions of mood and emotion [266]. This can be viewed as a first step towards separating, on the computer rendering side, the model that generates those aspects that are handled by the object and implicational subsystems on the human side. This separation is illustrated in Figure 4-7. In the figure, affect refers to emotive expressiveness or emotive properties [285, 286].

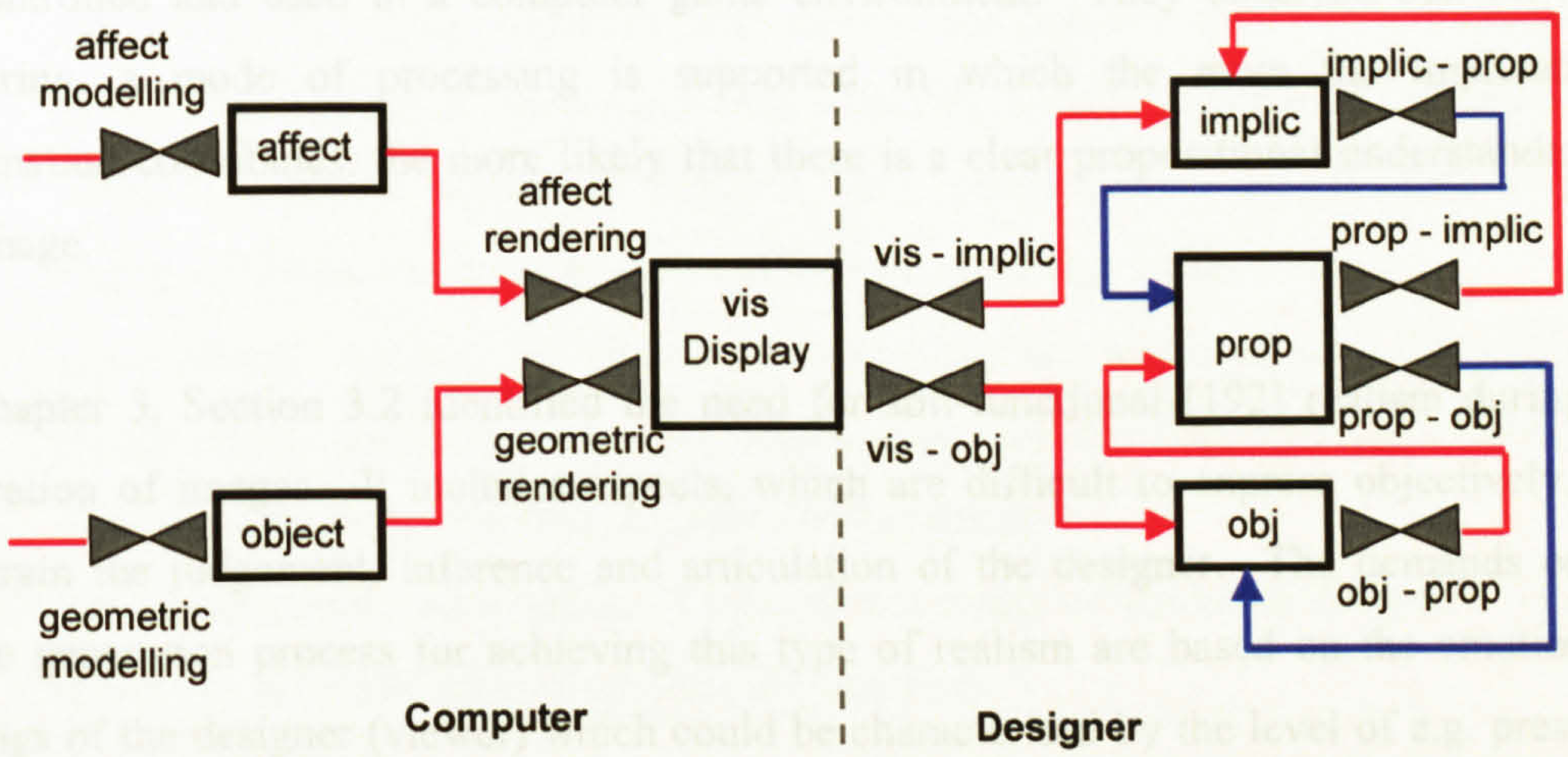


Figure 4-7: Trading of affect and object (adapted from [266])

On the computer rendering side, the separation of the two sources of information (object and affect) should be understood as two concerns. In practise, the cognitive process operating on the two sources of information for the propositional understanding of the displayed image is probably the same. That is, when interpretation is elicited, the blending of object and implicational information leads to propositional output that identifies the object with the intended affect.

Following this framework of separation are some works on NPR [205, 215, 216, 222, 243-246] that concentrated on modifying the drawing attributes that identify the object with the intended affect. In such works, the separation of object information and implicational information is made a *priori* and coded into the rendering algorithm.

4.5 Emotive implications

In this section, the notion of 'emotive implications' is introduced and defined as *the implicational information of images that imply or stimulate designers' emotive responses.*

The impetus for emotive implications stems from the role and impact of implicational information (see Section 4.4.2). The role and impact of implicational information has been outlined in a number of psychological studies (e.g., [171, 280-283]). Based on the evidence (e.g., [280-282]) that affective content is available, separate from structural object information, Duke et al [171] conducted a series of experiments to illustrate how rendering styles can convey implicational *meaning* and influence judgement, and how these effects can be controlled and used in a computer game environment. They observed that on using rendering, a mode of processing is supported in which the more the implicational information contributes, the more likely that there is a clear propositional understanding of the image.

In Chapter 3, Section 3.2 identified the need for soft-functional [192] realism during the generation of images. It includes aspects, which are difficult to express objectively, that constrain the judgement, inference and articulation of the designer. The demands on the image generation process for achieving this type of realism are based on the emotions or feelings of the designer (viewer) which could be characterised by the level of e.g. presence, excitement, comfort, recognition and detection. Such emotions or feelings pertain to high-level cognition. As can be seen in Figure 4-4 and delineated in Section 4.4.1, implicational *meaning* pertains to high-level cognition (emotional *meaning*) that is concerned with the emotive responses of the designer. Its broader function is to capture high-level *meaning* about the world rather than specific details. Thereby, soft-functional realism can be achieved through the presence of implicational information during the image generation process.

It is necessary, thereby, to determine the implicational information of images that contributes to (i) the propositional understanding of the images by the designers and (ii) soft-functional realism of the images. As such, *the implicational information of images that imply or stimulate designers' emotive responses* is termed here as emotive implications.

The importance and the inherent existence of implicational information in images and its potential in rendering have been recognised (see Section 4.4). However, nothing in CAD bears directly on the emotive implications of images.

4.6 Chapter summary

This chapter has presented a cognitive framework of human information processing between the visualisation of a generated computer graphics image and its interpretation. With the understanding of cognitive processing during visualisation and interpretation, it can be summarised that:

- There are four cognitive levels of information inherent in images: visual (*sensory*), object (*structural*), proportional and implicational (*meaning*).
- The two levels of *meaning*, propositional and implicational, are distinct. The propositional level is concerned with the referential knowledge, that is 'facts about the world', including properties and relationships between entities. In contrast, the implicational level is concerned with affective content relative to environmental contexts. In the words of Barnard [20], propositional and implicational are distinguished as non-emotional and emotional *meanings* respectively.
- Implicational *meaning* in cognitive processing is connected to a high-level of representation that brings affect (emotive response) into cognition. In essence, this level pertains to the emotive responses of the designer.
- The implicational information of images that imply or stimulate designers' emotive responses is termed here as emotive implications.
- It is necessary to determine emotive implications, since such emotive implications contribute to (i) the propositional understanding of the images and (ii) soft-functional realism in images.

Sections 4.4 and 4.5 described in this chapter provide the basis (1) to establish the key aspects for *visualisation and interpretation* (presented in Chapter 5), where the key aspects provide the basis for a critique of existing studies in rendering in Chapter 5, and (2) for the identification of emotive implications of computer graphic images as discussed in Chapter 7.

5. A critical review of existing works in rendering

The aim of this chapter is to present a critical review of existing works in rendering. The objectives are to (i) identify the inadequacies of these works that will need to be overcome in order to more comprehensively support rendering in conceptual design to enhance HCS and (ii) formalise the research problem based on the highlighted deficiencies of these existing works.

Prior works in rendering fall into two areas: (i) development of rendering systems for the generation of computer graphic images and (ii) studies on visualisation and interpretation of the generated computer graphic images. The literature reviewed in this chapter considers the relevant works within these two areas that were identified as the research focus in Chapter 2 (Step 3 and Step 4 in Figure 2-8).

In Sections 5.1 and 5.2, summaries and critical reviews of relevant existing works are presented in the areas of rendering systems for the generation of computer graphic images (Step 3) and visualisation and interpretation studies of the generated computer graphic images (Step 4) respectively. The works are critically reviewed with respect to a set of key aspects, which are defined in Sections 5.1.1 and 5.2.1 respectively.

Section 5.3 summarises the critical review by highlighting the deficiencies of existing works with these two areas and then formalises the research problem. Finally, Section 5.4 presents a summary of the chapter.

5.1 Rendering systems

The 1990s has seen the emergence of a number of rendering systems, the most relevant of which are summarised and critically reviewed in this section. The critical review is provided with respect to the key aspects for the generation of computer graphic images.

5.1.1 Key aspects for the generation of computer graphic images

The following key aspects for the generation of computer graphic images whilst rendering (Step 3 in Figure 2-8) are derived from the literature in Chapters 2 and 3 and the understanding of HCS in conceptual design (see Section 2.3):

1. **Computational requirements**: For an economical rendering, it should be possible to generate images using low resources such as memory storage, time.
2. **Intelligent Design Assistant (IDA) philosophy**: The computer to play the role of an Intelligent Design Assistant [55], that can be an active partner to the designer and actively participate in the image generation process (see Section 2.3.1 for information of the roles of a designer and an IDA in a CAD scenario).
3. **Realism**: Each variety of realism uses different criteria to determine if the image is realistic and thereby place different demands on the image generation process. The generated image should be characterised by:
   - Functional realism [177]: The demands on the image generation process for achieving this type of realism are based on the visual information the image provides. The generated computer graphics image should be capable of providing knowledge about the properties and relations of objects in a scene allowing a designer to make reliable visual judgement and to perform visual tasks.
   - Soft-functional realism (Emotive expressiveness): The demands on the image generation process for achieving this type of realism are based on the emotions or feelings of the designer (viewer) which could be characterised by the level of e.g. presence, excitement, comfort, recognition and detection. The generated computer graphics image should be capable of broadening the designer's ability to communicate such emotive information along with the object information.

   In practise, the generated image has to provide a balance between functional and soft-functional realism.
4. **Sketchy input**: To offer freedom to draw sketchy, rough drawings.
5. **Sketchy output**: To allow a sketchy style, which is an essential stimulus to the designer's imagination, of rendering to compensate for lack of detail in the computer generated image. This also refers to the ability to capture vagueness or vague information inherent in design sketches, maintain sketchy presentations and generate alternative representations to visualise different concepts.

5.1.2 Existing systems

This section presents a brief overview of the following rendering systems (see Table 3-3 in Chapter 3 for more examples of the representative works of PR and NPR), before evaluating them with respect to the key aspects in Section 5.1.3

a) PR based

1. RADIANCE

RADIANCE [52] is a physically based rendering system developed by Ward, with the goal to produce an accurate tool for lighting simulation and visualisation based on ray tracing. The term physically based rendering in the work is used to refer to rendering techniques based on physical principles of light behaviour for local and global illumination. Accuracy, generality and practicality are the challenges for the majority of lighting design and architectural applications. The principle design goals of RADIANCE were to ensure accurate calculation of luminance, model electric light and daylight, support a variety of reflectance models, support complicated geometry and take unmodified input from CAD systems.

The simulation uses a ray tracing method with extensions to handle specular, diffuse and directional-diffuse reflection and transmission in any combination to any level in the environment. The simulation blends deterministic and stochastic ray tracing techniques to achieve the best balance between speed and accuracy in its local and global illumination methods. RADIANCE has been used to solve problems for better lighting design over the years. The results have been grouped into two application areas, electric lighting problems and day lighting problems.

2. FLY

Ignatenko et al [198] presented a system, FLY, for real-time realistic rendering of 3D scenes. The system integrates different local and global illumination techniques using ray trace. Their system is aimed at providing physically correct visualisation to the extent possible by the modern graphics hardware. The system supports natural sunlight illumination, complex BRDF (Bidirectional Reflection Distribution Function [287]) materials, real-time specular reflections, integrated computations of illumination maps and lighting textures, tone mapping and control. Usually BRDF materials are required for visualisation of car paints and other complex metallic surfaces, e.g. in automative design. The main requirements of the system are physical realism and rendering speed to the extent possible by modern hardware [198]. Ignatenko et al presented solutions to integrate different global and local illumination techniques while keeping the rendering at interactive frame rates. FLY is based on modern rasterisation hardware. An advantage of rasterisation is high speed due to extensive hardware support.

b) NPR based

1. DeCarlo and Santella's system

DeCarlo and Santella [227, 288] presented a system, which involves a computational approach to stylising and abstracting photographs.

A human user interacts with the system to identify meaningful content of the image, by simply looking at the photograph for a short period of time. A perceptual model translates the data gathered from an eye-tracker into predictions about which elements of the image representation carry important information. The simplification process thereby applies a range of transformations, including collapsing away details, averaging across regions and overlaying bold edges, in a way that highlights meaningful visual elements. Thus the system transforms images into a line-drawing style using bold edges and large regions of contrast colour. Since the approach is aimed at abstraction, not at realism, it falls within the field of NPR.

It is opined that eye movements over imagery are directed in a meaningful and economical manner, and are tightly linked to cognition. Basically, this approach analyses eye movement and provides an objective measure of cognition. Regardless of the context in which the user is viewing the image, the common factor is the act of looking. This mediates all information that passes from the display to the user. Thereby, the rendering, of preserving the form predicted to be meaningful, is based on a user's observation of the original image. The authors felt that drawing such conclusions about rendering based on cognitive processes by observing eye movements is reasonable due to the close connection between cognition and looking.

2. OpenNPAR

Halper et al [289] provided a modular rendering system, OpenNPAR, that fits the needs for NPR image generation, which perform basic operations on images or 3D models and can be linked together to achieve certain visual effects. Based on this system, a user interface is provided that enables and encourages the user to 'play with ideas' in order to combine modifiers that affect the rendering pipeline without actually having to write any code. Each application of an idea generates a new image, such that each image in the process of the evolved idea can be seen. Visual feedback is provided to the user at any time and for any stage in the process. The basic idea of OpenNPAR is that instead of mimicking a visual effect that an artist has already produced, the process undergone by the artist to produce the image is mimicked.

The system [170, 284, 289, 290] provides support for a range of users (developers, programmers, designers) to create new visual effects without technical knowledge of how the effects are generated. This system is in contrast to other rendering systems, which demand the technical expertise to directly specify parameters in order to achieve the desired effects. It is comprised of modules that can be fitted arbitrarily into a rendering pipeline, which then compute, based on known psychological effects of NPR, the presentation style most likely to achieve the desired effect, while mimicking a designer's creative process with a novel interaction method. The effects achieved by OpenNPAR, range from silhouettes through interactive illustration, real-time shading to animation [290]. The effectiveness of the system lies in the flexibility of available modules.

3. <u>Piranesi</u>

Schofield [206] developed a prototype system, Piranesi, that gives users a wide variety of automatic rendering styles ranging from the almost PR, through the styles resembling artists' sketches or paintings, to abstract renderings of entirely new forms. The rendering system is much like a painting tool, allowing the user to paint on the model, and uses high degrees of automation in the final illustration. The basic approach of the Piranesi system is a standard rendering pipeline and human-interaction to drive the image creation.

The Piranesi system [206, 234, 248, 291] succeeds in shifting the boundary between the rendering and the finishing stage, making much more of the process direct and interactive. A basic rendering is made, without textures, and exported to Piranesi with a z-buffer, which gives the distance to each pixel, and a material buffer which encodes the layer or material in the model from which it is derived [291]. The presence of the z-buffer gives Piranesi many new capabilities of rendering including perspective space effects apart from image space effects. By using the z-co-ordinate to modulate painting effects, it becomes sensitive to depth. By differentiating the z-buffer, it can reconstruct the surface normal and so becomes sensitive to orientation. By differentiating twice it can recover curvature and detect physical edges. Thus, it reflects the perspective of the image and many other depth-related effects. In addition, the system saves temporary buffers to allow the user to revert to previous states, and the user can save and work on an image at a later date.

Piranesi is unique among painting systems because it does not need selection tools to limit painting to particular tasks. In traditional paint systems, the workflow keeps braking because of the selection for every operation. Piranesi instead uses *Locks* to constrain painting either by material or by geometry. It avoids numeric input and is very close of being keyboard free [291]. The major advantage of this system is a method that produces better, more varied images through a process that is much more rewarding and accessible than standard rendering systems [234]. Piranesi is an alternative to time-consuming, computationally expensive rendering that allows the user to iterate on the image rather than experiment with parameters, a process more intuitive to designers and artists [234]. Piranesi can achieve the effects of conventional PR, but is more realistic with NPR.

4. Saito and Takahashi's work

Saito and Takahashi [190] proposed a rendering system that produces 3D images with enhanced visual comprehensibility. Shape features can be understood if certain geometric properties are enhanced. Drawing algorithms such as discontinuities, edges, contour lines and curved hatching are developed to achieve enhancement. The algorithms are realised with 2D image processing operations so that they can be efficiently combined with conventional surface rendering algorithms.

The geometric properties are preserved as a set of G-Buffers (which are obtained by forming projection views and removing hidden-line surfaces). The basic enhancement operations are performed using G-Buffer contents during post-processing. Physical and artificial processes in rendering can use G-Buffers formed during geometric processes as well. Usually the rendering processes can be separated into the following three groups:

- Geometric processes, which are based on geometric factors such as object shapes and camera parameters.
- Physical processes, based on physical (optical) factors such as reflectance, colours and textures.
- Artificial processes, based on psychological or artistic factors (e.g., enhancement).

Since the G-Buffer set contains no physical (or optical) properties such as reflectance or colours, PR techniques can be used in post-processing. The premise is that most technical illustrations are clearer than photographic representations through their use of edge drawing and hatching techniques. The final intention is to add this extra layer of delineation on top of PR images.

By preserving geometric properties in G-Buffers and visualising properties in post-processes, various combinations of enhancement techniques for the original scene can be examined and a user can select the best enhancement technique efficiently. Therefore, this method is considered very powerful and flexible regarding concept for various purposes.

5. Salisbury et al's system

Salisbury et al [217] presented an interactive system for creating pen-and-ink illustrations. The system uses stroke textures, which are collections of strokes arranged in different patterns, to generate texture and tone.

The system places an emphasis on using continuous tone images as a reference for the user and thus provides a form of 'interactive digital half-toning' in which the user can introduce texture as an integral part of the resulting illustration. Since texture in an illustration is the collective result of many pen strokes, each individual stroke is not critical and need not be drawn precisely. A certain amount of irregularity in each stroke is desirable to keep the resulting texture from appearing too rigid or mechanical. Rather than focusing on individual strokes, the system tries to support directly the cumulative effect that the strokes can achieve: texture, tone and shape. The user paints with a desired stroke texture to achieve a desired tone and the computer draws all of the individual strokes. The system also allows users to draw individual strokes and provide controls for modifying stroke character through smoothing and substitution of various styles. To further aid the users in creating illustrations, the system allows scanned, rendered or painted images to be used as a reference for tone and shape. The system also supports edge extraction from images, which is useful for outlining. Finally, a range of editing capabilities is supported so that users are free to experiment or make mistakes. Thus, the overall goal of the system is to enable a user to easily generate effective and attractive illustrations directly on a computer.

6. Sketch-renderer

Strothotte et al [215] showed the design and implementation of a system, 'sketch-renderer' [215, 261, 292], for rendering sketches that are similar to the hand drawings with a pencil. Such sketch renderings differ from the usual PR or wire-frame output. The techniques for rendering such sketches allow the user to adjust the rendering of a scene to produce images using primitives with variable degrees of precision, from approximations that resemble sketches to more mature but still hand drawn images. They have shown that the extra degrees of freedom available widen the scope of possible alternative images.

The input of the 'sketch-renderer' is a 3D model in the standard format that is commonly used in CAD software. The 'sketch-renderer' first produces a wire-frame image as is normally produced in CAD. In order to give the user full control over the style of a presentation, the 'sketch-renderer' strictly separates the geometric model from the stylistic information that can be assigned to single objects. This enables the 'sketch-renderer' to read in models that were perhaps intended for another renderer, while keeping separate the stylistic information of which only the 'sketch-renderer' makes use. The user can tune the following parameters with the 'point and click' method using the interactive sketch editor:

- Line styles with width, edge quality, contour, waviness, colour saturation progression, length of segments, variation of segments from baseline and connection of segments, and
- Hatching styles with density of lines, line pattern, angle of lines, segmentation of hatching lines and deviation from regular hatching.

These parameters can be combined with each other, e.g. lines used for contours may be different from those used for cross-hatching. Hatching can be used to represent textures and shadows. With use of different widths and brightness of lines, it is possible to express different levels of detail. With lines of different brightness, the effect of depth-cueing can be stimulated. Lines with different width at the end and beginning can depict the surface shape of an object. Such differences in combination with different levels of detail and density of contours are used to direct the viewer's attention to a particular part of the picture. With 'sketch renderer' the user can produce more individual views of an object being planned, which is relevant in early stages of design.

5.1.3 Critique

In this section, the aforementioned systems are critiqued with respect to the key aspects outlined in Section 5.1.1.

1. Computational requirements

All the PR systems summarised in Section 5.1.2 have high computational requirements. To achieve a realness aspect in images, which match the appearance of the real environments (e.g. [52]), demands high resolution, which consumes high resources in terms of memory storage and time. Ignatenko et al's system [198], FLY, uses ray trace method which requires considerable computation time to generate realistic displays. The basic precondition to achieving such realistic displays is physically based lighting simulation, which is computationally demanding [241]. After modelling, to generate a PR image the designer needs to spend time setting lights, perspectives, applying textures and adjusting material properties in order to generate an image. All these issues place demands on high computational requirements for photorealism.

In comparison, the artistic rendering styles of NPR reduce computational requirements for geometric modelling, computation time and storage. For instance, pencil-like drawings [215, 261, 292], abstract renderings [206, 234, 248, 291], pen-and-ink illustrations [217] and line-drawing styles using bold edges and large regions of contrast colour [227, 288] require less storage and bandwidth than the streaming PR views.

2. Intelligent Design Assistant (IDA) philosophy

None of the summarised PR and NPR systems supports the IDA philosophy. This is because the existing systems either:

- Expect the designer to create the image from scratch (such as setting lights, perspectives, applying textures and adjusting material properties in order to generate a pleasing image [52, 198]) using complex interaction. Or
- Generate the image through automatic techniques (post-processing) using non run-time interaction. Examples of this trend include:
  - conversion of scanned images to pen-and-ink illustration [217],
  - create pencil-like drawings to the output of a renderer [215, 261, 292],
  - enhance visual comprehensibility of PR images in post-processing [190], and

- act as a re-rendering system [291], where the imported original image is retained throughout the process and is sampled in various ways as the new image is painted.

Adopting an IDA philosophy in the generation of computer graphic images whilst rendering is an interesting area for research, where there is an interactive and intelligent partnership between a designer and computer in the creative activities involved.

3. Realism

None of the summarised PR systems [52, 198] support functional or soft-functional realism. This is because the goal of such systems is photorealism, which produces the same visual response as the real environment. PR aims to create an image that is indistinguishable from a photograph of a scene and not a functionally realistic image that provides the observer with information about the properties and relations of objects. The 'completeness' and 'correctness' in PR images do not broaden the designer's ability to communicate thoughts, emotions and feelings through computers, thereby do not support soft-functional realism.

NPR, in comparison, represents a form of functional realism [230]. The NPR images are functionally realistic in that they provide the observer with information about the properties and relations of objects in a scene. For instance, pencil-like drawings [215, 261, 292], abstract renderings [206, 234, 248, 291], pen-and-ink illustrations [217] and line-drawing styles using bold edges and large regions of contrast colour [227, 288] provide the observer with information about the properties and relations of objects. Further, they qualitatively improve the dialogue between the architects and clients, in contrast to PR images.

NPR, in general, is capable of broadening the designer's ability to communicate thoughts, emotions and feelings through computers [201]. However, the systems currently reviewed here have focussed more on the functional than on the soft-functional aspects.

4. Sketchy input

None of the summarised PR systems support sketchy input [52, 198]. This is because PR systems tend to support precise input, where the light sources and optical characteristics of all the materials and surfaces are specified. PR systems are concerned with rendering images as 'realistically' as possible ([52, 198]), which demands a precise unmodified input from

CAD systems. The demands of PR for a precise model limit the opportunity to draw sketchy, rough drawings.

In NPR, out of the reviewed seven systems, only OpenNPAR and Piranesi support sketchy input:

- OpenNPAR [289] provides a user interface, called sketchpad, for quickly and easily designing images or scenes, without having to write any code. The main goal of the sketchpad is to capture the designer's creative process in generating ideas and visual effects.
- Piranesi [291] uses a tablet with a pressure sensitive stylus to paint effects on the imported 3D image. The feeling of complete connection between 'what you do is what you see' is stronger with tablet and stylus.

The mode of input for the remaining systems, other than DeCarlo and Santella's system [227, 288], is a 3D model in standard format to which:

- Basic enhancements operations are performed to create images with enhanced visual comprehensibility [190].
- Stroke textures are used to generate texture and tone for creating pen-and-ink illustrations [217]. In such systems, scanned or painted images are also supported as a mode of input to create illustrations.
- Line styles and hatching styles are fine-tuned using interactive sketch-editor to produce sketchy renderings [215, 261, 292].

In DeCarlo and Santella's system [227, 288], the method of input is different compared to other rendering systems. This is because an image or a photograph is selected for transformation and is displayed on the screen in the presence of an eye-tracker. The image is transformed to a line-drawing style, preserving the form predicted to be meaningful, by applying a model of human visual perception to the eye-movement data.

5. <u>Sketchy output</u>

PR is concerned with rendering images as realistically as possible via the integration of physics and rendering algorithms. The PR image is defined by the basic principle of appearing realistic as much as possible. Thereby, images created by PR techniques [52, 198] tend to look monolithic and finished. Such systems limit the ability to present vagueness, maintain sketchy presentations and generate alternative representations to visualise different concepts.

In NPR, to obtain sketchy output, imprecision is introduced in the post-processing. Although most of the reviewed NPR systems maintain a sketchy output, they do not capture the inherent vagueness of design sketches in conceptual design, since the information is already lost by the time the model reaches the post-processing stage. The following is a closer look at the remaining features of sketchy output (such as maintain sketchy presentations and generate alternative representations to visualise different concepts) in such systems:

- DeCarlo and Santella's system [227, 288] supports sketchy presentations. This is because the system transforms images into a line-drawing style using bold edges and large regions of contrast colour.
- OpenNPAR [170, 284, 289, 290]: The system, in overall, supports sketchy presentations and generates alternative representations to visualise different concept ideas. The modifiers in OpenNPAR influence the rendering output so that it produces a certain variation. Examples of such modifiers used include: scene modifiers (light intensity filter and base colour), stroke modifiers (silhouette generation, stroke thickness and stroke waviness) and image modifiers (lighten, dither and selector). These modifiers could be combined and connected to create desired effects or variations that range from silhouettes through illustrations, cartoon shading, pencil sketch shading to animation. Thereby, this system enables and encourages users to 'play with ideas' in order to combine modifiers that affect the rendering output. The users may take any image in their creative process and start a new direction of ideas. Each application of an idea generates a new image, such that each image in the process of an evolved idea can be seen.
- Piranesi system [206, 234, 248, 291] provides an alternative way of producing a range of images from the same geometric model. The system has the 'feel' of a paint system, where the user can 'paint' various effects into the CAD generated image. These effects range from artists' sketches and paintings, to abstract renderings of entirely new forms.
- Saito and Takahashi's system [190]: The goal of this system is comprehensible rendering of 3D shapes. The shape features are enhanced by discontinuities, edges, contour lines and curved hatching, which reflect sketchy presentations. By preserving geometric properties in G-Buffers and visualising properties in post-processes, various

combinations of enhancement techniques for the original scene can be examined and the user can select the best enhancement technique effectively.

- Salisbury et al's system [217] support sketchy presentations. This is because the system uses stroke textures for creating pen-and-ink illustrations. A certain amount of irregularity is maintained in each stroke for the resulting texture to appear rough, not rigid or mechanical.
- 'Sketch renderer' [215, 261, 292]: The images of 'sketch renderer' appear hand-drawn. Such drawings are characterised by the non-uniformity in line-quality due to irregular movements of the drawing hand as well as the changes in the drawing instrument and thereby support sketchy presentations. Strothotte et al [215] demonstrated that the extra degrees of freedom available widen the scope of possible alternative images.

Table 5-1 presents a matrix summarising the critical review of the existing rendering systems for the generation of computer graphic images. With regard to the table, for each work, a tick indicates that the key aspect, or an associated feature, is supported. Conversely, a cross indicates that support is not provided.

Table 5-1: A critical review of existing rendering systems (Step 3)

Key: √ Yes
× No

Existing rendering systems			Key aspects for the generation of computer graphic images							
					Realism			Sketchy output		
			Computational requirements	Intelligent Design Assistant (IDA) philosophy	Functional	Soft-functional	Sketchy input	Alternative representations	Sketchy presentations	Vagueness
	PR	RADIANCE	High	×	×	×	×	×	×	×
		FLY	High	×	×	×	×	×	×	×
	NPR	DeCarlo and Santella	Low	×	√	×	×	×	√	×
		OpenNPAR	Low	×	√	×	√	√	√	×
		Piranesi	Low	×	√	×	√	√	√	×
		Saito and Takahasi	Low	×	√	×	×	√	√	×
		Salisbury et al	Low	×	√	×	×	×	√	×
		Sketch-renderer	Low	×	√	×	×	√	√	×

5.2 Visualisation and interpretation studies

In contrast to the majority of the works on the development of *rendering* systems for the generation of computer graphic images discussed in Section 5.1, most of the works summarised and critically reviewed in this section have placed an emphasis on the information that passes from the display to the user and the user's perception of the displayed image (Step 4 in Figure 2-8). Such works conducted user perception studies (which are termed as visualisation and interpretation studies, in the context of this thesis) to investigate the communication adequacy of the rendering techniques or rendering systems in presenting the desired information. These studies are summarised and critically reviewed in this section. The critical review is provided with respect to the three key aspects for visualisation and interpretation.

5.2.1 Key aspects for visualisation and interpretation

The key aspects for visualisation and interpretation (Step 4 in Figure 2-8) are derived from the understanding of a cognitive framework of human information processing, between the visualisation of a generated computer graphics image and its interpretation, Chapter 4. This section introduces additional aspect 'effectiveness' as a key factor for evaluating the studies in rendering.

1. Cognitive levels of information

There are different levels of information inherent in the generated computer graphic images: sensory (visual), structural (object) and meaning, wherein there are two levels of meaning: propositional and implicational (see Figure 4-4). Propositional meaning regards specific semantic relationships and is usefully thought of as specific, "cold" and "rational". On the other hand, implicational meaning in cognitive processing is connected to a high-level of meaning that brings affect (emotive response) into cognition and is usually thought as both generic and potentially "affect-related". In essence, it pertains to the emotive responses of the designer.

2. Emotive implications

Emotive implications of images reflect the implicational information of images that imply or stimulate designers' emotive responses. It is necessary to determine emotive implications, since they contribute to (i) the propositional understanding of images and (ii) soft-functional realism of the images.

3. Effectiveness

In the computer graphics community, it is necessary to measure the ability and effectiveness of an image to communicate the designer's intent and expectation. Wherein effectiveness identifies which of the rendering techniques, in a given situation, is the most effective at communicating the desired information. The concept of effectiveness depends on both the capabilities of the perceiver and the communicative capabilities of the rendering technique.

The concept of effectiveness has long been a difficult problem for the HCI community, even if not addressed directly [293]. The Handbook of HCI [294] does not even index effectiveness or efficiency [293]. Mackinlay [295] identified effectiveness as one of the criteria for graphical presentations in the context of graphic design issues. Often effectiveness is considered from an objective point of view; that is, the assessment considers only the nominal outcome of an interaction rather than the subjective quality of the interaction from the standpoint of the respondents [293].

Current approaches to measurement of effectiveness tend to be indirect: they measure factors associated with effectiveness rather than effectiveness itself [293]. For instance, Agarwala [296, 297] demonstrated the effectiveness of his map design system, based on NPR, using attitudes and feedback from real users in a survey. The approach has been proven to be valuable since the survey assessed the attitudes of users, which have been linked to output factors like performance of the system. In another instance, an early study [298] looked at the time required to judge the position of features in photos and hand rendered illustrations in different styles such as shaded drawing, line drawing and cartoon. The study concluded that faster responses provided clearer illustrations. In such work, illustrations were judged effective based on the speed with which details were perceived.

The above examples indicate that effectiveness could be based on a number of factors. For example, the rendered image of a design can be judged effective when it can be interpreted accurately or quickly, when it has visual impact, or when it can be rendered in a cost-effective manner. The concept of effectiveness of a rendering technique is not very useful without a method of generating alternative rendered images of a design for comparison. The effectiveness of a particular rendering technique can be evaluated by proper use of psychological measures ranging from statistical analysis of user selection or user performance tasks to analysis of cognitive information processing for the selection [284]. That is, if the users are statistically better at performing tasks, given a certain type of rendering technique, then those rendering techniques are said to be more effective or support a given task through better communication.

5.2.2 Existing studies

The existing studies in rendering can be broadly divided into two categories depending on the methodologies used to evaluate the rendering techniques or rendering systems [299, 300]:

1. Survey-based: This method involves polling a representative number of respondents and collecting their opinions to find out how they respond to the rendering system (or its output).
2. Behavioural-based: In this method, respondents perform specific tasks on the sets of images from the rendering system (or its output). Relative task performance is then related to the effectiveness of the image.

In the remainder of this section a brief overview of each of the studies is given, before evaluating them with respect to the key aspects in Section 5.2.3.

a) <u>Survey-based</u>

1. <u>Rodger and Browse</u>

Rodger and Browse [301] conducted a series of experiments to assess the contributions of rendering parameters, such as occluding contour, smooth shading and specular highlights, to the perception of the shape of 3D objects. The goal of their investigation was to see how well a respondent could judge the global shape of a graphically depicted 3D object.

Observers viewed graphically rendered displays consisting of pairs of rotating objects and judged whether the shapes were the same or different (on a separate response sheet).

From the experiment, they found that contour information functions as a powerful cue for perceiving details of 3D shape and that diffuse shading adds measurably to the apprehension of object shape. Moreover, specular highlighting relates to the material properties or object identity.

2. Schumann et al

Using user surveys, Schumann et al [261] demonstrated the effectiveness of a rendering system 'sketch-renderer' (more details of the system could be seen in Section 5.1), which produces images that appear hand-drawn. They surveyed architects for their impressions of the output of the 'sketch-renderer' compared to standard output of CAD systems for architectural designs. Based on the results, they argued the suitability of sketchy renderings for conveying the impression of tentative or preliminary plans.

An empirical study was conducted with fifty-four architects and three computer generated images: a CAD plot (ordinary wireframe image with hidden-line removal, produced using AutoCAD), a shaded image (generated by 'RenderMan' renderer) and a sketch generated image (produced by 'sketch renderer'). After being shown the images, the respondents were asked various questions based on the usability of computer-generated images with respect to communicative goals. The responses were recorded on a five-point Likert scale [302].

The results showed that each of the rendering styles have a very different effect on viewers.

b) Behavioural- based

1. Duke et al

Duke et al [171] conducted a series of experiments to assess the affect of NPR styles on users' decisions and judgements in a computer game environment.

The overall experiment comprised of nine tests and a post-test questionnaire regarding age, gender, experience with computer games and attitude towards NPR. The tests were according to type: (1) assessment of danger and safety, (2) assessment of strength and weakness, (3) NPR world versus PR world expectation, and (4) goal-directed interactions. In each experiment, the respondent, under time pressure, had to make a judgement based on a displayed image. Respondents' responses and response times were recorded, along with demographic data.

They used a model of cognitive information processing to account for rendering and judgement results. The results demonstrated that the rendering styles have a significant effect on interpretation and that this effect can be controlled through NPR techniques such as stylised silhouettes. The experimental results suggested that computer game graphics can be extended by using NPR to (i) provide connotative effects and (ii) convey cues (particularly to novice players) about possible and appropriate actions, specifically relevant cues about the level of threat of objects or locations in an environment and (iii) provide guidance for choosing between options, such as which path to follow. The results confirmed that an NPR style could be applied in computer games and virtual reality [283].

2. Ferwada et al

The goal of Ferwada et al's study [26] was to determine if advanced rendering methods such as global illumination allow designers to make more accurate visual evaluations of their designs than standard rendering methods using lighting and shading parameters. Moreover, they intended to test how an additional factor such as viewpoint affects the ability to discriminate shape.

Two psychophysical experiments were conducted to measure respondents' sensitivity to shape differences between a physical model and rendered images of the model. In such experiments, the respondents compared rendered images of an object to its real physical counterpart, and further it was tested whether they were able to make fine discriminations of shape with advanced renderings than with standard renderings. The respondents were presented with a series of rendered images. For each image they were asked to rate how different the shape shown in the image was with respect to the shape of the physical model.

It was found that the type of rendering method used had a significant effect on the ability to discriminate shape. In particular, global illumination rendering improved sensitivity to shape differences; and viewpoint appeared to have an effect on the ability to discriminate shape. The results of their study had important implications for understanding of shape perception and for development of rendering tools for computer aided design. The conclusion drawn from the study was that global illumination rendering provides better visual information of shape differences and allows better discrimination of shape.

3. Gooch and Willemsen

Gooch and Willemsen [230] evaluated and validated the communication adequacy of NPR techniques within an immersive environment. A methodology was presented for quantitatively evaluating space perception in an immersive environment. The intent of the study was to determine how the functional realism of NPR could impart a sense of space to people viewing an immersive environment. In such work, a quantitative study evaluating one aspect of space perception, such as depth[21], in NPR immersive environments was described.

The experiment focussed on respondents' ability to walk blindly to a target location in order to understand spatial perception in an NPR immersive environment. The goal of the experiment was to perceive depth when they performed a direct walking task in a real (physical) hallway and in an environment, which was rendered only with feature edges (boundaries, creases and silhouettes drawn in black) and viewed through a HMD. The focus was on the perception of absolute egocentric distances in immersive environments. Absolute egocentric distance was defined to be the actual metric distance between an observer and an external object.

The results showed that there was a significant difference in performance between the real world condition and the immersive feature edge environment. The perceived distance was found to be 97% of the intended distance in the real world condition and 66% in the feature edge condition.

4. Gooch et al

Gooch et al [299, 305] presented an NPR method for creating black-and-white illustrations from photographs of human faces and, in addition, caricatures that highlight and exaggerate representative facial features. To illustrate the effectiveness of the resulting images (from facial illustration and caricature algorithms), the performance of respondents on recognition and learning tasks using photographs and NPR images of faces was compared.

In such tasks, the respondents were presented with facial illustrations, caricatures and photographs generated from caricature generated software to assess respondents' accuracy and speed in both recognition and learning tasks. The images were presented to the respondents in different combinations/conditions for each task.

The studies illustrated that the facial illustrations and caricatures generated using NPR techniques were as effective as photographs in recognition tasks. For the learning task, illustrations were learned two times faster than photographs and caricatures were learned one and a half times faster than photographs.

[21] Depth perception is particularly important in immersive environments and is controlled by several physiological and pictorial cues, including accommodation, convergence, familiar size, relative size, eye height, texture, shading, and motion parallax [230, 303, 304].

5. McNamara and Chalmers

McNamara and Chalmers [28] built an experimental framework for measuring perceptual equivalence (from a lightness perception point of view) between a real scene and a computer simulation of the same scene. Human judgements of lightness were compared in real scenes and synthetic images. Correspondence between these judgements was then used as an indication of the fidelity of the synthetic image. The study extended their previous work [306] to investigate comparisons using 3D objects as targets, rather than a simple region, which allowed examination of scene characteristics such as shadow, object occlusion and depth perception.

Ten images (one photograph and nine PR images) were considered for comparison to a real scene. A series of psychophysical experiments were conducted in which human observers were asked to compare regions of a real scene with regions of a computer-generated representation of that scene. The comparison involved lightness judgements in both generated image and real scene. They opined that by conducting a series of experiments, based on the psychophysics of lightness perception, an estimate of the closeness of a rendered image to the original scene could be made.

Results from these experiments showed that visual response to the real scene and a high fidelity rendered image was similar.

6. Santella and DeCarlo

Santella and DeCarlo [300] validated the effectiveness of their image based NPR system (more details of the system can be seen in Section 5.1), which creates artistic renderings from photographs, using flat regions of colour and bold black lines, with an alternative evaluation method.

An eye-tracking method was used to provide quantitative validation for the system. The methodology analysed eye movement and provided a link between the eye and cognition. Using eye trackers, the way respondents look at photographs and NPR images generated from the system was compared.

The results suggested that eye tracking could be a useful tool for evaluating NPR systems. Respondents examined the same number of locations in photos and in NPR images with uniformly high or low detail. In contrast, respondents were attracted to areas where detail was locally preserved in meaningfully abstract images. This accords with the idea that artists carefully manipulate detail to control interest and understanding.

7. Wanger et al

The study of Wanger et al [307] was based on cue theory, which states that the visual system computes the distances of objects in the environment based on the information from the posture of the eyes and from the patterns of light projected onto the retinas by the environment. The main aim was to determine the role of graphic display cues such as projection, shadow, object texture, ground texture, motion and elevation, in the perception of 3D spatial relationships.

Three experiments were presented to assess the influence of six pictorial cues on perceived spatial relations in computer-generated images. All the images were rendered using Phong illumination model and Gourand shading. Spatial manipulation tasks were performed. Where each experiment examined the accuracy with which respondents matched the position, orientation and size of a test object, using images containing different combinations of pictorial cues with a standard by interactively translating, rotating and scaling the test object.

The results illustrated that, in the positioning task, where respondents needed object location information to perform the task, shadow and perspective were the most significant cues. In the orientation task, where relative orientation of the object's faces were needed, perspective, shadow and motion were the significant cues. Finally, in the scaling task, where object location information and intrinsic size were relevant to the task, all six cues were individually effective.

Table 5-2 presents a summary of the aforementioned visualisation and interpretation studies of the generated computer graphic images, based on the methodology used, the rendering technique or system that was tested for effectiveness, the different stimuli used for comparison to evaluate the respective rendering technique or system and the type of perception analysed.

Table 5-2: Summary of existing visualisation and interpretation studies

			Effectiveness	Stimuli for comparison	Type of Perception
Existing studies on visualisation and interpretation	Survey - based	Rodger and Browse	PR	Different PR images	Shape
		Schumann et al	NPR	PR and NPR images	Inference of developed system
	Behavioural-based	Duke et al	NPR	Different NPR images	Affect
		Ferwada et al	PR	Physical and PR images	Shape
		Gooch and Willemsen	NPR	Real and NPR immersive environment	Space
		Gooch et al	NPR	Photographs and NPR images	Inference of developed system
		McNamara and Chalmers	PR	Real, Photograph and PR images	Lightness
		Santella and DeCarlo	NPR	Photographs and NPR images	Inference of developed system
		Wanger et al	PR	Different PR images	Spatial relationships

5.2.3 Critique

In this section, the aforementioned studies are critiqued with respect to key aspects outlined in Section 5.2.1.

1. <u>Cognitive levels of information</u>

The summarised studies concentrated on perceiving and interpreting different levels of information. Rodger and Browse [301], Ferwada et al [26], Gooch and Willemsen [230], McNamara and Chalmers [28] and Wanger et al [307] focused on the sensory or structural level. This is because the goal of these studies has been either on the visual aspects or object information such as illumination, shape, space and spatial perception. However, the studies were limited to focus on the surface levels of cognition, thereby excluding the cognitive levels of explanation and deeper levels of relationship across meanings.

In comparison, Schumann et al [261], Duke et al [171], Gooch et al [299, 305] and Santella and DeCarlo [300] focused on rather deeper levels of relationship across different levels of meanings. Where the goal of Schumann et al [261], Gooch et al [299, 305] and Santella and

DeCarlo [300], in particular, was investigating the respondents' impression on their systems or inference about their system. This type of assessment was about specific semantic relationships of the system, and hence pertains to a propositional level of meaning. Such studies exclude the high-level of meaning that brings affect (emotive response) into cognition. On the other hand, Duke et al [171] evaluated the affect of NPR styles on the respondents, in a computer game environment. In particular, the concentration was on the emotive responses of the respondents in a given situation, which pertains to a high-level implicational meaning.

Other than Duke et al's study [171], there is no other study that has concentrated on implicational information of images, which pertain to high-level cognition. Rather, the concentration has been on surface levels of cognition.

2. Effectiveness

Effectiveness identifies which of the rendering techniques, in a given situation, is the most effective at expressing the desired information. Table 5-3 gives an overview of the current approaches to evaluate effectiveness, based on the methodology used, the rendering technique tested for effectiveness, the different stimuli used for comparison to evaluate the respective rendering technique, the factors on which effectiveness was based (since the measurement of effectiveness is based on the elements associated with effectiveness rather than effectiveness itself), and the type of analysis used for evaluation and the reason for using.

Table 5-3: Overview of current approaches to evaluate effectiveness

		Situation to evaluate effectiveness	Stimuli for comparison	Factors for estimating effectiveness	Type of analysis of evaluation data	Reason
Survey-based	Rodger and Browse	Rendering parameters to the perception of shape of 3D objects	Different PR images	Accuracy of shape perception	ANOVA (Analysis of Variance)	To test significant differences between observations.
	Schumann et al	NPR images on viewers	PR and NPR images	Visual impression	Mean	To describe the central tendency of observations.
Behavioural-based	Duke et al	NPR styles in games environment	Different NPR images	Response time	Mean	To indicate mean response time.
					ANOVA	To test significant difference between observations.
					Chi-Square	To test statistical significance of results.
	Ferwada et al	Advanced PR rendering techniques on shape perception	Physical and PR images	Accurate discrimination of shape differences	Mean	To describe the central tendency of observations.
					ANOVA	To test statistical difference.
	Gooch and Willemsen	NPR in immersive environments	Real scene and NPR images	Accuracy at judging distances	Average	To describe the central tendency of observations.
					ANOVA	To test significant difference.
	Gooch et al	Facial illustrations and Caricature algorithms	Photographs and NPR images	Accuracy and speed in recognition and learning tasks	Mean	To indicate central tendency of the observations.
	McNamara and Chalmers	Comparing real and synthetic scenes using lightness perception	Real scene, Photograph and PR images	Image accuracy or visual response function	ANOVA	To test significant difference between observations.
					t-test	To determine direction of effects.
				Relationship between two variables	Correlation	To determine the extent of relationship.
	Santella and DeCarlo	Comparing photos and NPR illustrations	Photographs and NPR images	Visual/focus interest in a location	ANOVA	To test significance difference between images.
	Wanger et al	Visual cues for perceiving spatial relationships	Different PR images	Accuracy in performance tasks	Mean	To describe the central tendency.
					Multiple ANOVA	To examines factors with significant effects.
					t-test	To determine direction of effects.

It can be noted from Table 5-3 that the aforementioned studies compared the respective rendering technique either with respect to real scenes, photographs, PR images or NPR images. None of the reviewed studies compared different categories of PR or NPR in a unified manner. In essence, the focus has been on just one variety of either PR or NPR technique.

Both survey and behavioural-based studies have limitations. In surveys, the information desired may not be reliable to the respondents by introspection [300]. In behavioural study, for example, the goal of imagery is not always task related. For instance in advertising or decorative illustration, the goal is more to attract the eye than to convey information. In addition, both the user approval ratings and task performance assess only the quality of a system or a rendering technique as a whole. Neither of the methodologies directly imply why a pattern in experience or performance occurred [300]. To understand this, the system or a rendering technique needs to be systematically changed and the experiment repeated. This process can be costly and time consuming (or impossible). Owing to their simplicity, in spite of limitations, these two types of methodologies are often being preferred. In contrast to the majority of behavioural-based studies, survey-based studies are less concentrated on rendering.

3. <u>Emotive implications</u>

None of the summarised studies determined the emotive implications of images.

The focus of most of the studies has been on surface levels of perception (sensory or structural). Duke et al [171] investigated the affect of implicational information on viewers. In particular, they examined the emotive responses of the viewers with respect to NPR styles within a computer game environment. Their study addressed only the nature of implicational information in terms of how it can be used in a computer game environment, rather than determining the different types of implication information in computer graphic images. In short, none of the studies determined emotive implications of images to evaluate the effectiveness of rendering styles.

Table 5-4 presents a matrix summarising the critical review of studies on visualisation and interpretation of the generated computer graphic images. With regard to the table, for each work, a tick indicates that the key aspect, or an associated feature, is supported. Conversely, a cross indicates that support is not provided.

Table 5-4: A critical review of the existing visualisation and interpretation studies (Step 4)

Key: √ Yes, × No

			Key aspects for visualisation and interpretation						
			Cognitive levels of information				Effectiveness		Emotive implications
			Sensory (Visual)	Structural (Object)	Meaning		PR	NPR	
					Propositional	Implicational			
Existing visualisation and interpretation studies	Survey based	Rodger and Browse	×	√	×	×	√	×	×
		Schumann et al	×	×	√	×	×	√	×
	Behavioural-based	Duke et al	×	×	×	√	×	√	×
		Ferwada et al	×	√	×	×	√	×	×
		Gooch and Willemsen	×	√	×	×	×	√	×
		Gooch et al	×	×	√	×	×	√	×
		McNamara and Chalmers	√	×	×	×	√	×	×
		Santella and DeCarlo	×	×	√	×	×	√	×
		Wanger et al	×	√	×	×	√	×	×

5.3 Research problem

Table 5-5 presents a matrix summarising the critical review of the existing works in rendering, within the areas: (i) development of rendering systems for the generation of computer graphic images and (ii) studies on visualisation and interpretation of the generated computer graphic images, and highlighting the research problem.

Table 5-5: The research problem identification

Key: √ Yes; × No; (shaded) Research problem

Shaded (research problem) cells: Rodger and Browse and Schumann et al, in the rows Effectiveness – PR, Effectiveness – NPR and Emotive implications.

Key aspects		Existing works related to rendering																
		Rendering systems								Visualisation and interpretation studies								
		PR		NPR						Survey-based		Behavioural-based						
		RADIANCE	FLY	DeCarlo and Santello	OpenNPAR	Piranesi	Saito and Takahasi	Salisbury et al	Sketch-renderer	Rodger and Browse	Schumann et al	Duke et al	Ferwada et al	Gooch and Willemsen	Gooch et al	McNamara and Chalmers	Santella and DeCarlo	Wanger et al
Generation of computer graphic images (Step 3)	Computational requirements	High	High	Low	Low	Low	Low	Low	Low									
	Intelligent Design Assistant (IDA) philosophy	×	×	×	×	×	×	×	×									
	Realism – Functional	×	×	√	√	√	√	√	√									
	Realism – Soft-functional	×	×	×	×	×	×	×	×									
	Sketchy-input	×	×	×	√	√	×	×	×									
	Sketchy output – Alternative representations	×	×	×	√	√	√	×	√									
	Sketchy output – Sketchy presentations	×	×	√	√	√	√	√	√									
	Sketchy output – Vagueness	×	×	×	×	×	×	×	×									
Visualisation and interpretation (Step 4)	Cognitive levels – Sensory (Visual)									×	×	×	×	×	×	√	×	×
	Cognitive levels – Structural (Object)									√	×	×	√	√	×	×	×	√
	Cognitive levels – Meaning – Propositional									×	√	×	×	×	√	×	√	×
	Cognitive levels – Meaning – Implicational									×	×	√	×	×	×	×	×	×
	Effectiveness – PR									√	×	×	√	×	×	√	×	√
	Effectiveness – NPR									×	√	√	×	√	√	×	√	×
	Emotive implications									×	×	×	×	×	×	×	×	×

With regard to Table 5-5, for each work, a tick indicates that the key aspect, or an associated feature, is supported. Conversely, a cross indicates that support is not provided. The cross-hatchings in the table indicate the research problem, which refers to the challenge concerned with overcoming the inadequacies of existing works with respect to the key aspects.

The works critically reviewed in this chapter provide valuable contributions in the field of rendering. However, from Table 5-5, it can be seen that:

Rendering systems for the generation of computer graphic images (Step 3):

- Insufficient support for vagueness: None of the rendering systems capture the inherent vagueness of design sketches in conceptual design, although imprecision is introduced in the post-processing

Visualisation and interpretation studies (Step 4):

- None of the studies determined the emotive implications of computer graphic images, although the importance of implicational information has been emphasised.
- No previous established study exists for evaluating the effectiveness of rendering techniques based on emotive implications.
- None of the studies compared all the existing rendering techniques (PR and NPR). Thus, by implication, all of the techniques have not been integrated within a unified study to determine which of the rendering techniques, in a given situation, is the most effective at communicating the desired information.
- In contrast to the majority of behavioural-based studies, survey-based studies are less concentrated on rendering.
- All the studies are based on evaluation of generated rendering techniques, but none has concentrated on the characteristics and features of rendering to get a conceptual understanding of rendering in general.

Thus, the main outcome of the critical review is that there is scope for an integrated and holistic study that addresses the key aspects of rendering and overcomes the inadequacies of existing studies.

The research problem can be stated as the identification of the most effective rendering styles for conveying emotive implications. Considering the key aspects and inadequacies of existing studies on rendering, the research problem was detailed as:

- Evaluating the implications of rendering in conceptual design aims to identify the different characteristics and features of rendering in conceptual design.
- The identification of emotive implications of computer graphic images.
- Evaluating the degree of effectiveness of different rendering styles, which includes:
    - A methodology to evaluate existing PR and NPR styles.

- Evaluation of the existing PR and NPR styles by mapping the identified emotive implications.
- Statistical analysis of the evaluation data.

5.4 Chapter summary

The existing works in rendering within the areas: (i) development of rendering systems for the generation of computer graphic images and (ii) studies on visualisation and interpretation of the generated computer graphic images, have been critically reviewed with respect to key aspects for (i) the generation of computer graphic images and (ii) visualisation and interpretation. The resulting findings are summarised in Table 5-5. The review has highlighted the inadequacies of existing works and highlighted areas for further research and enhancement based upon these.

The work presented in Part 2 of this thesis focuses on the novel study for the identification of the most effective rendering styles for conveying emotive implications.

PART 2 – SOLUTION / INVESTIGATION

6. Implications of rendering

This chapter presents a survey-based study conducted to investigate the implications of rendering. The objective of the investigation is to gain insights into the nature of rendering, the nature of different rendering techniques and the limitations with current CAD systems. Further, the objectives are to provide the implications as the basis during the (1) identification of emotive implications of computer graphic images (discussed in Chapter 7), and (2) evaluation of the emotive effectiveness of different rendering styles (discussed in Chapter 8).

The study conducted was exploratory and not definitive. That is, the study should not be interpreted as a definitive investigation but rather an evaluation of characteristics and features in the field of rendering, and consequently to contribute to the overall knowledge and understanding of rendering. The characteristics and features of rendering evaluated were based on the (1) understanding of rendering in the design process and (2) literature of different rendering techniques for the generation of computer graphic images, in Chapter 3.

In Section 6.1, the experimental methodology of the study is presented. Section 6.2 presents the results of the study in the form of bar charts, means, standard deviations, hypothesis testing, correlation and ranking tests. In Section 6.3, the main findings of the study are discussed. Finally, Section 6.4 summarises the chapter.

6.1 Experimental methodology

This section presents the experimental methodology of the study, briefing the sample chosen, questionnaire design with respect to the objectives of the study and an overview of how the study and analysis was conducted.

Sample

Owing to the difficulties of studying and impinging on actual design practice in industry and taking into consideration the advantages of a *convenient* sample, the sampling choice for the study was academics and students, which represented the academic/education population. *Convenient* samples are the samples, chosen from a population for observation, that are easy to approach [308]. Indeed Howitt and Cramer opined that often in the case of university researchers, the most *convenient* sample typically consists of students [308]. This is because of the difficulties of studying on actual population (for instance, actual design practise in industry).

The sample selected for the study was the academics and undergraduate students in the Department of Design, Manufacturing and Engineering Management (DMEM), University of Strathclyde. The academics had more than five years of experience in CAD and the students were third year undergraduate product design engineering students. They already had spent two years carrying out sketching and rendering activities as a part of their curriculum. Based on the background of the sample selected, the findings resulting from the study can act as a basis for the subsequent investigations conducted and presented in this thesis (Chapters 7 and 8).

A total of sixty questionnaires were distributed, resulting in forty-seven returned responses (70%). Out of the forty-seven respondents, five were academics, another five were colleagues/fellow researchers and the remaining thirty-seven were the third year undergraduate product design engineering students. The majority of the respondents (81%) were males.

Design

The method of study was in the form of a group-administered questionnaire, owing to its advantages over other methods in terms of cost, convenience to administer in group settings, high response rate, length of the questionnaire, speed of data collection and opportunity for quantifying responses. The following standards were adopted for the questionnaire administration:

- The questions were specific, followed a logical order and were appropriate for the population of interest.
- The questionnaire was accompanied by a covering letter stating the purpose and objectives of the study and also confidentiality of the respondents was assured.

The questionnaire comprised of open-ended, closed-ended and scaled response formats that also included the opportunity for the respondents to input their own choices. The open-ended questions gave scope for the respondents to express their opinions freely without being hindered by a set of alternatives. A five-point likert scale [302] was used to measure the respondents' attitude towards particular aspects.

Annex-1 of Appendix A presents a full list of the questions contained in the questionnaire. Based on the objectives of the work, the questionnaire addressed the following relevant characteristics and features (which are referred to as 'aspects' here and in the remainder of this chapter) that were based on the (1) understanding of rendering in the design process and (2) literature of different rendering techniques for the generation of computer graphic images, in Chapter 3.

1. To determine the nature of rendering in the design process, the questions were based on the:
   (a) applicability of rendering in different stages of the design process,
   (b) importance of rendering, with respect to communication of design ideas, the quality of the image, time taken for designing and visualisation of the image,
   (c) assistance that rendering provides in design development,
   (d) precision of information used for rendering, such as vague and precise, and
   (e) impact of rendering in different dimensions (e.g. 2D, 3D).
   (f) importance of geometric aspects, such as lines, vague shapes and vague surfaces, during the generation of concepts.

2. To determine the nature of different rendering techniques, the questions were based on the:
   (a) relevance of different rendering techniques such as the:
      a.1. hand drawn and computer renderings, and
      a.2. existing PR and NPR.

   To gain further insights into the nature of different rendering techniques, the questions were based on the:
   (b) factors influencing rendering, such as aesthetics, image quality.
   (c) parameters associated with rendering techniques that vary the style of the resulting images, such as colour, light, material.

3. To determine the perceived limitations with current CAD systems, the question was based on the:
   (a) dissatisfying factors with present rendering tools.

Procedure

A draft questionnaire was prepared giving importance to appropriate question wording, content and response format. The questionnaire was then pre-tested with five colleagues/fellow researchers [309], who had two to three years of experience in CAD, to see how the targeted respondents (sample) drawn from the target population were likely to respond and react to the study approach. Colleagues/fellow researchers, in the CAD Centre of DMEM Department, University of Strathclyde, were chosen for the pilot study because they understood its purpose and had similar training as the author. Minor changes were done to the main questionnaire based on the feedback given. Subsequently, the actual sample was briefed with the purpose of the study and given instructions on how to fill in the questionnaire. In order to promote high co-operation and participation rate, the respondents were provided with a covering letter detailing the theme of the research, an incentive of a copy of results and a note of appreciation was added at the end of the questionnaire. Respondents were assured confidentiality and also were given the opportunity to decline to participate in the study. They were monitored while filling in the questionnaires and immediate clarifications were made upon request.

The study analysis consisted of quantitative compilation of the responses. The results for the open-ended questions were exemplified by presenting the most common answers in the form of quotes. The quotes, being the most common answers in the questionnaire, also serve to show the respondent's statements, rather than forming a statistical extraction. The data collected from the closed-ended and scaled response questions was analysed statistically. The statistical program SPSS (Statistical Package for the Social Sciences) for Windows 10.0 [310] was used to analyse the data. The graphical illustrations[22] such as bar charts were used to present the data as they exemplify impressive visuals, summary statistics and are also good for comparison. Descriptive and inferential statistics were used to present the opinion of the sample and the population in general.

With descriptive statistics, descriptions were made with what the data shows. The most frequently reported descriptive statistics are the *Mean* (M) and *Standard Deviation* (SD) [311]. The *mean* or average is the most commonly used method of describing central tendency of a sample (N). The *standard deviation* gives a measure of how much spread out the data is around the *mean*.

With inferential statistics, conclusions were reached about the given data. From the sample data, inferential statistics provide the basis to infer what the population, in general, might

[22] The graphical illustrations do not display the responses relating to 'do not know' option in the questionnaire as this may distract the reader from the essence of the results.

think and to make judgments of the probability (p) that an observed result is a significant one or one that might have happened due to random events in the study [310]. The usual significant levels used are 0.01 or 0.05. That is, a statistical significance of 0.01 ($p < 0.01$) or 0.05 ($p < 0.05$) means that there is probability of 1% or 5% chance that the effects seen are due to random events. Inferential statistics such as hypothesis testing, correlation analysis and ranking tests were used to make inferences from the data to more general conclusions. Hypothesis testing is a statistical method that uses the sample data to test claims/hypothesis about a population parameter, such as *mean*, *standard deviation* and a proportion or percentage. Pearson correlation analysis was used to identify the nature of relationship between different sets of variables. The Pearson correlation coefficient (r) is a numerical measure of the amount of linear association between two sets of variables. It ranges in number from +1.0 to -1.0. Therefore, as the number tends to ±1.0 there is either strong positive or negative correlation. Correlations above 0.5 are usually considered 'high' and those below 0.4 are 'low'. A non-parametric test such as Wilcoxon Signed Rank test was used to compare two paired groups. This test helps to determine whether ranks in one group of the paired data are typically larger or smaller than ranks in the other groups. For more details of the related descriptive and inferential statistics used for the work presented in this thesis, please refer [312].

The results were reported in the standard APA (American Psychological Association) style [311]. The *means* (M) and *standard deviations* (SD) were presented with just every statistical analysis. The reporting of the *mean values* was always followed by its *standard deviation*. When reporting the correlations, they were presented either in a correlation matrix (for more than three correlations) or in textual form (for less than three correlations) depending on the number of correlations reported. The correlations that are statistically significant were reported and others not reported to aid clarity of interpretation. The reporting of the statistical significance of results was followed for other statistical tests as well. Within the context of the work presented in this chapter, unless stated, the displayed results were statistically significant, at the noted significance levels (1% and 5%).

6.2 Results

The most significant results extrapolated from the study are presented in this section.

6.2.1 Nature of rendering

(a) Applicability of rendering in the design process

This question was designed to determine in which stage of the design process[23] rendering was considered the most applicable. The bar chart, Figure 6-1, shows the opinion of the respondents in *mean values*. The higher the *mean value*, in the bar chart, the higher the applicability and vice versa.

The *mean values* of requirements specification, conceptual design, embodiment design, detailed design and manufacture design stages are 1.2 (SD = 0.58), 3.0 (SD = 1.07), 3.9 (SD = 0.89), 3.9 (SD = 1.21), and 2.7 (SD = 1.27) respectively.

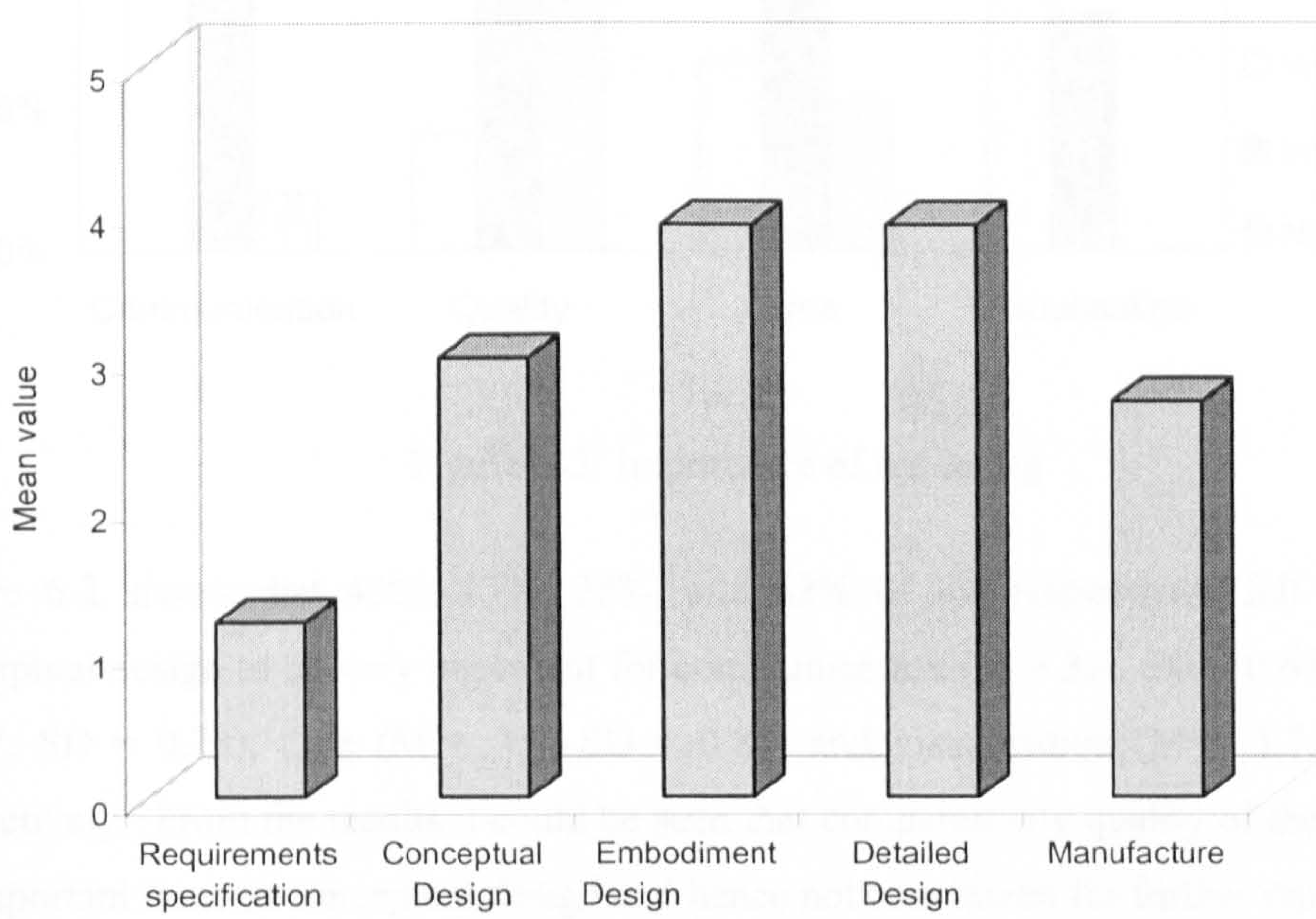


Figure 6-1: Applicability of rendering in the design process

As can be seen in the bar chart, the *mean values* of embodiment design and detailed design are the same and more than the other design stages. This implies that the applicability of rendering is the same in both stages and higher than other design stages. This result is synonymous with the observation that the realistic rendering techniques are used during the

[23] The different stages of the design process are based on British Standard BS7000 [313] process model. This was adopted mainly for simplicity and clarity. Though it is a four-stage process, requirement specification stage was added in the questionnaire to enhance the clarity of the overall design process to the respondents.

later stages of design to provide a realistic presentation of how the product looks when it is manufactured. Between the other design stages, applicability of rendering appears to be more productive in conceptual design.

(b) Importance of rendering in conceptual design

This question addressed the importance of rendering with respect to some key issues such as communication of design solutions or design ideas, quality of the image, time taken for designing (speed of rendering) and visualisation of the image.

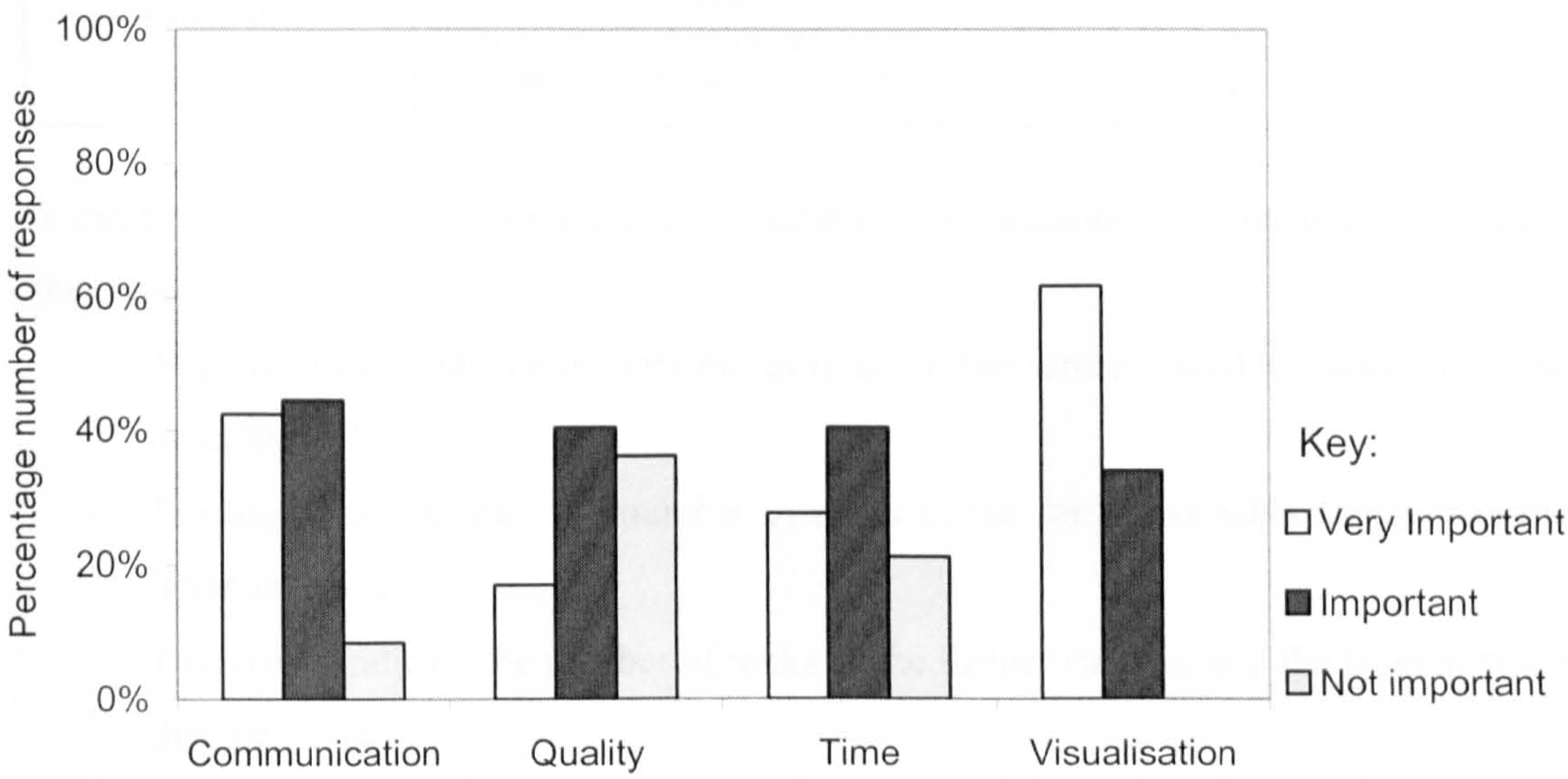


Figure 6-2: Importance of rendering

Figure 6-2 shows that 43%, 17%, 28%, and 62% of the respondents felt rendering in conceptual design to be very important for communication (M = 3.4, SD = 0.65), quality (M = 2.7, SD = 0.73), time (M = 3.0, SD = 0.89) and visualisation (M = 3.7, SD = 0.48) respectively. From the results it could be seen that comparatively quality of the image is not an important issue in conceptual design and hence not considered for further ranking.

The Wilcoxon signed rank[24] [314] test was conducted for ranking communication, time and visualisation (see Table 6-1).

[24] When a set of data is ordered from lowest to highest, the rank of a score is its position in this order.

Table 6-1: Ranking of communication, time and visualisation

	Ranks	Number of respondents
Time-Communication	Negative ranks, time < communication Positive ranks, time > communication Tied ranks, time = communication	21 11 12
Visualisation-Communication	Negative ranks, visualisation < communication Positive ranks, visualisation > communication Tied ranks, visualisation = communication	8 19 17
Visualisation-Time	Negative ranks, visualisation < time Positive ranks, visualisation > time Tied ranks, visualisation = time	4 23 17

As can be seen in the table, communication, time and visualisation were ranked against each other where:

- *Negative ranks* indicate the number of ranks of the former variable *smaller* than the latter variable.
- *Positive ranks* indicate the number of ranks of the former variable *larger* than the latter variable.
- *Tied ranks* indicate the number of ranks of the former variable and the latter variable that were *equal.*

From the table, communication, time and visualisation have *positive ranks* of 29 (21 + 8), 15 (11 + 4) and 42 (19 + 23) respondents respectively. That is, visualisation is being ranked higher than communication and time, and communication more than time.

In summary, the ranking of importance of rendering in conceptual design, as shown by ranking test and graphical illustration, is visualisation, followed by communication and then time.

(c) Assistance of rendering in design development

This question addressed the type of assistance provided by rendering in design development. The respondents were asked to comment, in an open-ended question, with their opinion about the type of assistance provided by rendering. The following were the common opinions:

- '*aesthetic development and to see the product when it is in progress*',

- '*communication and understanding*',
- '*conceive a product by applying real features of the product through the computer before actually a product is made*',
- '*gives better representation to designer's ideas*',
- '*marketing exercises*',
- '*promotion of ideas, visualisation and manipulation, and realism*',
- '*provide a realistic representation of how the product looks when it is manufactured*' and
- '*rendering of different contexts, tries to communicate through visualisation to others and acts as feedback to identify*'.

Given the respondents' opinions, it would seem that that rendering provides assistance in design development by giving a better presentation to designer's ideas, enabling a realistic view of how the product looks and promoting design ideas and communication through visualisation.

(d) Precision of information used for rendering

The information available in early stages of design is usually a mixture of both vague and precise [168]. The respondents were asked about the type of information used for rendering in conceptual design, with the precision ranging from *very vague* to *very precise*. An overview of the hypothesis testing conducted, to determine the precision of information used, is shown in Table 6-2.

Table 6-2: Hypothesis testing for precision of information used

Null hypothesis (H0)		Test statistic, Z	Critical value	Conclusion
Precision of information used	very vague	-11.33	-1.65	Failed to accept
	vague	-4.67		
	fairly vague (vague and precise)	2.0		Accept
	precise	8.67		
	very precise	15.33		

In the table, the null hypothesis (H0) represents a hypothesis under test. The *test statistic, Z,* is used to determine whether to accept or reject the null hypothesis. It gives how many standard deviations from the assumed mean is the average of the sample. The computed *test* *statistic*, Z, is then compared to the critical value for a standard normal distribution, to decide whether to accept or reject the hypothesis tested. Critical values indicate the beginning of the rejection (critical) region that would lead to rejection of the null hypothesis (see Figure 6-3). If the computed *test statistic*, Z, falls in the rejection region, the null hypothesis is rejected.

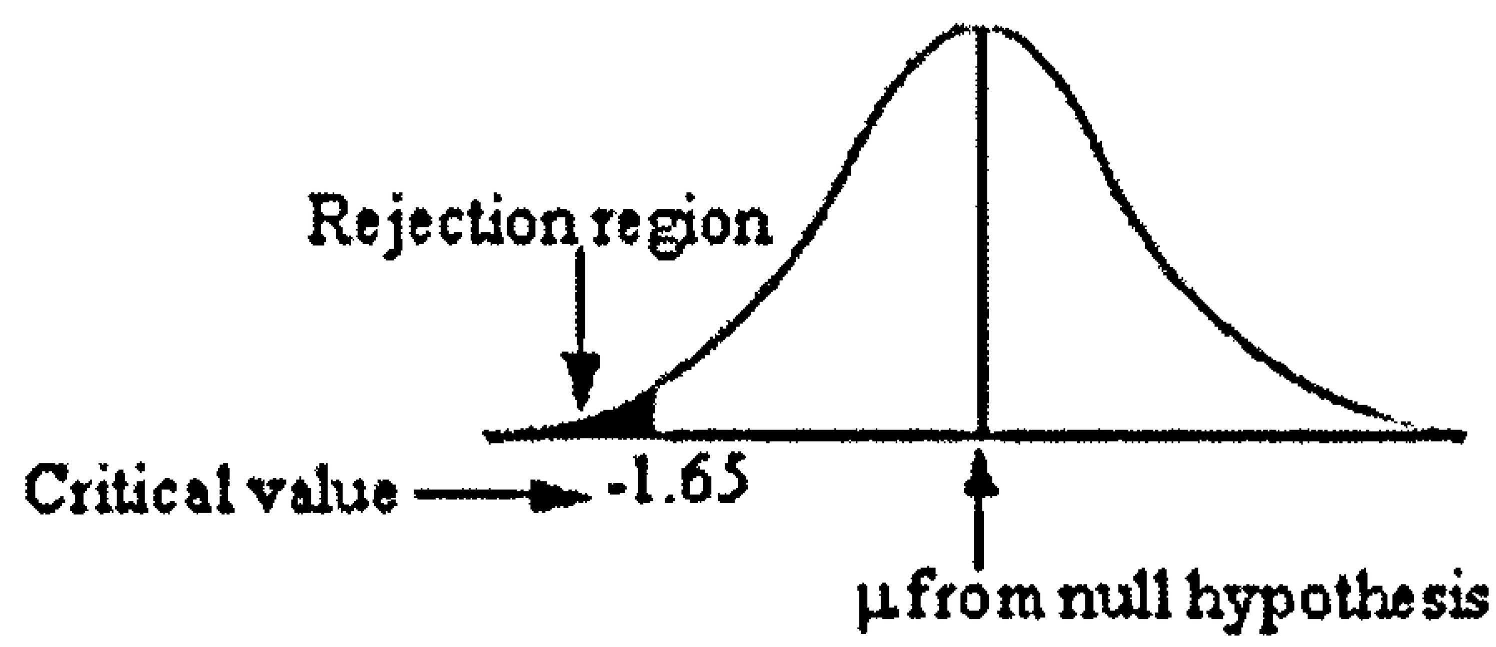


Figure 6-3: Normal distribution: One-tail test at 5% significant level

1. Let's postulate, the null hypothesis (H0): Precision of information used is *very vague* (H0; $\mu = 5$).
2. Alternate hypothesis (H1): Precision of information used is not very vague.
3. Since the null hypothesis stated the direction of the result, one tail test is justified in this hypothesis testing [312].
4. The critical value for a one-tail test at 5% significant level is −1.65 standard deviations from the assumed mean (μ) [312]. A one-tail test rejects the hypothesis for values of *test statistic*, Z, less than −1.65 (see Figure 6-3).
5. A *test statistic*, Z, is determined using Equation 6-1.

$$\textit{Test Statistic}\; \mathrm{Z} = \frac{\overline{\mathrm{X}} - \mu}{\textit{Standard Error}} \qquad \text{Equation 6-1}$$

   $\overline{\mathrm{X}}$, in Equation 6-1, is the sample mean, μ (assumed mean) is the population parameter and the *Standard Error* is the standard deviation of the sample mean. It indicates by how much the sample mean would be expected to differ if other samples from the same population are used. The sample mean ($\overline{\mathrm{X}}$) and S*tandard Error* for the precision of information used are 3.3 and 0.15 respectively.

6. The hypothesised value of μ is 5, 4, 3, 2 and 1, for the parameters (very vague, vague, fairly vague, precise and very precise) specified in the null hypothesis (see Table 6-2), which is substituted sequentially in Equation 6-1.

For example: $$\textit{Test Statistic } Z = \frac{3.3-5}{0.15} = -11.33$$

7. The resulting *test statistic*, *Z*, is compared to the critical value for a standard normal distribution, to decide whether to accept or reject the null hypothesis stated.
8. The *test statistic*, *Z* for the null hypothesis postulated (-11.33) is less than the critical value (-1.65), and therefore falls in the rejection region (see Figure 6-3). Hence the null hypothesis (H0) stated in Step 1 above is failed to be accepted.
9. Consequently the next degree of precision is tested, with changing the null hypothesis, and following Steps 1 to 8, until it is accepted.

From hypothesis testing, as can be seen in Table 6-2, the precision of information used for rendering seem to range from *fairly vague* to *very precise.*

The respondents were also asked to provide reasons, in an open-ended question, for preferring vague or precise information. The reasons given for vague information were:

- '*at conceptual design not all details are known*',
- '*conceptual rendering is an early indefinite stage, thereby no need to be precise or accurate*',
- '*most clients are happy to see what the aesthetics will do for their product. We make it clear from the sketches by showing form, layout, main features rather than detail*'. And
- '*shows brief view of concept visualisation*'.

Reasons for precise information were:

- '*conceptual design is just initial stage so rendering if done should be precise*',
- '*the intended meaning is shown if it is accurate*',
- '*rendering specifies actual features on a product so all parameters should be precise/accurate*', and
- '*vagueness is difficult in a medium that works with precision - tend to post process afterwards if required*'.

The reasons given for both types of information insinuate that both vague and precise information as being necessary for rendering because of the obvious advantages given by above.

From hypothesis testing and rationalising the comments given by respondents, there is some evidence that *fairly vague* to *very precise* information is required whilst rendering.

(e) Impact of rendering in different dimensions

The computer models and images can be presented in different dimensions such as linear, 2D, 3D, and mixture of 2D and 3D. This question determined the impact of rendering in different dimensions. The *mean values* (see Figure 6-4) for linear, 2D, 3D information in 2D, 3D, 2D and 3D, and 2D or 3D images were 2.7 (SD = 1.52), 3.7 (SD = 1.39), 3.8(SD = 1.45), 4.8(SD = 1.48), 4.5(SD = 1.57), and 4.5 (SD = 1.59) respectively.

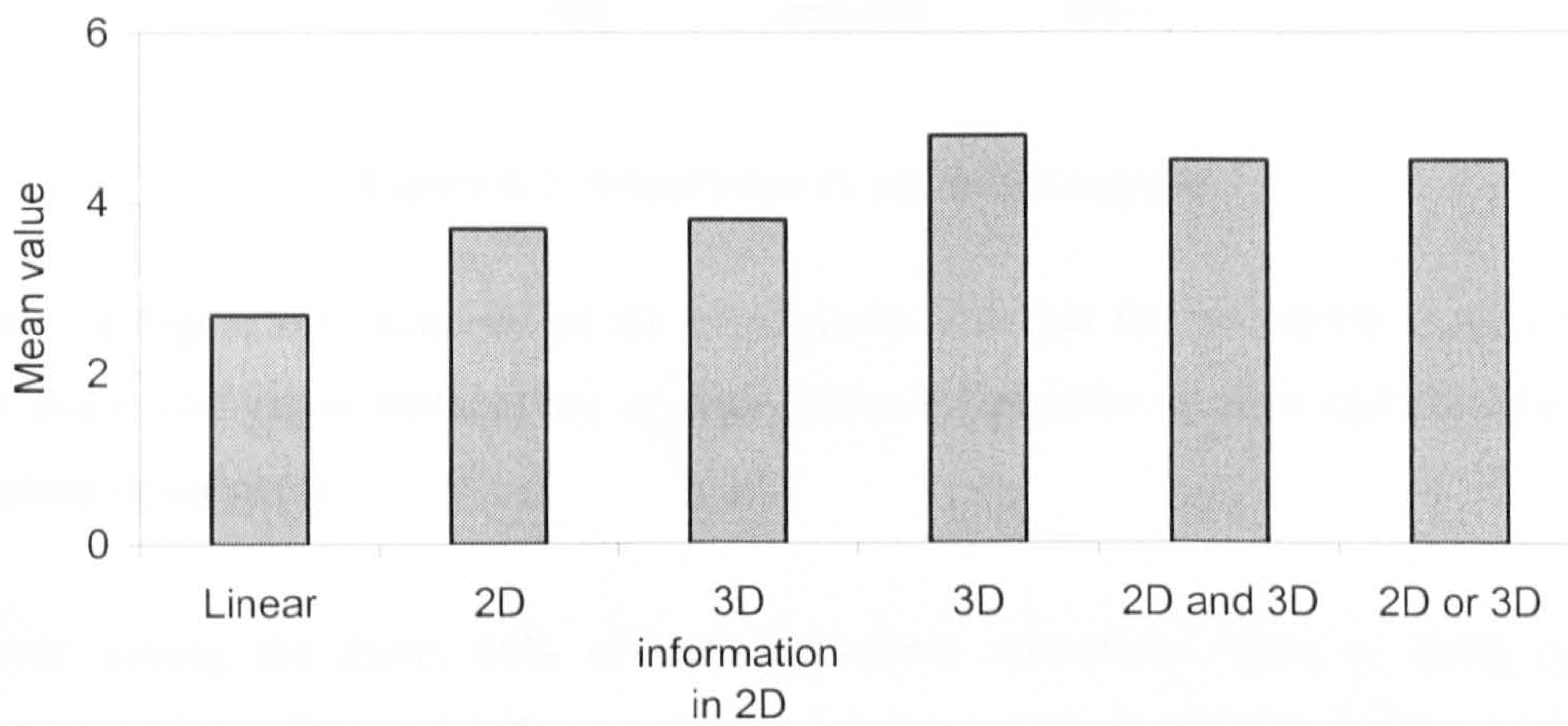


Figure 6-4: Impact of rendering in different dimensions

As can be seen from the bar chart, the impact of rendering is more in 3D compared to other dimensions, implying that 3D rendering provides better visualisation. The *mean values* of 2D and 3D, and 2D or 3D seem to be the same, implying that the impact of rendering in presenting images in both the dimensions (2D and 3D) and either of the dimensions (2D or 3D) as being the same. There is a marginal variation between 2D, and 3D information in 2D images, implying that the impact of rendering 2D images or 3D information in 2D images is more or less the same.

(f) Importance of geometric aspects

This question was designed to determine the importance of geometric aspects (based on classification in [56]) such as lines, vague shape and vague surface, compared to other product aspects (such as colour, light, material), during the generation of concepts.

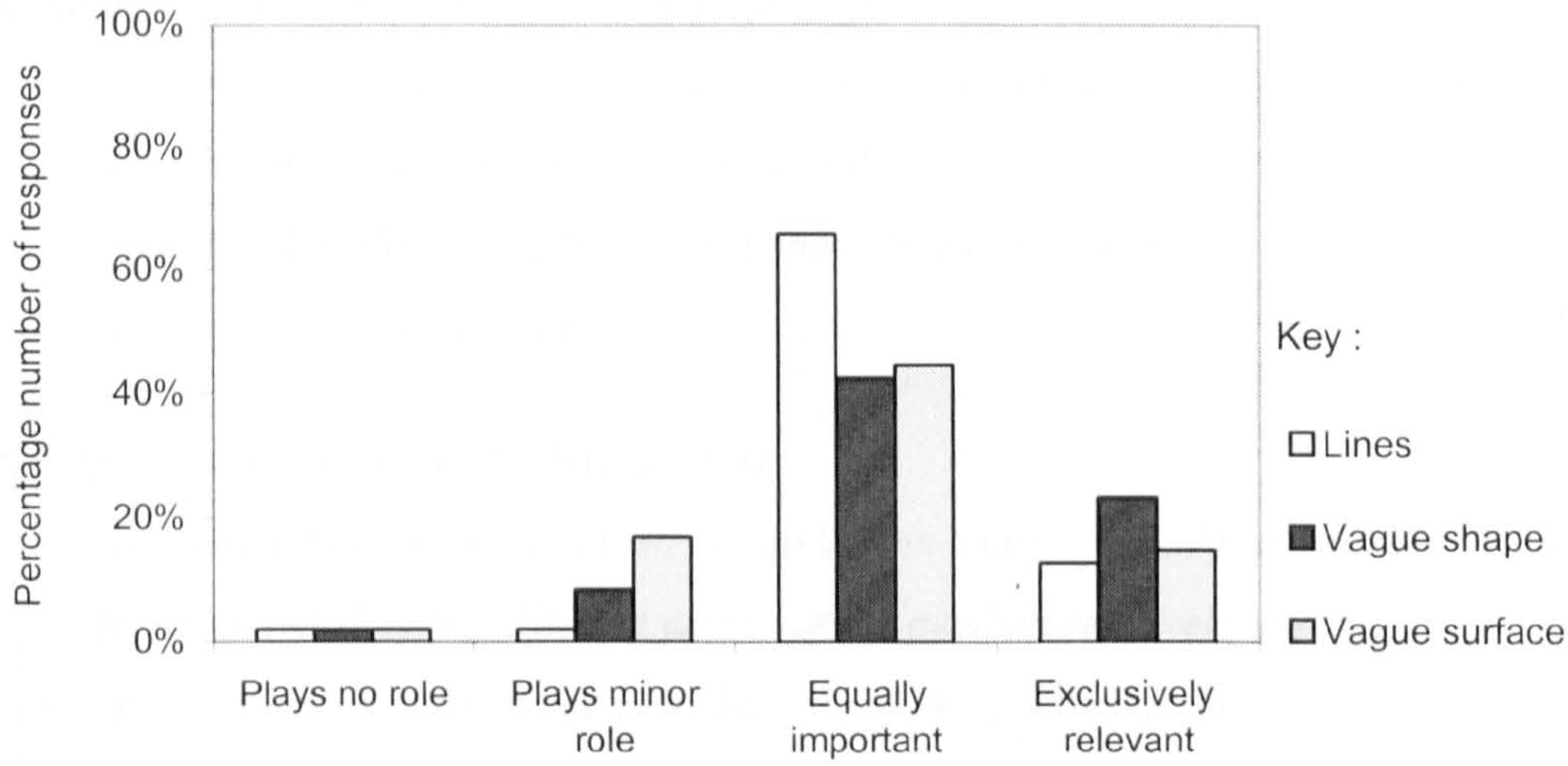


Figure 6-5: Importance of geometric aspects

As seen in Figure 6-5, majority of the respondents felt that the geometric aspects (lines, vague shape and vague surface) are *equally important* as other product aspects during the generation of concepts.

However among the three, 66% of the respondents interpreted lines as being *equally important*, whereas 43% and 45% respectively interpreted vague shape and vague surface as being *equally important*. This is in context of 13% considered lines as *exclusively relevant* compared to 23% and 15% for vague shape and vague surface respectively. In summary, 79% considered lines as being *equally important* or *exclusively relevant* compared to only 66% and 60% for vague shape and vague surface respectively. This implies that among the three, lines are being considered to be more prolific during the generation of concepts.

6.2.2 Nature of different rendering techniques

(a) <u>Relevance of rendering techniques</u>

a.1. *Hand drawn and computer renderings*

This question was designed to determine the importance of hand drawn and computer renderings. The *mean values* for hand drawn and computer renderings were 3.7 (SD = 0.99) and 3.9 (SD = 0.94) respectively. The respondents were also asked to provide reasons, in an open-ended question, for preferring hand drawn or computer renderings.

The opinions expressed for hand drawn renderings were:

- '*carry the ability to identify the status of the idea: key elements, relationships, annotations are important in supporting this*',
- '*fast and flexible, gives ideas quickly and effectively*', and
- '*high speed and instant changes*'.

Some opinions for computer renderings were:

- '*get full attention of the client by giving an indication of final appearance of the product and showing different angles of the product relatively easily*',
- '*gives better visualisation and a full view of the product*', and
- '*more appropriate and fast, more flexible and synchronous, more consistent and neater*'.

Given the respondents' opinions for hand drawn and computer renderings, it would seem that both approaches are advantageous.

a.2. *PR and NPR*

This question investigated the importance of PR and NPR techniques in the design process.

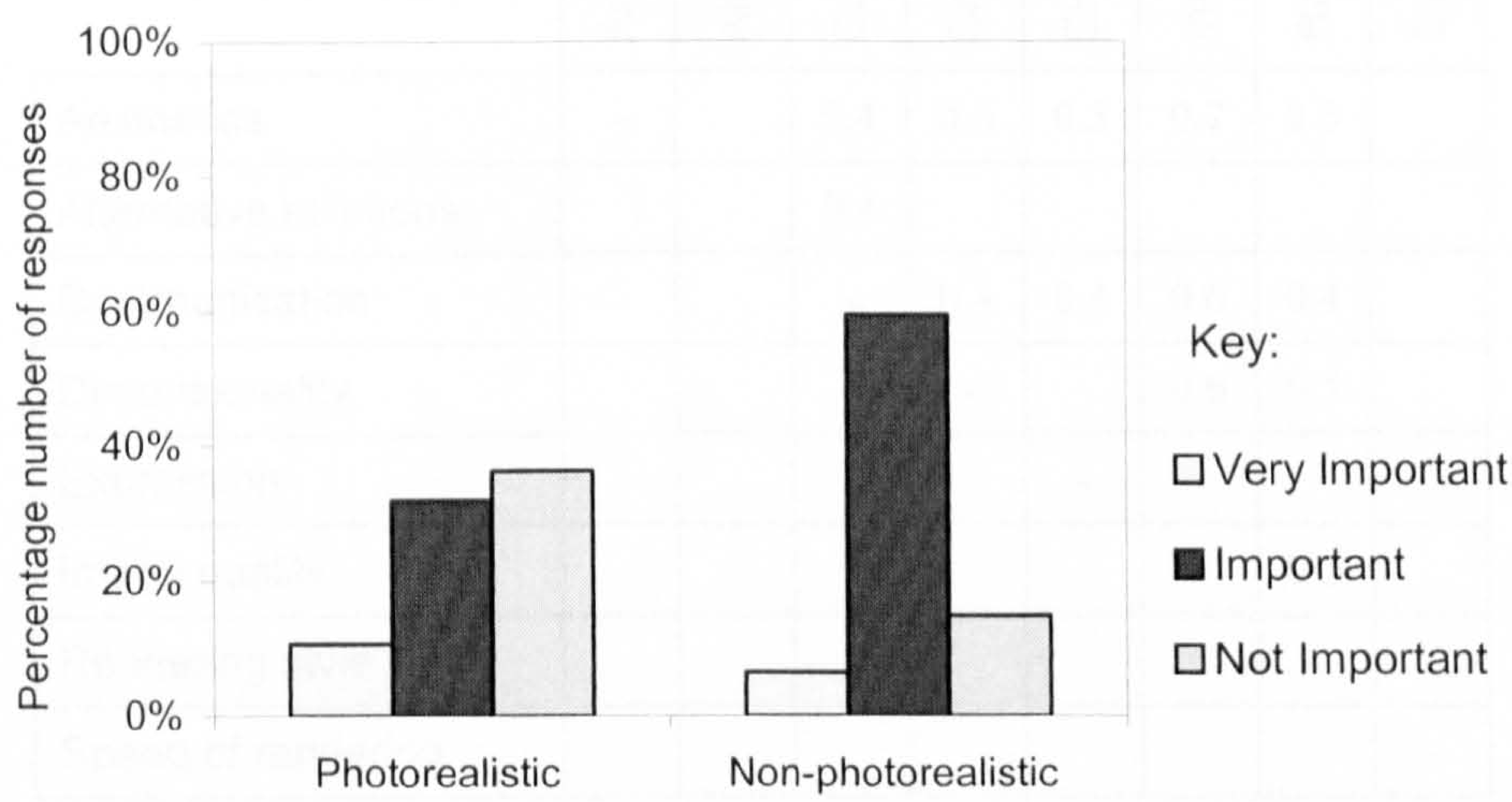


Figure 6-6: Photorealistic rendering (PR) and Non-photorealistic rendering (NPR)

From Figure 6-6, 11% of the respondents felt that PR (M = 2.6, SD = 0.91) was very important, whereas 6% of the respondents felt NPR (M = 2.7, SD = 0.77) as very important. This is in context of 32% considered PR as important compared to 60% for NPR. In summary, only 43% considered PR as very or important compared to 66% for NPR. Whereas, 36% of the respondents felt PR as not important compared to 15% for NPR. This implies that between the two, NPR is being considered more important in the design process.

(b) Factors influencing rendering

From the literature and understanding in Chapter 3, the following were contemplated to be some of the possible factors influencing rendering: aesthetics, alternative solutions, communication, dimensionality, expression, image quality, rendering style and speed of rendering (time). Correlation analysis was performed to find out the inter-correlations between the factors influencing rendering. Table 6-3 presents a 8 × 8 correlation matrix. Only one-half of the matrix is presented because the variables in the matrix are symmetric [311]. Thereby, the lower left hand corner of the matrix is left blank. However, the blank cells in the upper right hand corner of the matrix indicate the correlations that were not significant. The dash indicates the correlation of the factor with itself (= 1.0).

Table 6-3: Inter-correlations between factors influencing rendering

	Aesthetics	Alternative solutions	Communication	Dimensionality	Expression	Image quality	Rendering style	Speed of rendering
Aesthetics	-		0.4	0.6	0.5	0.7	0.5	
Alternative solutions		-	0.4					
Communication			-	0.4	0.4	0.6	0.4	
Dimensionality				-		0.6	0.5	
Expression					-			
Image quality						-	0.5	
Rendering style							-	
Speed of rendering								-

The positive correlations in the table indicate that there is some evidence that a relationship exists between the factors respectively.

- **Aesthetics** seem to have a strong positive correlation with image quality indicating that higher the aesthetically pleasing look in an image, the higher the image quality and vice-versa. Similarly aesthetics have a positive relationship with communication, dimensionality, expression and rendering style.

- **Alternative solutions** seem to have a positive relationship with communication indicating that the number of alternative solutions generated enable the communication of design solutions or design ideas more rapidly.
- **Communication** appears to have the most correlations than any other factors. It has positive correlations with aesthetics, alternative solutions, dimensionality, expression, image quality and rendering style. This indicates that there would be rapid communication of design solutions or design ideas when the generated image is aesthetically pleasing or with the number of alternative solutions generated or with 2D/3D rendering or when the image generated is more expressive. Further, the image quality and the rendering style influence the communication of design solutions or design ideas.
- **Dimensionality** seems to have a positive relationship with aesthetics, communication, image quality and rendering style. This indicates that the 2D/3D rendering tend to vary the aesthetically pleasing look in an image, communication of design solutions or design ideas, image quality and rendering styles.
- **Expression** appears to have a positive relationship with aesthetics and communication, indicating that expressiveness in an image influences the aesthetically pleasing look in an image and communication of design solutions or design ideas.
- **Image** quality seems to influence factors such as aesthetics, communication, dimensionality and rendering styles, because of its positive correlation with these factors.
- **Rendering style** appears to have a positive relationship with aesthetics, communication, dimensionality and image quality. This implies that the rendering style influences the aesthetically pleasing look in an image, communication of design solutions or design ideas, dimensionality and the quality of the generated image.
- **Speed of rendering** does not co-vary with any of the factors, which indicates its insignificance in the choice of factors influencing rendering. This result appears to be not in line with the observation in the literature that rendering speed is one of the main factors that is considered as an requirement for generation of rendering systems (e.g. [198]). However, keeping in line with the obtained result, this factor was excluded for further analyses in the study.

(c) Rendering parameters

When rendering images of 3D models, the models should not only look correct geometrically but also have a realistic visual appearance [239]. This is usually accomplished via a combination of parameters. From the literature and understanding different rendering techniques in Chapter 3, rendering parameters such as colour [201, 239], light [52, 239], lines [190, 224, 226], mapping [196], material [198, 239], shadows [164, 239], surfaces [239], textures [239], transparency [164] and vagueness in geometric design information [37] were contemplated to be important in creating the desired images and in providing the user with useful cues about the object placement.

Correlations with factors influencing rendering

To explore which factors influencing rendering correlate most with the specific rendering parameters, a correlation test was conducted (see Table 6-4)

Table 6-4: Correlations of factors influencing rendering and rendering parameters

		Rendering parameters									
		Colour	Light	Lines	Mapping	Materials	Shadows	Surfaces	Textures	Transparency	Vagueness
Factors influencing rendering	Aesthetics							0.4	0.4		
	Alternative solutions			0.6							0.5
	Communication	0.5									
	Dimensionality										
	Expression										
	Image quality							0.6			
	Rendering style		0.4			0.3			0.5	0.4	

The positive correlations between factors influencing rendering and rendering parameters indicate that there is some evidence that a relationship exists between each of them respectively. **Aesthetics** appears to co-vary with surfaces and textures. This implies varying surfaces and texture may vary the aesthetic look of the image. **Alternative solutions** seem to have positive relationship with lines and vagueness. This implies that the lines and vagueness in geometric design information may vary the number of alternative solutions in a design. **Communication** seems to be correlated only with colour. Colour is one of the important features in a visual presentation. The perceived depth and size of an object is influenced by its colour [315]. The observed relationship implies that colour as being to have more impact than other parameters in the communication of depth and size of an object. **Image quality** appears to have a strong correlation with surfaces. It would seem that varying the surface information varies the resulting quality in an image. **Rendering style** appears to have a positive relationship with light, materials, textures and transparency, implying that these parameters may vary the resulting rendering style in an image.

Correlations with rendering techniques

It has been seen in Table 6-5 that there is a correlation between rendering parameters and rendering style. In order to determine which parameters vary the style of PR, NPR and VR images, a further correlation test was conducted (see Table 6-5).

Table 6-5: Correlations of rendering parameters and rendering techniques

		PR	NPR
Rendering parameters	Colour		
	Light		
	Lines	0.3	0.3
	Mapping	0.4	
	Materials		
	Shadows		
	Surfaces		
	Textures	0.4	0.3
	Transparency	0.4	0.4
	Vagueness		

The positive correlations between rendering parameters and the different rendering techniques indicate that the related parameters as being important in enhancing the visual comprehensibility of images produced by the respective rendering technique. For instance, PR has a positive correlation with lines, mapping, textures and transparency. The relationship indicates that such parameters may enhance the visual comprehensibility of images produced by PR techniques. Similarly, NPR appears to have a positive relationship with lines, textures and transparency, implying that such parameters enhance the visual comprehensibility of images produced by NPR and provide the user with useful cues about the object placement.

6.2.3 Limitations with the current CAD systems

To determine the perceived limitations with current CAD systems that support rendering, the respondents were asked to ascertain their dissatisfaction with the present rendering tools in a closed-ended response question. Figure 6-7 shows that 32% of the respondents felt *absence of alternative solutions*, *exploring new ideas*, *sketchy look*, and 30% felt *lack of differentiation of essential and unessential information*, as being the most dissatisfying factors with present rendering tools.

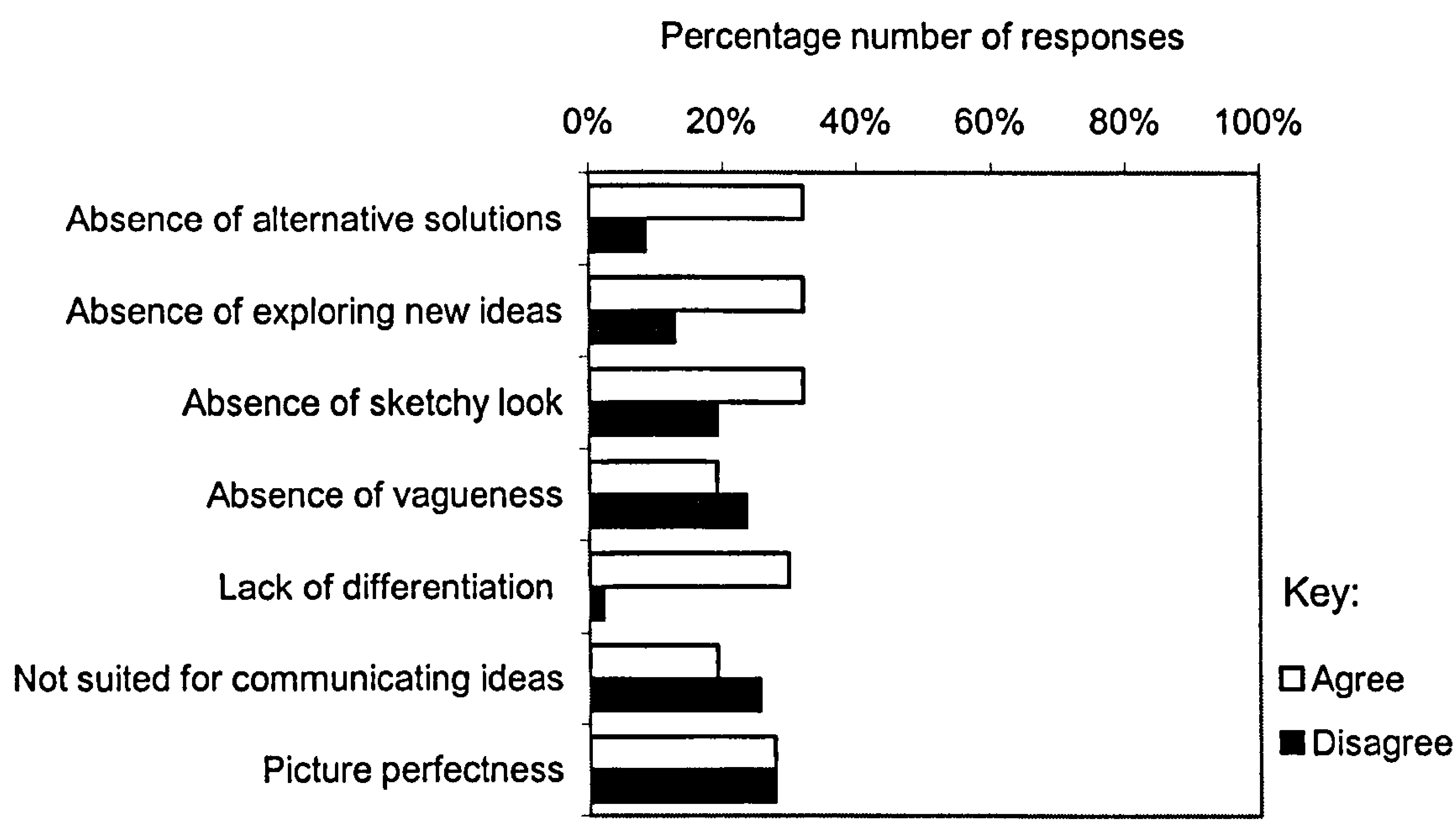


Figure 6-7: Dissatisfying factors

The respondents were asked, in an open-ended question, to relate any other possible dissatisfying factors in the present rendering tools. The dissatisfying factors stated by the respondents were:

- '*do not provide for making meanings at sketch level explicitly*',
- '*definition of abstract geometry*',
- '*interaction model not well matched to designers way of working at concept level*',

- '*modern tools lack different types of lighting*',
- '*no expression of constraints and easy way to edit structure*',
- '*time consuming, difficult to learn quickly*', and
- '*to get sketchy output work has to be done photo realistically then consider making it sketchy*'.

Given the respondents' comments, it would seem that there is insufficient support in the present rendering techniques for sketchy output or for the definition of abstract or vague geometry so that the output of the rendering system matches with the designer's way of working at the concept level.

The respondents were also asked to state possible solutions for the problems encountered with present tools. The following were the common solutions given:

- '*cater for sketching loosely while identifying lines, colours and shapes*',
- '*one that generates detailed drawings from sketches*',
- '*supports an underlying model of meaning, understandable but linkable to the surface graphical model*',
- '*support developing sketches into real exportable models (to CAD system for further development*', and
- '*use of Photoshop effects can help give rendering a sketch look which have to be started with finished computer rendering*'.

The solutions stated by the respondents seem to be in support of sketchy rendering. The solutions could possibly be taken into account during the development of rendering techniques for enabling user satisfaction with the generated images.

6.3 Main findings

The main findings from the study are summarised in Table 6-6, illustrating the objectives of the study, the investigated aspects and the deduced implications. The results suggest that the implications of rendering can be described by exploring (a) the nature of rendering, (b) the nature of different rendering techniques and (c) the limitations with current CAD systems. The meaning and potential of the results and insights gained from the study are discussed in this section, while the strengths and weaknesses of the study are delineated in Chapter 11 (see Section 11.2.4)

Table 6-6: Summary of the implications of rendering

		ASPECTS	IMPLICATIONS
Nature of rendering	Applicability		- Most effective in embodiment and detailed design. - More prolific in conceptual design.
Nature of rendering	Importance		- Visualisation and the communication of design solutions or design ideas.
Nature of rendering	Assistance		- Provides a realistic view of how the final product looks, and promoting ideas and communication through visualisation.
Nature of rendering	Precision		- Varies from fairly vague to very precise information.
Nature of rendering	Impact		- 3D rendering provides better visualisation, aesthetically pleasing, shows full view of the product, and good presentation of 2D/3D models. - NPR: more impact in encoding 3D information in a 2D model.
Nature of rendering	Importance of geometric aspects		- Lines, vague shape and vague surface are equally important as other product aspects (colour, material and light) during the generation of concepts. - Lines are more prolific than other aspects for the generation of concepts.
Nature of rendering techniques	Relevance	PR and NPR	- NPR more important than PR.
Nature of rendering techniques	Factors influencing rendering	Inter-correlations	- The higher the aesthetically pleasing look in an image, the higher the quality of the image. - The number of alternative solutions enables the communication of design solutions or design ideas more rapidly. - Communication of design solutions or ideas depends on the number of alternative solutions generated, 2D/3D rendering, image quality of the resulting image and rendering style. - 2D/3D rendering varies the aesthetic look in an image, communication of design solutions or ideas, image quality and rendering style. - Image quality is dependent on the aesthetic look of the image, communication of design solutions or ideas, 2D/3D rendering and rendering styles. - Rendering style influences the aesthetics, communication of design solutions or ideas, 2D/3D rendering and quality of the generated image.
Nature of rendering techniques	Rendering parameters	Correlations with factors influencing rendering	- Surfaces and textures convey a more aesthetically pleasing look in an image. - Lines and vagueness in geometric design information vary the number of alternative solutions in a design. - Colour has more impact in the communication of depth and size of an object. - Surfaces have more impact in varying the image quality of an image. - Light, materials, textures and transparency have more impact in influencing the rendering styles.
Nature of rendering techniques	Rendering parameters	Correlations with rendering techniques	- Lines enhance the visual comprehensibility of PR and NPR images and provide the user with useful cues about the object placement.
Limitations	Dissatisfying factors		- Absence of alternative solutions, absence of exploring new ideas, absence of sketchy look and lack of differentiation of essential and non-essential information.

a) ***Insights into the nature of rendering*** (Section 6.2.1)

The results indicate that rendering as being most effective in embodiment and detailed design and more prolific in conceptual design stage of the design process. There are a number of PR techniques that are popular [206], however such techniques are limited to the later stages of design, when many detailed decisions about the design have already been made. Rendering in conceptual design has received less attention to date, compared to later stages. The results (in Section 6.2.1) give some evidence that rendering can be extended in conceptual design for investigation of different ideas or concepts, specifically for visualisation of designs and the communication of design ideas, using *fairly vague* to *very precise* 3D information.

- One of the most important elements in a design work is visualisation of design. Visualisation is the act or process of interpreting in visual terms or of putting in visual form [165, 166]. Visualisation of the design is used as a means to analyse the progress of the design and identify the impediments in the design process. With visualisation, impediments may become more obvious and better to identify. In this regard rendering of the model being designed is a useful means of visualisation, where the identified impediments can be set as implications for methodological improvements in design.
- The primary purpose of most computer graphic images is communication, which ranges from the knowledge or information about the computer model visualised to a deeper emotional form. In other words, communication involves not just the surface perception of the computer model (the output as seen by the designer) but also meaning or more precisely deeper levels of cognition (such as judgement, articulation, emotion and inference) of the model [171]. More explanation on the information communicated by rendered images is provided in Chapter 4.
- The issue of dimensionality is usually of importance for the success of the information communicated using rendering. Teece [249] provided a taxonomy for NPR approaches according to whether they are 2D or 3D or user intervention is required. Most of the existing work in NPR has been static 2D images. However, NPR had been extended to create 3D illustrations by dealing with aspects (such as shape information, visual complexity, and cues) that are missing in 2D images and also to change 2D illustration rules for a 3D illustration [260]. In the present study, when asked to opinion the choice of dimensionality appropriate for rendering in an open-ended question, most of the respondents stated that 3D rendering provides better visualisation, is aesthetically pleasing, shows the full view of the product, a

good presentation of 2D/3D models, is the most suitable for 3D applications and provides capabilities that are limited with paper and pen. The result of a further correlation test between different rendering techniques and different dimensions of computer models or images showed that there is a relationship between NPR and encoding 3D information in a 2D model or image. The observed relationship from the study implies that NPR provides better presentation of 3D information in a 2D concept representation than other rendering techniques.

From the results, the observers consider geometric aspects, such as lines, vague shape and vague surface, as being *equally important* as other product aspects (e.g. colour, light, and material) during the generation of concepts (see Figure 6-5). It was found that lines are thought to be more prolific than other aspects during the generation of concepts. In NPR, several researchers have examined the types of lines [190, 223, 229, 252-254] to be drawn in computer generated images to maximise the amount of information conveyed. However, none of the works examined the amount of vague information conveyed. In the work presented in this thesis, a few possibilities of presenting vagueness visually through lines were evaluated to determine how these NPR line styles are understood and perceived (see Chapter 8).

b) ***Insights into the nature of different rendering techniques*** (Section 6.2.2)

Relevance of different techniques

The results were inconclusive in determining the importance of hand drawn and computer renderings in the design process. This is because of the advantages of both renderings. In this sense, several researchers developed pen-based systems [84, 106, 141, 316] to support sketching. The main aim of these works is to provide the benefits of hand drawings in CAD systems. That is, to provide computer images a 'human' touch as it gives immediate cues to the development of a solution and focus attention on particular aspects of a solution.

In the study presented in this thesis, from the existing computer renderings, NPR is conceived to be more important than PR in conceptual design. The value of a computer rendering lies in presenting information about the object (e.g. shape, spatial structure and artistic expression) that may not be apparent in actuality. In this regard NPR (e.g. painting [243-246], and pen-and-ink [205, 216, 222]) is now emerging as an alternative rendering method to PR. Despite much progress in the efficiency and quality of PR methods [240], the PR images may not always be the best way to present information in conceptual design because the resulting image is fully determined and there is not much left for imagination. This is appropriate in some instances, but there are times when something fuzzier, more tentative is required in conceptual design, either because ideas are only partially worked out, or to encourage discussion. In fact, the way things are judged has shifted from technical virtues such as the smoothness of shading, the sharpness of textures, or the size of highlights to pictorial qualities, focus an issue and stimulate an imagination or support a discussion [291].

Factors influencing rendering

The perception and understanding of the rendered images are influenced by a variety of factors. From the inter-correlations of the factors influencing rendering (see Table 6-3), it would seem that rendering styles have a positive relationship with aesthetics, communication, dimensionality and image quality. From this relationship, it may be appropriate to interpret that a rendering style is effective in influencing the aesthetically pleasing look in an image, communication of design solutions or design ideas, 2D/3D models or images and the quality of the generated image.

Rendering parameters

Rendering parameters usually vary the style of the resulting images in terms of its visual appearance and geometrical correctness. The correlation study of rendering parameters and rendering styles (see Table 6-4) demonstrate a relationship between them. A further correlation test was conducted (see Table 6-5) to determine the rendering parameters that vary the style of PR, NPR and VR images. One of the parameters that seem to be common for all the techniques was lines. In fact, rendering of lines are important in CAD for seeing the underlying model facets and discerning the object's shape [239]. As observed in NPR works (such as [217, 229]), lines are also useful in highlighting a selected object and in areas such as technical illustration. Further, some works (such as [190]) concentrated on rendering techniques that produce PR images with enhanced visual comprehensibility through the use of line drawings in the post-processing.

c) ***Insights into limitations with the current CAD systems*** (Section 6.2.3)

The insights gained by the identification of the limitations with the current CAD systems could aid in preventing dissatisfaction in future design works. The resolution of the identified limitations is to set them as implications for computer support tools or for methodological improvements.

The *absence of a sketchy look, lack of differentiation between essential and non-essential information, absence of alternative solutions* and *absence of exploring ideas* were perceived in the study as some of the most dissatisfying factors with the current CAD systems. It would seem that aspects such as the *provision of a sketchy look, differentiation between essential and non-essential information, provision of alternative solutions* and *provision of exploring ideas* were perceived to be lacking in the present rendering systems and need to be incorporated for better presentation of computer graphic images. Thereby, these aspects are identified as some of the implications for the presentation of computer graphic images (in Chapter 7).

From the observed results of the dissatisfying factors with current CAD systems (through closed-ended responses) and rationalising respondents' comments (through open-ended responses) it would seem that there is insufficient support in the present rendering techniques for sketchy output or for the definition of abstract or vague geometry so that the output of the rendering system matches with the designer's way of working at the concept level.

d) ***Insights into factors involved in designing and running experiments***

In addition, the exploratory study gave insights into the factors involved in designing and running experiments, such as the nature of sample selected, sample size, response formats in the questionnaire, the importance of correct wording, importance of proper rationalising and consistent experimental instruction.

- *Nature of sample selected*: The students with background in product design engineering and the academics in the department with more than five years of experience in CAD could understand the theme of the investigation on rendering. Especially, the academics offered valuable information in the open-ended questions. This confirmed that the experience and type of sample selected plays a major role in the outcome of the studies.
- *Sample size*: The sample size was large enough to produce reasonable level of accuracy of the results in the study and to draw conclusive evidence about the implications of rendering in conceptual design. This highlighted the importance of sample size in running experiments.
- *Response format*: The scaled response format questions proved to be successful as they facilitated quick completion and a detailed quantification of results.
- *Importance of correct wording*: The wording used in the questionnaire was sometimes unclear. The respondents had problems with understanding the meaning.

  - In Section 6.2.1, the importance of rendering with respect to some key issues such as communication, visualisation, quality and time (speed of rendering) was addressed. However there was no clarity as to what 'speed of rendering' here meant. In another question on the impact of rendering in different dimensions, different options such as *linear, 2D, 3D information in 2D, 3D, 2D and 3D*, and *2D or 3D* were presented. However the option *2D or 3D* could be excluded from the range of options, since the options 2D and 3D were already provided separately. This confirms that care should be taken while wording the questions and providing options.

- *Importance of proper rationalising of the choices provided in the response formats*: The factors influencing rendering and rendering parameters (Section 6.2.2), collected from literature, were sometimes not rationalised properly.
  - Factors such as 'expression' were confusing, since there was no clarity of what the word 'expression' meant. Subsequently, there were problems while articulating the results of correlation analysis using the word 'expression'. This factor could be avoided from the overall selection of factors influencing rendering.
  - Rendering parameters such as 'surfaces' and 'mapping' were confusing, especially 'mapping' because it is the process of associating a group of elements or qualities with an equivalent group, according to a particular model or formula [1]. It could not be termed as a parameter. In addition, 'surfaces' and 'mapping' as individual rendering parameters are misleading, however they could have been reworded as 'surface textures' or 'texture mapping'. Where, texture is one of the important features to visualise a surface; and 'texture mapping', used for adding surface detail, is to map texture patterns onto the surfaces of objects.

  Consequently, the analysis became cumbersome because there were problems while articulating the results using the above-mentioned ambiguous words in textual form. This confirms that care should be taken to rationalise the choices provided in the response formats.

Based on these insights, a consistent experimental instruction was followed in subsequent experimental designs (Chapter 8) by providing definitions for the ambiguous terminology used in the questionnaire and also measures were taken to provide correct wording in the questions and to rationalise choices in the questions.

6.4 Chapter summary

This chapter has presented a survey-based study that investigated the implications of rendering to gain insights into the nature of rendering and its different techniques, and the limitations with current CAD systems.

In Section 6.1, the experimental methodology of the study was introduced. In Section 6.2, the findings of the study were presented in the form of bar charts, means and standard deviations, hypothesis testing, correlations and ranking tests. In Section 6.3, the main findings of the study were discussed and presented in Table 6-6, summarising the results, including the aspects of rendering investigated and the deduced implications.

The insights gained from the study, especially the following implications for the presentation of computer graphic images and implications of NPR styles, provide a basis (1) for the identification of emotive implications of computer graphic images as discussed in Chapter 7, and (2) for collecting and evaluating NPR line styles to determine how they are understood and perceived (discussed in Chapters 8 and 9), respectively:

Implications for the presentation of computer graphic images:

- Aspects such as the *provision of a sketchy look, differentiation between essential and non-essential information, provision of alternative solutions* and *provision of exploring ideas* need to be incorporated for better presentation of computer graphic images.

Implications of NPR styles

- NPR styles, especially *lines*, are of paramount importance in presenting vagueness visually.

7. Identification of emotive implications

In Chapter 4, it was stated that emotive implications of images reflect the implicational information that imply or stimulate designers' emotive responses. This chapter focuses on the identification of the emotive implications of computer graphic images. The identified emotive implications will provide the basis for assessing the emotive effectiveness of different rendering styles, which will be discussed in Chapter 8. In this chapter, Kansei Engineering is established as a means for (1) identifying emotive implications and (2) evaluating the degree of emotive effectiveness of different rendering styles (discussed in Chapter 8).

Section 7.1 presents an exploratory pilot study conducted as part of the research presented in this thesis. In Section 7.2, an overview of Kansei Engineering methodology is given. The identified fourteen emotive implications are presented in Section 7.3. Finally, the chapter is summarised in Section 7.4.

7.1 Pilot study

An exploratory pilot study was conducted with eight respondents to gain insights into the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles. The respondents selected for the study were six academics, one fellow researcher/colleague and one MEng student from the DMEM Department (see Annex-1 of Appendix B for details of the respondents). The sample size for the pilot studies was kept to a minimum in order to reserve the sample for the main experiment (Chapter 8). The method adopted for the study was in the form of group-administered questionnaire (see Annex-2 of Appendix B) . Based on the exploratory nature of the pilot study, different kinds of ideas and questions were investigated. The questionnaire also provided the opportunity for the respondents to input their comments.

For the study, (i) different emotive implications that were considered appropriate were collected from the literature, and (ii) different rendering styles were searched and rendered images of nine different models (such as cuboid, rectangle, ring, cup, compound object, funnel, nut, and spiral) were selected, which were considered appropriate for assessing the effectiveness. The intention was to measure respondents' responses and variability to the given rendered images. Having been presented with a selection of rendered images, the respondents were asked to assess each image using the emotive implications, given on the semantic differential scale [317]. Each image was rated against the same set of semantic differential scales. The objective of this kind of evaluation was to find out whether or not the images were perceived as eliciting the emotions described on the semantic differential scales. It was contemplated that this type of evaluation enabled the identification (i) of the appropriate emotive implications and (ii) the level at which the respondents could perceive information in the different rendered images provided.

Observations

The analysis of the responses from the pilot study became confusing and cumbersome because of the following reasons:

- Firstly, random selection of emotive implications and rendered images. The emotive implications, collected from literature, given on the semantic differential scales, were not rationalised properly and the different rendered images presented to the respondents were collected randomly. Consequently the analysis was confusing, since there was no proper basis for the rendered images collected. That is, the rendered images collected could not be pertained to any particular rendering style and thus correlation of the results to styles was not possible. There was a lack of justification for the emotive implications and rendered images used in the pilot experiment.
- Secondly, the respondents felt that the wording used for the emotive implications on the semantic differential scales was at times unclear. They had problems with understanding what the words meant. In addition, too many words were given on the semantic differential scale and it became difficult for the respondents to assess each image using these words. Thereby the analysis became cumbersome. Furthermore, a rigorous statistical analysis was not possible due to the high number of variables (words given on the semantic differential scales) and the small sample size. Because of the small sample size the results were imprecise to draw any conclusive evidence about the effectiveness of rendering styles in eliciting emotions as described by the words given on the semantic differential scale.

Insights gained

From the pilot studies, the following insights were gained about the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles.

Identifying emotive implications

- *Systematic methodology*: One of the insights gained from the pilot studies was that there was no actual rigour or systematic methodology behind the selection and rationalisation of emotive implications presented on semantic differential scales to evaluate their suitability. This highlighted the need for a systematic basis for identifying the emotive implications of images.

Assessing the emotive effectiveness of rendering styles

- *Selection of emotive implications*: The emotive implications provided the basis for assessing the emotive effectiveness of different rendering styles, thereby a systematic methodology, as highlighted above, should be followed for identifying the emotive implications of images. In essence, the emotive implications should be rationalised on a systematic basis before they are utilised for assessing the emotive effectiveness of rendering styles.
- *Selection of rendering styles*: To assess the emotive effectiveness of different rendering styles, the rendering styles should not be selected randomly but rather cover a broad range of rendering styles that pertain to a particular rendering category. This enables the researcher to have a proper comparison of different rendering styles and assess their degree of effectiveness.
- *Size of the sample*: The sample size should be large enough to draw conclusive evidence about the degree of effectiveness of different rendering styles. This is because if the sample size is small the results might tend to be imprecise to make any accurate decisions about the effectiveness of rendering styles. In such cases, the data gathered becomes unproductive. Often, the minimum sample size is thirty for a normal distribution of the observations from the sample [312].
- The emotive implications for assessing the rendering styles should not be excessive in number. This is because it might be exhausting for the respondents to assess each rendering style using the number of emotive implications.
- The emotive implications provided on the semantic differential scales should be clear. In essence, the respondents should be able to understand the meaning carried by each of the emotive implications. This enables clarity and proper interpretation of the rendered images based on the information provided.
- *Presentation of rendered images*: The rendered images provided for assessment in the pilot study were presented as black and white illustrations. The respondents had problems while judging the different features in the images and thereby, in

understanding the emotions elicited by the rendered images. This confirmed that the rendered images presented for assessment should be of better quality to enable the respondents to perceive the images better and thereby, facilitate better interpretation of the emotions elicited by the images.

In essence, the observations have shown that there was little formal foundation for the conducted pilot studies. Later experiments should address the insights gained from these exploratory pilot studies in order to provide a better foundation for the work and results. These insights highlight the need for a systematic methodology for rationalising and identifying the emotive implications and assessing the effectiveness of different rendering styles, which in turn forms the background to Kansei Engineering methodology adopted in this thesis.

7.2 Kansei Engineering methodology

Whilst Kansei Engineering has never been applied before in the computer graphics, given (i) its wide range of applicability (e.g. [21, 22, 24, 318-320]) and advanced development over other methods in terms of evaluating the users' emotional relationship with artefacts, leading to more informed decision-making in the design process, and, in particular, (ii) the concept of *Kansei* being closely related to emotive responses at the implicational level leading to interpretation, imagination and judgement, Kansei Engineering methodology was adopted as the means for (1) identifying emotive implications as discussed in Section 7.3 and (2) evaluating the degree of effectiveness of different rendering styles as discussed in Chapter 8.

Kansei is a Japanese term, which when translated into English might mean users' psychological feeling or mental image of an artefact [321]. It is an individual subjective impression from a certain artefact, environment or situation [286, 322]. Within the context of the work presented in this thesis, *Kansei*, from a computer graphics perspective, refers to the users' subjective impressions from a displayed computer graphics rendered image. Kansei Engineering [24], from a product development perspective, is a methodology for translating consumers' feelings or perceptions on existing products or concepts into design solutions or design elements for new products or concepts. The standard methodology involves the following phases:

1. Collection of *Kansei* words of the products, e.g. sporty, warm, cute, elegant. The *Kansei* words describe the product domain in the form of adjectives, nouns or verbs.

In order to get a collection of *Kansei* words, all the available sources have to be used, even if the words emerging seem to be similar or the same. Suitable sources include: existing literature, experienced users, experts, magazines, manuals and relating Kansei studies. An important issue in this phase is to translate ideas and visions from the sources into *Kansei* words.

2. Kansei experiment: Evaluation of product samples using a semantic differential scale [317] questionnaire. That is, the semantic differential scales are defined with a number of contrasting *Kansei* words at each end, on which respondents check the position which best represented the direction and intensity according to their point of view. This enables the designer to investigate the relevance of certain *Kansei* words and its related design elements of the product. In essence in Kansei Engineering, evaluations with semantic differential scales are done twice. The first is to evaluate the suitability of many *Kansei* words collected from various kinds of sources. The second is to evaluate different product samples using the selected *Kansei* words to identify those design elements that correlate most with consumers' feelings.
3. Analysis of evaluation data: The data is analysed to identify those design elements that correlate most with consumer's feelings. Therefore, the designers can decide which design elements to adopt in the final design of the product.

7.3 Emotive implications identification

The identification of the emotive implications of computer graphic images was attained through the methodology illustrated in Figure 7-1, in accordance with the Kansei Engineering methodology.

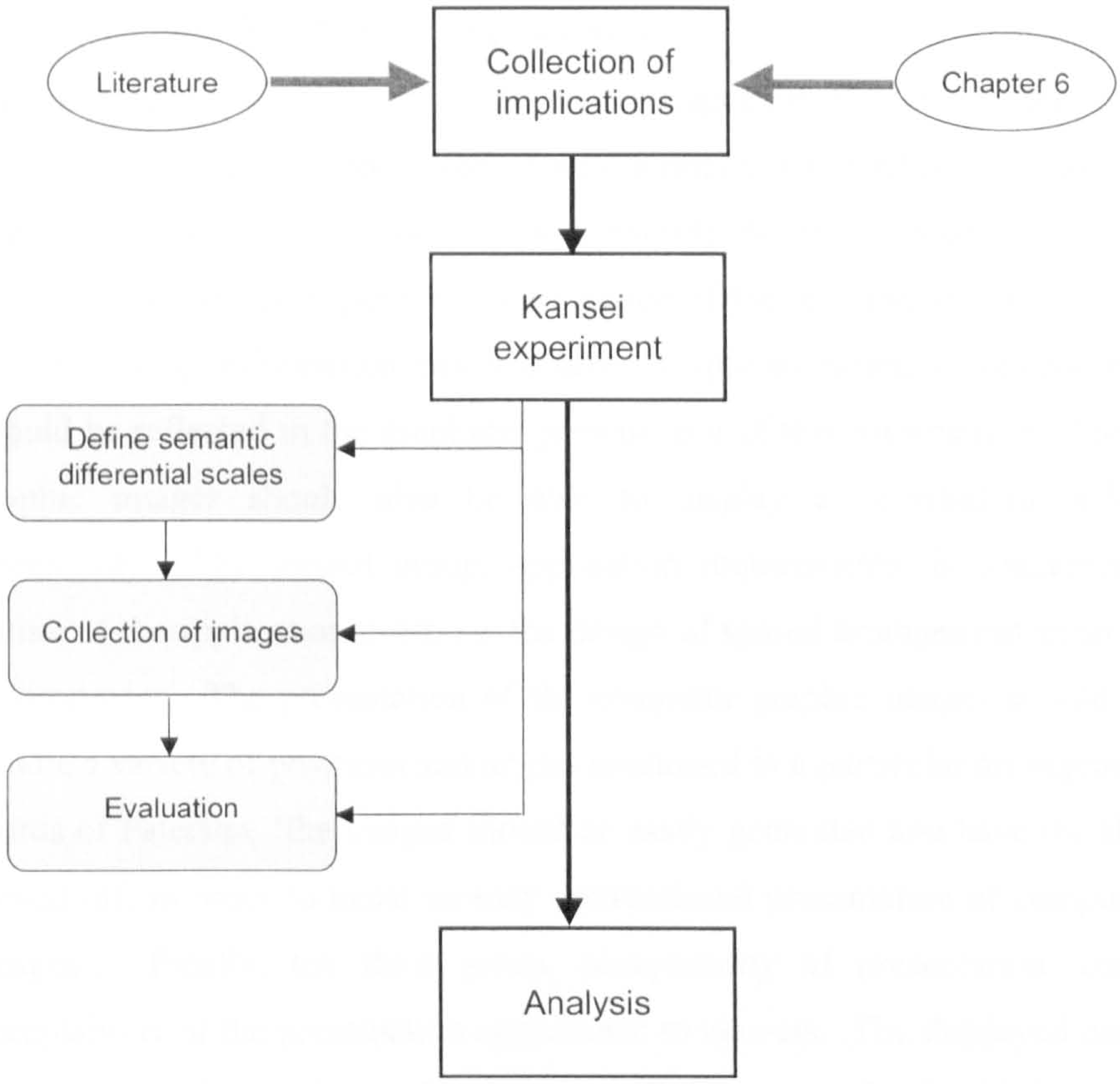


Figure 7-1: Methodology for emotive implications identification

With regard to Figure 7-1, from the existing literature and Chapter 6 in the thesis, the implications of computer graphic images were collected. Using the collected implications, a Kansei experiment was conducted. This involved defining semantic differential scales and collecting images rendered with different styles. The rendered images were then evaluated, by the respondents, using the implications given on the semantic differential scales. The emotive implications were identified on analysing the respondents' responses.

Phase 1. Collection of implications

In this phase all the implications of computer graphic images were included in the first gathering of implications in the form of adjectives, verbs and nouns. They were collected from the following sources:

i Explicit implications based on existing literature [261, 323].

ii The study on implications of rendering (Chapter 6 in the thesis).

1. *Explicit implications based on existing literature*

   - Paterson [323] divided the implications of images for the development of computer graphic presentations into three groups namely, (i) display of information, (ii) application requirements and (iii) acceptability of presentation. The first group, display of information, pertains to the nature of the information to be displayed. If the underlying information has a degree of approximation or uncertainty, then it should be reflected in the graphical presentation of this information. The computer graphic images should also be able to display a distribution reflecting the uncertainty. The second group, application requirements, is concerned with the nature of the application itself, i.e. the design of spatial arrangement in an interactive environment. The presentation of the computer graphic images should be able to handle a variety of positions and angles contained in a particular arrangement. In the words of Paterson, 'the images should be easily generated and have the ability to be turned off, in order to make an easy conventional presentation of computer graphic images'. Finally, the third group, acceptability of presentation, concerns the acceptability of the presentation appearance to viewers. The displayed image should be recognisable as the underlying bounded space. It should be immediately understandable. Paterson opined that the presentation should be perceived as a drawing that reflects the approximations of information and also colour, if appropriate. Lastly, the presentation of the computer graphic images should be unambiguous. That is, the attributes used for the presentation should not be confused with any other attribute.
   - The work of Schumann et al [261] referred to the classification scheme of Peeck (see Houghton [324], where the possible implications of images were divided into three groups namely, (i) affective, (ii) cognitive and (iii) motivational. An affective group is concerned with assessing emotional aspects, like how interesting or imaginative an image appears. A cognitive group pertains to aspects like the understandability or clarity of the images. Finally, the motivational group describes to what extent the users are encouraged to participate in the design process.

2. *Implications derived from the study on implications of rendering*

   - From the exploratory study on the implications of rendering (Chapter 6), the provision of a sketchy look, differentiation between essential and non-essential information, provision of alternative solutions and provision of exploring ideas, were identified as the aspects that need to be incorporated for better presentation of computer graphic images in conceptual design. These are the functions to be performed for better presentation of the images and could be named together as a functional group.

In total thirty-one implications of computer graphic images were collected from the above-mentioned sources. Table 7-1 presents the collected implications and the groups under which they were categorised.

Table 7-1: Collected implications

Source	Group	Implication
Paterson [323]	Display of information	1. Reflect the approximation of information
		2. Allow the specification of uncertainty
		3. Display of distribution reflecting the uncertainty
		4. Reflect different level of details
	Application requirements	5. Deal with a variety of positions and angles
		6. Deal with geometric properties
		7. Easily generated
		8. Able to be turned off
	Acceptability of presentation	9. Graphically represent a spatial arrangement
		10. Immediately understandable
		11. Work on colour and mono monitors
		12. Unambiguous
Schumann [261]	Affective	13. Artificial
		14. Conveys emotions
		15. Creative
		16. Imaginative
		17. Individual
		18. Interesting
		19. Lively
		20. Pleasant
		21. Satisfied
	Cognitive	22. Comprehensible
		23. Recognisable
		24. Simple
	Motivational	25. Stimulating to discussion
		26. Stimulating to changes
		27. Stimulating to look at
Chapter 6 in this thesis	Functional	28. Sketchy look
		29. Differentiation of information
		30. Alternative solutions
		31. Exploring new ideas

Phase 2. Kansei experiment

This phase evaluated the suitability of the collected thirty-one implications from Phase 1 by conducting a retrospective Kansei experiment on the pilot study which involved (i) defining semantic differential scales, (ii) collecting images of different rendering styles and (iii) respondents' evaluations of the collected rendered images using the defined semantic differential scales in a questionnaire.

(i) Define semantic differential scales

On scrutinising the thirty-one implications for defining the semantic differential scales, the following was deduced:

- For implications such as *allow the specification of uncertainty*, *display of distribution reflecting the uncertainty*, *able to be turned off* and *work on colour and mono monitors*, contrasting words could not be derived to describe them. Because they are expressions developed for use within a particular group, under which they were categorised, and are difficult for others to understand.
- Implications such as *interesting* and *lively* were considered to convey the same meaning.
- For implications such as *individual*, contrasting words were deemed not be meaningful or relevant.

Based on these deductions, the semantic differential scales were defined with twenty-two contrasting implications at each end.

(ii) Collection of rendered images

Rendered images of nine different models (such as, cuboid, rectangle, ring, cup, compound object, funnel, nut, and spiral) were collected. The models selected for this purpose were common and easily available.

(iii) Evaluation

Evaluation by the respondents for the identified twenty-two implications was performed to find out (1) how strongly they felt each of the implications was appropriate and (2) whether or not the rendered images were perceived as eliciting the emotions described using the twenty-two implications. This enabled the suitability of the implications collected to be assessed. On the semantic differential scales, with a number of contrasting implications at each end, the respondents checked the positions which best represented the direction and intensity according to their point of view. In addition, they were also asked to state any other specific implications of images that they felt were relevant.

Phase 3. Analysis

The outcome of the evaluations (please refer to Annex-2 of Appendix B for an example of an evaluation by one of the respondents) was two-fold:

- Firstly, the respondents felt the extreme points 1 and 5 of the semantic differential scale as particularly overt statements and the remaining three points were not sufficient for making a proper estimation of the emotions elicited by the rendered images. Consequently, semantic differential scales ranging from +2 to –2 were suggested for later experiments, where the midpoint of the scale enables the respondents to indicate a neutral feeling towards the image and then estimation can be made towards each end of the scale. In addition, the respondents felt that the placement of contrasting implications at each end was inconsistent. This implies that consistency should be maintained in the placement of the contrasting implications at each end of the scale either by placing the implications towards the left extremity and the corresponding opposite on the other extremity or vice-versa.
- Secondly, implications such as *imaginative* and *creative* were interpreted to have the same meaning. Implications such as *deals with a variety of positions and angles*, *easily generated* and *graphically represent a spatial arrangement* seem to not describe any emotions elicited by computer graphic images. Implications such as *convey emotions*, *level of details* and *geometric* were contemplated to be implicit in images and, further, not in line with the other implications provided. In addition, some other specific implications of images (such as *invite assumptions*) that the respondents felt relevant were suggested.

On further scrutinising the implications provided on the semantic differential scales, it was observed that implications such as *comprehensible*, *satisfied* and *alternative solutions* from the collected implications (see Table 7-1) were not included for evaluation. Thereby, based on the input from the respondents and further inspection, fourteen implications were finally identified. These fourteen implications of images reflect the information of images that imply or stimulate designers' emotive responses. Hence, the resulting fourteen implications are termed here, and in the remainder of this thesis, as the *emotive implications of images*. Table 7-2 presents the identified fourteen emotive implications along with their meanings.

Table 7-2: Fourteen emotive implications of computer graphic images

GROUP	EMOTIVE IMPLICATION	MEANING
Affective	1. Comfortable	The experience of being at ease with the image.
	2. Imaginative	Ability of the images to stimulate viewers to think about new ideas.
	3. Interesting	Ability of the images to attract the attention of the viewers.
	4. Real	How well the presentation style reflects physical reality.
	5. Satisfied	The experience of feeling content or pleasure associated with the image.
Cognitive	6. Approximation of information	Ability of the images to display approximate or fuzzy information of the design concepts.
	7. Comprehensible	How well the image is understood as reflecting the aspects of the graphical objects in the scene.
	8. Recognisable	How well the graphical objects in the scene can be identified.
Functional	9. Differentiation of information	Ability of the images to differentiate essential and unessential information.
	10. Exploration of alternative solutions	Ability of the images to stimulate the thought that the solution can further have alternative solutions or needs further development.
	11. Invite assumptions	Whether the presentation of the image denotes the actual form of an object using cues.
Motivational	12. Stimulating to changes	Whether the presentation is accessible to make any variations.
	13. Stimulating to discussion	Whether the style of presentation encourages discourse about a design with others or with oneself.
	14. Stimulating to look at	Whether the presentation style provides a 'feel good' factor or is thought provoking.

From the understanding of existing classifications of images [261, 323, 324] and discussions with respondents, it was felt that images have a psychological impact such as affective, cognitive, functional and motivational, apart from their effect on the design process, the designer-client relationship and modelling issues. Hence, the fourteen emotive implications were further classified into four groups: ***affective***, ***cognitive***, ***functional*** and ***motivational***, (Table 7-2).

7.4 Chapter summary

In this chapter, the emotive implications of computer graphic images are identified as part of the research presented in this thesis.

In Section 7.1, the chapter presented an exploratory pilot study to gain insights into the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles. One of the insights from the pilot study is that there was no formal procedure behind the pilot study conducted. This examination highlighted the need for a systematic methodology for identifying the emotive implications and assessing the effectiveness of different rendering styles, which in turn formed the background to the Kansei Engineering methodology adopted for the work presented in this thesis. An overview of Kansei Engineering methodology is presented in Section 7.2. In Section 7.3, a systematic methodology for emotive implications identification is presented. The resulting fourteen emotive implications are presented in Table 7-2.

The major outcome of the chapter is that the insights gathered from the pilot studies and Kansei experiment, summarised in Table 7-3, indicate a future direction for the main experimentation and data gathering for assessing the emotive effectiveness of different rendering styles (Chapter 8).

Table 7-3: Insights into the main factors involved in designing and running experiments

FACTORS	IMPLICATIONS
Sample size	– Minimum thirty
Selection of rendering styles	– Cover a broad range of rendering styles
Response format (semantic differential scales)	– Range from +2 to –2 – Emotive implications on left extremity of the scale and their opposites on other extremity.
Proper interpretation	– Enable respondents with meanings of the emotive implications. – Better quality rendered images for assessment.

The identified fourteen emotive implications, along with the insights gained into factors involved in designing and running experiments, provide the basis for assessing the emotive effectiveness of different rendering styles, which will be discussed in Chapter 8.

8. Assessing the emotive effectiveness of different rendering styles

In Chapter 7, the pilot study and Kansei experiment for identifying the emotive implications provided insights into the main factors involved in designing and running experiments for assessing the emotive effectiveness of different rendering styles. The aim of this chapter is to present the main experimental study conducted to assess the emotive effectiveness of different rendering styles. The objective of the study was to evaluate the degree of emotive effectiveness of existing PR and NPR styles using Kansei Engineering methodology. In order to validate the resulting findings, the rendering styles will be cross-evaluated with a cross-section of design practitioners from industry, which is presented in Chapter 9.

In Section 8.1, the experimental methodology of the study is presented. Section 8.2 presents the results of the study in the form of tables, bar charts, line-charts, mean values, factor analysis and frequency percentages. In Section 8.3, the main findings of the study are discussed. Finally, Section 8.4 summarises the chapter.

Estimation of effectiveness

In Chapter 5, it was formalised that the estimation of effectiveness is based on a number of factors (see Table 5-3). A rendered image of a design, for example, is judged effective when it can be interpreted accurately or quickly, or when it has visual impact, or when it can be rendered in a cost-effective manner. The critically reviewed studies in Chapter 5 based the measurement of effectiveness on factors that varied from accuracy in performing tasks to visual impression and visual interest that the images make on communication of particular affects. There are other studies (e.g. [22, 24, 319, 320]) that have evaluated effective designs with respect to the relationship between the perception of the users and corresponding designs, to assist the user in selecting an effective design that best fits (correlates with) their perception, among a variety of designs.

Dealing with multiple, perhaps conflicting, effectiveness factors is not a paramount issue in this research. Consequently, keeping in line with existing studies and the research focus, for the work presented in this thesis, effectiveness was estimated in terms of 1) *impact* of the rendering styles in conveying emotive implications and 2) *correlation* of the rendering styles with the emotive implications, where (see Figure 8-1):

- *Impact* is the degree of impression of rendering styles in conveying emotive implications. An indication of the *impact* can be reflected through the *mean*[25] *value* of the perception and emotional responses of the respondents. Thus, the higher the *mean value* the higher the *impact* and vice versa.
- *Correlation* is the degree and direction of relationship between the rendering styles and emotive implications. An indication of *correlation* can be reflected through *factor analysis*, where the *factor loadings* in *factor analysis* indicate the *correlation* coefficient[26]. The *factor loadings* indicate the degree of relationship between the rendering styles and the perception and emotional responses of the respondents. Thus, the higher the *factor loading* the higher the degree of relationship and vice versa.

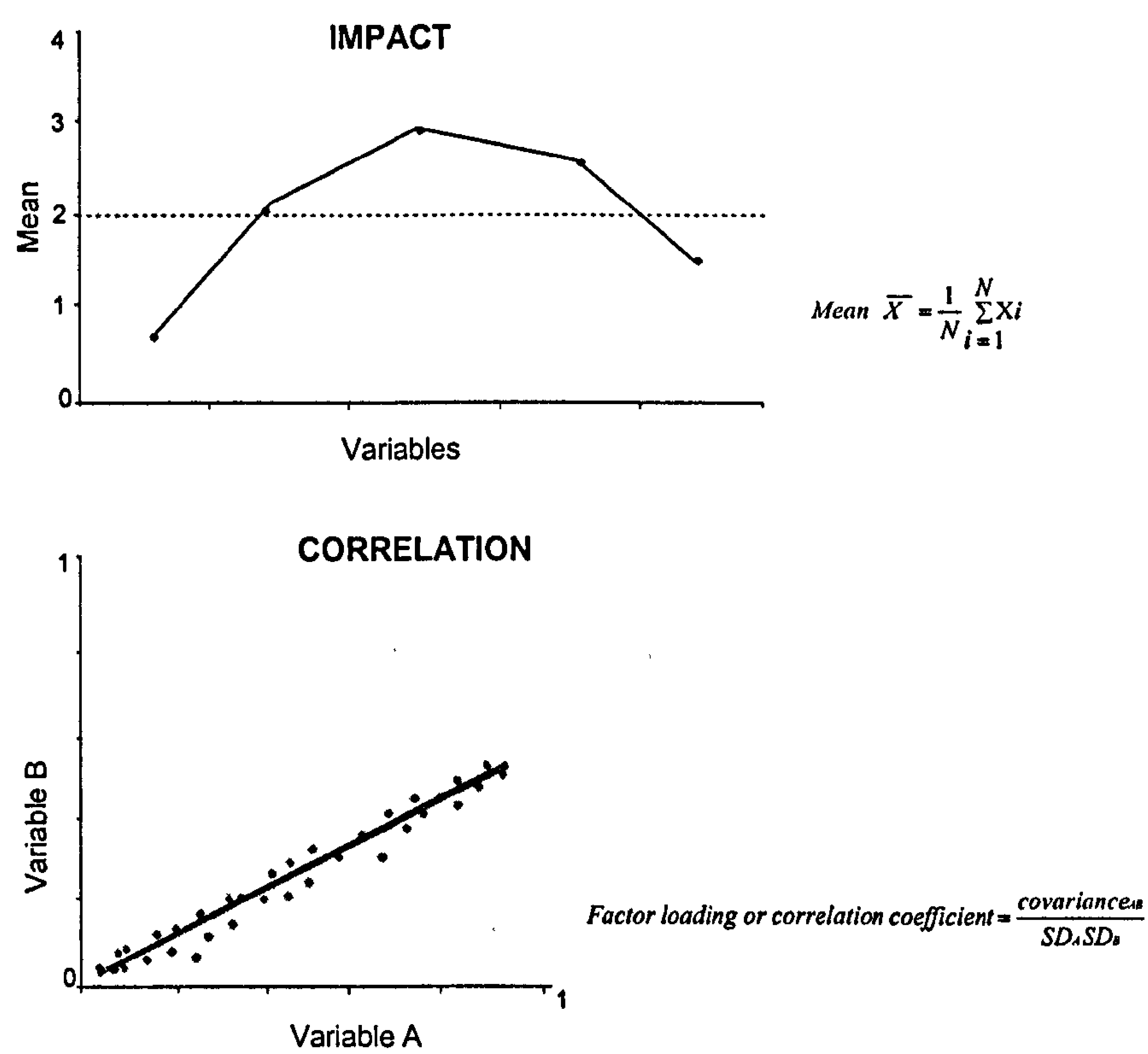


Figure 8-1: Impact and Correlation

[25] *Mean*, $\overline{X}$, is the most common method for describing the central tendency.

[26] Correlation coefficient is a numerical measure of the amount of linear association between two variables.

8.1 Experimental methodology

This section presents the experimental methodology for evaluating the degree of emotive effectiveness of existing PR and NPR styles. The methodology is illustrated in Figure 8-2, in accordance with the Kansei Engineering methodology (see Section 7.2).

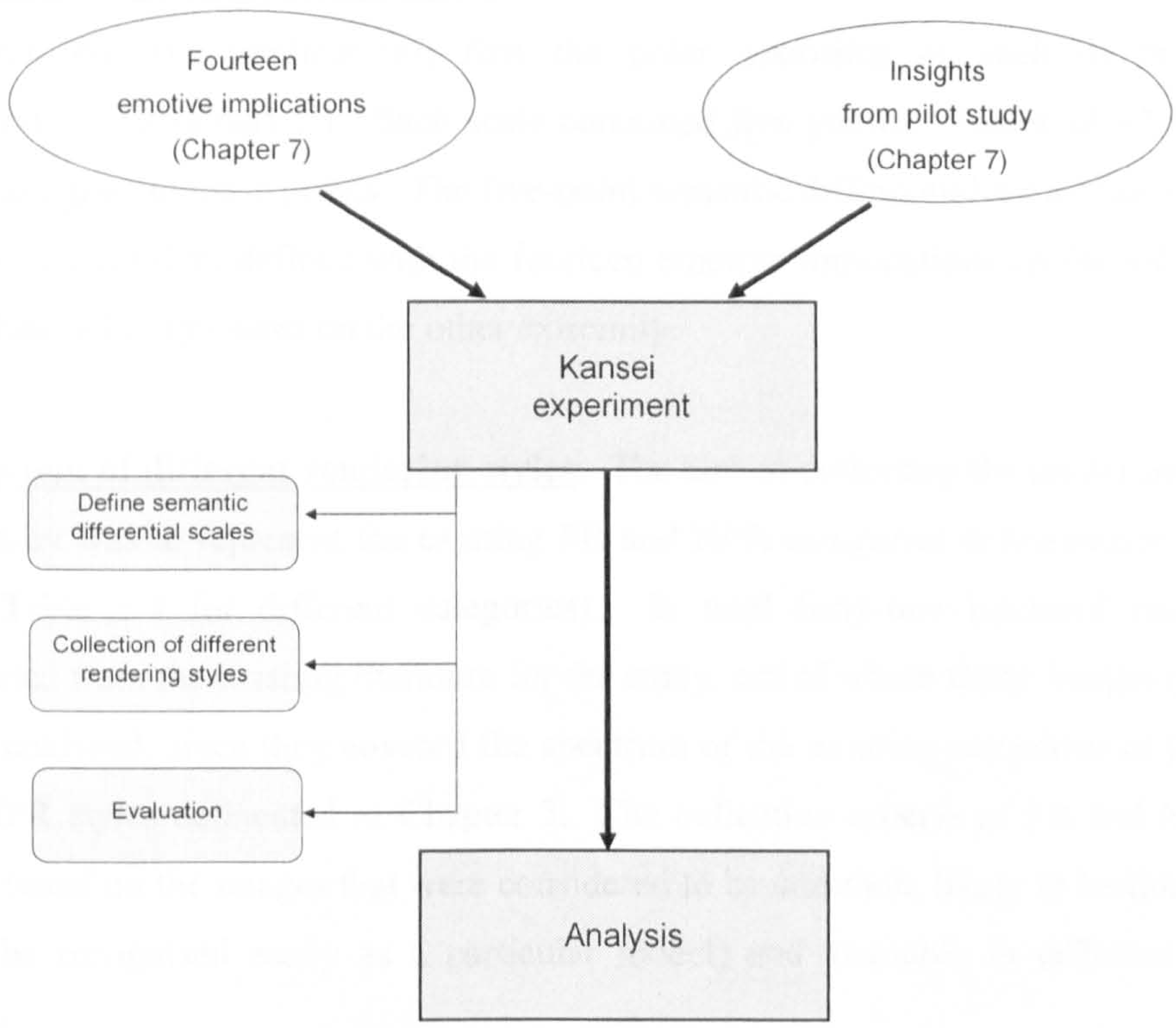


Figure 8-2: Experimental methodology for assessing emotive effectiveness

With regard to Figure 8-2, using the identified fourteen emotive implications and insights gained into the main experimentation from the pilot study (as described in Chapter 7), a Kansei experiment was conducted. The Kansei experiment involved (i) defining semantic differential scales with the fourteen emotive implications, (ii) collecting different rendering styles and (iii) evaluating the collected rendering styles using the emotive implications provided on the semantic differential scales, by the respondents. The data gathered from the respondents was analysed to evaluate the degree of effectiveness of different rendering styles in conveying emotive implications.

In the remainder of this section, the methodology of each of the phases: 1) Kansei experiment and 2) Analysis, is discussed in detail.

Phase 1. Kansei experiment

This phase utilised the identified fourteen emotive implications (see Table 7-2) along with the insights gained into the main factors involved in designing and running experiments (see Table 7-3). The Kansei experiment involved the following three stages.

(i) **Define semantic differential scales**: To define the semantic differential scales with the fourteen emotive implications, first the polar opposites of each of the emotive implications were derived. Each scale contained five points. Values of +2 through -2 were assigned to these points. The five-point semantic differential scales that range from +2 to –2 were then defined with the fourteen emotive implications on the left extremity and their polar opposites on the other extremity.

(ii) **Collection of different rendering styles**: The aim of collecting the rendering styles for the study was to represent the existing PR and NPR categories delineated in Chapter 3 (see Table 3-4 for different categories). In total forty-one rendered images were collected from the existing literature for the study, out of which thirty images (Figure 8-) were analysed, since they covered the spectrum of the existing categories of (a) PR and (b) NPR styles delineated in Chapter 3. The collection criteria of PR and NPR styles were based on the images that were considered to be common, likely to be familiar (as it may be recognised easily as a particular model) and available in different rendering styles.

The following gives a brief description of the thirty different rendering styles, as shown in Figure 8-3, analysed for the study presented in this thesis.

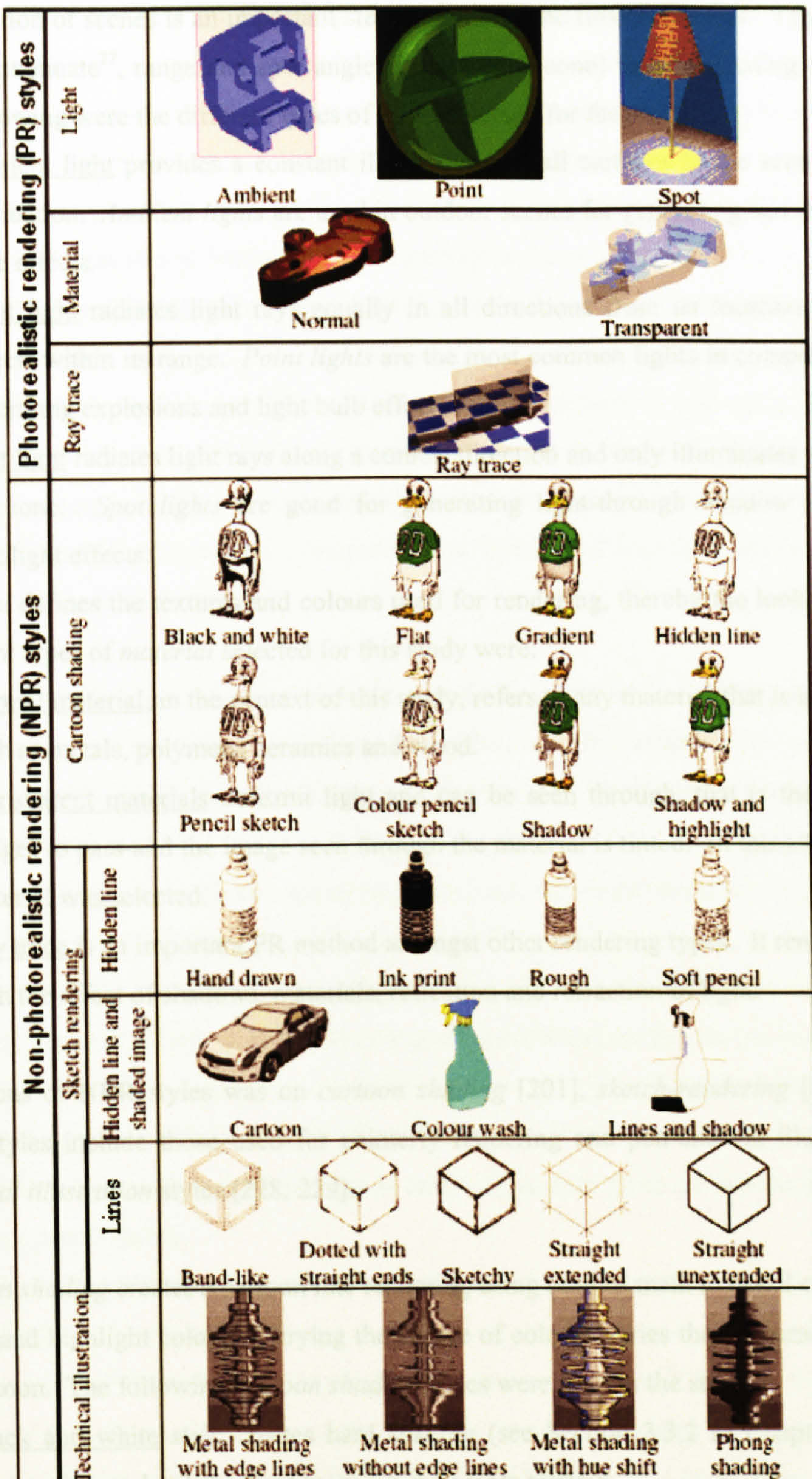


Figure 8-3: Rendering styles analysed for the study ([13, 201, 228, 229, 325])

The focus of **PR** styles was on images created using realistic *lights*, *materials* and *ray trace*, which is a common PR method. *Lights* are used to illuminate the scenes. Proper illumination of scenes is an important step to generate the final PR image. Typically a light defines attenuate[27], range and spot angle (angle of the cone) for illuminating scenes [326]. The following were the different types of *lights* selected for the study:

1. Ambient light provides a constant illumination to all surfaces in the scene and has no attenuation. *Ambient lights* are used in outdoor scenes for generating sun and moonlight style effects.
2. Point light radiates light rays equally in all directions from its location, affecting all objects within its range. *Point lights* are the most common lights in computer games for generating explosions and light bulb effects.
3. Spot light radiates light rays along a conical direction and only illuminates objects within the cone. *Spot lights* are good for generating light-through window style and car headlight effects.

Material defines the textures and colours used for rendering, thereby the look in the image. Different types of *material* selected for this study were:

4. Normal material, in the context of this study, refers to any material that is not transparent such as metals, polymers, ceramics and wood.
5. Transparent materials transmit light and can be seen through, that is they allow clear images to pass and the image seen through the material is tinted. In this study blue glass material was selected.
6. Ray trace is an important PR method amongst other rendering types. It renders the scene with the effect of shadows, materials, reflection and refraction of light.

The focus of **NPR** styles was on *cartoon shading* [201], *sketch-rendering* [325], wherein these styles include those used for painterly rendering and pen-and-ink illustrations, and *technical illustration* styles [228, 229].

Cartoon shading creates a cartoon like rendering using base or main material colour, shadow colour and highlight colour. Varying the choice of colours varies the appearance or style of the cartoon. The following *cartoon shading* styles were used in the study:

7. Black and white style creates hard shading (see Section 3.3.2 in Chapter 3 for more information on hard shading) by using gray scale texture.
8. Flat shading style uses the same base colour for both shadowed and illuminated areas for shading.

[27] Attenuate: This property determines whether the light diminishes with increasing distance.

9. Gradient style creates a smooth gradient starting from shadow colour on one side to a highlighted colour on the other side.
10. Hidden line style fills the polygon mesh, representing a surface, with the background colour to create the illusion that only silhouettes have been rendered.
11. Pencil sketch style uses the textures created from pre-scanned pencil strokes, to render a model. The sketch is drawn on a paper background texture.
12. Colour pencil sketch style uses colours based on the main material colour to shade the pencil strokes.
13. Shadow style uses shadow coloured texels (texture elements). Increasing the number of shadow colour texels increases the amount of shadow shown on the model.
14. Shadow and highlight style uses highlight colour texels apart from using base or material colour and shadow colour. Increasing the number of highlight texels increases the highlight area on the mesh.

The *sketch rendering* styles selected for this study were hidden line, hidden line and shaded image, and vague line styles. In hidden line styles, only line information is processed and the surface style assigned to the objects is not relevant. The following hidden line styles were used in the study:

15. In hand drawn style, objects are rendered as lines, where the line colour is different from the background colour.
16. Ink print style gives the impression of a photographic negative of a line drawing. In this style, the entire image is rendered in a given ink-colour, except for the lines that are left as gaps.
17. Rough pencil style produces an effect as if an artist had drawn each line several times and each time with a small margin of error. This style gives an impression of a rough, quick pencil sketch.
18. Soft pencil style stimulates the effect of a pencil drawing with a soft pencil, which in places leave hardly any marks.

Hidden line and shaded image styles generate a combination of hidden line and shaded images. The colour information of the resulting images is created from the surface styles assigned to the objects and faces. The following hidden line and shaded image styles were selected for the study:

19. Cartoon style creates a cartoon like rendering, where silhouette and boundary edges are drawn in bold lines and uses simplified and stylised colours.

20. In colour wash style, the edges are drawn in solid lines and the surfaces are filled with a simplified colour, which appears to be washed out to look like pastel colour.
21. Lines and shadow style combines the effects of a hidden line drawing with a monochrome shaded effect for areas in shadow.

In vague line styles, the images are created with the intent to stimulate vagueness by using different line types. The following different line types were selected for the study:

22. Band-like: In this line style, objects are rendered using thick band-like lines.
23. Dotted with straight ends: In this style, the lines are dotted but are straight towards the end points.
24. Sketchy: This style produces a sketch-like effect.
25. Straight extended: In this style, a simple thin line is extended at the vertices.
26. Straight unextended: In this style, a simple thin line is unextended and the end points of the lines meet to form a closed surface.

The use of lines, shading and shadowing in objects produces *technical illustrations*. The following styles [229] were selected from a variety of *technical illustration* styles:

27. Metal shading with edge lines: In this style, the object is metal shaded, where alternating dark and light bands represents the metallic surface and its edge lines (the set containing surface boundaries, silhouettes and discontinuities) are drawn in black.
28. Metal shading without edge lines: In this style, the object is metal shaded without any edge lines.
29. Metal shading with hue shift: In this style an artificial hue shift to shading is created by using cool (blue, green and violet) to warm (orange, red and yellow) tones, so that the edge lines and highlights remain clearly visible in the metal shaded object
30. Phong shading: In this style, the object is phong shaded without any edge lines and hue changes in shading.

The next step in the Kansei experiment after collecting rendering styles is their evaluation to assess their degree of emotive effectiveness (see Figure 8-2).

(iii) Evaluation: For evaluation of different rendering styles:

a. A sample of academics, undergraduate and postgraduate students was obtained through a *convenient* sampling procedure [308]. The population of interest for the evaluation were people who have had exposure to CAD systems. Owing to the difficulties of studying and impinging on actual design practise in industry, the *convenient* sample of academics and students, which represented the academic/education population, was chosen. The sample comprised of the academics, fourth and fifth year undergraduate students and postgraduate students in the DMEM Department.

b. The method of study was in the form of a group-administered questionnaire, owing to the advantages over other methods, especially in terms of the length of the questionnaire and the opportunity for providing number of visual presentations for assessment. The other advantages include convenience to administer in group settings, high response rate, opportunity for quantifying responses and speed of data collection.

In total, three questionnaires were prepared for evaluating the different rendering styles. The three questionnaires were identical, except for the number and type of rendered images to be assessed. An example of the questionnaire can be found in Annex-1 of Appendix C. To enable the respondents to perceive the rendered images and get some feeling of a computer graphics technique, the rendered images were presented by printing them as high quality ink jet illustrations. Having been presented with a selection of rendered images, the respondents were asked to evaluate the image according to how much they felt a particular emotion applied to the rendering style. In essence, they were asked to assess each image using the fourteen emotive implications on the semantic differential scales. To enable proper interpretation and clarity in meaning, the respondents were provided with a definition list of the emotive implications along with the questionnaires to aid them while assessing the rendered images (see Annex-2 of Appendix C). The respondents were asked to give their immediate 'gut' response to the images when using the scales. Immediate 'gut' responses from respondents provide valuable insights on which to base decision-making [192].

Phase 2. Analysis

This phase involved the analysing procedures after collecting data from the evaluations during the Kansei experiment (see Figure 8-2). The evaluation data was analysed using *mean values* and *factor analysis* to identify the *impact* of rendering styles in conveying the emotive implications and those rendering styles that *correlate* most with the respondents' feelings respectively.

Factor analysis [327] was also used in the study to determine (1) the number of different factors needed to explain the pattern of relationships among the variables (in this context emotive implications) used in the study and (2) the nature of the factors that describe the variables. The factors extracted from the analysis were influenced to a greater or lesser extent by each of the original variables. The influence of each original variable on a factor is expressed as a *factor loading* coefficient. *Factor loadings* above 0.6 are usually considered 'high' and those below 0.4 are 'low'. The variables with high *factor loadings* are listed to see if any patterns define the factor. Usually a cut-off point for *factor loading* is used to list variables under each factor generated. The variables with *factor loadings* greater than or equal to the cut-off point are then listed. The next step in *factor analysis* is to put a psychological interpretation on the emerged factors. That is, to decide the common theme in these high loading variables corresponding to each factor. At this stage either the factors emerged are recognised and named intuitively, or they are picked out as being in parallel with psychological explanations that were expected from theory or prior research [327].

The relations between rendering styles and emotive implications can be established by mapping all the rendering styles tested on to the extracted factors. This is possible by analysing the *correlation* matrices of ratings on emotive implications for every rendering style. Thereby the relations between the rendering styles and emotive implications can be recognised. Important design insights such as those rendering styles that *correlate* most with respondents' feelings can thereby be deduced.

In the remainder of this section, the overall procedure of the study administration is discussed.

Procedure

The study, in overall, was divided into three questionnaires for evaluating the emotive effectiveness of PR and NPR. Since it could be tiresome for the respondents to assess all the rendering styles at the same time, the study was divided into three questionnaires. In addition, the aim for the distribution of rendering styles into three questionnaires was to reduce the confounding effect of item bias[28]. Each questionnaire was distributed to the respondents (academics, fourth and fifth year undergraduate students and postgraduate students) each week. However, care was taken to distribute each questionnaire to the same

[28] An item may be biased if it contains content that is differentially familiar to respondents or if the item structure or format is differentially difficult for respondents [328].

respondents every week in the same settings, with the aim of maintaining consistency of responses. The order of distribution of these questionnaires was varied to avoid any contamination in the responses due to the order of the presentation. The study was conducted in a lecture room where distractions from noise and human activity were minimal [308]. In order to promote high co-operation and participation rate, the respondents were provided with a covering letter detailing the theme of the research, an incentive of a copy of results and also a note of appreciation was added at the end of the questionnaire. Respondents were assured confidentiality and also were given the opportunity to decline to participate in the study. They were monitored while filling in the questionnaires and immediate clarifications were made upon request. The data was collected over a period of six weeks.

In total, ninety questionnaires (for each of the three questionnaires) were distributed. The percentage number of responses was 68% (sixty-one returned responses) for each of the four questionnaires. Out of the 61 responses, 6 (10%) were academics, 22 (36%) were fourth and fifth year undergraduate students and 33 (54%) were postgraduate students. The respondents were from architecture, computer aided engineering design, marine, mechanical and product design backgrounds. Figure 8-4 shows the level of experience of the respondents ($M = 2.7$, $SD = 0.85$) in CAD.

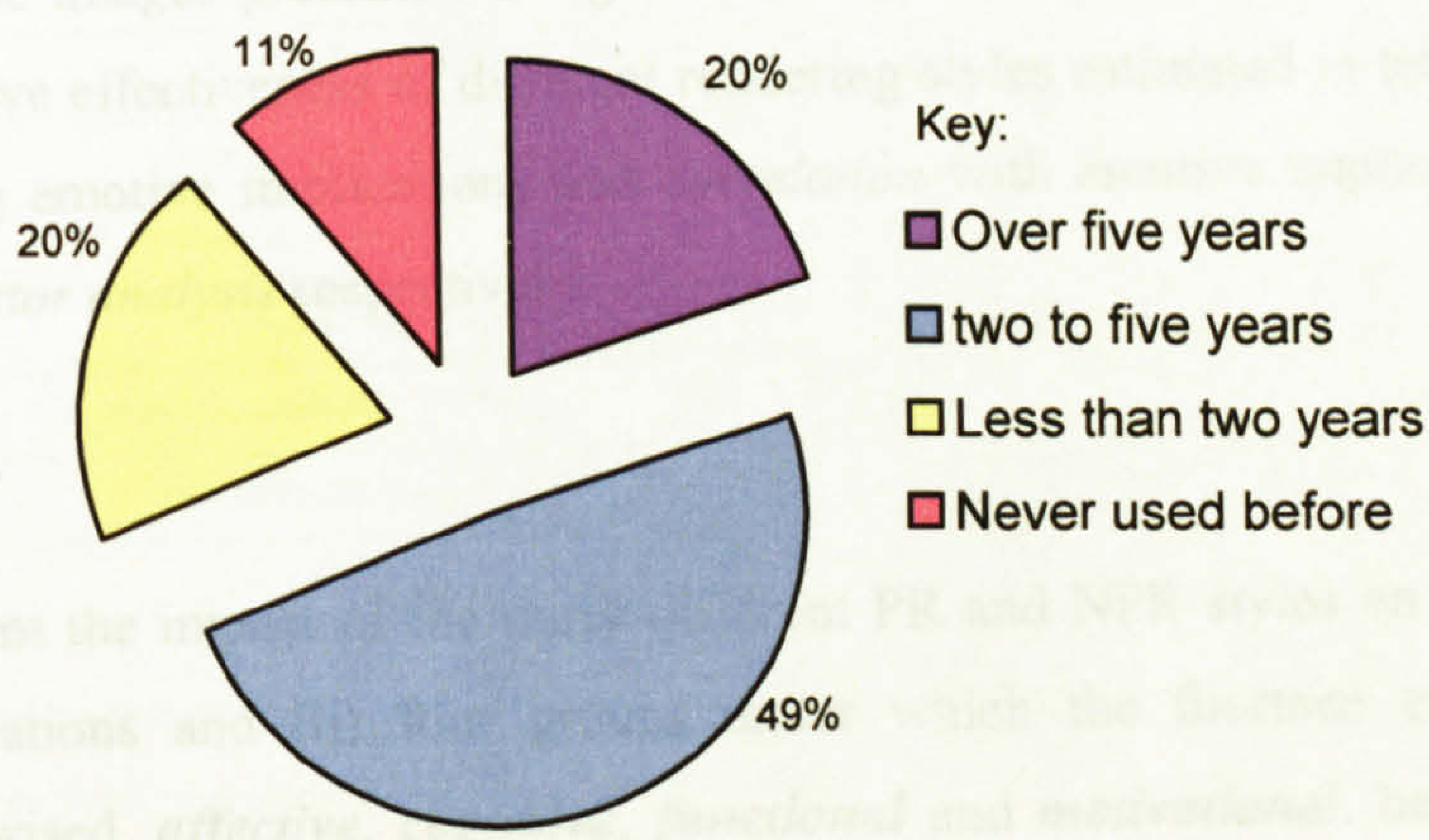


Figure 8-4: Experience in CAD

As can be seen from Figure 8-4, 20% of the respondents had over five years experience in CAD, 49% had two to five years experience, 20% had less than two years experience and 11% of the respondents never used CAD before. This implies that the majority of the respondents had moderate experience in CAD. Based on the background and experience of the sample selected, the findings resulting from the study can act as a basis for future work (see Section 11.4).

The study analysis consisted of quantitative compilation of the responses. The data collected from the semantic differential scales and closed-ended response questions was analysed using the statistical program SPSS [310]. Descriptive statistics such as *mean* and *total frequency percentages* and inferential statistics such as *factor analysis* were used to analyse the data to present the opinion of the sample and the population in general.

The graphical illustrations such as bar charts and line charts were used to present the data analysed using *mean* and *factor analysis*. Bar charts were used to provide profiles of the rendering styles evaluated as they allow ready comparison. A line chart plots the value of the variable as a specific point and then the adjacent points are connected forming a continuous line. Line charts contain more data in a compact space than the other types of charts. They are used when a large number of points are to be plotted and when several series are being compared. They are better at implying a trend.

8.2 Emotive effectiveness of PR and NPR styles

The respondents' ratings on the semantic differential scales indicate their perception and emotional responses to the images presented using these rendering styles. The following sections present the emotive effectiveness of different rendering styles estimated in terms of their *impact* in conveying emotive implications and *correlation* with emotive implications using *mean values* and *factor analysis* respectively.

8.2.1 Impact

Tables 8-1 and 8-2 present the impact of the thirty different PR and NPR styles on the (i) fourteen emotive implications and (ii) four groups under which the fourteen emotive implications were categorised, ***affective***, ***cognitive***, ***functional*** and ***motivational***, based on the understanding and existing classifications in the literature (see Table 7-2). The rows in the tables present the fourteen emotive implications and the four groups respectively. The columns present the thirty different rendering styles that covered a spectrum of existing categories of PR and NPR styles. The perception and emotional responses to different PR, and NPR styles are presented as *mean values* in the tables. The *mean values* indicate the *impact* of the rendering styles on the fourteen emotive implications and four groups respectively.

Table 8-1: Impact of thirty different rendering styles on fourteen emotive implications (in *mean values*)

Key:

- ***x*** : Strong positive emotive response
- ~~*x*~~ : Strong negative emotive response
- x : Neutral emotive response
- x : Moderate positive/negative emotive response

		Photorealistic rendering (PR)						Non-photorealistic rendering (NPR)																							
		Light			Material			Cartoon shading								Sketch rendering												Technical illustrations			
																Hidden line				Hidden line and shaded image			Lines								
		Ambient	Point	Spot	Normal material	Transparent material	Ray trace	Blank and white	Flat shading	Gradient	Hidden line	Pencil sketch	Colour pencil sketch	Shadow	Shadow and highlight	Hand dawn	Ink print	Rough pencil	Soft pencil	Cartoons	Colour wash	Lines and shadows	Band-like	Dotted with straight ends	Sketchy	Straight extended	Straight unextended	Metal shadin with edge lines	Metal shading without edge lines	Metal shading with hue shift	Phong shading
Affective	Comfortable	2.6	2.8	***3.0***	***3.1***	1.8	***3.1***	2.0	***3.4***	***3.0***	1.2	1.3	1.5	2.2	***3.0***	2.0	2.7	2.2	1.5	2.8	2.5	2.1	2.0	2.4	2.1	1.4	***3.0***	2.8	***3.3***	2.9	2.8
	Imaginative	2.5	2.7	***3.0***	2.7	2.6	***3.3***	1.9	2.7	2.4	1.9	1.6	1.8	2.1	2.3	2.4	1.9	2.5	1.8	2.4	2.3	2.2	2.4	2.3	2.4	2.0	1.6	2.6	2.0	***3.1***	2.3
	Interesting	2.3	2.5	***3.1***	***3.2***	2.2	***3.5***	1.9	***3.3***	2.9	~~*1.0*~~	1.3	1.4	2.5	2.8	2.2	2.3	2.0	1.2	2.9	2.6	2.0	2.3	2.3	2.4	1.7	2.1	2.7	1.9	***3.2***	2.5
	Real	2.1	2.3	***3.1***	***3.5***	1.2	***3.1***	1.9	***3.2***	2.8	~~*0.8*~~	1.1	1.4	2.1	2.6	1.5	2.9	1.6	~~*1.0*~~	2.0	2.6	2.1	1.8	1.9	1.9	1.1	***3.0***	2.3	1.8	1.9	***3.0***
	Satisfied	2.4	2.5	2.7	***3.1***	1.8	***3.1***	2.0	***3.3***	2.7	~~*0.9*~~	1.3	1.4	2.3	2.8	1.9	2.6	2.1	1.3	2.8	2.4	2.0	2.1	2.3	2.1	1.5	***3.0***	2.7	1.7	2.7	2.7
Cognitive	Approximation of information	2.1	2.3	2.0	2.0	2.6	2.0	2.1	2.0	2.2	2.1	2.3	2.3	2.4	2.3	2.5	1.7	2.4	2.4	2.1	2.6	2.3	2.2	2.4	2.5	2.2	1.9	2.2	2.1	2.2	1.9
	Comprehensible	2.6	2.8	***3.1***	***3.2***	1.6	***3.1***	2.5	***3.3***	***3.0***	1.6	1.6	1.9	2.7	***3.0***	2.0	***3.1***	2.0	1.4	2.9	2.8	2.5	2.2	2.6	2.3	2.0	***3.3***	2.9	2.0	***3.1***	***3.1***
	Recognisable	2.6	2.8	***3.4***	***3.4***	1.5	***3.1***	2.5	***3.5***	***3.2***	2.0	2.0	2.2	***3.0***	***3.3***	2.2	***3.4***	2.3	1.7	***3.3***	***3.1***	2.8	2.7	***3.0***	2.5	2.4	***3.4***	***3.0***	2.2	***3.2***	***3.2***
Functional	Differentiation of information	2.5	2.5	2.4	***3.0***	1.4	2.8	2.3	***3.1***	2.4	1.4	1.5	1.8	2.3	2.7	1.8	2.8	1.9	1.5	2.5	2.5	2.3	1.8	2.3	1.7	1.7	2.6	2.8	1.5	2.8	2.3
	Exploration of alternative solutions	2.2	2.3	2.4	2.4	2.4	2.6	2.0	2.1	2.3	2.4	1.8	2.0	2.1	2.3	2.3	1.9	2.4	2.1	1.9	2.2	2.3	2.3	2.4	2.4	2.2	1.7	2.4	1.9	2.9	2.1
	Invite assumptions	2.5	2.6	2.6	2.7	2.4	2.8	2.1	2.5	2.5	2.1	2.1	2.2	2.3	2.4	2.4	2.3	2.2	2.1	2.5	2.5	2.6	2.6	2.6	2.3	2.2	2.4	2.5	2.3	2.7	2.6
Motivational	Stimulating to changes	2.2	2.4	2.3	2.4	2.5	2.6	2.2	2.1	2.0	2.8	2.3	2.2	2.1	2.1	2.4	1.9	2.6	2.1	2.0	2.2	2.6	2.2	2.4	2.3	2.5	1.7	2.5	2.2	2.3	2.3
	Stimulating to discussion	2.4	2.6	2.7	2.8	2.6	***3.1***	2.3	2.6	2.5	2.2	2.0	2.2	2.4	2.3	2.2	2.3	2.3	1.9	2.3	2.2	2.3	2.6	2.5	2.3	2.4	1.7	2.5	2.1	2.8	2.7
	Stimulating to look at	2.5	2.5	***3.1***	***3.1***	2.2	***3.5***	2.1	***3.2***	***3.0***	1.2	1.4	1.8	2.6	2.8	2.1	2.4	2.2	1.4	2.6	2.4	2.1	2.3	2.6	2.4	1.8	2.2	2.8	1.7	***3.1***	2.7

Table 8-2: Impact of thirty different rendering styles on four groups of emotive implications (in average *mean values*)

	PR						NPR																							
	Light			Material			Cartoon shading								Sketch rendering												Technical illustrations			
															Hidden line				Hidden line and shaded image			Lines								
	Ambient	Point	Spot	Normal Material	Transparent material	Ray trace	Blank and white	Flat shading	Gradient	Hidden line	Pencil sketch	Colour pencil sketch	Shadow	Shadow and highlight	Hand dawn	Ink print	Rough pencil	Soft pencil	Cartoons	Colour wash	Lines and shadows	Band like	Dotted with straight ends	Sketchy	Straight extended	Straight unextended	Metal shading with edge lines	Metal shading without edge lines	Metal shading with hue shift	Phong shading
Affective	2.4	2.6	3.0	3.1	1.9	3.2	1.9	3.2	2.8	1.2	1.3	1.5	1.3	1.5	2.7	2.8	2.1	2.6	1.4	2.0	2.1	2.1	2.2	2.2	1.5	2.5	2.1	2.5	2.6	2.5
Cognitive	2.4	2.6	2.8	2.9	1.9	2.7	2.4	2.9	2.8	1.9	2.0	2.1	2.0	2.1	2.7	2.8	2.1	2.7	1.8	2.2	2.2	2.4	2.7	2.4	2.2	2.9	2.5	2.8	2.8	2.7
Functional	2.4	2.5	2.5	2.7	2.1	2.7	2.1	2.6	2.4	2.0	1.8	2.0	1.8	2.0	2.3	2.8	1.9	2.6	1.9	2.2	2.2	2.2	2.4	2.1	2.0	2.2	2.4	2.4	2.3	2.3
Motivational	2.4	2.5	2.7	2.8	2.4	3.1	2.2	2.6	2.5	2.1	1.9	2.1	1.9	2.1	2.6	2.7	2.0	2.6	1.8	2.2	2.4	2.4	2.5	2.3	2.2	1.9	2.3	2.3	2.3	2.2

Impact of rendering styles on the fourteen emotive implications

The overall perception and emotional responses to PR and NPR styles are presented in the form of a bar chart, see Figure 8-5, where 4 indicate strong positive emotive responses to the statements made on the x-axis. Figure 8-5 shows the average *mean values* of PR and NPR styles for the fourteen emotive implications.

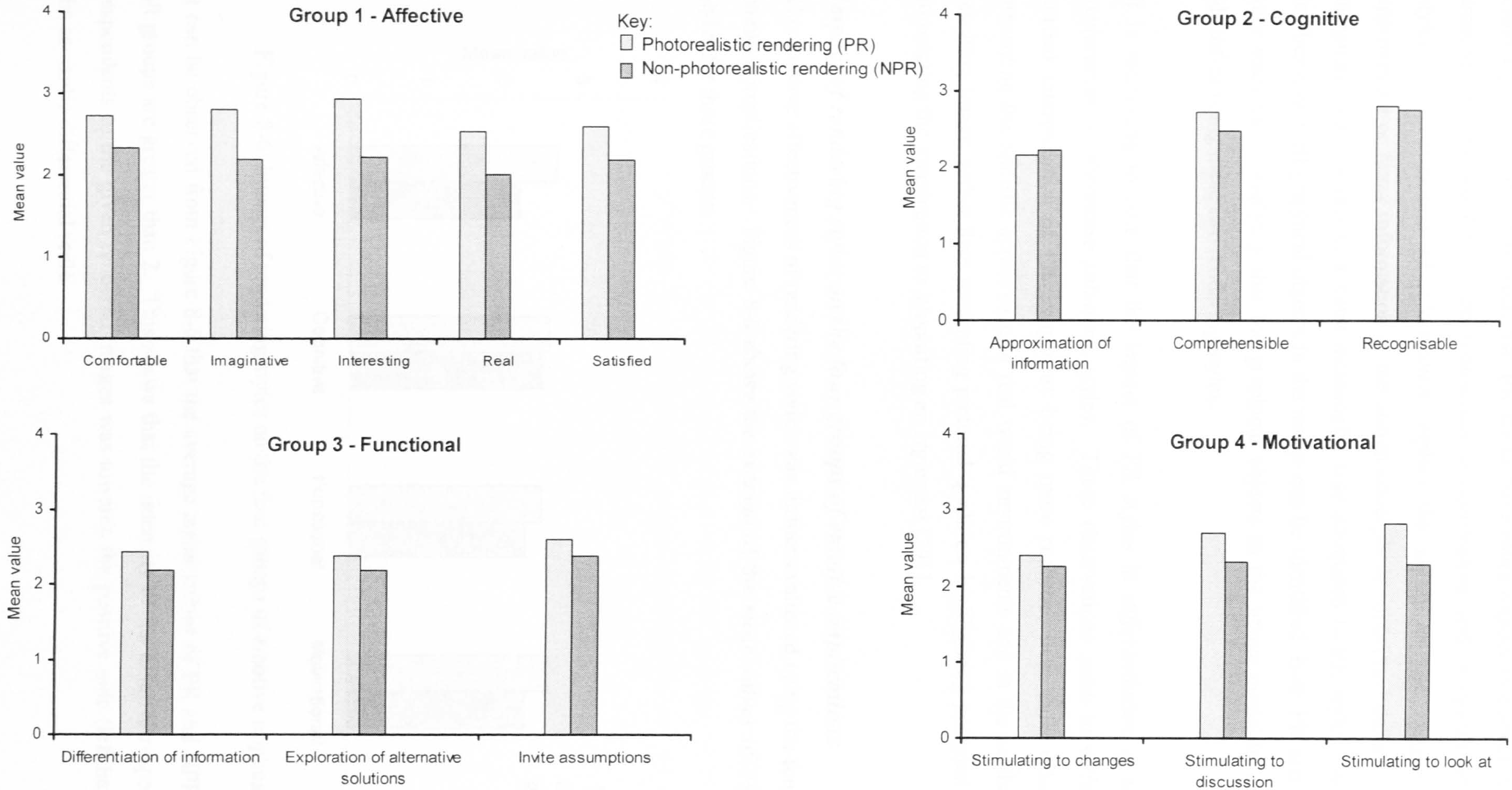


Figure 8-5: Impact of rendering styles on the fourteen emotive implications

From Figure 8-5, it can be seen that PR styles have more *impact* in conveying all of the emotive implications (except *approximation of information* and *recognisable*) than NPR styles. *Approximation of information* implies the ability of the images to display approximate or fuzzy information of the design concepts in conceptual design. NPR styles marginally convey this in a more meaningful way compared to PR styles. *Recognisable* implies how well graphical objects in the image can be identified. Both PR and NPR styles vary marginally, implying that the graphical objects in the image could be equally well identified using these two rendering styles.

It is interesting to note that the *impact* of PR styles in *differentiation of information*, *exploration of alternative solutions*, styles. These observations seem to differ from the normal interpretation of PR images as being more realistic, with their value being in presenting the realistic appearance of real world environments and in the aesthetics of the resulting image, rather than presenting pictorial qualities, highlighting potential issues and stimulating the imagination or supporting an argument [291].

Impact of rendering styles on the four groups of emotive implications

The emotive effectiveness of rendering styles was further evaluated using the four groups of emotive implications. Figure 8-6 shows the average of the *mean values* of PR and NPR styles for these groups.

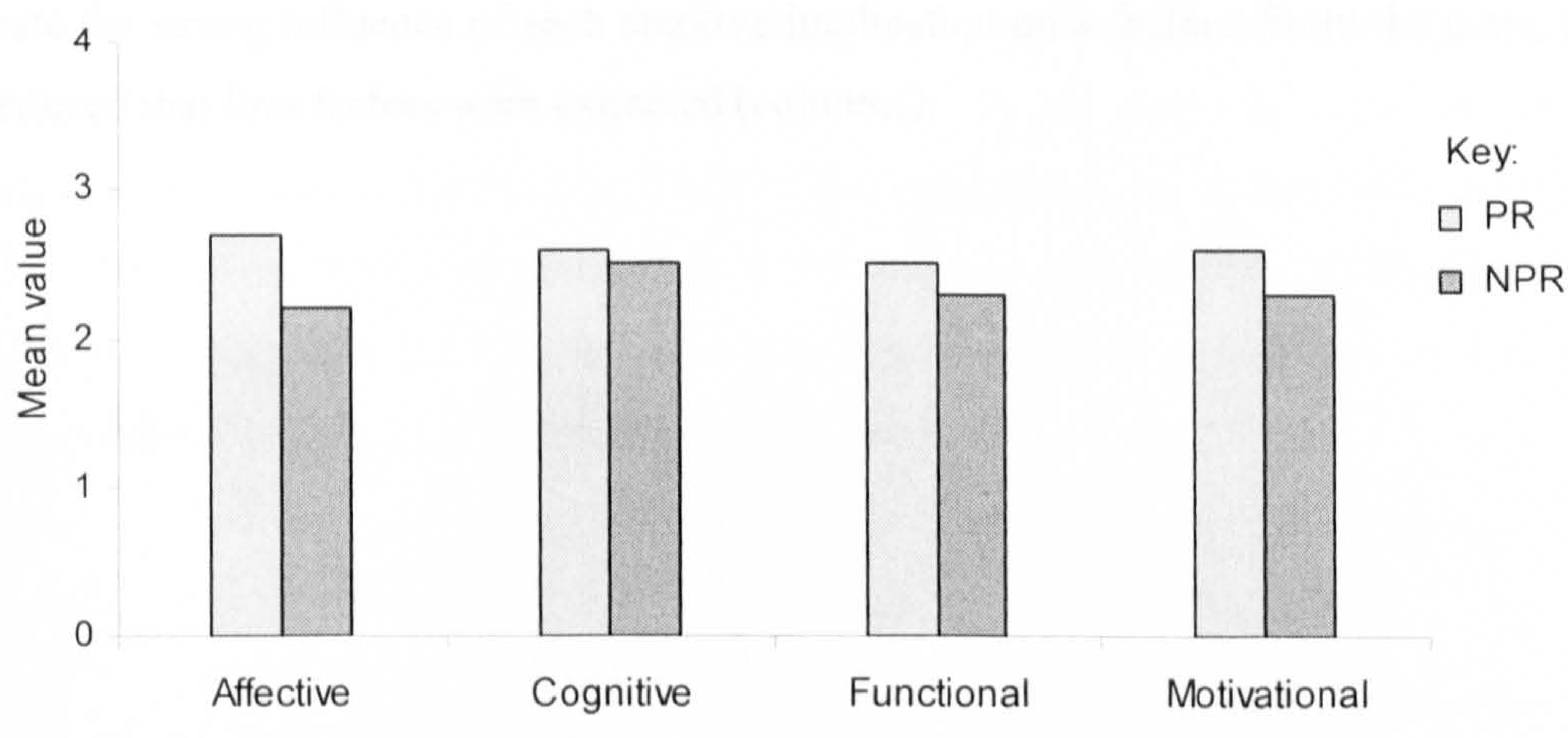


Figure 8-6: Impact of rendering styles on the four groups of emotive implications

It can be observed from Figure 8-6 that the average *mean values* of PR and NPR styles for all groups are greater than 2. This shows that the intensity of the emotive responses of the respondents to the given rendered images was towards the positive side (left hand side) of the semantic differential scale.

PR styles seem to have more *impact* in conveying ***affective***, ***functional*** and ***motivational*** content (except for ***cognitive*** where there is a marginal variation) than NPR. The ***cognitive*** group is concerned with understandablility of the displayed information such as *approximation of information*, *comprehensibility* and *recognisability* of an image. There is only a marginal variation between PR and NPR styles for the ***cognitive*** group, indicating that the *impact* of all the three styles in conveying ***cognitive*** content is more or less the same.

8.2.2 Correlation

The effectiveness of the rendering styles in terms of their *correlation* with the emotive implications was further investigated using *factor analysis*. In this form of analysis the variables in the study (in this context the emotive implications) are reduced to a smaller number of factors that are influenced to a greater or lesser extent by each of the original variables. Two basic analyses were conducted to firstly examine the pattern of relationships among the emotive implications identified and secondly to establish the *correlation* between the different rendering styles and emotive implications.

(i) *Pattern of relationships among the emotive implications*

From the first analysis, Table 8-3 shows the factors extracted and their respective *factor loadings*. *Factor loadings* are the *correlation* coefficients between the factors (columns) and the emotive implications (rows). The strong *correlations* (*factor loadings* > 0.5) in the table indicate the strong influence of each emotive implication on a factor. From the table, it can be deduced that four factors were extracted (columns).

Table 8-3: Pattern of relationships among the fourteen emotive implications

Emotive implication	Factor 1	2	3	4
Satisfied	0.8	0.0	0.2	0.2
Interesting	0.8	0.2	0.1	0.2
Imaginative	0.8	0.4	0.1	-0.1
Stimulating to look at	0.8	-0.3	0.3	0.1
Stimulating to changes	0.2	0.8	0.2	-0.1
Approximation of information	-0.1	0.7	0.1	0.2
Exploration of alternative solution	0.2	0.7	0.4	-0.2
Invite assumptions	0.1	0.6	**0.5**	0.2
Stimulating to discussion	0.2	0.2	0.8	-0.2
Real	0.0	0.1	0.7	**0.5**
Differentiation of information	0.2	0.2	0.6	0.1
Comfortable	0.4	0.3	0.5	0.1
Recognisable	0.1	0.1	0.1	0.9
Comprehensible	0.4	-0.1	0.0	0.8

The emotive implications with high *factor loadings* (*correlations*) were listed to see the patterns that defined the factors. *Factor loadings* above 0.6 are considered 'high' and those below 0.4 are 'low' [327]. Therefore, a cut-off point of 0.5 for *factor loading* was used to list the emotive implications under each factor generated. The emotive implications with *factor loadings* greater than or equal to 0.5 were listed under each factor. The four groups of emotive implications were given different shadings in the table to show the emotive implications constituting a particular factor. The cross-hatchings in the table indicate the overlap of emotive implications with high *factor loadings* into different factors, which will be discussed in Section 8.3.1. The influence of each emotive implication on a factor is shown in Figure 8-7.

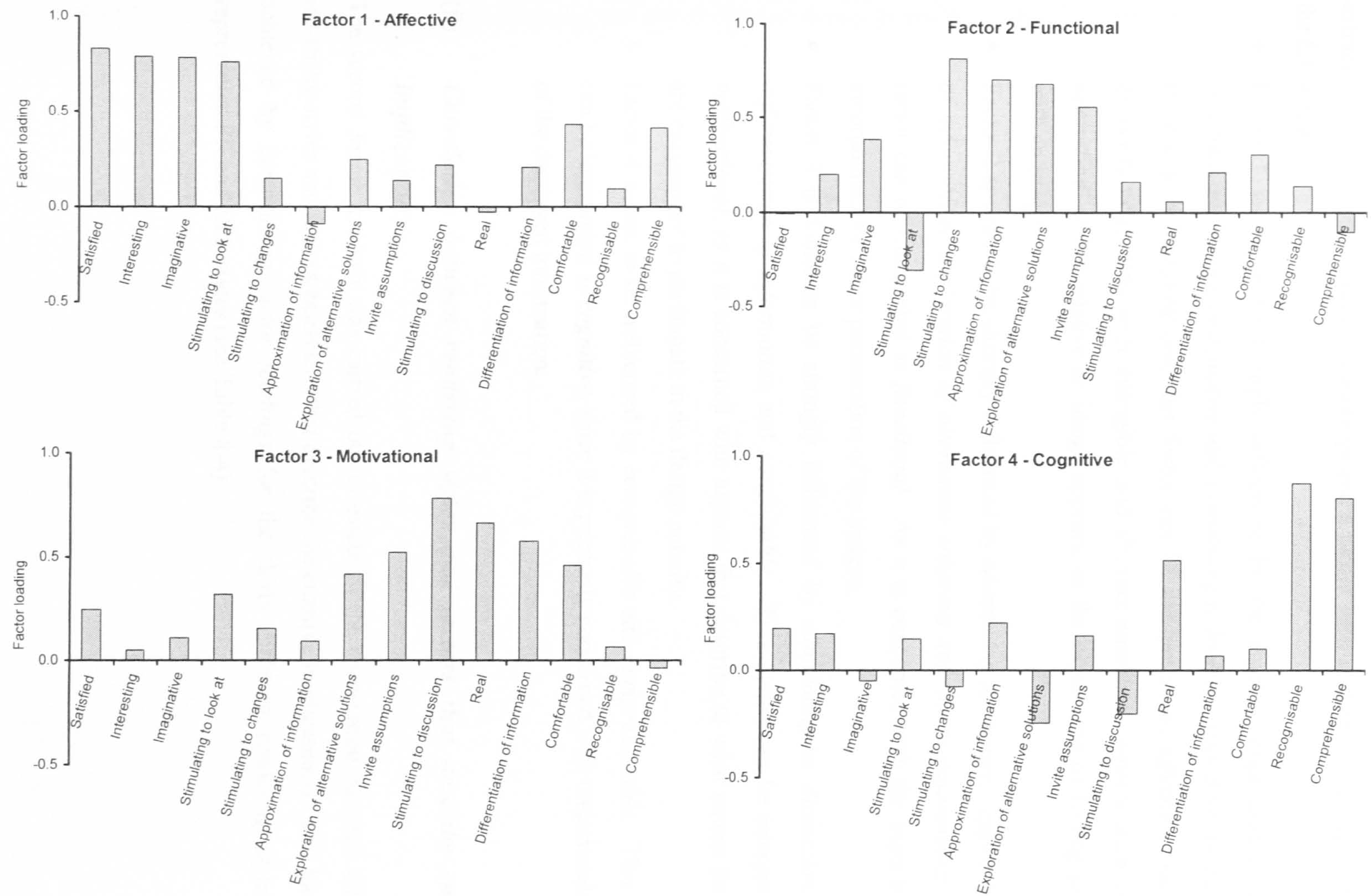


Figure 8-7: Influence of each emotive implication on each factor

Figure 8-7 shows graphically how the emotive implications can be grouped based on the experimental study of the respondents' perception of the rendered images. The factors extracted have some interpretable meanings and a closer look at them in the figure reveals the following:

- Factor 1 seems to be strongly influenced by the emotive implications such as *satisfied, interesting, imaginative* and *stimulating to look at.* Based on the nature of these emotive implications, this factor can be interpreted as ***affective***, since it is primarily concerned with intangible and abstract emotional aspects such as how interesting, or imaginative an image appears, or the experience of feeling satisfied with an image.
- Factor 2 appears to be strongly influenced by *stimulating to changes, approximation of information, exploration of alternative solutions* and *invite assumptions.* This factor can be interpreted as ***functional.*** As it is concerned with the aspects to be incorporated for better presentation of the images.
- Factor 3 is found to be strongly influenced by *stimulating to discussion, real, differentiation of information* and *comfortable.* This factor can be interpreted as ***motivational***, as it is concerned with aspects that describe to what extent the users are encouraged to participate in the design activity.
- Factor 4 seems to be influenced by *recognisable* and *comprehensible.* This factor can be interpreted as ***cognitive***, since it is primarily concerned with understandability of the displayed information.

(ii) *Correlation between rendering styles and factors that describe emotive implications*

The second *factor analysis* was carried out to establish the *correlation* between different rendering styles and factors extracted (that describe the emotive implications). This has been achieved by determining *factor loadings* for the thirty different rendering styles that represented PR and NPR styles (see Table 8-4).

Table 8-4: Correlation of thirty different rendering styles with the four factors extracted (in average *factor loadings*)

	PR						NPR							
	Light			Material			Cartoon shading							
	Ambient	Point	Spot	Normal material	Transparent material	Ray trace	Black and white	Flat	Gradient	Hidden line shading	Pencil sketch	Colour pencil sketch	Shadow	Shadow and highlight
Affective	0.7	0.8	0.7	0.7	0.7	0.8	0.8	0.7	0.7	0.8	0.7	0.7	0.7	0.8
Cognitive	0.3	0.8	0.0	0.3	0.0	0.8	0.7	0.7	0.7	0.2	0.7	0.8	0.7	0.7
Functional	0.6	0.7	0.0	0.0	0.1	0.7	0.7	0.0	0.8	0.8	0.1	0.0	0.9	0.7
Motivational	0.7	0.6	0.7	0.7	0.8	0.7	0.7	0.6	0.8	0.7	0.7	0.7	0.7	0.7

	NPR															
	Sketch rendering												Technical illustrations			
	Hidden line				Hidden line and shaded image			Lines								
	Hand drawn	Ink print	Rough pencil	Soft pencil	Cartoons	Colour wash	Lines and shadows	Band-like	Dotted with staright ends	Sketchy	Straight extended	Straight unextended	Metal shading with edge lines	Metal shading without edge line	Metal shading with hue shift	Phong shading
Affective	0.8	0.8	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.8	0.7	0.9	0.7	0.7	0.7	0.7
Cognitive	0.7	0.8	0.7	0.0	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.8	0.5	0.9	0.7	0.8
Functional	0.7	0.7	0.7	0.6	0.7	0.6	0.7	0.7	0.0	0.0	0.6	0.6	0.7	0.6	0.7	0.7
Motivational	0.0	0.7	0.7	0.6	0.7	0.8	0.8	0.7	0.9	0.7	0.7	0.8	0.0	0.1	0.8	0.7

Figure 8-8 shows the average *factor loadings* of PR and NPR styles for the factors ***affective***, ***cognitive***, ***functional*** and ***motivational***.

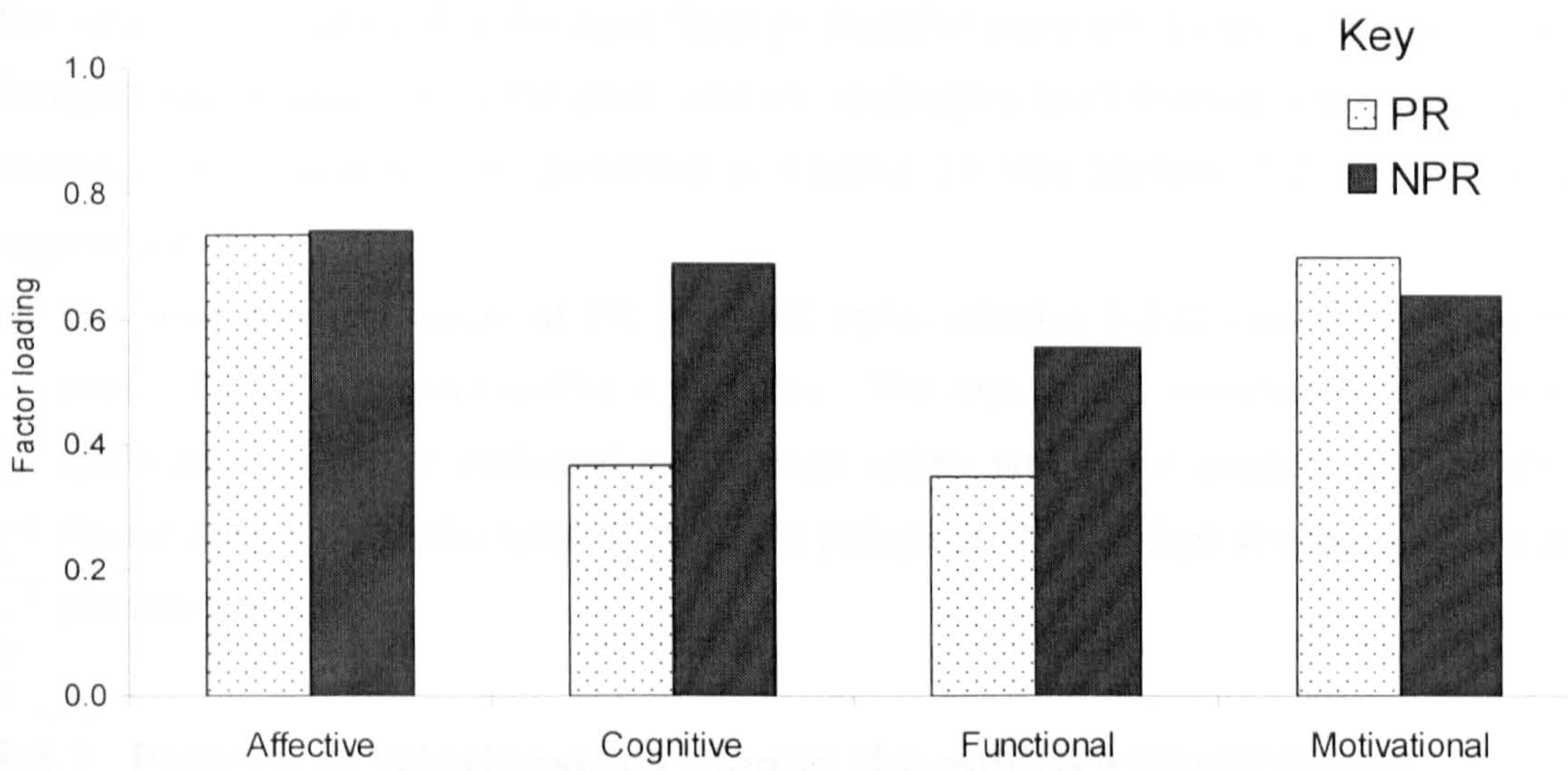


Figure 8-8: Correlations of rendering styles and factors that describe emotive implications

It can be observed from Figure 8-8 that the average *factor loadings* of ***functional*** factor are low compared to the other factors. This implies that the *correlation* of rendering styles with ***functional*** factor is low and thereby in conveying ***functional*** content.

The average *factor loadings* of PR and NPR for ***affective*** factor appears to be the same, indicating that both styles have the same *correlation* with ***affective*** content and show the same intensity in conveying affective content. NPR styles were conceived more *correlated* with the ***cognitive*** factor and making the content of the displayed information more understandable than PR. This implies that NPR styles are considered to be most effective for conveying this content. The *factor loading* of NPR styles for the ***functional factor*** is considerably more compared to PR. This implies that NPR styles are being more *correlated* with the ***functional*** content and thereby most effective to convey such content. Further, PR styles seem to be more *correlated*, because of their high *factor loadings*, with ***motivational*** factor than NPR styles. Given the high correlation, it would seem that PR styles are most effective compared to other styles in encouraging users to participate in design process.

8.3 Main findings

The meaning and potential of the main findings from the study are discussed here while the strengths and weaknesses of the study and the techniques used (Kansei Engineering and statistical *factor analysis*) are delineated in Chapter 11 (see Section 11.2). The results suggest that:

1) The emotive effectiveness of PR and NPR styles (Section 8.2.1) can be estimated in terms of their a) *impact* and b) *correlation*. The *impact* and *correlation* of different rendering styles were evaluated using *mean values* and *factor analysis* respectively. *Factor analysis* was also used to study the pattern of relationships among the fourteen emotive implications.

8.3.1 Pattern of relationships among the emotive implications

Using *factor analysis* for examining the pattern of relationships among the fourteen emotive implications, four factors were extracted. The strong *correlations* (*factor loadings* > 0.5) in Table 8-3 illustrate that the fourteen emotive implications (identified in Chapter 7) deserve their place in the repertoire of the implications of images.

The classification of the fourteen emotive implications (into four factors) obtained through *factor analysis* does not correspond directly to the prior classification (see Table 7-2) of the fourteen emotive implications (into four groups) based on existing literature. Table 8-5 shows the mismatch between the classifications of emotive implications into four groups/factors based on:

(i) Existing literature (see Table 7-2).

(ii) Results of the experimental study on the perception and emotive responses of academics and students to different rendered images (see Table 8-3).

Table 8-5: Classification of emotive implications

Literature (Chapter 7)	**Groups/ Factors**	**Experimental study** (Chapter 8)
Comfortable Imaginative Interesting Real Satisfied	Affective	Imaginative Interesting Satisfied **Stimulating to look at**
Approximation of information Comprehensible Recognisable	Cognitive	Comprehensible Recognisable
Differentiation of information Exploration of alternative solutions Invite assumptions	Functional	Approximation of information Exploration of alternative solutions Invite assumptions Stimulating to changes
Stimulating to changes Stimulating to discussion **Stimulating to look at**	Motivational	*Comfortable* Differentiation of information Real Stimulating to discussion

The reasons for the mismatch might be attributed to the following:

(i) The classification based on the understanding from literature is subjective and open to human interpretation with respect to the emotive implications constituting a particular group. Consequently, the classification may not be definitive.

(ii) In *factor analysis*, often a variable with high *factor loading* overlaps into two or three different factors and there will always be two or three variables that load into an inappropriate factor [329]. For instance, in Table 8-3 it could be seen that:

- The emotive implication *invite assumptions* overlapped into two different factors such as Factor 2 (***functional***) and Factor 3 (***motivational***) with high *factor loadings* 0.6 and 0.5 respectively. However, *invite assumptions* was listed under Factor 2 (***functional***), since its *factor loading* is higher in Factor 2 (***functional***). Similarly, another emotive implication, *real*, overlapped into Factor 3 (***motivational***) and Factor 4 (***cognitive***), with high *factor loadings* 0.7 and 0.5

respectively. Since its *factor loading* is higher in Factor 3 (***motivational***) than in Factor 4 (***cognitive***), *real* was listed in Factor 3 (***motivational***).

- Further emotive implications such as *real* and *comfortable* load in Factor 4 (***motivational***), which seems and may be inappropriate since it is difficult to see how they are motivational. They seem more intangible and abstract emotional aspects that fit closer to the ***affective*** factor, which is concerned with such aspects. Similarly there are other emotive implications such as *stimulating to changes* that loaded in Factor 2 (***functional***) instead of Factor 3 (***motivational***).

The loading of emotive implications into two or three different factors, or in inappropriate factors, implies that *factor analysis* does not prove that a real entity exists corresponding to each factor identified. It simply provides supporting evidence to claim that concepts could be arranged in a particular pattern and *factor analysis* does not refute this. Nevertheless, the statistical extraction of four factors supported the prior classification of the fourteen emotive implications into four groups as described in Chapter 7. Based on the classification, with respect to literature and the statistical derivation, it can be emphasised that, in general, four underlying *constructs* describe the emotive implications of images. Though naming them is a matter of subjectivity and possible dispute, based on prior research [261] and understanding in the field, the four underlying *constructs* were interpreted as ***affective***, ***cognitive***, ***functional*** and ***motivational***. Thereby, within the context of the work presented in this thesis, the four *constructs* of the emotive implications of images refer to ***affective***, ***cognitive***, ***functional*** and ***motivational***.

8.3.2 Emotive effectiveness of PR and NPR styles

The main findings of the emotive effectiveness of PR and NPR styles are summarised in Table 8-6. This table is derived from observations of the most effective rendering styles from Figure 8-6 and Figure 8-8, which show the effectiveness of rendering styles in terms of their *impact* and *correlation* in conveying the four *constructs* of the emotive implications.

Table 8-6: Summary of the emotive effectiveness of rendering styles

IMPACT		Constructs	CORRELATION	
PR	NPR		PR	NPR
√		Affective	√	√
√	√	Cognitive		√
√		Functional		√
√		Motivational	√	

From Table 8-6, with respect to:

Impact: PR styles seem to be most effective for conveying ***affective***, ***cognitive***, ***functional*** and ***motivational*** content and NPR styles for conveying ***cognitive*** content. As seen in the table, there is significant difference in the way the ***cognitive*** and other *constructs* differ. ***Cognitive*** *constructs* are supported significantly by both rendering styles, while the remaining *constructs* are significantly better with PR styles only. This implies that the ***cognitive*** content (such as comprehensibility of the image) is effectively conveyed by both rendering styles.

Correlation: There is significant difference in the way the ***affective*** and other *constructs* differ. ***Affective*** *constructs* are supported significantly by both rendering styles, while the remaining *constructs* are significantly better either with PR or NPR. This implies that ***affective*** content (such as how interesting or imaginative an image appears) is effectively conveyed by both rendering styles. PR styles are most effective for conveying ***affective*** and ***motivational*** content only. NPR styles are most effective for conveying ***affective***, ***cognitive*** and ***functional*** content.

The results, based on *impact* and *correlation*, indicate that PR styles are interpreted to encourage discourses about a design. This observation differs from the norm that PR presents the realistic appearance of real world environments and in the aesthetics of the resulting image, rather than presenting pictorial qualities, highlighting potential issues and stimulating an imagination or supporting an argument [291].

There are differences in the results of the emotive effectiveness of PR and NPR styles, based on their *impact* and *correlation.* The differences might be attributed to the following reasons:

(i) The two measures, *impact* (degree of impression) and *correlation* (degree and direction of relationship), are represented on a different scale such as *mean values* and *factor analysis* respectively (see Figure 8-1). The scale *mean* is a measure of central tendency and is obtained by summing all the values (respondents' ratings) and dividing by the number of responses. The range of *mean values* is between 4 and 0, where 4 indicate a high *impact* and, conversely, 0 indicate least *impact* of the rendering styles in conveying emotive implications (placed on the left extremity of the semantic differential scales). The closer the *mean value* is to 4, the stronger the *impact* of rendering styles on the emotive implications. On the other hand, the *factor loading* in *factor analysis* is a measure of the tendency (degree and direction) of relationship between two variables. It is obtained by calculating the *correlation* coefficient, which reflects the covariance of the variables (deviations of the two variables from the mean) divided by the product of the standard deviations (SD) of the two variables. The range of values it takes is between -1 and +1. A negative value indicates (inverse relationship) that the two variables move in opposite directions; a positive value indicates (direct relationship) that the two variables move in the same direction; a zero value indicates that the two variables are independent of each other; the closer *correlation* coefficient is to -1 and +1, the stronger the relationship between the two variables. Consequently, the different scales of measurement give different results in terms of *impact* (degree of impression) and *correlation* (degree and direction of relationship).

(ii) The number and type of emotive implications constituting the four *constructs*, ***affective, cognition, functional*** and ***motivational,*** are not the same in some instances when measuring *impact* and *correlation* (see Figure 8-5 and Figure 8-7). The variation in the number and type of emotive implications involved during measurement could have possibly resulted in variations in *impact* and *correlation.* Consequently, this might have possibly resulted in the differences in emotive effectiveness of rendering styles, based on their *impact* and *correlation.*

8.3.3 Specific rendering styles to stimulate emotive implications

Based on the observations from Table 8-6, Table 8-7 presents the particular PR and NPR styles that are most effective (based on *impact* and *correlation*) for stimulating ***affective, cognitive, functional*** and ***motivational*** content. This has been achieved by identifying the particular PR and NPR styles with high average *mean values* for *impact* and high average *factor loadings* for *correlation* for the four *constructs*; ***affective***, ***cognitive***, ***functional*** and ***motivational***. The average *mean values* and average *factor loadings* for all the thirty different rendering styles can be found in Table 8-2 and Table 8-4 respectively.

Table 8-7: Specific rendering styles to stimulate constructs of emotive implications

IMPACT		Constructs	CORRELATION	
PR	NPR		PR	NPR
Ray trace		Affective	Point light Ray trace	Black and white shading Hidden line shading Shadow and highlight shading Hand drawn Ink print Lines and shadow Straight unextended
Normal material	Flat shading Straight unextended lines	Cognitive		Metal shading without edge lines Straight extended
Normal material Ray trace		Functional		Shadow shading
Ray trace		Motivational	Transparent material	

It can be observed from the results that different kinds of rendering styles have a different effect on the viewers, which are in tune with the observations of Schumann et al [261]. The results identified some of the most effective rendering styles, within the styles analysed in this thesis, to stimulate the emotive implications of images based on *impact* and *correlation* such as:

a) *Impact*

- PR styles are interpreted to be most effective for conveying ***affective***, ***cognitive***, ***functional*** and ***motivational*** content. That is
  - PR styles such as *ray trace* are considered most effective for conveying ***affective*** content,

- PR styles such as *normal material* for conveying ***cognitive*** content,
- PR styles such as *normal material* and *ray trace* for ***functional*** content, and
- PR style such as *ray trace* for ***motivational*** content.

- NPR styles such as *flat shading* and *straight unextended lines* are interpreted to be most effective for conveying ***cognitive*** content.

The influence of emotive implications on *constructs*, ***affective***, ***cognitive***, ***functional*** and ***motivational***, based on literature and experimental study has been shown in Table 8-5. The *impact* and *correlation* of rendering styles on the four *constructs* has been calculated based on the literature classification and statistical derivation of emotive implications respectively.

Based on *impact*, from Table 8-5 (classification of the emotive implications based on literature and experimental study) and Table 8-6 (summary of the emotive effectiveness of rendering styles), it would seem that:

- PR styles stimulate most effectively *all* of the emotive implications.
- NPR styles stimulate most effectively emotive implications such as *approximation of information, comprehensible* and *recognisable.*

More specifically

- PR styles such as *ray trace* and *normal material* stimulate most effectively *all* of the emotive implications.
- NPR styles such as *flat shading* and *straight unextended* line styles stimulate most effectively emotive implications such as *approximation of information, comprehensible* and *recognisable.*

b) *Correlation*

- PR styles are interpreted to be most effective to convey affective and motivational content. That is:
- PR styles such as *point light* and *ray trace* are being considered to be most effective for conveying ***affective*** conten*t, and*
- PR styles such as *transparent material* for conveying motivational content
- NPR styles are interpreted to be most effective for conveying ***affective***, ***cognitive*** and ***functional*** content. That is

- NPR styles such as *black and white shading, hidden line shading, shadow and highlight shading, hand drawn, ink print, lines and shadows* and *straight unextended* line styles are being considered to be most effective for conveying ***affective*** content,
- NPR styles such as *metal shading without edge lines* and *straight extended line* styles for conveying ***cognitive*** content, and
- NPR styles such as *shadow shading* for conveying ***functional*** content.

Based on *correlation*, from Table 8-5 and Table 8-6, it would seem that:

- PR styles stimulate most effectively emotive implications such as *imaginative, interesting, satisfied, stimulating to look at*; and *comfortable, differentiation of information, real* and *stimulating to discussion.*
- NPR styles stimulate most effectively emotive implications such as *imaginative, interesting, satisfied, stimulating to look at*; *comprehensible, recognisable*; and *approximation of information, exploration of alternative solution, invite assumptions* and *stimulating to changes.*

More specifically, the following are the implications for the rendered images assessed:

- PR styles such as *point light* and *ray trace* stimulate most effectively emotive implications such as *imaginative, interesting, satisfied* and *stimulating to look at*; and PR styles such as *transparent material* stimulate most effectively emotive implications such as *comfortable, differentiation of information, real* and *stimulating to discussion.*
- NPR styles such as *black and white shading, hidden line shading, shadow and highlight shading, hand drawn, ink print, lines and shadows* and *straight unextended line* styles stimulate most effectively emotive implications such as *imaginative, interesting, satisfied, stimulating to look at*; NPR styles such as *metal shading without edge lines* and *straight extended* line styles stimulate most effectively emotive implications such as *comprehensible* and *recognisable*; and NPR styles such as *shadow shading* stimulate most effectively emotive implications such as *approximation of information, exploration of alternative solution, invite assumptions* and *stimulating to changes.*

8.4 Chapter summary

This chapter presented an experimental study conducted to assess the effectiveness of different rendering styles.

The study investigated user perception and emotional responses to different rendering styles to evaluate the degree of emotive effectiveness of existing PR and NPR styles using the Kansei Engineering methodology.

The study involved a sample of sixty-one respondents, which included academics, fourth year and fifth year undergraduate and postgraduate students, and three questionnaires. The three questionnaires were for evaluating the emotive effectiveness of different PR and NPR styles. Each respondent answered the three questionnaires pertaining to the different rendering styles that covered a spectrum of existing PR and NPR styles. The questionnaires consisted of fourteen emotive implications (which were identified through Kansei experiment, Chapter 7) defined on semantic differential scales to rate the respondent attitude towards the different rendering styles. The three questionnaires were identical, except for the number and type of rendered images to be assessed.

The emotive effectiveness of PR and NPR styles (Section 8.2.1) was estimated in terms of their a) *impact* (degree of impression) in conveying the emotive implications and b) *correlation* (degree and direction of relationship) with the emotive implications. The *impact* and *correlation* of different rendering styles were evaluated using *mean values* and *factor analysis* respectively. *Factor analysis* was also used to study the pattern of relationships among the fourteen emotive implications.

On using *factor analysis* for analysing the pattern of relationships among the fourteen emotive implications, the strong *correlations* (*factor loadings* > 0.5) in Table 8-3 established that the fourteen emotive implications (identified in Chapter 7) deserve their place in the repertoire of the implications of images. Based on literature classification and statistical derivation, the four *constructs* of the fourteen emotive implications (see Section 8.3.1) were confirmed as:

- *Affective* consists of intangible and abstract emotional aspects, such as how interesting, or imaginative an image appears, or the experience of feeling satisfied with an image.

- ***Cognitive*** is primarily concerned with understandability of the displayed information.
- ***Functional*** is primarily concerned with the aspects to be incorporated for better presentation of the images.
- ***Motivational*** consists of aspects that describe to what extent the users are encouraged to participate in the design activity.

Results regarding the emotive effectiveness of different rendering styles showed that the type of rendering style used had a definite and significant effect on the responses (see Section 8.3.2) with respect to *impact* and *correlation*. Table 8-8 summarises the findings discussed from Tables 8-5, 8-6 and 8-7. The table presents the specific rendering styles to stimulate specific emotive implications based on *impact* and *correlation*. Given the perception of the respondents, these rendering styles are interpreted to be most effective to convey those specific emotive implications in computer graphic images. The use of these results depends on the situation/intent of the user. For instance, if the intent of the user is to convey specific emotive implications such as *exploration of alternative solutions* or *invite assumptions* in an image using rendering styles that have high *impact* in conveying such emotive implications or that *correlates* most with the users' feelings. It is then recommended that PR styles such as *ray trace*, *normal material* or NPR line styles such as *shadow shading* are appropriate to convey such intent respectively.

The implications of the findings are of interest because design insights such as those rendering styles that have high *impact* or *correlate* most with the user's feelings, has been deduced. Design inferences can be drawn from the obtained relations of rendering styles of different images and user' feelings. This information is expected to aid in generating a computer graphics image using the rendering styles that elicit desired responses.

Table 8-8: Specific rendering styles to stimulate specific emotive implications

	IMPACT			CORRELATION		
Emotive implications	PR	NPR	Constructs	PR	NPR	Emotive implications
Comfortable Imaginative Interesting Real Satisfied	Ray trace		Affective	Point light Ray trace	Black and white shading Hidden line shading Shadow and highlight shading Hand drawn Ink print Lines and shadow Straight unextended	Imaginative Interesting Satisfied Stimulating to look at
Approximation of information Comprehensible Recognisable	Normal material	Flat shading Straight unextended lines	Cognitive		Metal shading without edge lines Straight extended	Comprehensible Recognisable
Differentiation of information Exploration of alternative solutions Invite assumptions	Normal material Ray trace		Functional		Shadow shading	Approximation of information Exploration of alternative solutions Invite assumptions Stimulating to changes
Stimulating to changes Stimulating to discussion Stimulating to look at	Ray trace		Motivational	Transparent material		Comfortable Differentiation of information Real Stimulating to discussion

Although different images provide different results, within the context of the images provided for assessment, the study produced a picture of users' perception of existing rendering styles. However, the analysis was restricted to the academic/education sample. To validate the consistency of the results and generality of the emotive effectiveness of PR and NPR styles, a similar study of perception and emotional responses using a cross-section of design practitioners from industry was conducted and presented in Chapter 9.

It should be noted that validating the results of the emotive effectiveness of existing PR and NPR styles with design practitioners is beyond the scope of this work (see Chapter 1), due to the number of existing rendering styles involved and the time restrictions of the design practitioners. Hence the validation with the design practitioners from industry, as described in Chapter 9, was carried out only for the results relating to NPR line styles.

PART 3 – VALIDATION, DISCUSSION AND CONCLUSION

9. Industrial validation

From Chapter 8 it was concluded that the existing rendering styles could be used in an effective manner by academics and students for conveying certain emotive implications.

This chapter presents a survey-based study, involving design practitioners from industry, conducted to validate the results of the effectiveness of rendering styles, especially NPR line styles in conveying emotive implications obtained from the study with academics and students (as described in Chapter 8). The outcome is the generality of the emotive effectiveness of NPR line styles and the implications of line styles in order to be used in an effective manner for conveying emotive implications.

In Section 9.1, the methodology of the investigation is described. Section 9.2 presents the results of the investigation of the effectiveness of line styles in conveying emotive implications. In Section 9.3, a comparison of the findings resulting from the studies (with academics and students, and design practitioners) is presented to check for any variability. Thereafter, the generality of the effectiveness of line styles is presented in Section 9.4. Finally, Section 9.5 summaries the validation by highlighting the implications of line styles.

9.1 Validation methodology

The type of validation conducted in the work presented in this chapter is referred to as external validity [330]. External validity is the degree to which the conclusions in the study would hold for other populations in other places and at other times [331]. Population validity is a type of such external validity that refers to how widely the findings apply or the results reflect different kinds of people. In order to check the results obtained from the study with academics and students (as presented in Chapter 8), the investigation was carried out with a cross-section of design practitioners from industry.

The methodology for assessing the effectiveness of rendering styles in conveying emotive implications was discussed in Chapter 8. The work described in this chapter utilises the same methodology to aid the investigation through industrial validations.

The questionnaire was in line with the one used for the academics and students to maintain consistency of the methodology. The method adopted for the study was in the form of an email survey owing to the advantages over other methods, such as interviews, in terms of reaching a number of designers from industry, time taken and cost. The sources for the sample selection were from design forums, the directory of design capability in Glasgow, contacts from industry, and contacts from academics in the DMEM Department. In total, one hundred emails were sent to the respondents explaining the theme of the research along with the questionnaire to be filled. The respondents were provided with the opportunity to give feedback at the end of the questionnaire. To enable the respondents to understand the terminology used in the questionnaire, a definition list was included. Annex 1 of Appendix D contains the mailing letter and questionnaire sent to the respondents. Schaefer and Dillman [332] opined that multiple contacts are effective in increasing response rates to email surveys. Thereby, in order to increase the response rate, follow-up emails were sent to all the respondents after one week as a reminder to fill the questionnaire, an example of which is contained in Annex 2 of Appendix D. Over a period of three weeks, the total number of returned responses was thirty-three. The filled questionnaires were returned either by return email or post. Figure 9-1 shows the background and the level of experience of the thirty-three respondents, of which 91% were males.

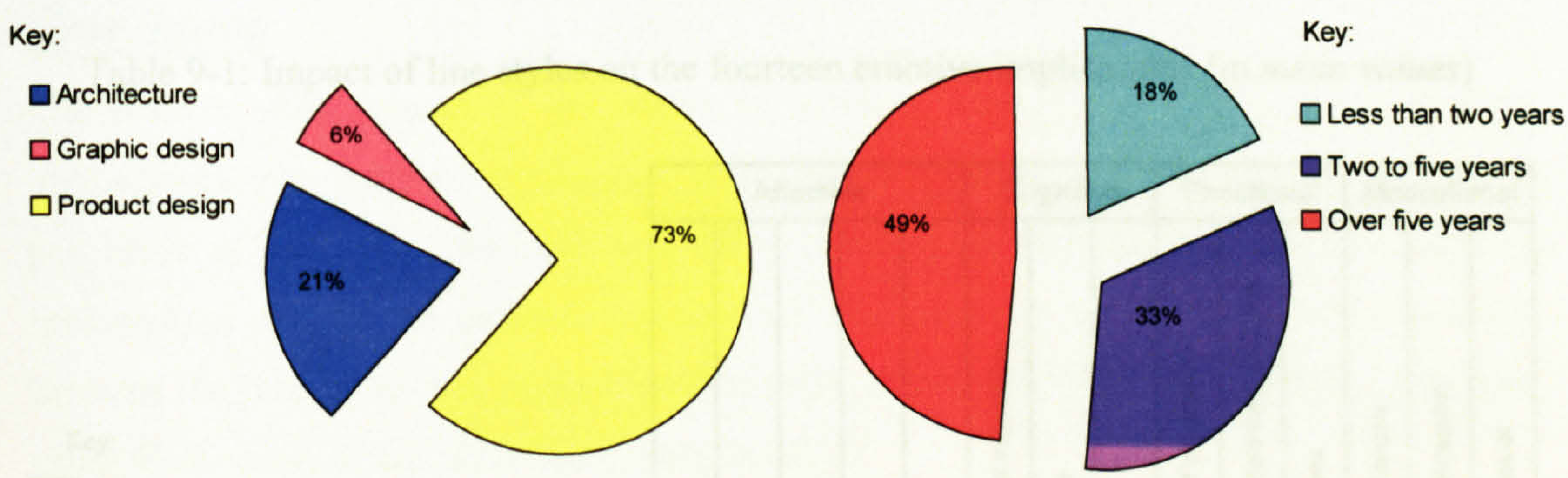


Figure 9-1: Background and level of experience in CAD

As can be seen from the figure, the respondents constituted a cross-section of architects (21%), graphic designers (6%) and product designers (73%). 49% of them had over five years experience in CAD, 33% had two to five years experience and 18% had less than two years experience. Comparatively, in the academic/education sample (see Figure 8-5) only 20% of the respondents had over five years experience in CAD, the majority of them (49%) had two to five years experience and the remaining either had less than two years experience

(20%) or never used CAD before (11%). This implies that the design practitioners had more working experience in CAD than the academic/education sample.

The data collected from the questionnaire was analysed for evaluating the effectiveness of line styles in conveying emotive implications using the analysing procedures, *mean values*, and *factor analysis*, described in Section 8.1.

9.2 Emotive effectiveness of line styles

The effectiveness of line styles is estimated in terms of their *impact* in conveying emotive implications and *correlation* with emotive implications using *mean values* and *factor analysis* respectively.

Impact

Table 9-1 presents the *impact* of line styles on the fourteen emotive implications, where the designers' perception and emotional responses to different line styles are presented as *mean values*. The rows in the table present the different line styles and the columns present the fourteen emotive implications and the groups under which they were classified.

Table 9-1: Impact of line styles on the fourteen emotive implications (in *mean values*)

Key:
- x : Strong positive emotive response
- x : Strong negative emotive response
- x : Neutral emotive response
- x : Moderate positive/negative emotive response

	Affective					Cognitive			Functional			Motivational		
	Comfortable	Imaginative	Interesting	Real	Satisfied	Approximation of information	Comprehensible	Recognisable	Differentiation of information	Exploration of alternative solutions	Invite assumptions	Stimulating to changes	Stimulating to discussion	Stimulating to look at
Band-like	***0.9***	1.7	1.3	***1***	1.1	2.8	1.5	1.9	1.1	2	1.8	2.3	2	1.5
Dotted with straight ends	2.1	2.7	2.6	1.6	2.2	2.7	2.7	2.7	2.5	2.7	2.6	2.6	2.5	2.1
Sketchy	2.1	***3.1***	2.5	1.8	2	***3.3***	2.5	2.9	2	2.7	2.6	2.8	2.9	2.6
Straight extended	2.2	2.7	2.7	1.6	2.1	2.4	2.6	2.7	2	2.6	2.7	2.7	2.6	2.4
Straight unextended	***3.3***	1.6	2.2	***3.4***	***3.3***	***0.7***	***3.6***	***3.6***	2.2	1.1	2.3	1.4	1.8	1.9

The emotive effectiveness of line styles was evaluated using the four groups of emotive implications. The overall perception and emotional responses to line styles are presented in the form of a bar chart in Figure 9-2, which shows the average *mean values* for the four groups.

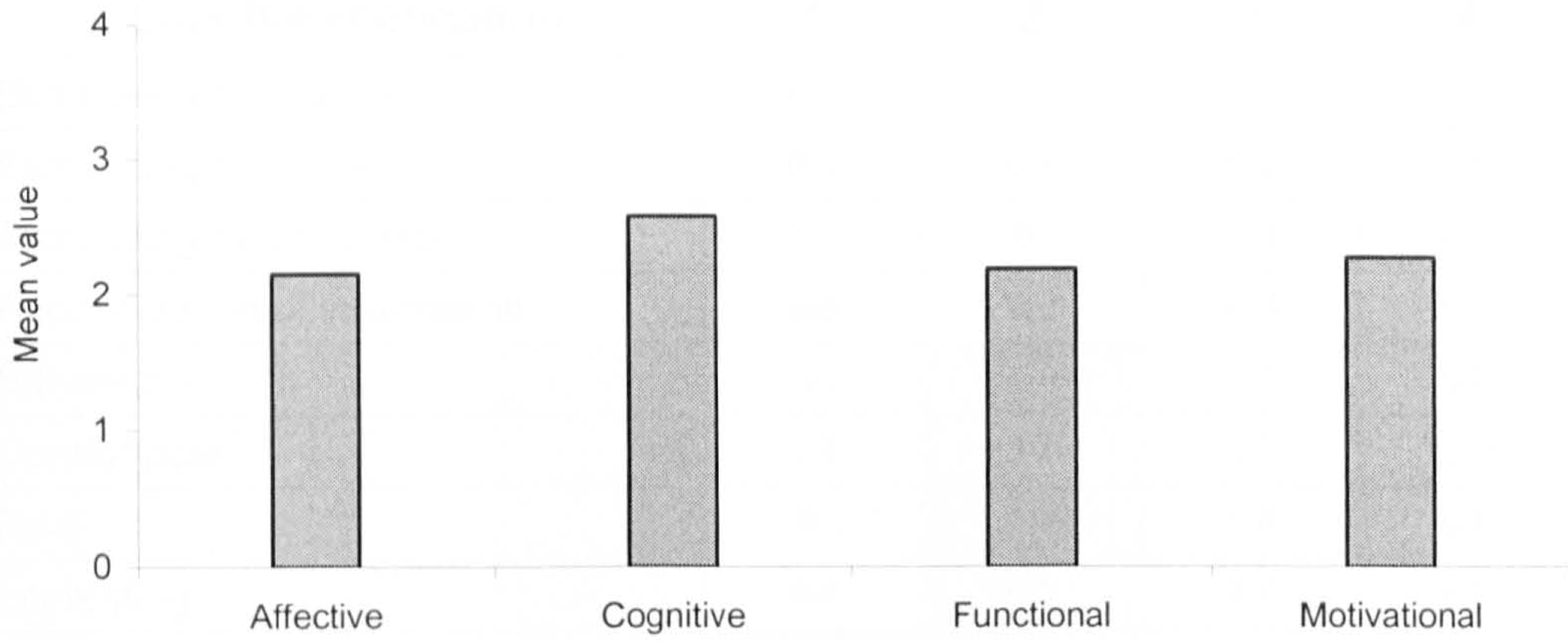


Figure 9-2: Impact of line styles on the four groups of emotive implications

From Figure 9-2, it can be seen that line styles have more *impact* in conveying ***cognitive*** content. For the remaining, line styles marginally convey ***motivational*** content more than ***affective*** and ***functional*** content. The average *mean value* of line styles is the same for both ***affective*** and ***functional*** groups, implying that the designers felt that the intensity of line styles in conveying such content is the same.

Correlation

The emotive effectiveness of line styles in terms of their *correlation* with the emotive implications was further investigated using *factor analysis*. Based on the designers' perception of line styles, two basic analyses were conducted to firstly examine the pattern of relationships among the emotive implications and secondly to establish the *correlation* between the line styles and emotive implications. More details of the analysing procedure using *factor analysis* can be found in Section 8.2.2.

(i) *Pattern of relationships among the emotive implications*

From the first analysis, Table 9-2 shows the factors extracted and their respective *factor loadings*. From the table, it can be deduced that four factors were extracted (columns).

Table 9-2: Pattern of relationships among the fourteen emotive implications

	Factor			
Emotive implication	**1**	**2**	**3**	**4**
Stimulating to changes	0.9	-0.1	0.0	0.1
Stimulating to look at	0.9	0.1	0.2	0.0
Stimulating to discussion	0.8	-0.1	-0.1	0.1
Approximation of information	0.6	0.2	-0.4	0.1
Satisfied	-0.3	0.8	0.3	0.0
Comfortable	0.2	0.8	0.1	-0.2
Real	-0.2	0.8	0.0	0.0
Interesting	0.4	0.7	0.0	0.3
Imaginative	**0.5**	0.6	0.1	0.1
Recognisable	-0.1	0.1	0.9	0.0
Comprehensible	0.1	0.3	0.7	0.2
Invite assumptions	0.3	0.1	-0.1	0.7
Differentiation of information	-0.4	0.0	0.2	0.7
Exploration of alternative solutions	0.4	-0.2	0.2	0.7

The emotive implications with high *factor loadings* (i.e., *factor loadings* ≥ 0.5) were listed to see the patterns that defined the factors. The four groups of emotive implications were given different shadings in the table to show the emotive implications constituting a particular factor. The cross hatching in the table indicates the overlap of *imaginative* into Factor 1 and Factor 2 with high *factor loadings* 0.5 and 0.6 respectively. However *imaginative* was listed under Factor 2, since its *factor loading* is higher in Factor 2 than in Factor 1. The influence of each emotive implication on a factor is shown in Figure 9-3.

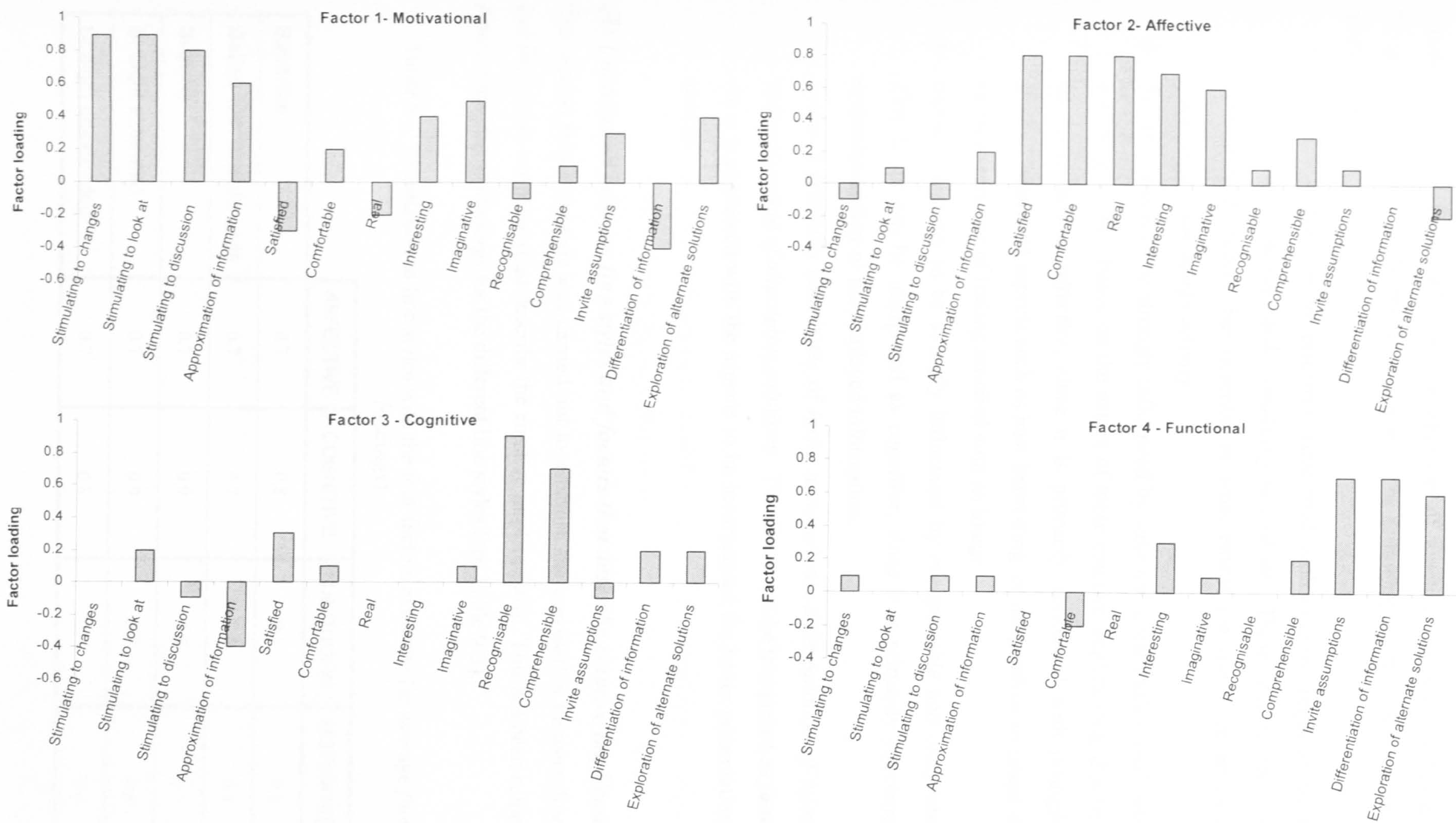


Figure 9-3: Influence of each emotive implication on each factor

Figure 9-3 shows graphically the classification of emotive implications based on the designers' perception of the rendered images. The following are the interpretations of the factors extracted:

- Factor 1 appears to be primarily concerned with emotive implications such as *stimulating to changes* and *stimulating to look at*. These implications pertain to ***motivational*** aspects that describe to what extent the users are encouraged to participate in the design activity.
- Factor 2 seems to be strongly influenced by *satisfied*, *comfortable*, *real*, *interesting* and *imaginative*. Based on the nature of these emotive implications, this factor can be interpreted as ***affective***, since it is primarily concerned with intangible and abstract emotional aspects such as how interesting, or imaginative an image appears, or the experience of feeling satisfied with an image.
- Factor 3 appears to be strongly influenced by *recognisable* and *comprehensible*. This factor can be interpreted as ***cognitive***, since it is primarily concerned with understandability of the displayed information.
- Factor 4 primarily constitutes of *invite assumptions*, *differentiation of information* and *exploration of alternative solutions*. This factor can be interpreted as ***functional***. As it is concerned with the aspects to be incorporated for better presentation of the images.

(ii) *Correlation between line styles and factors that describe emotive implications*

The second *factor analysis* was carried out to establish the *correlation* between line styles and the factors extracted (that describe the emotive implications). This has been achieved by determining *factor loadings* for the different line styles (see Table 9-3).

Table 9-3: Correlation of line styles with the four factors extracted (in average *factor loadings*)

	AFFECTIVE	COGNITIVE	FUNCTIONAL	MOTIVATIONAL
Band-like	0.7	0.8	0.7	0.8
Dotted with straight ends	0.7	0.7	0.8	0.7
Sketchy	0.7	0.9	0.9	0.7
Straight extended	0.7	0.9	0.7	0.8
Straight unextended	0.7	0.8	0.7	0.8

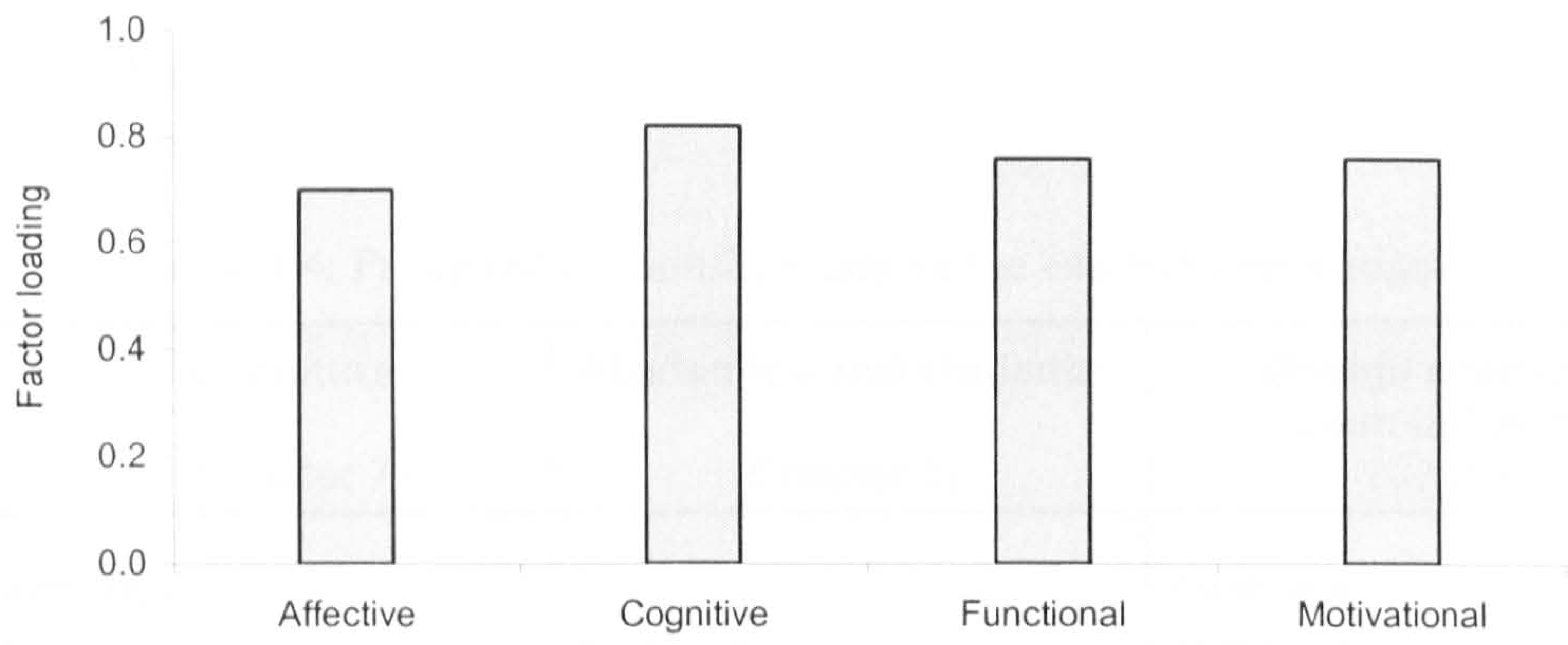


Figure 9-4: Correlations of line styles and factors that describe emotive implications

Figure 9-4 shows the average *factor loadings* of line styles for the factors ***affective***, ***cognitive***, ***functional*** and ***motivational***. Firstly, the high *correlations* in Figure 9-4 indicate that line styles *correlated* strongly with designers' feelings. Secondly, the *factor loading* of line styles for ***cognitive*** factor appears to be high, however there is only a marginal variation for ***functional*** and ***motivational*** factor, indicating that the *correlation* of line styles with ***cognitive***, ***functional*** and ***motivational*** content is more or less the same. The *factor loadings* of line styles for these factors are high compared to ***affective*** factor, indicating that line styles are more *correlated* with ***cognitive***, ***functional*** and ***motivational*** content and are most effective to convey such content than ***affective*** content.

9.3 Comparison of academic/education and industrial findings

In this section, the findings resulting from the studies with academics and students, and design practitioners from industry described in Chapters 8 and 9 are compared to check for any variability and, thereby, validate the generality of the findings of NPR line styles.

9.3.1 Pattern of relationships among the emotive implications

Using *factor analysis* in the studies for examining the pattern of relationships among the fourteen emotive implications, four factors were extracted. Table 9-4 presents a comparison of the classification of the fourteen emotive implications into four groups/factors based on:

(i) Existing literature (see Table 7-2).

(ii) Results of the experimental study with academics and students (see Table 8-3).

(iii) Results of the survey study with the design practitioners from industry (see Table 9-2).

Table 9-4: Pattern of relationships among the emotive implications

	Literature (Chapter 7)	**Academics and students** (Chapter 8)	**Design practitioners from industry** (Chapter 9)
Affective	Comfortable Imaginative Interesting Real Satisfied	Imaginative Interesting Satisfied **Stimulating to look at**	Comfortable Imaginative Interesting Real Satisfied
Cognitive	Approximation of information Comprehensible Recognisable	Comprehensible Recognisable	Comprehensible Recognisable
Functional	Differentiation of information Exploration of alternative solutions Invite assumptions	**Approximation of information** Exploration of alternative solutions Invite assumptions **Stimulating to changes**	Differentiation of information Exploration of alternative solutions Invite assumptions
Motivational	Stimulating to changes Stimulating to discussion Stimulating to look at	**Comfortable** **Differentiation of information** **Real** Stimulating to discussion	**Approximation of information** Stimulating to changes Stimulating to discussion Stimulating to look at

As can be seen in the table, from the experimental study with academics and students the classification of fourteen emotive implications obtained through *factor analysis* corresponds (except for *stimulating to look at*, *approximation of information*, *stimulating to changes*, *comfortable*, *differentiation of information* and *real*) to the prior classification based on existing literature. Significantly, the classification obtained through *factor analysis* from the survey study with practicing designers corresponds directly (except for *approximation of information*) to the prior classification based on existing literature.

As highlighted in Chapter 8 (see Section 8.3.1), the reasons for the mismatch of some of the emotive implications between the classification based on existing literature and classification based on *factor analysis* might be attributed to the following:

(i) The classification based on the understanding from literature is subjective and open to human interpretation with respect to the emotive implications constituting a particular group. Consequently, the classification may not be definitive.

(ii) In *factor analysis*, often a variable with high *factor loading* overlaps into two or three different factors and there will always be two or three variables that load into an inappropriate factor.

One emotive implication that has been a common mismatch between the classification based on existing literature and both studies was *approximation of information* (see Table 9-4). *Approximation of information* implies the ability of the images to display approximate or fuzzy information of the design concepts in conceptual design. From both studies it was found that *approximation of information* was not loaded into the ***cognitive*** factor, which is concerned with the understandability of the displayed information. This observation provides evidence that *approximation of information* cannot be classified under the ***cognitive*** group, but possibly ***functional*** or ***motivational***. However, there is no strong evidence to categorise *approximation of information* in either ***functional*** or ***motivational*** since it was loaded in different factors each time in both studies. Thereby, it can be deduced that there was insufficient evidence to classify *approximation of information* in ***cognitive***, ***functional*** or ***motivational*** groups.

The following are attributed from the observations from both studies:

- Firstly, the strong *correlations* (*factor loadings* > 0.5, see Table 8-3 and Table 9-2) in both studies indicate the strong influence of each emotive implication on a factor. Further, they emphasise that the fourteen emotive implications, identified through the Kansei experiment (see Table 7-2), deserve their place in the repertoire of the implications of images.
- Significantly, the classification obtained from the study with the design practitioners closely corresponds (except for *approximation of information*) to the prior classification based on literature. Thereby, the results based on the design practitioners strongly support the prior classification of emotive implications based on existing literature.
- Based on the classification with respect to literature and the statistical derivations in the two studies, it can be emphasised that, in general, four underlying *constructs* describe the emotive implications of images. Though naming them is a matter of subjectivity and possible dispute, based on prior research [261] and understanding in

the field, the four underlying *constructs* were ascertained as ***affective***, ***cognitive***, ***functional*** and ***motivational***.

9.3.2 Emotive effectiveness of line styles

The main findings of the emotive effectiveness of line styles from both studies are summarised in Table 9-5. This table is derived from the observations from Tables 8-2 and 8-4 and Figures 9-2 and 9-4, which show the emotive effectiveness of line styles in terms of their *impact* and *correlation* (expressed in the form of *mean values* and *factor loadings* respectively).

Table 9-5: Summary of the emotive effectiveness of line styles (*impact* and *correlation*)

Academics and students			Design practitioners from industry	
IMPACT	CORRELATION		IMPACT	CORRELATION
2.1	**0.8**	Affective	2.2	**0.7**
2.5	**0.8**	Cognitive	**2.6**	**0.8**
2.2	0.4	Functional	2.2	0.8
2.3	**0.8**	Motivational	2.3	**0.8**

As can be seen in the table, the *mean values* and *factor loadings*, which indicate the *impact* and *correlation* respectively, of line styles are relatively close, except for *correlations* with ***functional***, in both studies. This observation provides evidence that the findings of the effectiveness of line styles in conveying emotive implications are consistent in both studies.

Impact: Both the academics and students, and the design practitioners believed the line styles to be most effective to convey ***cognitive*** content, with the highest *mean values* of 2.5 and 2.6 respectively.

Correlation: The academics and students believed the line styles to be most effective to convey ***affective***, ***cognitive*** and ***motivational*** content, with the highest *correlation* values of 0.8 respectively, and least effective to convey ***functional*** content, with a *correlation* value of 0.4. The design practitioners felt the same with respect to ***cognitive*** and ***motivational*** content, with highest *correlation* values of 0.8 respectively, and differently with respect to ***functional*** content. They also believed the line styles to be most effective in conveying ***functional*** content, with the highest *correlation* value of 0.8.

On rationalising the results from both studies, it can be deduced that with respect to *impact*, line styles are thought to be most effective in conveying ***cognitive*** content. With respect to *correlation*, line styles are expected to be most effective in conveying ***affective***, ***cognitive*** and ***motivational*** content. Regarding the *correlation* of line styles with ***affective*** content, it can be seen from that table that the *correlation* value differs only by 0.1 values in both studies. Owing to the minimal difference in *correlation* value in both studies, it is ascertained that line styles are most effective for conveying ***affective*** content. Regarding the effectiveness of line styles in conveying ***functional*** content, owing to significant difference in the opinions, with *correlation* values of 0.4 and 0.8 respectively, resulting from both studies, it is deduced that there was insufficient evidence to ascertain that line styles are most effective in conveying ***functional*** content.

9.3.3 Specific line styles to stimulate emotive implications

Based on the observations and deductions from Table 9-5, Table 9-6 presents the particular line styles that are most effective (based on *impact* and *correlation*) for stimulating ***affective***, ***cognitive***, ***functional*** and ***motivational*** content. This has been achieved by identifying the particular line styles with high average *mean values* for *impact* and high average *factor loadings* for *correlation* for the constructs: ***affective***, ***cognitive***, ***functional*** and ***motivational***. The average *mean values* and average *factor loadings* for all the different line styles can be found in Tables 8-2 and 8-4 (academics and students) and Tables 9-1 and 9-3 (design practitioners) respectively.

Table 9-6: Specific line styles to stimulate constructs of emotive implications

Academics and students			Design practitioners from industry	
IMPACT	CORRELATION		IMPACT	CORRELATION
	Straight unextended	Affective		All NPR line styles
Straight unextended	Straight extended	Cognitive	Sketchy Straight unextended	Sketchy Straight extended
		Functional		
	Dotted with straight ends	Motivational		Band-like Straight extended Straight unextended

Impact: The academics and students believed the *straight unextended* line styles to be most effective to convey ***cognitive*** content. The design practitioners believed that not only *straight unextended* line styles but also *sketchy* line styles to be most effective to convey such content.

Correlation: *Straight unextended, straight extended* and *dotted with straight ends* line styles were perceived by the academics and students to be the most effective to convey ***affective***, ***cognitive*** and ***motivational*** content respectively. The design practitioners believed that all the NPR line styles convey ***affective*** content effectively. It was perceived that *sketchy* and *straight extended* line styles to be most effective to convey ***cognitive*** content and *band-like*, *straight extended* and *straight unextended* line styles for ***motivational*** content.

There are differences in the results of the specific line styles to stimulate emotive implications, based on their *impact* and *correlation*. The reasons for the differences in the results were delineated in Section 8.3.2.

9.4 Generality of the emotive effectiveness of line styles

In the preceding section, the findings of the emotive effectiveness of line styles resulting from the studies with academics and students, and design practitioners from industry were compared to check for any variability. With the findings of the effectiveness of line styles rationalised thereafter, Table 9-7 presents a matrix of the generality of the effectiveness of line styles in:

- Conveying emotive implications, based on *impact* and *correlation*:

The blank cells in the table indicate either the rendering styles are least effective or moderate in conveying emotive implications or presenting vagueness.

Table 9-7: Generality of the effectiveness of line styles (in terms of *impact* and *correlation*)

Key:

√ : Most effective (impact)

√: Most effective (correlation)

	Emotive implications													
	Affective					Cognitive			Functional			Motivational		
	Comfortable	Imaginative	Interesting	Real	Satisfied	Approximation of information	Comprehensible	Recognisable	Differentiation of information	Exploration of alternative solutions	Invite assumptions	Stimulating to changes	Stimulating to discussion	Stimulating to look at
Band-like	*√*	*√*	*√*	*√*	*√*	*√*						*√*	*√*	*√*
Dotted with straight ends	*√*	*√*	*√*	*√*	*√*								*√*	
Sketchy	*√*	*√*	*√*	*√*	*√*	√	*√* √	*√* √						
Straight extended	*√*	*√*	*√*	*√*	*√*	*√*	*√*	*√*				*√*	*√*	*√*
Straight unextended	*√*	*√*	*√*	*√*	*√*	*√* √	√	√				*√*	*√*	*√*

Findings regarding the emotive effectiveness of line styles showed that (i) based on *impact*, NPR line styles seem to be effective for conveying ***cognitive*** content and (ii) based on *correlation*, line styles are effective for conveying ***affective, cognitive*** and ***motivational*** content. Detailed descriptions of the implications of each of the line styles for conveying emotive implications (as shown in Table 9-7) are presented in Section 9.5.

9.5 Chapter summary

This chapter presented a survey-based study, involving design practitioners from industry, conducted to validate the results of the NPR line styles obtained from the study with academics and students (as described in Chapter 8).

The study involved a sample of thirty-three design practitioners from industry, which constituted a cross-section of architects, graphic designers and product designers, and an email survey questionnaire. The questionnaire and the analysing procedures utilised in the study were in line with the ones used for the academics and students for evaluating the effectiveness of NPR line styles in conveying emotive implications. The study investigated the designers' perception and emotional responses to different line styles to validate the findings of the emotive effectiveness of line styles obtained from the study with academics and students.

The resulting findings of the emotive effectiveness of NPR line styles from the study described in this chapter were found to be consistent with the findings obtained from the study described in Chapter 8 (see Table 9-5), except for the following:

- Effectiveness of line styles in conveying ***functional*** content. This is because of the polarised opinions resulting from both studies regarding the effectiveness of line styles in conveying ***functional*** content. Where the academics and students, and the designers felt the NPR line styles to be least and most effective to convey ***functional*** content, with *correlation* values of 0.4 and 0.8 respectively.

The generality of the emotive effectiveness of line styles (see Table 9-7) was obtained by comparing and rationalising the findings resulting from the study with academics and students (presented in Chapter 8) and design practitioners (presented in this chapter). Findings regarding the emotive effectiveness of NPR line styles showed that (i) based on *impact*, NPR line styles are effective for conveying ***cognitive*** content and (ii) based on *correlation*, NPR line styles are effective for conveying ***affective, cognitive*** and ***motivational*** content.

The generality of the effectiveness of the line styles could serve as a foundation for the generation of computer supported NPR techniques in conceptual design. The implications of NPR line styles are identified as:

- Line styles can be used to convey ***affective, cognitive*** and ***motivational*** content and approximate or incomplete object information in an image. More specifically:
  - *Band-like* line styles can be used to render an object for eliciting intangible and abstract emotions, presenting approximate information, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. The styles can be effective in rendering different types of vagueness such as incomplete information.
  - *Dotted with straight ends* line styles can be used for eliciting intangible and abstract emotions in an image and stimulating discussion. These lines styles are

not suited for presenting aspects based on different types of vagueness such as approximate and incomplete information.

- *Sketchy* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information and making the displayed information understandable and recognisable. They can also be used to render different types of vagueness such as approximate information.
- *Straight extended* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information, making the displayed information understandable and recognisable, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. They can be effective in presenting aspects of incomplete information such as dimensional accuracy greater than given values.
- *Straight unextended* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information, making the displayed information understandable and recognisable, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. They can be effective in rendering different types of vagueness such as incomplete information.

10. Research insights

The aim of this chapter is to present the main research findings resulting from the studies. The chapter reviews the main findings from Chapters 6 to 9 with a view to summarising the key insights gained. Consequently, the main findings from each chapter are duplicated but the objective of the chapter is to consolidate the key outcomes.

Before presenting the main findings, it is appropriate to recapitulate the studies conducted. Thereby an overview of the studies conducted and the respective chapters in which they were delineated in this thesis is given, after which the main findings from Chapter 6, implications of rendering, are presented in Section 10.1. In Section 10.2, the key findings from Chapter 7 that described the identification of emotive implications are presented. The findings of the emotive effectiveness of different rendering styles resulting from Chapter 8 are presented in Section 10.3. The findings of the implications of NPR line styles obtained from Chapter 9 are presented in Section 10.4. Finally, in Section 10.5, the key outcomes are consolidated.

Figure 10-1 presents the order in which the studies were conducted. The arrow lines in the figure indicate that some of the findings resulting from the studies provided a basis for subsequent studies.

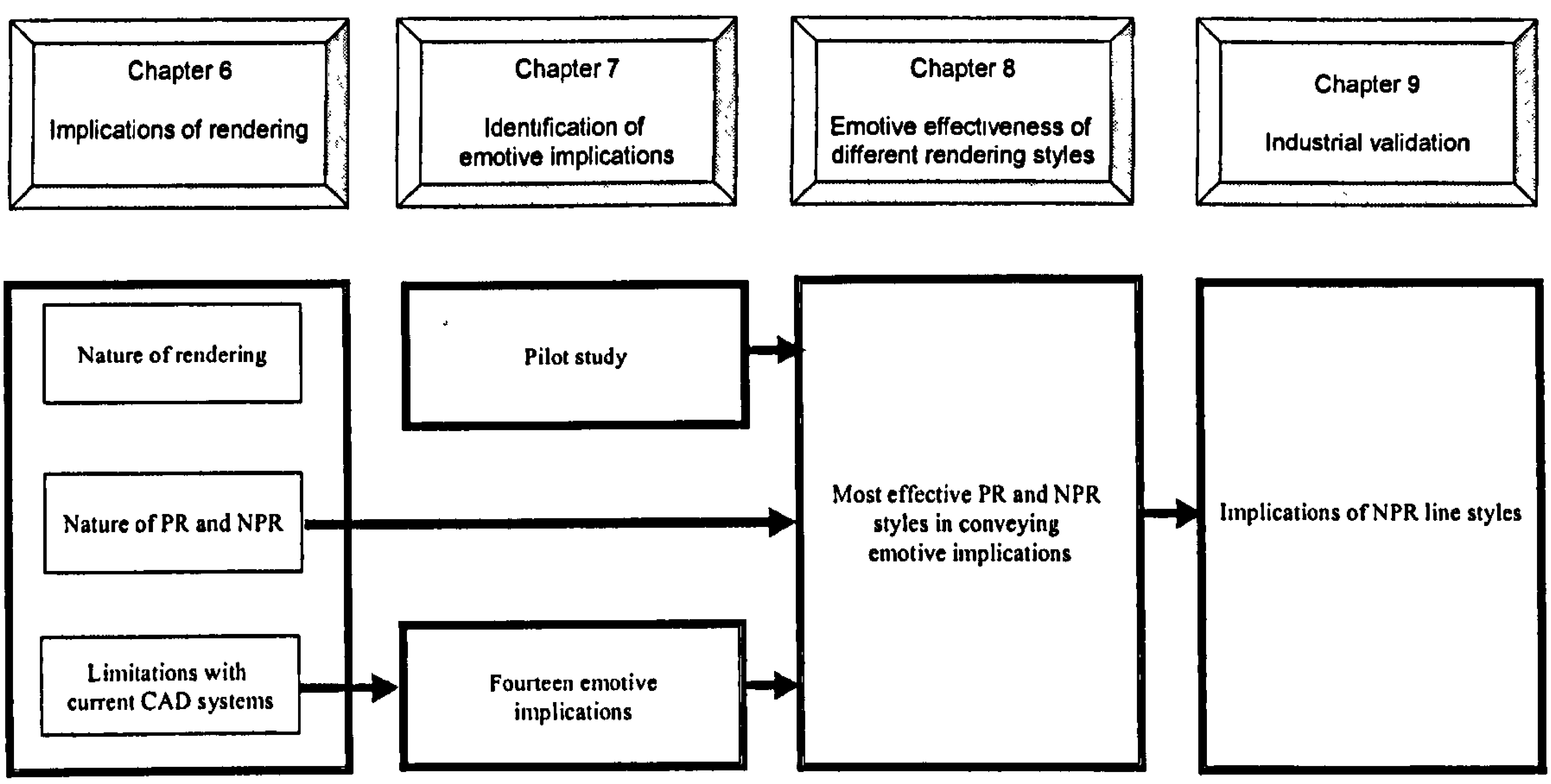


Figure 10-1: An overview of the studies conducted

With regard to Figure 10-1, firstly, a survey-based study, as presented in Chapter 6, investigated the implications of rendering to gain insights into the nature of rendering, the nature of different rendering techniques and the limitations with current CAD systems. The insights gained from the study, especially the (1) implications for the presentation of computer graphic images provided a basis for the identification of emotive implications of computer graphic images (Chapter 7), and (2) implications of NPR styles provided a basis for collecting and evaluating NPR *line* styles to determine the effectiveness of line styles in conveying emotive implications (Chapters 8 and 9).

Secondly, an exploratory pilot study, as presented in Chapter 7, investigated the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles. The identified fourteen emotive implications provided a basis for assessing the emotive effectiveness of different rendering styles (Chapter 8). Further, the pilot study and Kansei experiment for identifying the emotive implications provided insights into the main factors involved in designing and running experiments for assessing the effectiveness of different rendering styles (Chapter 8).

An experimental study with academics and students, as described in Chapter 8, investigated the rendering styles that are anticipated to be most effective for conveying emotive implications, from which the emotive implications of different rendering styles resulted.

Finally, as described in Chapter 9, a survey-based study involving design practitioners from industry investigated the validity of the prior findings relating to NPR line styles, from which the implications of line styles resulted.

10.1 Implications of rendering

In Chapter 6, a survey-based exploratory study investigated the implications of rendering to gain insights into the nature of rendering, the nature of different rendering techniques and the limitations with current CAD systems. The following are the key findings from the investigation (see Table 6-6 in Section 6.3):

(i) Nature of rendering

- Rendering is found to be most effective in embodiment and detailed design and more prolific in conceptual design compared to other design stages.

- Rendering can be extended in conceptual design for investigation of different ideas or concepts, visualisation of designs and the communication of design ideas, using *fairly vague* to *very precise* 3D information.
- 3D rendering provides better visualisation, shows the full view of the product and provides good presentation of 2D/3D models.
- Geometric aspects such as lines, vague shape and vague surface are found to be equally important as other product aspects (such as material, colour, light) during the generation of concepts.
- NPR styles, especially *lines*, are of paramount importance in conveying vagueness.
- Varying *lines* will vary other geometric aspects such as vague shape and vague surface.
- It was found that rendering of lines are important to enhance the visual comprehensibility of the images produced by PR and NPR techniques.

(ii) Nature of different rendering techniques

- NPR is more relevant in conceptual design for highlighting potential issues, and stimulating an imagination or supporting an argument compared to PR.
- NPR provides better presentation of 3D information in a 2D concept representation than other rendering techniques.

(iii)Limitations with current CAD systems

- The *absence of a sketchy look, lack of differentiation between essential and non-essential information, absence of alternative solutions* and *absence of exploring ideas* were perceived as some of the most dissatisfying factors with the current CAD systems.
- Insufficient support in the present rendering techniques for sketchy output or for the definition of abstract or vague geometry so that the output of the rendering system matches with the designer's way of working at the concept level.

The insights gained from the study, especially the (1) implications for the presentation of computer graphic images, that aspects such as the *provision of a sketchy look, differentiation between essential and non-essential information, provision of alternative solutions* and *provision of exploring ideas* need to be incorporated for better presentation of computer graphic images, provided a basis for the identification of emotive implications of computer graphic images (Chapter 7), and (2) implications of NPR styles, that NPR *line* styles are of paramount importance in presenting vagueness visually, provided the basis for collecting and evaluating NPR *line* styles to determine the effectiveness of line styles in conveying emotive implications (Chapters 8 and 9).

10.2 Emotive implications of computer graphic images

In Chapter 7, the following fourteen emotive implications were identified through Kansei Engineering (see Section 7.3):

1. *Comfortable* is an intangible or an abstract emotion, which implies the experience of being at ease with the rendered image.
2. *Imaginative* is an intangible or an abstract emotion that implies the ability of the rendered image to stimulate viewers to think about new ideas.
3. *Interesting* is another intangible or an abstract emotion, which refers to the ability of the rendered image to attract the attention of the viewers.
4. *Real* is an intangible or an abstract emotion that implies how well the rendered image reflects physical reality.
5. *Satisfied* is also an intangible or an abstract emotion. It implies the experience of feeling content or pleased with the rendered image.
6. *Approximation of information* refers to the ability of the rendered image to display approximate or fuzzy information of the design concepts in conceptual design.
7. *Comprehensible* implies how well the rendered image is understandable as reflecting all the aspects of the graphical objects in the scene.
8. *Recognisable* implies how well the graphical objects in the rendered image can be identified.
9. *Differentiation of information* refers to the ability of the rendered image to differentiate essential and unessential information.
10. *Exploration of alternative solutions* refers to the ability of the rendered image to stimulate the thought that an image/solution can have alternative solutions or needs further development.
11. *Invite assumptions* refer to whether the graphical presentation of the image denotes the actual form of an object using cues.
12. *Stimulating to changes* implies whether the graphical presentation of the image is accessible to make any variations.
13. *Stimulating to discussion* implies whether the computer graphics image presented encourages discourse about a design with clients or with oneself.

14. *Stimulating to look at* implies whether the generated computer graphics image provides a 'feel good' factor or is thought provoking.

Pattern of relationships among the emotive implications

It was observed from the following that, in general, four underlying *constructs* describe the fourteen emotive implications of images:

- existing literature (see Table 7-2),
- results of the experimental study with academics and students (see Table 8-3) and
- results of the survey-based study with the design practitioners from industry (see Table 9-2).

The four underlying *constructs* were ascertained as:

- ***Affective*** consists of intangible and abstract emotional aspects, for example, how interesting, or imaginative an image appears, or the experience of feeling satisfied with an image.
- ***Cognitive*** is primarily concerned with understandability of the displayed information.
- ***Functional*** is primarily concerned with the aspects to be incorporated for better presentation of images.
- ***Motivational*** consists of aspects that describe to what extent the users are encouraged to participate in the design activity.

The identified fourteen emotive implications, along with the four *constructs*, provided a basis for assessing the emotive effectiveness of thirty different PR and NPR styles (Chapter 8). In essence, their emotive effectiveness was determined by mapping the thirty different rendering styles with the identified fourteen emotive implications.

10.3 Emotive effectiveness of PR and NPR styles

In Chapter 8, an experimental study with academics and students investigated the (i) degree of emotive effectiveness of existing PR and NPR styles using the Kansei Engineering methodology.

Given the perception of the respondents, the following are the key findings of the rendering styles that seem to be most effective for conveying emotive implications of images, based on *impact* and *correlation* (see Table 8-8). Where *impact* is the degree of impression of rendering styles in conveying emotive implications and *correlation* is the degree of relationship of the rendering styles with the emotive implications.

(i) To convey ***affective*** content:

Impact:

- PR styles such as *ray trace* are most effective for conveying ***affective*** content.

Correlation:

- PR styles such as *point light* and *ray trace*, NPR styles such as *black and white shading, hidden line shading, shadow and highlight shading, hand drawn, ink print, lines and shadows* and *straight unextended lines* are most effective for conveying ***affective*** content.

In essence, the above-mentioned rendering styles *point light, ray trace, black and white shading, hidden line shading, shadow and highlight shading, hand drawn, ink print* and *lines and shadows* and *straight unextended lines* are thought to be most effective to convey intangible and abstract emotional aspects.

(ii) To convey ***cognitive*** content:

Impact:

- PR styles such as *normal material,* NPR styles such as *flat shading* and *straight unextended lines* are most effective for conveying ***cognitive*** content.

Correlation:

- NPR styles such as *metal shading without edge lines* and *straight extended* line style for ***cognitive*** content.

That is, the above-mentioned rendering styles *normal material, flat shading, straight extended* and *straight unextended lines* are thought to be most effective in making the displayed information understandable and recognisable.

(iii)To convey ***functional*** content:

Impact:

- PR styles such as *ray trace* and *normal material* are most effective for conveying ***functional*** content.

Correlation:

- NPR styles such as *shadow shading* for conveying ***functional*** content.

In essence, the above-mentioned rendering styles *ray trace, normal material* and *shadow shading* are thought to be most effective in differentiating essential information from unessential information in an image, stimulating the thought that the image can have alternative solutions or needs further development and denoting the actual form an object in the image by using cues.

(iv)To convey ***motivational*** content:

Impact:

- PR styles such as *ray trace* are most effective for conveying ***motivational*** content.

Correlation:

- PR styles such as *transparent material* for ***motivational*** content.

In essence, the graphical presentations of the images rendered with *ray trace* or *dotted with straight ends line* styles are thought to be accessible to make changes, to encourage discourse about a design and to provide a 'feel good' factor or are thought provoking.

10.4 Implications of NPR line styles

In Chapter 9, a survey-based study involving design practitioners from industry investigated the validity of the prior findings relating to NPR styles. In essence, the study validated the findings of the effectiveness of NPR line styles in conveying emotive implications obtained from the study with academics and students (Chapter 8).

The implications of line styles were identified as:

- Line styles can be used to convey ***affective, cognitive*** and ***motivational*** content and approximate or incomplete object information in an image. More specifically:
    - *Band-like* line styles can be used to render an object for eliciting intangible and abstract emotions, presenting approximate information, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. The styles can be effective in rendering different types of vagueness such as incomplete information.
    - *Dotted with straight ends* line styles can be used for eliciting intangible and abstract emotions in an image and stimulating discussion. These lines styles are

not suited for presenting aspects based on different types of vagueness such as approximate and incomplete information.

- *Sketchy* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information and making the displayed information understandable and recognisable. They can also be used to render different types of vagueness such as approximate information. These line styles can be effective only in presenting approximate information and for presenting aspects based on incomplete information its effectiveness is minimum.
- *Straight extended* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information, making the displayed information understandable and recognisable, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. They can be effective in presenting aspects of incomplete information such as dimensional accuracy greater than given values.
- *Straight unextended* line styles can be used for eliciting intangible and abstract emotions, presenting approximate or incomplete information, making the displayed information understandable and recognisable, making the displayed information accessible to make changes, stimulating discussion and providing a 'feel good' factor. They can be effective in rendering different types of vagueness such as incomplete information.

10.5 Consolidation

In summary, the insights gained from Chapter 6 especially the (1) implications for the presentation of computer graphic images provided the basis for the identification of emotive implications of computer graphic images (Chapter 7), and (2) implications of NPR styles provided the basis for collecting and evaluating NPR *line* styles to determine the effectiveness of line styles in conveying emotive implications (Chapters 8 and 9). The identified fourteen emotive implications provided basis for assessing the emotive effectiveness of PR and NPR styles (Chapter 8). This led to the identification of the rendering styles that are found to be most effective, within the rendering styles tested for their effectiveness,, for conveying emotive implications:

- *Point light, ray trace, black and white shading, hidden line shading, shadow and highlight shading, hand drawn, ink print, lines and shadows* and *straight unextended lines* for conveying intangible and abstract emotional aspects.

- *Normal material, flat shading, straight extended, metal shading without edge lines* and *straight unextended lines* for making the displayed information understandable and recognisable.
- *Ray trace, normal material* and *shadow shading* for differentiating essential information from unessential information in an image, stimulating the thought that the image can have alternative solutions or needs further development and denoting the actual form an object in the image by using cues.
- *Ray trace* and *transparent material* styles for making the displayed information accessible to changes, encouraging discourse about a design and providing a 'feel good' factor.

11. Discussion

In this chapter, the strengths and weaknesses of the research outcome, research techniques and research methodology presented in this thesis are discussed, and the future research directions are identified.

Section 11.1 discusses the research outcomes in terms of their ability to meet the requirements (defined in Chapter 2), and to address the inadequacies of existing studies (outlined in Chapter 5). In Section 11.2, the techniques used for the work presented in this thesis are discussed. In Section 11.3, the research methodology undertaken to conduct the work presented in this thesis is summarised. Finally, future works are identified in Section 11.4.

11.1 Research outcome

The outcome of the research is in the form of insights into the emotive implications of different rendering styles. In this section, the insights into the emotive implications of different rendering styles described in Chapter 10 are evaluated according to the (a) requirements set in Chapter 2 and (b) key aspects outlined in Chapter 5 with respect to *visualisation and interpretation* to identify the strengths and weaknesses.

11.1.1 Requirements to enhance HCS in conceptual design

The following discusses the insights with respect to the requirements to enhance human computer symbiosis (HCS) in conceptual design (see Section 2.5).

(i) *Facilitating computer generated presentations that are closer to the mental models of the design concepts*

The work involved determining which rendering style elicits particular subjective response from respondents. Therefore, it is anticipated that on displaying a design by the computer graphic images using the rendering styles that elicit desired responses would facilitate computer presentations that are closer to the mental models of the design concepts.

It was identified in Section 2.3.3 that often there is a significant difference between a design displayed by the computer graphic images and the designers' mental model of the design concept. This difference could act as a barrier to the computer supported design at the early conceptual stages, and can lead to misinterpretations, and, in many cases possible criticism and avoidance of the computer system [142]. With the insights of the emotive implications of rendering styles, it is possible to facilitate computer presentations that could match designer intent and expectations. This is because design insights such as those rendering styles that are anticipated to have high *impact* and *correlate* most with the respondent feelings were deduced. Thus, the insights could possibly act as a guide for designers to base their decision for using the respective rendering style/emotive implication paradigms in their drawings for generating presentations that elicit desired responses.

(ii) ***Supporting the emotive information***

From the work, it was deduced that emotive information could be expressed through rendering styles. The work investigated the emotive implications of different rendering styles by assessing the users' emotive responses. Results regarding the emotive effectiveness of different rendering styles showed that the type of rendering style used had a definite and significant effect on the responses. In addition, they illustrated the link between rendering styles and different types of emotive information.

(iii) ***Minimising the loss of information during the design loop***

It was highlighted in Section 2.3.3 that the refinement of the design concepts in conceptual design in a CAD system involves loss of vague information and original design intent. In addition, during *visualisation and interpretation* (Step 4 in Figure 2-5), often there is loss of information and design intent, when there is a significant difference between a design displayed by the computer and the designer's mental model of the design concept.

The insights might enable designers to minimise the loss of information during the design-loop. This is because of the following reasons:

- In the work, the implications to develop computer supported NPR techniques using line styles have been identified. Generating images using NPR techniques minimise the loss of information during refinement as such rendering reflects the design concepts in conceptual design. .
- In the work, the emotive implications of rendering styles provided insights into the rendering styles that are thought to be, within the context of this thesis, most effective in conveying specific emotive implications. Displaying a design using the specific rendering style/emotive implications paradigm that elicit desired responses

could possibly minimise the loss of information and design intent during *visualisation and interpretation*.

11.1.2 Key aspects for visualisation and interpretation

The following discusses the study presented in this thesis with respect to the key aspects for *visualisation and interpretation* (see Section 5.2.1) and addresses the inadequacies of existing studies (outlined in Section 5.2.3).

(i) ***Cognitive levels of information***

Cognitive levels were referred as the different levels of cognitive information inherent in the images. The study evaluated the affect of different existing photorealistic rendering (PR), and non-photorealistic rendering (NPR) styles on the respondents. In particular, the focus was on the emotive responses of the respondents, which pertains to a high-level cognition (implicational *meaning*).

In comparison, the summarised studies in Chapter 5 other than Duke et al [171] focused on surface levels of cognition. Although the focus of Duke et al was on the emotive responses of the respondents, which pertains high-level cognition, it was limited to a particular type of NPR styles only.

(ii) ***Effectiveness***

Effectiveness identifies which of the rendering techniques, in a given situation, is the most effective at expressing the desired information. In the study presented in this thesis (see Table 11-1), the focus was on the effectiveness of existing PR and NPR styles in conveying emotive implications. The emotive effectiveness of PR and NPR styles (Section 8.2) was estimated in terms of their a) *impact* (degree of impression) in conveying the emotive implications and b) *correlation* (degree and direction of relationship) with the emotive implications. The *impact* and *correlation* of different rendering styles were evaluated using *mean values* and *factor analysis* respectively. *Factor analysis* was also used to study the pattern of relationships among the fourteen emotive implications.

Table 11-1: Overview of the study presented in this thesis to evaluate effectiveness

	Situation to evaluate effectiveness	Stimuli for comparison	Factors for estimating effectiveness	Type of analysis of evaluation data	Reason
Survey-based	PR and NPR in conveying emotive implications	Thirty different PR and NPR images	Impact	Mean	To describe the central tendency of observations.
			Correlation between two variables	Factor analysis	To examine the pattern of relationships among variables. To establish the correlation between two variables.

In comparison, the existing studies critically reviewed in Chapter 5 (see Table 5-3) based the measurement of effectiveness on factors that varied from accuracy in performing tasks, through relationship between two variables, to visual impression and visual interest that the images make on communication of particular affects. Such studies compared the respective rendering technique either with respect to real scenes or photographs or PR images or NPR images. None of the studies compared different categories of PR or NPR in a unified manner. In essence, the focus was on just one variety of either PR or NPR techniques. Whereas, in the study presented in this thesis, thirty different rendering styles that covered the spectrum of the existing categories of (a) PR and (b) NPR styles were compared and tested for their effectiveness.

(iii) *Emotive implications*

Emotive implications of images reflect the implicational information of images that imply or stimulate designers' emotive responses. The study presented in this thesis identified the emotive implications to evaluate the effectiveness of rendering styles. Fourteen emotive implications were identified using the Kansei Engineering methodology. In essence, the different types of implicational information were identified in the work presented in this thesis. Although Duke et al [171] addressed the nature of implicational information, in terms of how implicational information can be used in a computer game environment, the different types of implicational information in computer graphic images were not addressed.

11.2 Research techniques

The aim of this section is to discuss the techniques employed for the work presented in this thesis, in terms of their suitability with respect to the intended purpose. Four techniques are discussed:

- ***Interacting Cognitive System (ICS)***
- ***Kansei Engineering***
- ***Factor analysis***
- ***Survey-based study***

11.2.1 Interacting Cognitive System (ICS)

ICS was chosen as the foundation for the work presented in this thesis to reason the cognitive principles underpinning the *visualisation and interpretation* of the generated computer graphics rendered image (Step 4 in Figure 2-5).

Cognitive science is required for the understanding of human information processing between the visualisation of a generated computer graphics image and its interpretation. The earliest cognitive theories of visual perception are 'bottom-up' and 'top-down' [267]. These theories are limited to reason about the surface levels of the image and do not take into account emotion. In this sense ICS [20, 277] is one of the more developed theories that account for human information processing and explains a broad range of phenomenon, including aspects such as visual perception, cognition, emotion and inference.

Given its comprehensibility, the provision of a framework in which the operation of different micro-theories of cognition (such as 'bottom-up', 'top-down') can be situated and organised, its broad range of applicability in the context of HCI and Computer Graphics (e.g. [171, 266, 270, 273-275]) and in particular its re-appraisal in the context of rendering (e.g. [169, 170]), ICS was chosen as the basis for the research. Thus, the interactions of cognitive processes in the human mind to form an understanding and interpretation of the displayed computer graphics image can be explained in terms of ICS (see Step 4 in Figure 11-1).

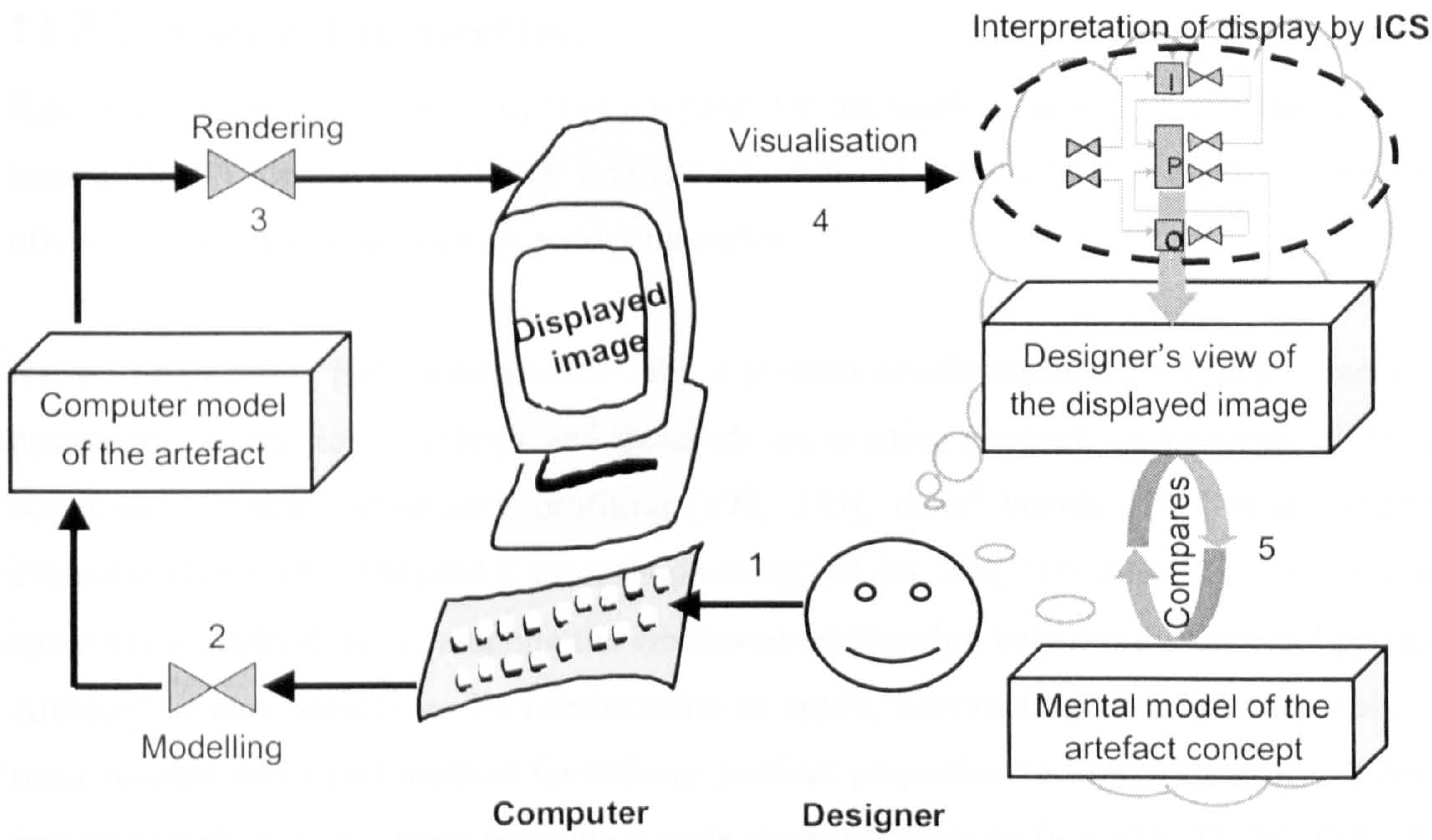


Figure 11-1: Human computer symbiosis in conceptual design

For the work presented in this thesis, ICS enabled the comprehension and formulation of important aspects in the visual interpretation of computer graphic images including (but not limited to):

- The existence of four cognitive levels of information in images, such as visual (*sensory*), object (*structural*) and proportional and implicational (*meaning*). The two levels of *meaning*, propositional and implicational, are distinct and distinguished as non-emotional and emotional *meanings* respectively.
- The significance of object and implicational information for the human understanding or interpretation of the image generated using rendering.
- The role and impact of implicational information, especially that emotion and cognition come together at this level of information in cognitive processing.
- The delineation of emotive implications of computer graphic images.

The major outcome of ICS was the delineation of emotive implications and their potential in contributing to (i) the propositional understanding of the images and (ii) soft-functional realism of the images.

11.2.2 Kansei Engineering

Kansei Engineering methodology was adopted, for the work presented in this thesis, as the means for (1) identifying emotive implications and (2) evaluating the degree of emotive effectiveness of existing and new rendering styles.

Kansei Engineering [24], which is formally a product development methodology, translates customers' impressions, feelings and demands on existing products or concepts to design solutions. Product personality profiling [192, 333], mood boards [192] visual product evaluation [192, 333, 334] and Kansei Engineering [21-24, 286, 319, 320, 322, 335-342] are some of the methods for evaluating the emotional relationship between the user and product. Although it may sometimes be cumbersome to apply, Kansei Engineering is arguably the most reliable and valid method for linking product properties to user responses. It has a proven record in applications covering a wide range of products (e.g. [21, 22, 24, 318-320]) and has proved as effective approach to creating designs that match the user expectations.

Whilst Kansei Engineering has never been applied before in Computer Graphics, given its (i) wide range of applicability and advanced development over other methods in terms of evaluating the users' emotional relationship with artefacts, leading to more informed decision-making in the design process, and in particular (ii) the concept of *Kansei* being closely related to emotive responses at the implicational level leading to interpretation, imagination and judgement, Kansei Engineering methodology was adopted for the research.

The strength of Kansei Engineering lies in its ability to link artefact properties with user responses and create designs that match user intent and expectations [343]. The works of Nagamachi [22, 24, 338] used the semantic differential method [317] for evaluating designs of products and analysing relations. It has been the most powerful quantitative analysing method for affective meanings. For the work presented in this thesis, semantic differential method was used for identifying the emotive implications of computer graphic images and evaluating thirty different existing and new rendering styles. Kansei Engineering proved to be valuable for the research in identifying the emotive implications of images and the most effective rendering styles.

However, the weaknesses of Kansei Engineering were also identified, which include:

- It relies on statistical analysis to link rendering styles with user responses. Such methods appear to offer the most reliable and valid means for linking rendering styles to user responses. However, when many rendering styles are involved, such methods become unwieldy and time consuming. This is because designing thirty different rendering styles and asking respondents to mark over 420 semantic differential scales (30 rendering styles × 14 emotive implications) simply in order to give input to the best rendering style, seems excessive.

- Central to Kansei Engineering is the respondents' opinion. Hence, the identified emotive implications and the most effective rendering styles were the result of the respondents' perception and opinion. Thus, it relies on the honesty and accuracy of the respondents. It was assumed that the respondents opined honestly and accurately about the emotions elicited by the different rendered images. If the respondents were not honest and accurate in their opinions, it would result in misleading analysis results (e.g. false identification of the most effective rendering style to convey emotive implications).

11.2.3 Factor analysis

In the work presented in this thesis, statistical *factor analysis* was conducted to (i) examine the pattern of relationships among the fourteen emotive implications and (ii) identify those rendering styles that *correlated* most with the respondents' feelings.

Factor analysis has been reported as being used for studying patterns of relationship among many variables, with the goal of inferring the nature of the factors that affect them [344]. Factors statistically derived from the analysis are said to account for the relationships shown in the correlation matrix [327]. In the work presented in this thesis, on using *factor analysis* for studying the patterns of relationships among the fourteen emotive implications, four factors were extracted. Based on the existing literature and statistical derivation, it was emphasised that four underlying *constructs* explained the effects of computer graphic images. Though naming them is a matter of subjectivity and possible dispute, based on prior research [261] and understanding in the field, they were ascertained as ***affective***, ***cognitive***, ***functional*** and ***motivational***. The variables with *factor loadings* greater than or equal to 0.5 were listed under each factor to see the patterns that defined the factors. However, often in *factor analysis* a variable with high *factor loading* overlaps into two or three different factors and there will always be two or three variables that load into an inappropriate factor [329]. *Factor analysis* does not prove that a real entity exists corresponding to each factor identified. It simply provides supporting evidence (based on *correlations* in the correlation matrix) to claim that concepts could be arranged in a particular pattern and that the *factor* *analysis* does not refute this. *Factor analysis* is merely a statistical process that supports existing literature.

At present in the work, *factor analysis* was conducted separately for each of the thirty different rendering styles. The evaluation data of the thirty different rendering styles from the *factor analysis* was manually analysed to identify those rendering styles that *correlated* most with respondents' feelings, which is time consuming. This is because a common problem in running *factor analysis* for all the thirty rendering styles together is the requirement of large computer memory. For instance, if the *factor analysis* were conducted for the thirty rendering styles together, the resulting correlation matrix would be 420 × 420. Most of the modern statistical programs have a limit on the number of variables. Computation is often impossible because of the memory consumption of variables' correlation matrix and its operation. Although *factor analysis* is reliable for examining pattern of relationships and linking rendering styles to user responses, the disadvantages include large memory consumption, time consuming difficult for general users to deal with many variables because of small personal computers and the need for the user to be an expert in statistics [22]. Ishihara et al [22] used neural networks-based analysis for the Kansei experiment data instead of *factor analysis* to enable easy, speedy and flexible analysis. In the future, such neural networks-based analysis could be adopted for the evaluation data.

11.2.4 Survey-based study

Studies in rendering can be broadly divided into survey-based and behavioural-based [299, 300]. The studies presented in this thesis were survey-based, which involved polling a representative number of respondents and collecting their opinion to find out how they respond to a particular rendering style.

Based on the reasons, discussed in the research, the survey method adopted for the studies (presented in Chapters 6 to 9) was in the form of group-administered and email survey questionnaires. Discussed in Sections 6.1, 8.1.1 and 9.1, this was mainly due to their advantages over other methods in terms of cost, convenience to administer, high response rate, length of the questionnaire, speed of data collection, opportunity for quantifying responses and opportunity for providing number of visual presentations for assessment. It is admitted that other survey methods such as interviews should have been used. The questionnaires proved to be a valuable tool for gaining insights into the implications of rendering, identification of emotive implications of computer graphic images, the emotive effectiveness of different rendering styles and the implications of NPR line styles. The scaled response formats (likert scale [302] and semantic differential scale [317]) in the questionnaires proved to be successful as they facilitated quick completion and a detailed quantification of results. However, there are some limitations such as:

- In semantic differential scale response formats, respondents may have a tendency towards a 'position bias' where they habitually mark at the extreme end of the scale (or do not use extreme ends at all) without considering possible stronger or weaker responses [327]. This can occur with likert scale as well. However, it is more likely to occur in semantic differential as the scale points lack the likert verbal designations (such as strongly agree, strongly disagree).
- There can be different interpretations of the ratings at the middle point of the scale. This could imply either the respondents do not have any of the subjective/emotional opinions or have neutral/indifferent subjective/emotional opinions of the images tested.

Problems did arise with respect to the terminology used in the questionnaire especially in the study on the implications of rendering and pilot study presented in Chapter 6 and Chapter 7 respectively. Thereby, measures were taken in subsequent studies (relating to the effectiveness of different rendering styles and industrial validation of NPR line styles presented in Chapter 8 and Chapter 9 respectively) by providing definitions for the ambiguous terminology used in the questionnaire and measures were also taken to provide correct wording in the questions.

The academics in the department with more than five years experience in CAD offered the most valuable information in the open-ended questions in the study on the implications of rendering presented in Chapter 6 and pilot studies presented in Chapter 7. In the introductory questions, the respondents were asked to indicate how many years of experience they had in CAD to gauge the ease with which they answered. The high number of respondents (in the study on the effectiveness of different rendering styles and industrial validations presented in Chapters 8 and 9 respectively) with more experience in CAD indicate that they were at ease while marking in the cells of the fourteen emotive implications they thought applicable to the depicted rendered images. Although the responses varied from respondent to respondent, the results were extrapolated to the general academic/education and industrial population using inferential statistics.

An exploratory pilot study was conducted as part of the research presented in this thesis, with eight respondents to gain insights into the main factors involved in identifying the emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles. Since it was exploratory in nature, the questionnaire had different motivations and different questions [345]. The subject numbers were kept small in order to reserve the sample for the main experimentation (for assessing the emotive effectiveness of different rendering styles). Creating pilot studies is an important part of conducting user studies [345]. The most important issue is that the data gathered from these types of studies can only indicate a possible direction for main experimentation and data gathering, and does not provide concluding evidence for or against the hypothesis of the pilot study [230].

The exploratory pilot study, along with the study presented in Chapter 6, provided a number of insights into the main factors involved in designing and running experiments, including (but not limited to):

- Consistency in the placement of contrasting emotive implications on the extreme ends of the semantic differential scales.
- Importance of correct wording in the questions to avoid confusion and enable proper interpretation.
- Importance of proper rationalising of the choices provided in the response formats to avoid cumbersome analysis and the problems while articulating the results using the ambiguous words in textual form.
- Nature of sample selected for the outcome of the studies.
- Presentation of rendered images for better interpretation of the emotions elicited by the images.
- Range of values to be designated on the semantic differential scales.
- Sample size to produce reasonable level of accuracy of the results in the study.
- Type of response formats for quick completion and detailed quantification of results.

One of the major outcomes from the pilot study was that there was no systematic methodology behind the (i) selection and rationalisation of emotive implications presented on the semantic differential scales to evaluate their suitability and (ii) selection of rendering styles to have proper comparison of different rendering styles and assess their degree of effectiveness. Based on these insights, it was contemplated that a standard procedure should be followed to identify the emotive implications and assess the effectiveness of different rendering styles. Hence a suitable methodology was searched, which resulted in the recognition of Kansei Engineering, a product development methodology, as a means to identify the emotive implications and evaluate the degree of effectiveness of different rendering styles.

For the study on the emotive effectiveness of different rendering styles, the three questionnaires consisted of fourteen emotive implications defined on semantic differential scales to rate the respondents' attitude towards the different rendering styles that covered a spectrum of PR and NPR styles. The respondents were to evaluate different rendering styles on fourteen emotive implications. Each respondent responded to three questionnaires pertaining to the different rendering styles.

The weaknesses of the study were identified, which included:

- Multiple images were provided for assessment on the same semantic differential scales. This should have been avoided to enable the respondent to concentrate on one image at a time for interpretation. In future, individual assessment semantic differential scales should be provided for each image and should not be combined into the same question.
- The rendered images were presented as high quality ink-jet illustrations to the respondents for assessment in the questionnaires. Instead, they should have been simulated in the computer to get the feeling of a computer graphics technique. This would have enabled the respondents to perceive the images better and facilitated better interpretation of the emotions elicited by the images.
- The respondents felt tired evaluating thirty rendered images in terms of fourteen emotive implications given on the semantic differential scales. Based on this issue, there are opportunities for the quality of the responses to be varied.

11.3 Research methodology

The research presented in this thesis was conducted in accordance with the methodology presented by Duffy and O'Donnel [54] as illustrated in Figure 1-1, Chapter 1. Based on the methodology the research was divided into three parts:

- ***research problem formalisation***, i.e. design problem and research problem,
- ***solution / investigation***, and
- ***validation***.

Despite the issues, such as time management, that arise when conducting research, the advantages of undertaking the research based on the above-defined methodology include:

- The methodology has acted as an overall guide to conducting the research work by providing a basis to map the research activity and progress.
- The philosophical and practical balance of work.
- Whilst dividing the research into three parts has provided a useful guide for conducting the work and presentation in this thesis, it has also enabled the relationships between the three parts to be identified more easily. In Chapter 12, the constituents of each of the parts and the dependencies between them are illustrated in Figure 12-1.

Despite following the aforementioned methodology, the manner in which the research was conducted could have been improved through more effective validation of the work.

Validation focuses on ascertaining the consistency and generality of a particular result. In order to enable the validation of the results obtained from the study with academics and students, an investigation was carried out with a cross-section of thirty-three design practitioners from industry. The validation was used to check the consistency of the results of the effectiveness of NPR line styles, in conveying emotive implications, obtained from the study with academics and students, and, thereby, derive the generality of the effectiveness of NPR line styles.

One of the positive outcomes of the validation was the deduction that NPR line styles can be anticipated to be used in an effective manner by academics, students, architects, graphic designers and product designers to convey ***affective***, ***cognitive*** and ***motivational*** content. However, the following weaknesses were identified:

- Lack of full validation. Validation of the work was discussed above. The validation was limited to the prior findings relating to NPR line styles only. This is because validation of the findings of the effectiveness of the existing thirty different rendering styles with the design practitioners is time consuming due to the number of existing rendering styles involved. Complete testing of the findings in an industrial environment is required. Full validation will be investigated in future studies to realise the potential of the obtained results fully (see Section 11.4.1).
- It relies on an email survey. The designers responded to the questionnaires sent by an email. This limits the opportunity for immediate clarification, for example if they

were unclear of the meaning of a question. This would affect the honesty of the responses and there are opportunities for the quality of the responses to be varied based on the lack of immediate clarification. In essence, it relies on asynchronous methods of communication where synchronous may be more beneficial.

11.4 Future work

In this section, future research directions are identified by extending the work presented in this thesis.

11.4.1 Further exploration of the emotive implications of rendering styles

This section discusses the key aspects for further exploration of the emotive implications of different rendering styles.

Systematic study within actual design practise

The work presented in this thesis has focused on academics and students' perception to different rendering styles to evaluate the degree of emotive effectiveness of existing PR and NPR styles using Kansei Engineering methodology. Discussed in Sections 6.1 and 8.1, this was mainly due to the difficulties of studying and impinging on actual design practise in industry, the *convenient* sample of academics and students was chosen. *Convenient* samples are the samples, chosen from a population for observation, that are easy to approach [308]. Although study within design practice was employed for the work presented in this thesis, it was limited to validate the prior findings relating to NPR line styles only. In the future, the research can be extended by carrying out a systematic study using Kansei Engineering methodology to cross-evaluate the existing PR and NPR styles with the perception of design practitioners from industry. The perception of academics, students and design practitioners might be different. Although the students were at ease while marking in the cells of the fourteen emotive implications they thought applicable to the depicted rendered images, they are still in their learning stage and generally have limited working experience. As such, the difference between their perceptions can be reflected in the emotive effectiveness of different rendering styles. For example, the identification of the most effective rendering styles to convey emotive implications may be different from those of academics/education sample. In essence from such a systematic study, insights regarding those rendering styles that correlated most with the designer feelings can be deduced.

As a result of the aforementioned scope for further research on the emotive implications of rendering styles, a research proposal is being formalised in relation to 'A cognitive based approach to rendering in computer supported creative design' under the EPSRC Cognitive Systems initiative. This proposal is in conjunction with Professor Alex Duffy (DMEM Department, University of Strathclyde), Dr Kenneth MacCallum (Visiting Professor to DMEM Department, University of Strathclyde) and Dr Alison Sanford (Department of Psychology, University of Strathclyde). The intention of the proposal is to use the design insights drawn from the obtained relations of rendering styles and designers' feelings to build a computer-based prototype system that can predict the rendering techniques to best reflect a designer's intended emotive implications. The ultimate aim is to be able to develop a more mature IDA (Intelligent Design Assistance) system that supports human creativity during conceptual design (see Section 2.3.1 for information of the role of an IDA within a CAD scenario).

11.4.2 Further investigation of an alternative rendering approach

This section discusses the key aspects for further investigation of an alternative rendering approach in conceptual design.

In Chapter 3 (see Section 3.3.3), it was inferred from the examination of existing PR and NPR techniques that there is loss of information and designer intent during the generation of computer graphic images, as these rendering systems require the vague design concepts in conceptual design to be defined into precise concepts. Such rendering has hitherto been considered to be most effective towards the end of design but not to investigate and inspire different ideas or concepts in conceptual design. With the increase of an interest about the importance of conceptual design stage, the interest about vagueness also started to increase by a few researchers [56, 346-348]. Although NPR conveys a sense of imprecision, they do not preserve vague information. Therefore, a significant challenge is to discover how to present and maintain inherent vagueness of ill-defined concepts whilst allowing rendering.

In the future, research can be extended for the development of an alternative rendering approach that facilitate the use of vague information and its presentation to embed design intent and uncertainties in conceptual design. In such an approach, one key aspect to be developed is a uniform way of handling vague information, together with precise information. With respect to this, a number of methods based on the theories of probability, fuzzy-set, off-setting operations and interval algebra are available from existing works on vagueness representation and manipulation, and could be incorporated into the rendering approach to support early design concepts. The logic for the development of such an approach could be based on the following procedure. The generation of a computer graphics image, usually, is split into two stages: modelling, for the generation of a geometric model, and secondly, rendering, turns this geometric model into a graphical image. In these stages, vagueness could possibly be maintained in the following way:

- In the first stage, vague information using vagueness modelling methods (such as the traditional fuzzy set, interval algebra, offsetting operations, parametric and constraint-based and probability-based modelling) can be used for the generation of a vague geometric model.
- In the second stage, the generated vague geometric model can be imported to the rendering system to produce a rendered image.

This type of approach could possibly enable the vague information to be carried to the rendering stage to turn the abstract geometric model to a rendered image that reflects the true nature of the design concepts, such as inherent vagueness. Thereby, the concentration of this approach is not in the post-processing stage, unlike the present NPR techniques where the hand drawn appearance is simulated on the images that were scanned (e.g. [246]) or on the output from a 3D renderer (e.g. [217, 222, 224]) to give a fuzzy or a vague impression. In this way, the alternative approach facilitates the modelling of vague design concepts, the use of approximate and incomplete information in the modelling process and its presentation to support early design concepts. In essence, such an approach:

- Allow design through minimum commitment (i.e. keeping the design solution as ill-defined as possible while still supporting its evolution).
- Allow retention of potentially useful information.
- Promote unexpected discovery.
- Support flexibility in design concept modelling.

A particularly challenging and interesting area of applying the aforementioned approach can be found in ship hull design. Ship hulls are irregular in shape and thus leave much room for vagueness in modelling and interpretation. The aforementioned approach provides a means to support early stage conceptual ship design by:

- Capturing vague geometric information of hull forms by vague modelling, without losing any potentially useful information.,
- Providing a means to visualise and interpret the vague hull by rendering.

12. Conclusion

Based on the research methodology introduced in Section 1.2 (Figure 1-1), the work presented in this thesis has provided insights into the emotive implications of different rendering styles in conceptual design. Figure 12-1 provides a summary of the work presented in this thesis by indicating the research contributions and the dependencies between them. In addition, an indication is given regarding the chapters and parts of the thesis corresponding to each aspect of the work.

In summary, the review on computer supported sketch systems provided a foundation to identify the design problem during human computer symbiosis (HCS) in conceptual design; the requirements to enhance HCS; and the research focus on rendering from a cognitive perspective. Key aspects for rendering were derived from the review of rendering techniques and cognitive theories. Existing works related to rendering were critically reviewed with respect to the identified key aspects. The research problem in this thesis was then formalised. A pilot study was conducted to investigate the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles. Studies on the implications of rendering, identification of emotive implications of computer graphic images and the effectiveness of different rendering styles, apart from the pilot study, were conducted. Insights into the emotive implications of different rendering styles were derived based upon the investigation results. The results were then validated with design practitioners from industry. The insights into the emotive implications of rendering styles derived from the investigation were evaluated by a predefined set of requirements and key aspects. Finally, the strengths and weaknesses of the work and future research directions were identified.

In the remainder of this chapter, the conclusions with respect to the overall aim and objectives of the work are detailed.

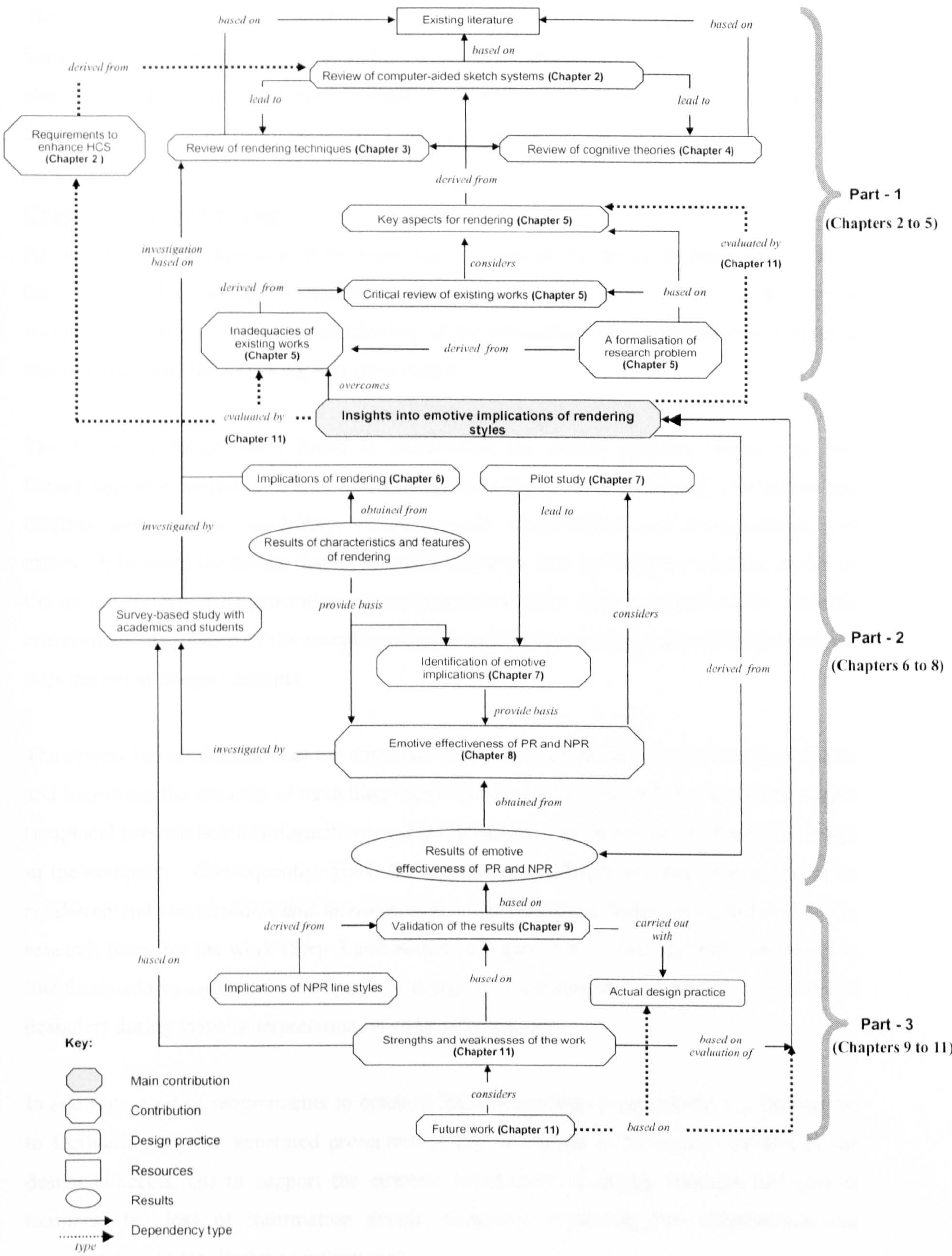


Figure 12-1: Summary of the work

The overall aim of the work presented in this thesis is to provide insights into the emotive implications of different rendering styles in conceptual design. The following discusses the objectives of the work undertaken to meet the overall aim and the resulting outcomes (the following headings are based on the objectives outlined in Section 1.1).

Computer-aided sketching

An objective of the main aim of the work was to establish the design problem and focus of the research. To achieve this objective, literature from computer supported sketch systems was reviewed, from which an understanding of the computational conceptual design process was obtained, and the following was determined.

The following factors were found to characterise the design problem during cognitive human-computer activities in conceptual design (see Figure 2-5): (i) loss of information and original intent during *modelling, rendering* and *visualisation and interpretation*, (ii) mismatch between the design displayed by the computer and the designer's mental model of the design concept, (iii) generation of inappropriate images, (iv) misinterpretation, possible criticism and avoidance of the computer system and (v) insufficient support for the emotive information in design concepts.

The review has established that the emphasis has been more on sketch input (online/offline) and improving the capacity of modelling (Step 1 and Step 2 in Figure 2-8) than on the output (graphical presentation of information) and the designers' perception of the displayed design in the computer. Consequently, given the significant challenge and potential in this area, *rendering* and *visualisation and interpretation* of the displayed image was identified as the research focus for the work (Step 3 and Step 4 in Figure 2-8). Thus, the work presented in this thesis adopts a cognitive viewpoint of design by focussing on the cognitive processes of designers during visual interpretation, in conceptual design.

In addition, a set of requirements to enhance HCS in conceptual design was established: (i) to facilitate computer generated presentations that are closer to the mental models of the design concepts, (ii) to support the emotive information of design concepts and (iii) to minimise the loss of information during *modelling, rendering* and *visualisation and interpretation* of the displayed information.

Features and key aspects of rendering

Knowledge of different kinds of realism depicted in computer graphic images was obtained. It was established that there is insufficient support for 'soft-functional' realism in images, which is characterised by less tangible issues such as the emotions of the designers. Based on the review of literature dedicated to rendering, knowledge of contemporary rendering techniques, their features, applications, conventions and representative works, and their role during the design process was obtained. The common feature observed from the literature was that rendering systems require a precise geometric model (obtained from modelling) to convert into a graphical image for display. Such systems require the vague design concepts in conceptual design to be defined into precise models whilst allowing rendering. This involves loss of information and design intent as such rendering do not reflect the true nature of design concepts in conceptual design and produce an image, whose appearance is difficult to modify, except by post-processing (output). The review established that an appropriate technique that reflects the qualities of the nature of the design concepts, such as inherent vagueness, and works in a pre-processing stage is required.

In addition, knowledge of the key aspects for the generation of computer graphic images was established, namely: computational requirements, intelligent design assistant (IDA) philosophy, realism, sketchy input and sketchy output. Computational requirements were expressed as the type of requirements (low/high) needed for the generation of computer graphic images. The IDA philosophy was defined as the role the computer plays in the image generation process. Realism was described as the type of realism that the generated computer graphics image has to depict. Sketchy input and sketchy output were expressed as the type of input and output to be supported by the rendering systems.

Features and key aspects during visual interpretation

In order to identify the cognitive principles underpinning the visual interpretation of a displayed computer graphics image, perceptions from existing cognitive theories to vision were used as a starting point. It was established, from the understanding of Interacting Cognitive System (ICS), that at an implicational level cognitive and affective (emotive) concerns come together and constrain judgement, decision-making and overt behaviour. Thus, *the implicational information of images that imply or stimulate designers' emotive responses* was termed as *emotive implications of images.*

In addition, knowledge of the key aspects for the visual interpretation studies was established, namely: cognitive levels of information, emotive implications and effectiveness. Cognitive levels were expressed as the different levels of cognitive information inherent in the images. Emotive implications were reported to contribute to (i) the propositional understanding of the images and (ii) soft-functional realism of the images. Effectiveness was reported to identify which of the rendering techniques, in a given situation, is the most effective at expressing the desired information.

Inadequacies of existing works

In order to identify the need for further research in the area of rendering, existing works were critically reviewed. Specifically, the most relevant works of rendering within the areas: (i) development of rendering systems for the generation of computer graphic images and (ii) visual interpretation studies of the generated rendered images, were critiqued based on their respective key aspects.

As a result of the critical review, it was identified that there is insufficient support for vagueness and none of the reviewed rendering systems seem to capture the inherent vagueness of design concepts in conceptual design, although imprecision is introduced in the post-processing. Further, again with respect to visual interpretation studies, knowledge of the inadequacies that these studies exhibit was established, i.e. none of them (i) determined emotive implications of computer graphic images, although the importance of implicational information has been emphasised by some works, (ii) evaluated the effectiveness of rendering styles based on emotive implications, and (iii) integrated all the existing PR and NPR styles within a unified work to determine the most effective rendering styles for conveying the desired information.

Insights into emotive implications of different rendering styles

The main contribution of the work presented in this thesis is in the form of insights into emotive implications of different rendering styles. The insights were derived from a novel study conducted with the aim of addressing the inadequacies of existing studies and satisfying the requirements to enhance HCS in conceptual design.

The overall idea of gaining the insights is to support the designer in creating and influencing the emotional impact of a new design. As such, the insights embody the rendering styles that are found to be most effective, based on the perception of the respondents to the rendering styles provided for assessment, in conveying specific emotive implications. The insights could possibly act as a guide for designers to base their decisions in using the respective rendering style/emotive implication paradigms when creating designs that elicit desired responses. Thus, the work presents an innovative aspect to conceptual design and development by understanding the emotive implications of different rendering styles and influencing the emotional impact of a new design. Thereby, the insights provide significant contribution in the field of rendering, specifically cognitive based rendering.

The systematic study comprised of four stages[29]:

Stage 1. A survey-based study investigated the implications of rendering to gain insights into the nature of rendering, the nature of different rendering techniques and the limitations with current CAD systems.

Stage 2. An exploratory pilot study investigated the main factors involved in identifying emotive implications and running experiments for assessing the emotive effectiveness of different rendering styles.

Stage 3. Identifying the emotive implications of computer graphic images.

Stage 4. An experimental study investigated academics' and students' perception and emotional responses to evaluate the emotive effectiveness of existing PR and NPR styles using Kansei Engineering methodology.

The insights gained from Stage 1, especially:

- The implications for the presentation of computer graphic images, that aspects such as the *provision of a sketchy look*, *differentiation between essential and non-essential information*, *provision of alternative solutions* and *provision of exploring ideas* need to be incorporated for better presentation of computer graphic images, provided a basis for the identification of emotive implications of computer graphic images (Stage 3).
- The implications of NPR styles, that NPR *line* styles are of paramount importance in presenting vagueness visually, provided a basis for collecting and evaluating NPR *line* styles to determine the effectiveness of line styles in conveying emotive implications (Stage 4).

[29] The main findings from Stages 1, 3 and 4 are detailed in Sections 10.1 to 10.3 respectively.

The exploratory pilot study (Stage 2) provided insights such as:

- the need for a systematic methodology to identify the emotive implications (Stage 3) and to assess the effectiveness of different rendering styles (Stage 4), and
- the future direction for the main experimentation to assess the emotive effectiveness of different rendering styles (Stage 4).

The following fourteen emotive implications were identified using the Kansei Engineering methodology (Stage 3):

- (1) *comfortable,* (2) *imaginative,* (3) *interesting,* (4) *real,* (5) *satisfied,* (6) *approximation of information,* (7) *comprehensible,* (8) *recognisable,* (9) *differentiation of information,* (10) *exploration of alternative solutions,* (11) *invite assumptions,* (12) *stimulating to changes,* (13) *stimulating to discussion* and (14) *stimulating to look at.*

In addition, knowledge of the underlying *constructs* that describe the fourteen emotive implications was established, namely: ***affective***, ***cognitive***, ***functional*** and ***motivational.***

- ***Affective*** was stated as being primarily concerned with intangible and abstract emotional aspects. ***Cognitive*** was described as being primarily concerned with understandability of the displayed information. ***Functional*** was expressed as being primarily concerned with the aspects to be incorporated for better presentation of the images. ***Motivational*** was reported as being primarily concerned with aspects that describe to what extent the users are encouraged to participate in the design activity.

The identified fourteen emotive implications, along with the four *constructs*, provided a basis for assessing the emotive effectiveness of different rendering styles (Stage 4).

The emotive effectiveness of thirty different PR and NPR styles was determined (Stage 4). Given the perception of the respondents, the following are the key findings of the rendering styles that seem to be most effective for conveying emotive implications of images

- *Point light*, *ray trace*, *black and white shading*, *hidden line shading*, *shadow and highlight shading*, *hand drawn*, *ink print*, *lines and shadows* and *straight unextended line* styles for conveying intangible and abstract emotional aspects.
- *Normal material*, *flat shading*, *straight unextended line*, *metal shading without edge lines* and *straight extended* line styles for making the displayed information understandable and recognisable.
- *Ray trace*, *normal material* and *shadow shading* styles for differentiating essential information from unessential information in an image, stimulating the thought that the

image can have alternative solutions or needs further development and denoting the actual form an object in the image by using cues.

- *Ray trace* and *transparent material* styles for making the displayed information accessible to changes, stimulating discourse about a design and providing a 'feel good' factor.

Validation of the results

A survey-based study involving thirty-three design practitioners from industry was used for the validation of the results of the effectiveness of NPR line styles, in conveying emotive implications, obtained from the study with academics and students. Based on the validation, knowledge was derived regarding how well the results were consistent and the generality of the effectiveness of NPR line styles. The results relating to effectiveness of NPR line styles from both studies were found to be consistent, except for the following:

- Effectiveness of line styles in conveying ***functional*** content.

Regarding the generality of the effectiveness of NPR line styles, it was derived that the line styles may be appropriate to be used in an effective manner by academics, students, architects, graphic designers and product designers for eliciting intangible and abstract emotions, presenting approximate or incomplete information, making the displayed information understandable, recognisable and accessible to changes, stimulating discussion and providing a 'feel good' factor. The generality of the effectiveness of the line styles could serve as a foundation for the generation of computer supported NPR techniques in conceptual design. The implications of the line styles to develop such techniques are detailed in Section 10.4.

Strengths and weaknesses of the work

The research outcome in the form of insights into emotive implications of rendering was evaluated with respect to the requirements to enhance HCS in conceptual design. It showed that the insights could (i) facilitate computer presentations that are closer to the mental models of the design concepts, (ii) support the emotive information and (iii) minimise the loss of information during the design loop.

Knowledge was derived regarding how well the study presented in this thesis addressed the inadequacies of existing studies, i.e. the study (i) determined fourteen emotive implications of computer graphic images, (ii) evaluated the effectiveness of rendering styles based on emotive implications and (iii) integrated thirty different rendering styles that covered the spectrum of the existing categories of PR and NPR styles to determine the anticipated most effective rendering styles for conveying emotive implications in conceptual design.

The techniques used for the work presented in this thesis were effective, i.e. (i) ICS enabled the comprehension of the cognitive principles underpinning the *visualisation and interpretation* of the generated computer graphics rendered image, (ii) Kansei Engineering provided a means to identify the emotive implications of images and the most effective rendering styles, (iii) statistical factor analysis enabled the identification of patterns of relationships among the fourteen emotive implications and those rendering styles that correlated most with the respondent feelings and (iv) scaled response formats (likert and semantic differential scales) in the questionnaires facilitated quick completion and a detailed quantification of results. The methodology utilised for the research was effective by acting as an overall guide for conducting the research and presentation in this thesis.

The main drawbacks of the work, with respect to the techniques and research methodology employed, were also identified, including:

- Kansei Engineering relied on the honesty and accuracy of the respondents. The work was under the assumption that the respondents opined honestly and accurately about the emotions elicited by the different rendered images.
- The Kansei experiment and statistical factor analysis used to analyse the Kansei experiment data was time consuming.
- The limitation of the presentation of the rendered images in the form of high quality ink-jet illustrations for assessment in the questionnaires.
- The non-inclusion of individual assessment semantic differential scales for each image to allow the respondents to concentrate on one image at a time for interpretation.
- The limitation of survey methods used for the studies presented in this thesis, in that only group-administered and email survey questionnaires were used.
- The limitation of the validation of the prior findings relating to NPR line styles only.

<u>*Future work*</u>

Two main directions for future work were proposed:

a) Further exploration of emotive implications of rendering styles:

- Extend the study presented in this thesis with more investigations of actual design practice.

b) Further investigation of an alternative rendering approach to facilitate the use of vague information and its presentation to support early design concepts.

In conclusion, the work presented in this thesis: established the design problem, requirements to enhance HCS and focus of the research; derived key aspects for rendering; recognised the inadequacies of existing works in rendering; defined the research problem; investigated the effectiveness of different PR and NPR styles in conveying emotive implications; produced novel results concerning the fourteen emotive implications of images, the four underlying constructs that describe the fourteen emotive implications and the emotive implications of different rendering styles; validated the research results; analysed the strengths and weaknesses of the work presented in this thesis; and identified avenues for future research based on the current research findings.

Appendix A: Study on the implications of rendering

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Annex-1: Questionnaire

UNIVERSITY OF STRATHCLYDE IN GLASGOW

Limitations of Current Support for Rendering

20 November 2002

Dear Sir/Madam

Our quest for automation in the last few decades has resulted with computers taking a major role in many of the things we see around us. This has been made possible by the amount of research that has been put into incorporating computer support for design and the way we visualise the computerised designs. As you may know, several computer packages are available in the market today to offer support in the later stages of design, however, it is well known that computer support in early stage design is not sufficient. Techniques are being developed worldwide to address this issue by giving computer support to preserve and utilize as much information as possible in the early design stages.

The enclosed questionnaire is part of research at the CAD Centre, University of Strathclyde. Our current investigations are directed towards the support of rendering in the early stage design. Rendering is an image processing technique that combines the geometrical precision of computer graphics with the representational freedom of painting. Rendering techniques enable the visualisation and manipulation of final products that was not previously possible using traditional techniques. It involves such things as shading, hidden line and surface removal, textures, colour, light, animations and other realistic features. There are currently many tools used in rendering however there is insufficient support for sketching, vagueness, fuzziness and uncertainty.

The main aim of this questionnaire is to get a clear picture of the limitations of current support for rendering in the early design stage. The identified limitations will give us a foundation for specifying future system requirements. It will be of great importance to receive your feedback for this research in identifying areas that need attention/future development. You may be assured that the confidentiality of your response will be respected.

The results of this questionnaire will be summarised in a report and sent to all interested participants.

I would be very happy to answer any questions you may have and could be contacted on 0141 548 3056 or by email.

Thank you for your assistance

Raji Tenneti

Ms Rajyalakshmi Tenneti
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Glasgow G1 1XJ
UK

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THE UNIVERSITY OF STRATHCLYDE IN GLASGOW

Limitations of Current Support for Rendering

This questionnaire, which is being sponsored by the University of Strathclyde, will produce findings about rendering in the early stage design. All responses will be treated confidentially. Please complete the questions with a brief description wherever applicable. It should not take more than 20 minutes to answer the questions. A copy of the report compiled from this questionnaire will be sent to all the respondents upon request.

Name:	Address:
Email:	
Phone:	
Position:	

Guide to completing the questionnaire:
This questionnaire consists mainly of rating scales and scaled responses. Some scales may include a description while others include a percentage range 0-100%. In each case we are only looking for a rough estimate on the given range. Just mark a cross as shown:

0%						100%
			X			

	Very important	Important	Not important	Do not know
		X		
			X	

1. a) Please rate the following stages of design process with regard to the applicability of rendering in each stage?

		0-20	20-40	40-60	60-80	80-100	
Requirements specification	0%						100%
Conceptual (Early Stage Design)	0%						100%
Embodiment	0%						100%
Detailed	0%						100%
Manufacture/Production	0%						100%

b) What do you consider the importance of sketch rendering to be in the early stage design with respect to the following? *(Please indicate the appropriate box)*

	Very important	Important	Not important	Do not know
Communication				
Speed of rendering (time)				
Visualization				
Quality				
Other reasons (Please specify)				

2 a) In your opinion what is the best way to convey a designer's idea? *(Please indicate the appropriate box)*

		0-20	20-40	40-60	60-80	80-100	
Hand Drawn Renderings	0%						100%
Computer Renderings	0%						100%
Others (Please specify)--------							

b) Please justify your opinion in (a)

---

3 a) Please give your opinion on the following rendering methods in early stage design.
(Please indicate the appropriate box)

	Very Important	Important	Not Important	Do not know
Photo realistic method				
Non-photo realistic method				
Others (Please specify)				

b) How does rendering assist in design development?

---

4 a) With respect to dimensionality of data sources (models and images), where is rendering more feasible in early stage design? *Please rank in relation to each other the appropriate box using the following scale* 1= most appropriate 2= more appropriate 3=appropriate 4=least appropriate 5= not appropriate 6= do not know

	1	2	3	4	5	6
Linear representation (e.g text, 1D table)						
Two-dimensional representation						
Encoding three-dimensional information in two-dimensional representation						
Three-dimensional representation						
Two dimensional and three dimensional representations						
Two dimensional or three dimensional representations						
Others (please specify)						

b) Why did you choose the above?

____

c) What information do you convey in the above chosen option?

____

5. Below is a list of attributes considered for rendering. *Please indicate their importance by marking the column that best suits your answer.*

	Great Importance	Some Importance	No Importance	Do Not Know
Line factor				
Shadows				
Texture				
Light				
Surfaces				
Material				
Transparency				
Colors				
Mapping				
Vagueness				
Others (please specify)---				

6 (a) What type of information do you use while rendering in conceptual stage?

	0-20%	20-40%	40-60%	60-80%	80-100%	
Precise/accurate						Vague

(b) How confident are you that the intended meaning is conveyed by the above decision?

	0-20%	20-40%	40-60%	60-80%	80-100%	
Not Confident						Very Confident

(c) Briefly justify your answer in 6(b)?

____

____

____

____

7. Of what importance is the following during the generation of concepts, compared to other product aspects (such as material, light, color) to you? *(Please tick the most appropriate box)*

	Plays no role	Plays minor role	Equally important	Exclusive relevance	Do not know
Lines					
Vague shape					
Vague surface					
Others (Please specify)					

8 Thinking about different factors that influence rendering, how important are the following for a good sketch rendering system? *(Please indicate the appropriate box)*

	High Importance	Some Importance	No Importance	Do not know
Rendering style (realistic/ non realistic)				
Expression				
Dimensionality				
Aesthetics				
Communication				
Speed of rendering				
Computational requirement				
Image quality				
Alternative Solutions				
Others (please specify)				

9 (a) Here are some possible reasons given for dissatisfaction with the present rendering tools/methods. Please consider your own reasons in relation to these and indicate each of them (add additional reasons if necessary) that you believe best describes your opinion. *(Please indicate the box that describes your opinion)*

	Agree	Disagree	Uncertain	Do not know
Absence of sketchy look				
Not suited for communicating ideas				
Picture perfectness				
Absence of vagueness				
Absence of exploring new ideas				
Absence of alternative solutions				
Lack of differentiation between essential and extraneous information				
Others (Please specify)----------				

(b) Are there any other comments regarding effects? (e.g. what are the limitations you face with current systems?)

____

____

____

____

(c) Do you have any ideas on how you would address the above problems that you encountered? (Your possible solutions to the problems you highlighted in 9(b))

____

____

____

____

10. For each of the following statements in the columns, please tick the factors necessary for the statements *(more than one may be ticked).*

	Designer takes into account while rendering	Criteria for rendering	Convey information to the client	Characteristics from traditional methods of rendering missing in current methods
Enhancing spatial structure				
Clarifying shape				
Level of details				
Accuracy (Precise/Approximation)				
Completeness (Complete/Incomplete)				
Differentiation between necessary and unnecessary information				
Regular and sterile looking lines				
Vivid, incorrect, sketch like drawings				
Others reasons (please specify)				

11. a) What rendering tools / programs do you often use?

____
____
____
____

(b) What are the limitations of the current rendering systems in terms of their use and functionality?

____
____
____
____

c) Suppose you were requested to create an ideal sketch rendering system, which specific features /tasks would you prefer to be improved or added?

____
____
____
____

We appreciate your help so far with this questionnaire. Finally, we would like any feedback or thoughts that may be relevant and aid us in our study.

Use the space below to supply your answer.

- **Thank you for your assistance**

Would you like a copy of the report compiled from this questionnaire when they become available?
(Please tick one box)

Yes ☐
No ☐

Appendix B: Pilot study

ANNEX-1: Respondents' details

1. David A Stevenson is a teaching assistant in DMEM at the University of Strathclyde for the past 10 years. His primary teaching areas are Design Methodology and Graphical Communication (engineering drawing, predominantly). Prior to that he worked for a number of years as a research assistant, with a particular focus on graphical interface provision, in particular graphical representation of uncertain/incomplete information in the context of early-stage design, where design choices and decisions are progressing from vagueness towards completeness. This remains a background research interest. Prior to that he worked for many years in architectural offices as an architectural assistant.

2. Frank Gaddis is a teaching assistant in DMEM at the University of Strathclyde since 1994. His education and work experience centres on Industrial/Product Design and has specialised knowledge particularly in the field of aesthetics, ergonomics, and computer support for industrial/product design. The Product Design Engineering course module that he delivers include sketching, rendering, model making, aesthetics, ergonomics, project research and creative design techniques. The computer support he provides for design activities specialising in Ideas, 3D Studio Max, and a variety of other 3D modelling graphics and DTP packages. Prior to his role in DMEM Department, he worked as a Secondary School Technical Teacher for Standard Grade Graphic Communication, Craft and Design. He also worked as a Research Assistant at Engineering Design Research Centre (EDRC) for Development of design tool based on visual interpretation of design data, information, or knowledge in the years 1990 to 1993.

3. Andrew Wodehouse is a design lecturer in DMEM at the University of Strathclyde since September 2003. He graduated as a MEng in Product Design Engineering at the University of Glasgow/ Glasgow School of Art and Ing from the Hanzehoge school Groningen, the Netherlands, before working as a product design engineer for Cambridge Consultants Ltd., a technology consultancy in Cambridge, England. Currently undertaking a PhD in interactive digital environments to support collaborative engineering design teams, he is a researcher on the Digital Libraries for Distributed Innovative Design Education and Teamwork (DIDET) collaboration between the University of Strathclyde and Stanford University.

4. Izzy Ali-Maclachlan had worked as a design lecturer in DMEM at the University of Strathclyde. His primary teaching areas are Design Graphics, and CAED systems for the undergraduate and postgraduate students. The Design Graphics class that he delivered included topics such as freehand sketching in 2D and 3D, presentation graphics, scaled drawing, and also application of basic graphic communication skills in a design context.

5. Ian Whitfield is a research fellow in CAD Centre in DMEM at the University of Strathclyde from 1999. Prior to that he was a senior research associate at Engineering Design Centre at University of Strathclyde. He is a design engineer with a proven track record in world-class engineering design research and significant ability within the development of Computer Aided Engineering Design solutions.

6. Zhichao Wu is a research fellow in CAD Centre in DMEM at the University of Strathclyde. He has a PhD degree on Artificial Intelligence in Design, and a first degree of Civil engineering. He had experience (mainly through lectures in his first degree) of engineering drawing. He has about 4 years research experience (as a research fellow) in CAD Centre. His research interests include collective learning in design, design creativity, system integration, knowledge management, and data and process management in distributed design.

7. Wenjuan Wang is a third year PhD student in CAD Centre in DMEM at the University of Strathclyde. Her research interests are design product and design process knowledge, knowledge modelling. Before she came to Glasgow, she obtained her Master and First degree in Northwestern Polytechnic University, Xi'an China, majoring in Computer Aided Design and Aircraft Manufacturing Engineering respectively.

8. Ahmad Beltagni was a MEng product design student from DMEM Department with two to five years of experience in CAD.

ANNEX-2: An example of a questionnaire for the pilot study

DAS wed 14 apr 04

University of Strathclyde Glasgow — cad centre DMEM

Sketch Rendering

The purpose of the following questionnaire is to find how vagueness can be represented visually and which ways of describing it would be understandable to the designers while mapping their mental model.

Each answer you provide is a contribution to our work. The results of this questionnaire will be summarised in a report and sent to all interested participants.

The contents of this form are absolutely confidential. Information identifying the respondent will not be disclosed under any circumstances

I would be happy to answer any questions you may have and could be contacted on 0141 548 3056 or by email.

Once you have completed the questionnaire, we would like any feedback or thoughts that may be relevant and aid us in our study.

Use the space below to supply your ~~answer:~~ comments

Ms Raji Tenneti
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Glasgow
G1 1XJ
UK

Tel: +44(0) 141 5483056
Email: raji@cad.strath.ac.uk

Guide to completing the questionnaire:

This questionnaire contains closed type questions where you are required to put a tick mark in the appropriate box.

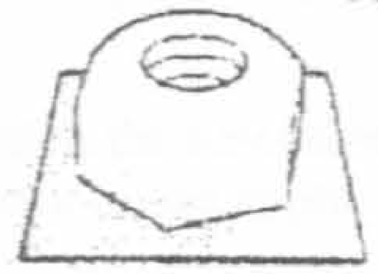
It should not take more than 15 minutes to answer the questions.

Name:	DAVID A. STEVENSON	Age	15-30	☐
Gender:	M ☑		30-45	☐
	F ☐		45-60	☑
			Above 60	☐

Level of experience in design drawings:

- Highly experienced (over 5 years of experience) ☑
- Some experience (two to five years experience) ☐
- Little experience (less than 2 years experience) ☐
- No experience (never used before) ☐

Please assess the figure in accordance with the adjective pairs given below, using a scale of one to five. Please put a tick mark in the appropriate box



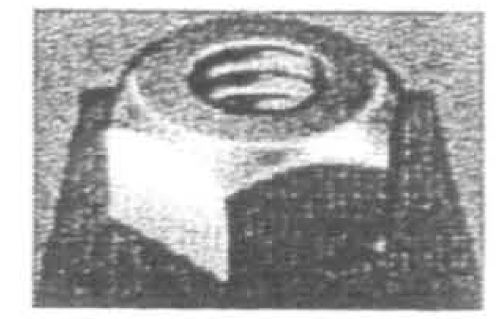
use of word ?

	1	2	3	4	5	
Acceptability of presentation						
Creative			●			Non creative
Differentiate essential and non essential information	●					Not differentiable
Imaginative/exploring ideas			●			Non imaginative
Immediately understandable	●					Not understandable
Interesting/lively		●				Not interesting
Stimulating to changes /modification					●	Non stimulating to changes
Stimulating to discussion /communication			●			Non stimulating to discussion
Stimulating to look at			●			Non stimulating to look
Unambiguous		●				Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)			●			Exact /Precise information
Conveys emotions					●	Does not convey
Level of details (Less)			●			Level of details (High)
Pleasant			●			Annoying
Realistic		●				Unrealistic
Recognisable	●					Unrecognisable
Reflects uncertainty					●	Does not reflect
Rough/sketchy				●		Detailed/clear
Emergent properties						
Geometric	●		●			Organic
Simple						Complex
Spatial Relations						
Deals with variety of positions/angles	●					Does not deal
Easily generated				●		Not easy to generate
Graphically represent a spatial arrangement/bounded area	●					Does not represent

no context for this ?

?

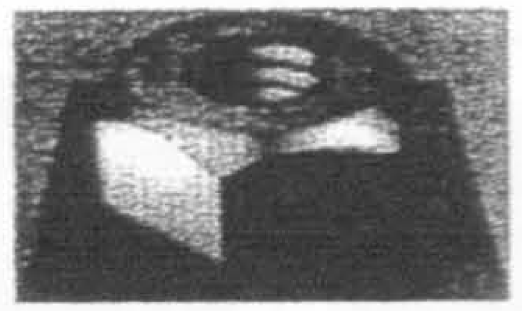
Please assess the figure in accordance with the adjective pairs given below, using a scale of one to five. Please put a tick mark in the appropriate box



	1	2	3	4	5	
Acceptability of presentation						
Creative			●			Non creative
Differentiate essential and non essential information			●			Not differentiable
Imaginative/exploring ideas					●	Non imaginative
Immediately understandable	●					Not understandable
Interesting/lively	●					Not interesting
Stimulating to changes /modification					●	Non stimulating to changes
Stimulating to discussion /communication	●					Non stimulating to discussion
Stimulating to look at	●					Non stimulating to look
Unambiguous	●					Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)					●	Exact /Precise information
Conveys emotions			●			Does not convey
Level of details (Less)					●	Level of details (High)
Pleasant		●				Annoying
Realistic	●					Unrealistic
Recognisable	●					Unrecognisable
Reflects uncertainty					●	Does not reflect
Rough/sketchy					●	Detailed/clear
Emergent properties						
Geometric	●					Organic
Simple			●			Complex
Spatial Relations						
Deals with variety of positions/angles	●					Does not deal
Easily generated					●	Not easy to generate
Graphically represent a spatial arrangement/bounded area	●					Does not represent

30/35 mins to get this far

Please assess the figure in accordance with the adjective pairs given below, using a scale of one to five. Please put a tick mark in the appropriate box



	1	2	3	4	5	
Acceptability of presentation						
Creative			•			Non creative
Differentiate essential and non essential information				•		Not differentiable
Imaginative/exploring ideas					•	Non imaginative
Immediately understandable	•					Not understandable
Interesting/lively		•				Not interesting
Stimulating to changes /modification					•	Non stimulating to changes
Stimulating to discussion /communication	•					Non stimulating to discussion
Stimulating to look at		•				Non stimulating to look
Unambiguous	•					Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)				•		Exact /Precise information
Conveys emotions		•				Does not convey
Level of details (Less)				•		Level of details (High)
Pleasant		•				Annoying
Realistic	•					Unrealistic
Recognisable	•					Unrecognisable
Reflects uncertainty					•	Does not reflect
Rough/sketchy				•		Detailed/clear
Emergent properties						
Geometric	•					Organic
Simple			•			Complex
Spatial Relations						
Deals with variety of positions/angles	•					Does not deal
Easily generated					•	Not easy to generate
Graphically represent a spatial arrangement/bounded area	•					Does not represent

← interesting; just noticed: it's I've assumed nut; a normal nut; but that's not actually a thread ... maybe another question here: does it invite assumptions? ... use of "symbolic" representation? (it's not actually how a thread looks, but we understand/assume that's what it's meant to be)

* applies to all, but I haven't gone back and changed my earlier choices

Please assess the figure in accordance with the adjective pairs given below, using a scale of one to five. Please put a tick mark in the appropriate box

2 1 ∅ -1 -2

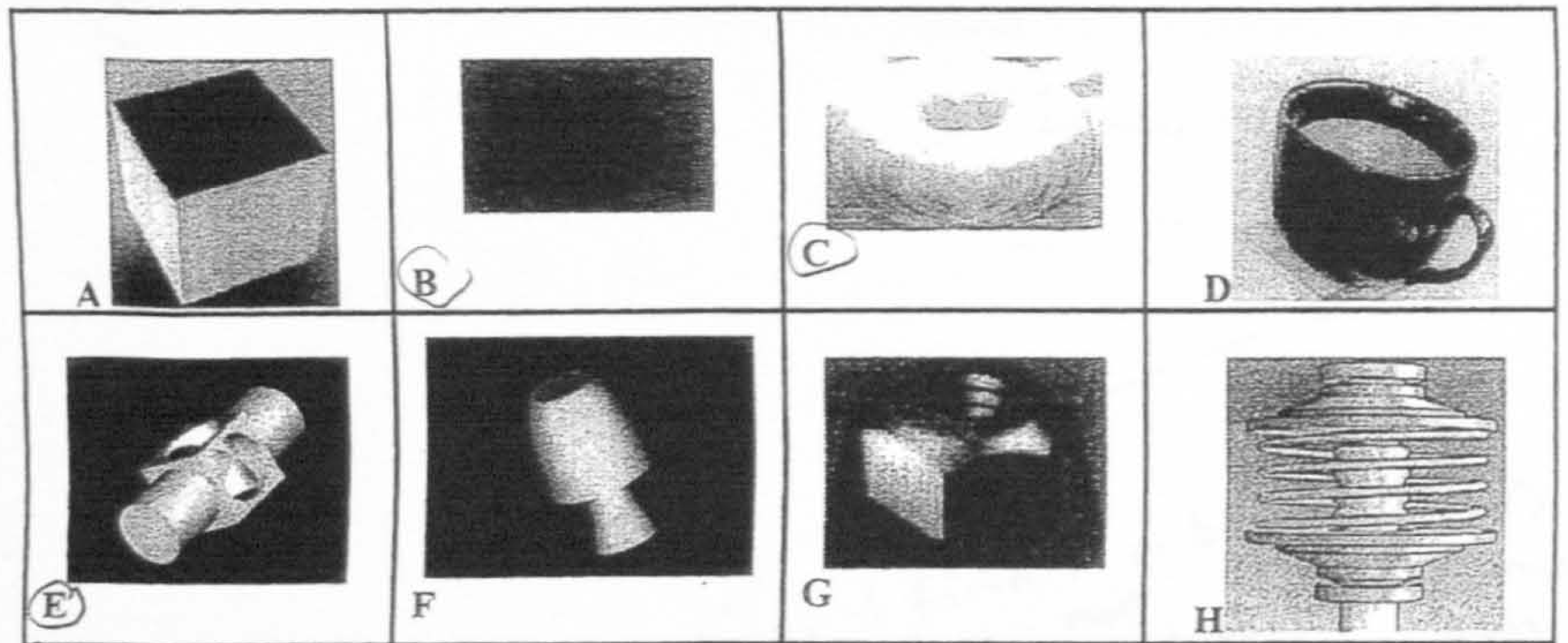
	1	2	3	4	5	
Acceptability of presentation						
Creative			•			Non creative
Differentiate essential and non essential information			•			Not differentiable
Imaginative/exploring ideas		•				Non imaginative
Immediately understandable			•			Not understandable at all
Interesting/lively		•				Not interesting
Stimulating to changes /modification	•					Non stimulating to changes
Stimulating to discussion /communication	•					Non stimulating to discussion
Stimulating to look at		•				Non stimulating to look
Unambiguous				•		Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)	•					Exact /Precise information
Conveys emotions			•			Does not convey
Level of details (Less)			•			Level of details (High)
Pleasant			•			Annoying
Realistic		•				Unrealistic
Recognisable			•			Unrecognisable
Reflects uncertainty	•					~~Does not~~ reflect uncertainty?
Rough/sketchy		•				Detailed/clear
Emergent properties						
Geometric		•				Organic
Simple			•			Complex
Spatial Relations						
Deals with variety of positions/angles						Does not deal
Easily generated		•				Not easy to generate
Graphically represent a spatial arrangement/bounded area	•					Does not represent

← diff scale

+5 …. ∅

as against +5 …. ∅ ….

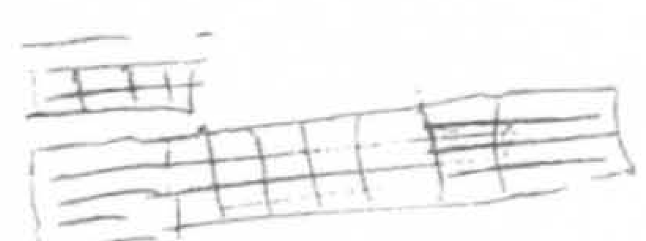
Please assess each picture in accordance with the adjective pairs given below, using a scale of one to five. (Put the figure number in the appropriate box)



	1	2	3	4	5	
Example ~~appearance~~	E. G	A	D	B	F.C.H	
~~Acceptability of~~ presentation						
Creative		BC	AD			Non creative
Differentiate essential and non essential information	A	CD	B			Not differentiable
Imaginative/exploring ideas	C	B		D	A	Non imaginative
Immediately understandable	ACD		B			Not understandable
Interesting/lively	C	ABD				Not interesting
Stimulating to changes /modification			C	BD	A	Non stimulating to changes
Stimulating to discussion /communication		BD	C	A		Non stimulating to discussion
Stimulating to look at		BD	A			Non stimulating to look
Unambiguous	ACD	B				Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)				C	ABD	Exact /Precise information
Conveys emotions		C	ABD			Does not convey
Level of details (Less)				ABCD		Level of details (High)
Pleasant		ABCD				Annoying
Realistic	AD	BC				Unrealistic
Recognisable	AD	BC				Unrecognisable
Reflects uncertainty				B	ACD	Does not reflect
Rough/sketchy				B	ACD	Detailed/clear
~~Emergent~~ properties						
Geometric	A	D	BC			Organic/natural
Simple	A		CD	B		Complex
~~Spatial Relations~~						
Deals with variety of positions/angles	BD		AC			Does not deal
Easily generated				A	BCD	Not easy to generate
Graphically represent a spatial arrangement/bounded area	ACD	B				Does not represent

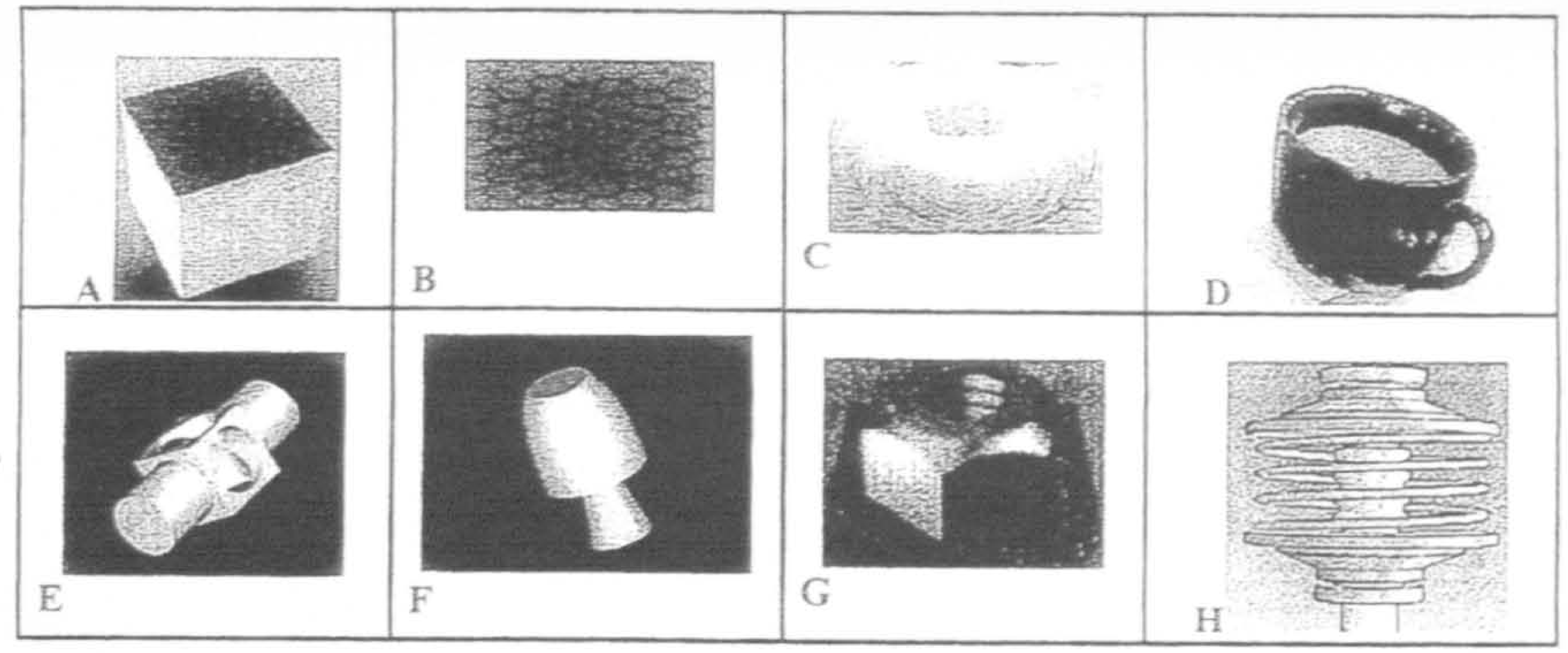
how do we mean by ? creative

↑ need a lot more width in the columns ! — stretch over full page?



P

Please assess each picture in accordance with the adjective pairs given below, using a scale of one to five. (Put the figure number in the appropriate box)



	1	2	3	4	5	
Example	*E. G*	*A*	*D*	*B*	*F.C.H*	
Acceptability of presentation						
Creative		EFH	G			Non creative
Differentiate essential and non essential information	E		GH	F		Not differentiable
Imaginative/exploring ideas		EH		F	G	Non imaginative
Immediately understandable	G	FH		E		Not understandable
Interesting/lively	GH	EF				Not interesting
Stimulating to changes /modification		FH		E	G	Non stimulating to changes
Stimulating to discussion /communication	E	FGH				Non stimulating to discussion
Stimulating to look at	E	FGH				Non stimulating to look
Unambiguous		FGH		E		Ambiguous
Display of information						
Approximation of Information (*e.g. size, shape, orientation, location….*)			H	FG	E	Exact /Precise information
Conveys emotions		H	EFG			Does not convey
Level of details (Less)			F	GH	E	Level of details (High)
Pleasant		EGH	F			Annoying
Realistic	EF	GH				Unrealistic
Recognisable	G	EFH				Unrecognisable
Reflects uncertainty				FH	EG	Does not reflect
Rough/sketchy				FGH	E	Detailed/clear
Emergent properties						
Geometric	EG	FH				Organic
Simple		F	G	EH		Complex
Spatial Relations						
? → Deals with variety of positions/angles	EFGH					Does not deal
Easily generated					EFGH	Not easy to generate
Graphically represent a spatial arrangement/bounded area	EFGH					Does not represent

- so, I find it a bit ambiguous, not quite understandable - but that's not a function of the non/photorealistic representation, it's too small just that it's the rep to see what the rep actually looks like!

this is too small for - can't tell what's going on, and don't know if that's just because it's too small or if there's something wrong with the "model"

(B + C also could be bigger)

mm, "creative" again ... finding myself thinking in what way might it be creative - interesting/ stimulating/pleasant, exploring ideas, etc. ... all of that adding up to "yes, it's quite creative" ....

?

Appendix C: Study on the emotive effectiveness of different rendering styles

Annex-1: An example of a questionnaire for emotive effectiveness of different rendering styles

Annex-1: Questionnaire

11 November 2004

Dear student

Computer Rendering - Questionnaire

The enclosed questionnaire is part of research at the CAD Centre, Department of Design Manufacture and Engineering Management, University of Strathclyde. Our current investigations are directed towards support of real time co-operation between humans and computers. For this it is necessary to make use of different principles of communication and control, such as different rendering approaches to support geometric modelling. Rendering is an image processing technique that combines the geometrical precision of computer graphics with the representational freedom of painting. Rendering techniques enable the visualization and manipulation of final products that was not previously possible using traditional techniques. It involves such things as shading, hidden line and surface removal, textures, colour, light, animations and other realistic features. There are currently many tools used in rendering however there is insufficient support for sketching, vagueness, fuzziness and uncertainty.

The purpose of the questionnaire is to measure designer's responses to graphical images that were rendered using different methods and use the results to identify the appropriate methods for best visualisation. Each answer you provide contributes to our work. You may be assured that the confidentiality of your response will be maintained.

I would be very happy to answer any questions you may have and could be contacted on 0141 548 3056 or by email.

Thank you for your assistance

Raji Tenneti

Ms Raji Tenneti
CAD Centre
DMEM Department
James Weir Building
University of Strathclyde
75 Montrose Street
Glasgow, G1 1XJ

Tel: +(44) 141 548 3056
Email: raji@cad.strath.ac.uk

Guide to completing the questionnaire:

The questionnaire contains closed type questions and rating scales where you are required to put a mark or letter in the appropriate box as shown.

e.g.

M [√]
F [ ]

	+2	+1	0	-1	-2	
Real	*A*	*C*		*B, D*		*Artificial*

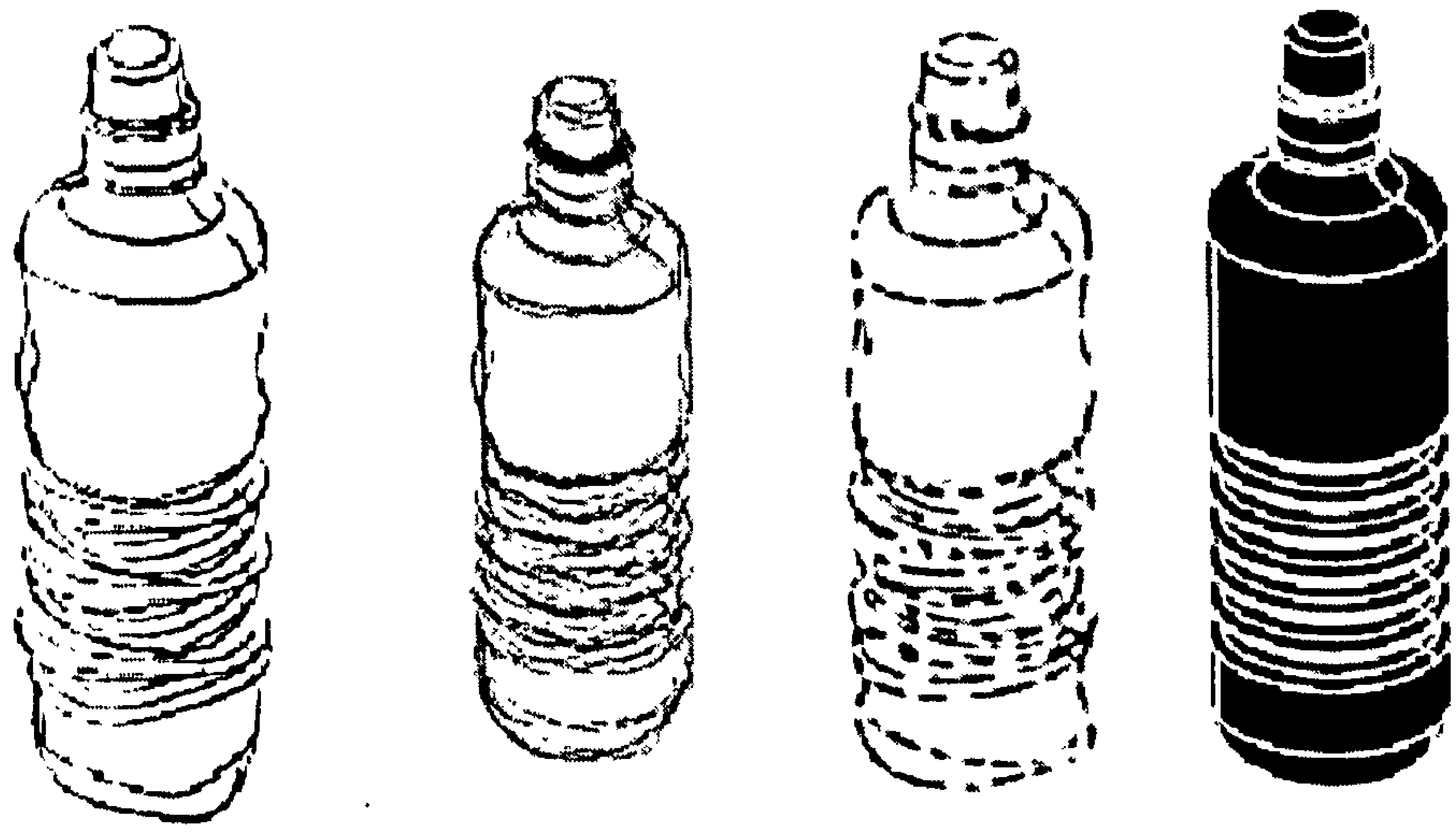
It should not take more than 20 minutes to answer the questions.

Name:	
Gender:	M [ ] F [ ]
Course:	CAED [ ] ED [ ] PDE [ ] PDI [ ] Any Other [ ]
Background/Discipline: (*E.g. mechanical, production or any other*)	[ ]
Level of experience in design drawings:	Highly experienced (over 5 years of experience) [ ] Some experience (two to five years experience) [ ] Little experience (less than 2 years experience) [ ] No experience (never used before) [ ]

1.If you were presented with pictures A, B C and D given below, what information as following would you perceive from them? Please assess each picture (from A to D) with the adjective pairs given below, using a scale of –2 to +2. (Put each figure in the appropriate box)

e.g.

	+2	+1	0	-1	-2	
Real	*A*	*C*		*B, D*		*Artificial*



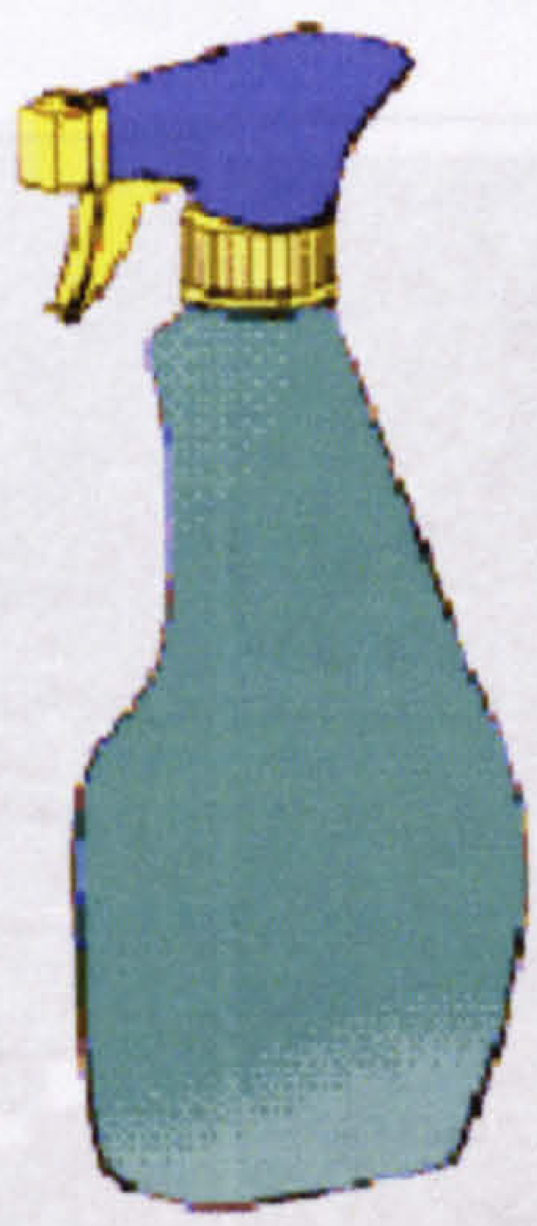
Picture A Picture B Picture C Picture D

	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternate solutions						Non-exploration
Invites assumptions						Not understandable
Approximation of Information (*e.g. size, shape, orientation,*						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes						Non stimulating to changes
Stimulating to discussion						Non stimulating to
Stimulating to look at						Non stimulating to look

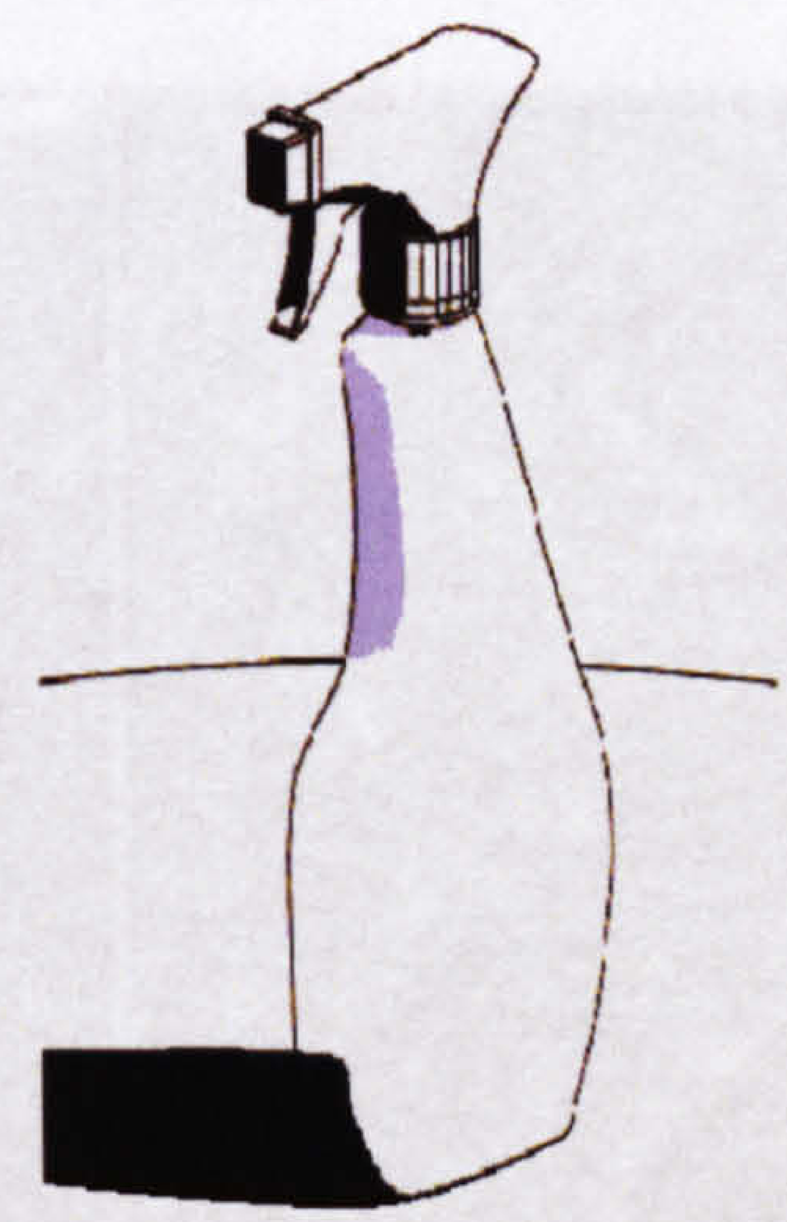
2.If you were presented with pictures A, B C and D given below, what information as following would you perceive from them? Please assess each picture (from A to D) with the adjective pairs given below, using a scale of –2 to +2. (Put each figure in the appropriate box)

e.g.

	+2	+1	0	-1	-2	
Real	*A*	*C*		*B,D*		*Artificial*



Picture A



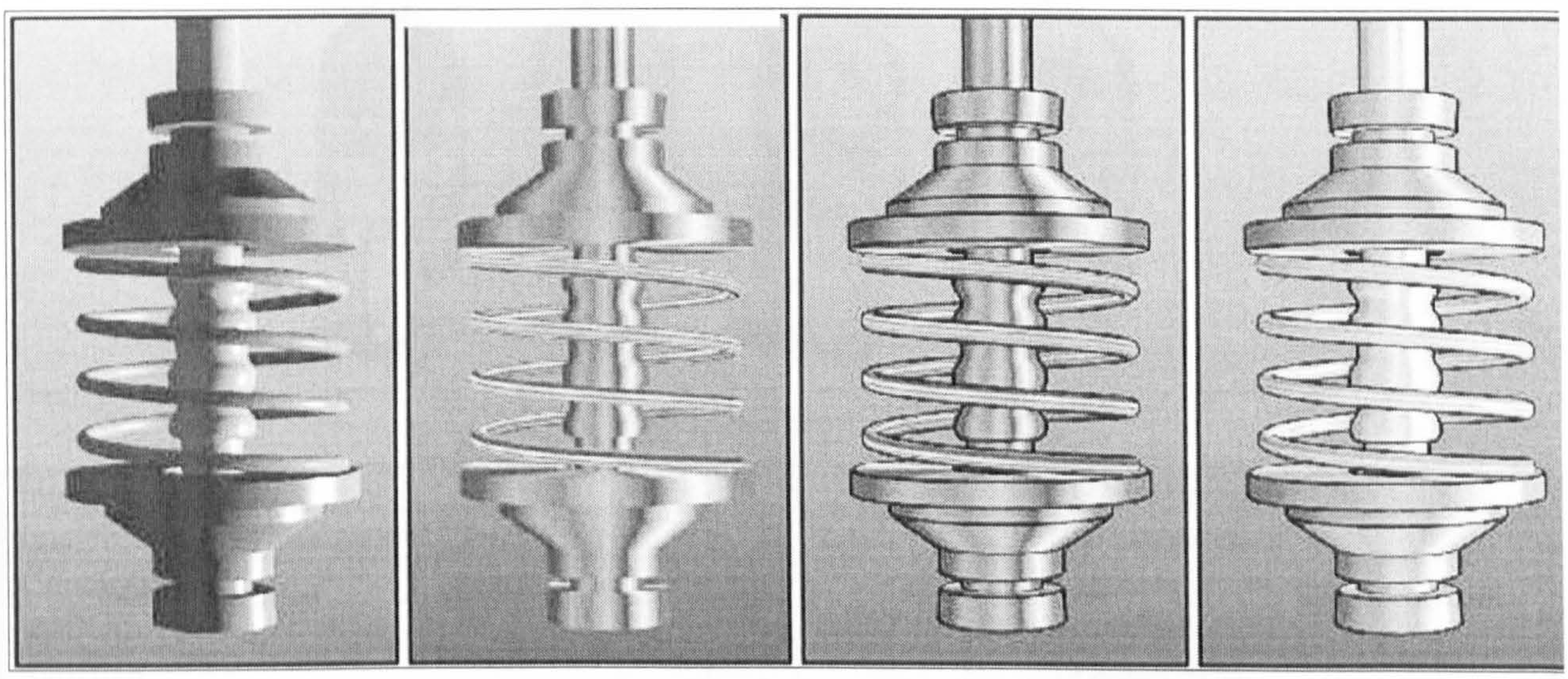
Picture B

	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternate solutions						Non-exploration
Invites assumptions						Not understandable
Approximation of Information (*e.g. size, shape, orientation, location….*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes						Non stimulating to changes
Stimulating to discussion						Non stimulating to
Stimulating to look at						Non stimulating to look

3.If you were presented with pictures A, B C and D given below, what information as following would you perceive from them? Please assess each picture (from A to D) with the adjective pairs given below, using a scale of –2 to +2. (Put each figure in the appropriate box)

e.g.

	+2	+1	0	-1	-2	
Real	*A*	*C*		*B, D*		*Artificial*



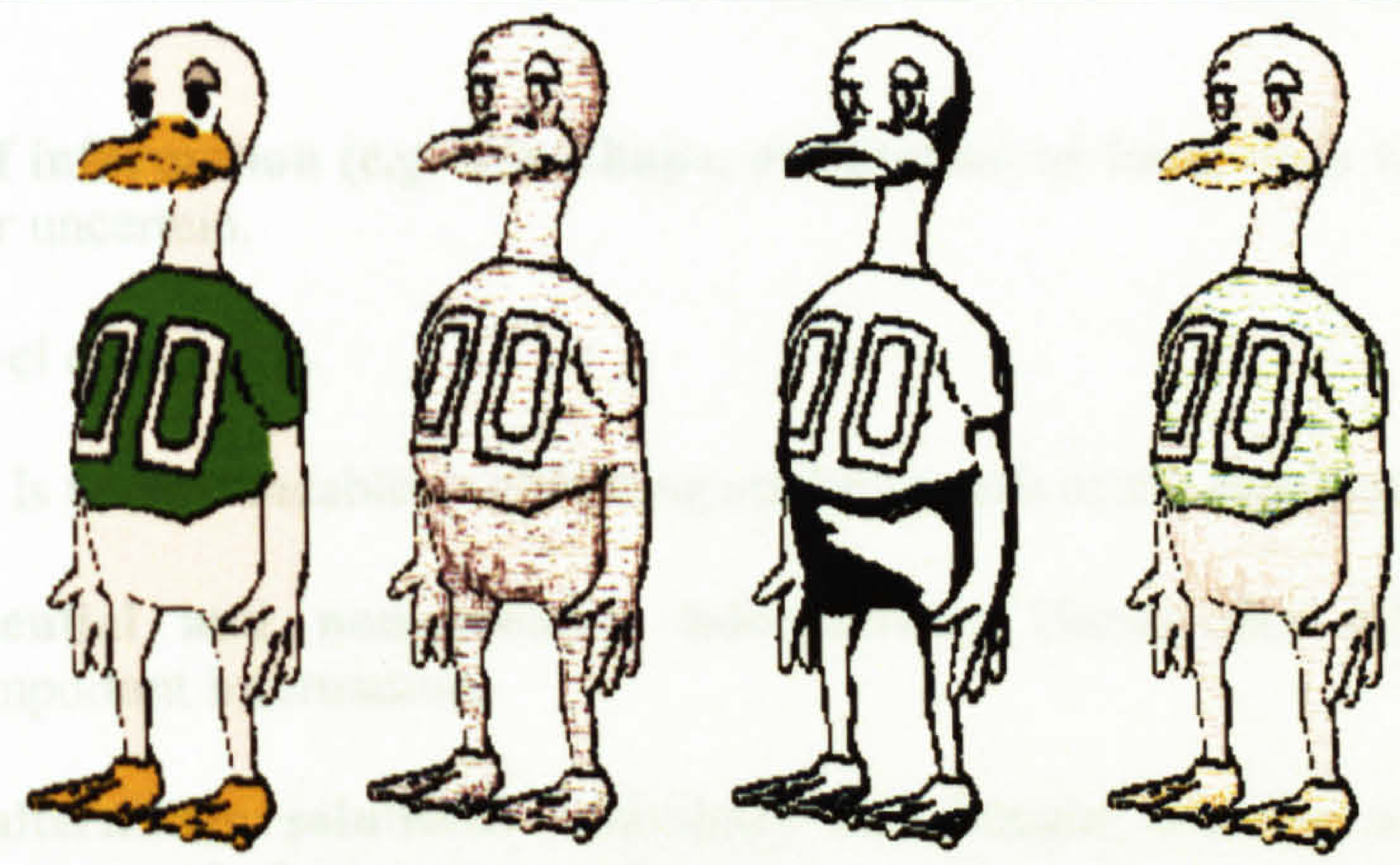
Picture A Picture B Picture C Picture D

	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternate solutions						Non-exploration
Invites assumptions						Not understandable
Approximation of Information (*e.g. size, shape, orientation, location….*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes						Non stimulating to changes
Stimulating to discussion						Non stimulating to
Stimulating to look at						Non stimulating to look

4. If you were presented with pictures A, B C and D given below, what information as following would you perceive from them? Please assess each picture (from A to D) with the adjective pairs given below, using a scale of –2 to +2. (Put each figure in the appropriate box)

e.g.

	+2	+1	0	-1	-2	
Real	*A*	*C*		*B,D*		*Artificial*



A B C D

	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternate solutions						Non-exploration
Invites assumptions						Not understandable
Approximation of Information (*e.g. size, shape, orientation, location....*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion						Non stimulating to
Stimulating to look at						Non stimulating to look

We appreciate your help so far with this questionnaire. Finally we would like any feedback or thought that may be relevant and aid us in our study.

Use the space below to supply your answer

- **Thank you for your assistance**

Annex-2: An example of a definition list

The following definitions address the interpretation or response the presentation style gives you as a viewer.

Approximation of information (e.g. size, shape, orientation or location.): Information that is fuzzy, imprecise or uncertain.

Comfortable: Level of emotion.

Comprehensible: Is understandable as reflecting all the aspects of the graphical object.

Differentiate essential and non-essential information: Gauge the difference between important and unimportant information.

Exploration of alternative solutions: Stimulates the thought that the solution can have alternative solutions or needs further development.

Invites assumptions: Assume the actual form with the presentation style.

Interesting/Inspiring: Is attention grabbing.

Imaginative/ Exploring ideas: Stimulates you to think about new ideas.

Real: How well does the presentation style reflect physical reality?

Recognisable: The graphical object can be identified.

Satisfied: Feeling content/pleased.

Stimulating to changes /modification: Whether the presentation is accessible to make any variations.

Stimulating to discussion /communication: Whether the style of presentation is inspiring to communicate design ideas with your colleague or design clients.

Stimulating to look at: Whether the presentation style provides a 'feel good' factor or is thought provoking.

Appendix D: Industrial study

ANNEX-1: An example of mailing letter and questionnaire

Raji Tenneti

From: Raji Tenneti [raji@cad.strath.ac.uk]
Sent: 17 October 2005 13:02
To: tim@4cdesign.co.uk
Bcc: Rachel@scottoiler.com; Rory@scottoiler.com; Mike@srs.rumic.co.uk; john@srs.rumic.co.uk; graeme.leitch@terex.co.uk; pete@4cdesign.co.uk; gedwhyte@yahoo.co.uk
Subject: Questionnaire

Hi

I am a PhD student from University of Strathclyde and my supervisor is Prof. Alex Duffy. My research area is on Rendering and its affect. I am in the final stage of my research where I need external validity for my findings from a previous study on different rendering styles. I need a questionnaire to be filled by designers with architecture/graphics/product design background and have design experience in CAD. The questionnaire consists of different presentation styles and one need to assess how much information each presentation style is portraying based on a scale provided. I provided a definition list at the end of the questionnaire for the terminology used in the questionnaire to assist while filling. It would take 15 minutes to fill the questionnaire

I am attaching the questionnaire with the covering letter and instructions. Could you please fill and mail back the filled questionnaire. Could you please let me know of any other designers who could fill the questionnaire. Your help is very much appreciated and will contribute to my research.

Hoping to hear from you soon.

Kind regards

Raji

Ms R Tenneti
CAD Centre
DMEM Department
University of Strathclyde
75 Montrose Street
Glasgow, G1 1XJ, UK

Phone : +(44) 141 548 3056
Email: raji@cad.strath.ac.uk

University of Strathclyde Glasgow

07 October 2005

Dear Sir/Madam

Computer Rendering - Questionnaire

In most of the design applications during the conceptual stage design, the information used is often incomplete or approximate. To avoid misinterpretation, it is important to convey this incomplete or approximate information via the graphics interface to display a meaningful model of the information the designer is working with. Hence the following questionnaire examines different presentation styles of conveying these approximations graphically.

This questionnaire has been developed to measure designers' responses to several graphical presentation styles used for conveying incomplete or approximate information. The results will be used to improve designers experience with the graphical images.

Each response you provide contributes to our work. You may be assured that the confidentiality of your response will be maintained.

I would be very happy to answer any questions you may have and could be contacted on 0141 548 3056 or by email.

Thank you for your assistance.

Raji Tenneti

Ms Raji Tenneti
CAD Centre (M209)
DMEM Department
James Weir Building
University of Strathclyde
75 Montrose Street
Glasgow, G1 1XJ, UK

Tel: +(44) 141 548 3056
Email: raji@cad.strath.ac.uk

Guide to completing the questionnaire:

This questionnaire contains closed type questions and rating scales ranging from +2 to –2. We are looking for a rough estimate on the given range. You are required to put a mark in the appropriate box.

e.g.

M	√
F	

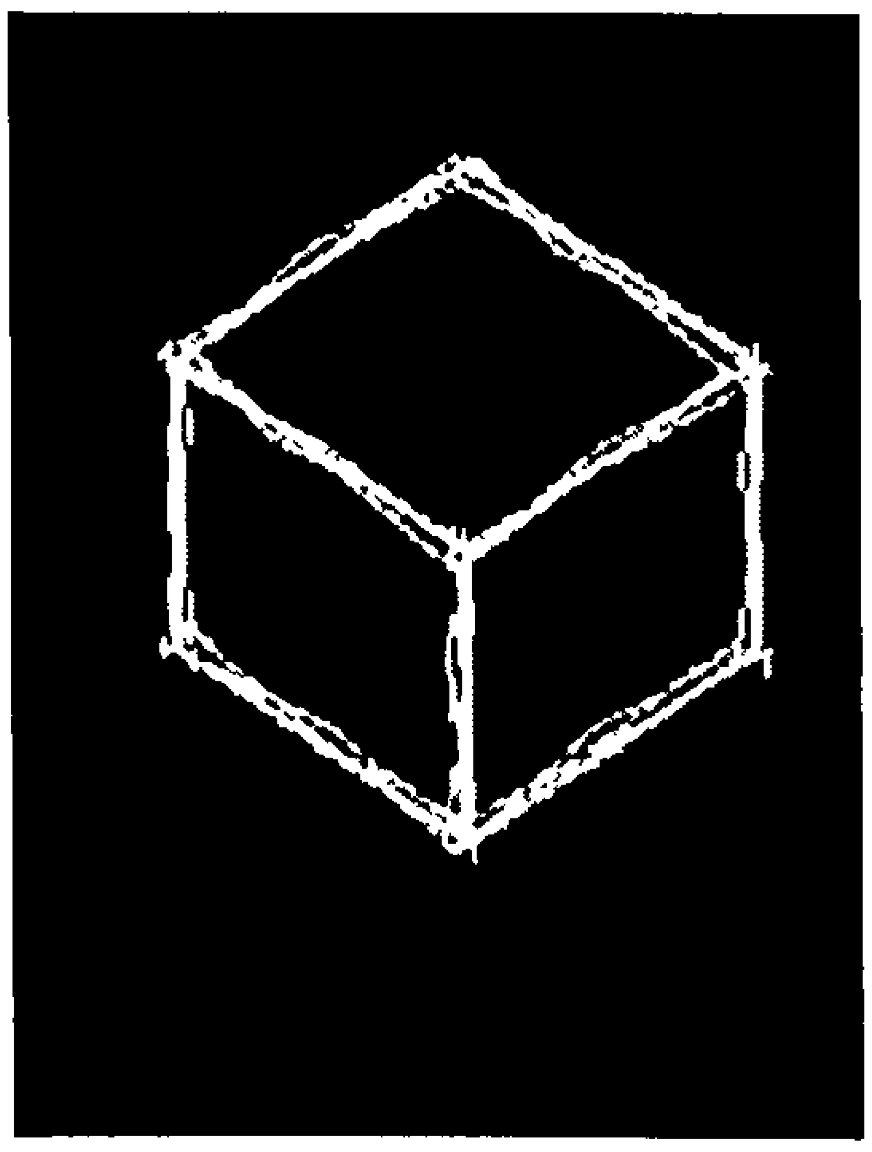
	+2	+1	0	-1	-2	
Real		√				*Artificial*

It should not take more than 20 minutes to answer the questions.

Name:
Email:
Contact Address:
Design background (*e.g. architecture, graphic, product design, or any other):*
Level of experience in design work, predominantly CAD: Highly experienced (over 5 years of experience) ☐ Some experience (two to five years experience) ☐ Little experience (less than 2 years experience) ☐ No experience (never used before) ☐

The following pictures in this section convey different presentation styles for rendering. Please assess each picture, with regard to the interpretation or response the presentation style gives you as a viewer, using the adjective pairs given. The definition for each of the adjectives used is provided at the end of the questionnaire.

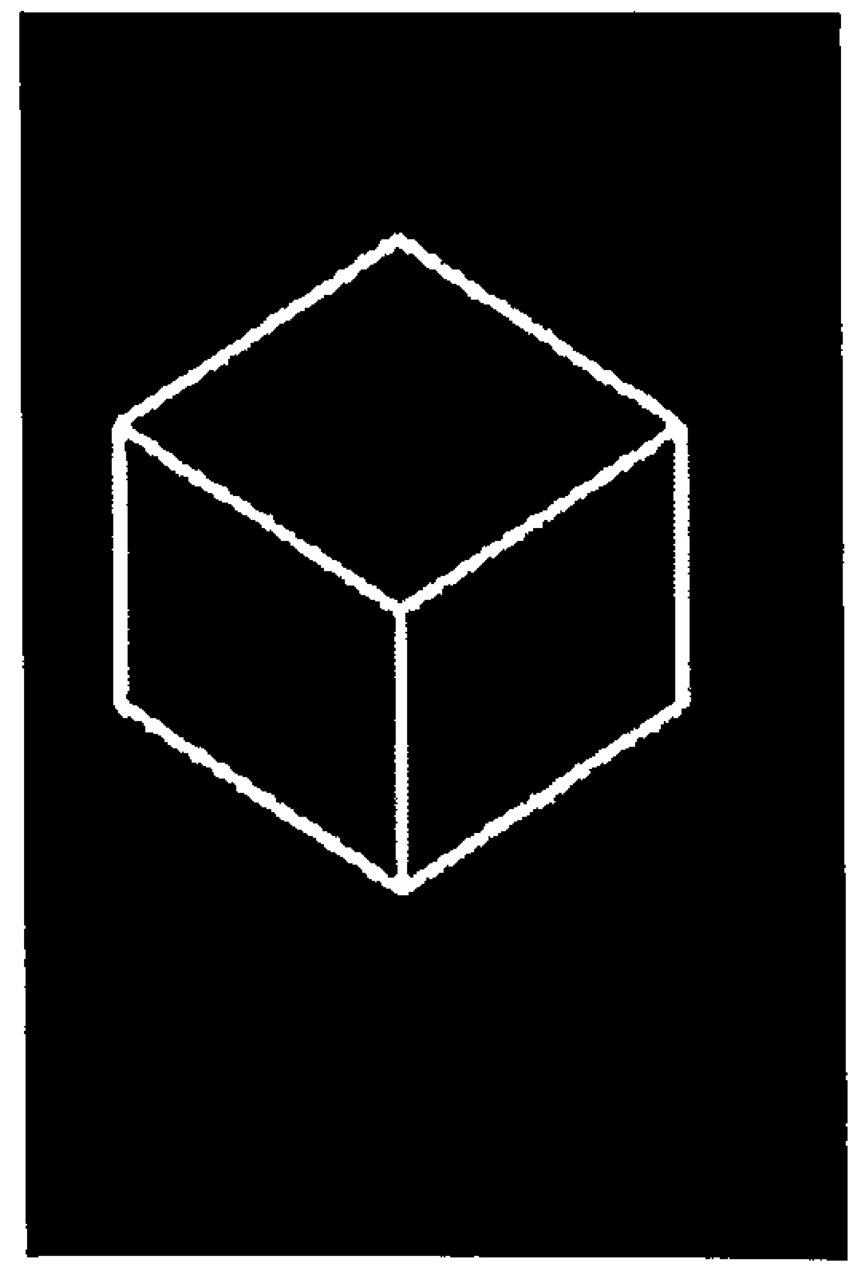
A)



	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternative solutions						Non-exploration
Invites assumptions						Not understandable immediately
Approximation of information (*e.g. size, shape, orientation, location....*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion /communication						Non stimulating to discussion
Stimulating to look at						Non stimulating to look

(Please mark in the appropriate box for all the adjective pairs given).

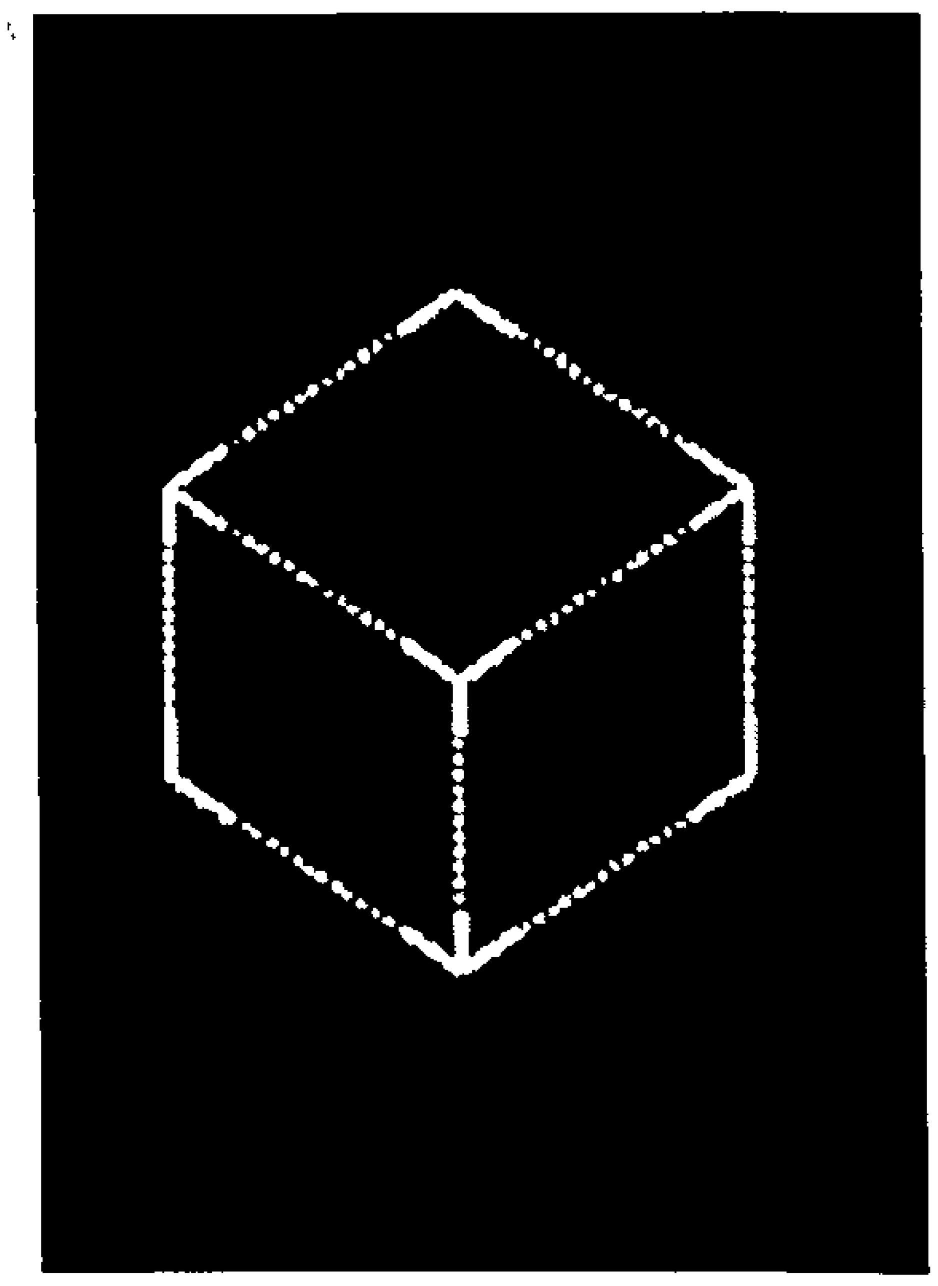
B)



	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternative solutions						Non-exploration
Invites assumptions						Not understandable immediately
Approximation of information (e.g. size, shape, orientation, location....)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion /communication						Non stimulating to discussion
Stimulating to look at						Non stimulating to look

(Please mark in the appropriate box for all the adjective pairs given)

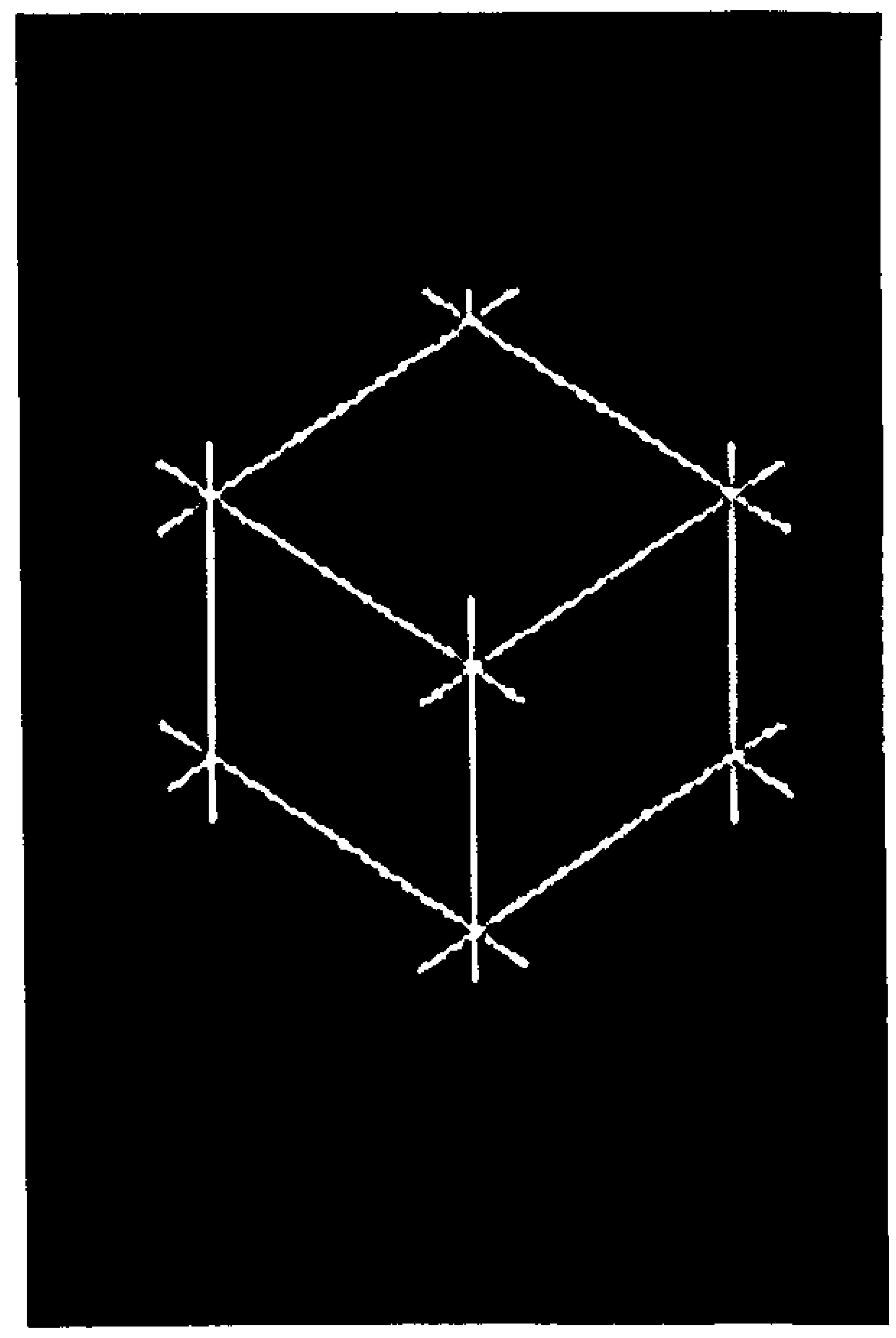
C)



	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternative solutions						Non-exploration
Invites assumptions						Not understandable immediately
Approximation of information (*e.g. size, shape, orientation, location….*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion /communication						Non stimulating to discussion
Stimulating to look at						Non stimulating to look

(*Please mark in the appropriate box for all the adjective pairs given*)

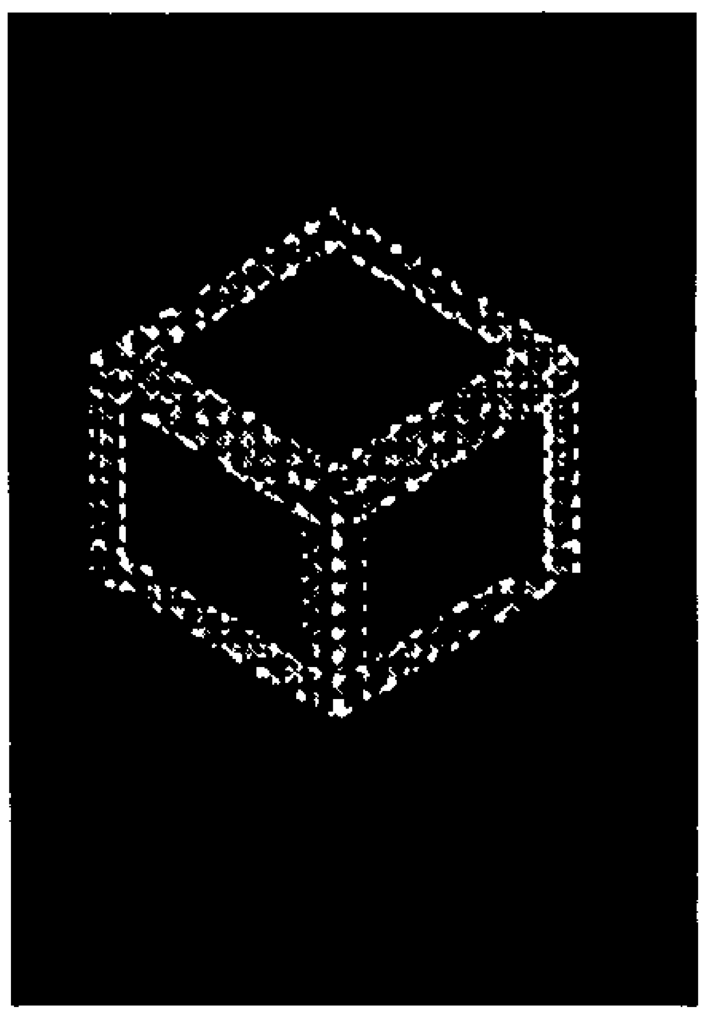
D)



	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternative solutions						Non-exploration
Invites assumptions						Not understandable immediately
Approximation of information (*e.g. size, shape, orientation, location….*)						Exact /Precise information
Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion /communication						Non stimulating to discussion
Stimulating to look at						Non stimulating to look

(Please mark in the appropriate box for all the adjective pairs given)

E)



	+2	+1	0	-1	-2	
Interesting/Inspiring						Uninteresting/Uninspiring
Imaginative/ Exploring ideas						Unimaginative
Comfortable						Uncomfortable
Real						Artificial
Satisfied						Dissatisfied
Differentiate essential and non essential information						Not differentiable
Exploration of alternative solutions						Non-exploration
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Comprehensible						Incomprehensible
Recognisable						Unrecognisable
Stimulating to changes /modification						Non stimulating to changes
Stimulating to discussion /communication						Non stimulating to discussion
Stimulating to look at						Non stimulating to look look at

(*Please mark in the appropriate box for all the adjective pairs given*)

We appreciate your help so far with this questionnaire. Finally we would like any feedback or thoughts that may be relevant and aid us in our study

Use the space below to supply your feedback.

- **Thank you for the assistance**

Definitions for Section-2

The following definitions address the interpretation or response the presentation style gives you as a viewer.

Approximation of information (e.g. size, shape, orientation or location.): Information that is fuzzy, imprecise or uncertain.

Comfortable: Level of emotion.

Comprehensible: Is understandable as reflecting all the aspects of the graphical object.

Differentiate essential and non-essential information: Gauge the difference between important and unimportant information.

Exploration of alternative solutions: Stimulates the thought that the solution can have alternative solutions or needs further development.

Invites assumptions: Assume the actual form with the presentation style.

Interesting/Inspiring: Is attention grabbing.

Imaginative/ Exploring ideas: Stimulates you to think about new ideas.

Real: How well does the presentation style reflect physical reality?

Recognisable: The graphical object can be identified.

Satisfied: Feeling content/pleased.

Stimulating to changes /modification: Whether the presentation is accessible to make any variations.

Stimulating to discussion /communication: Whether the style of presentation is inspiring to communicate design ideas with your colleague or design clients.

Stimulating to look at: Whether the presentation style provides a 'feel good' factor or is thought provoking.

ANNEX-2: An example of reminder letter