

Interactive Visual Artefacts

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Education

1942-1950	Hymers College Hull
1951-1954	Hull College of Technology
1954-1958	Imperial College

Appointments (in reverse sequence)

2007-	Honorary Professor, University of Waikato, New Zealand
2002	Visiting Erskine Fellow, University of Canterbury, New Zealand
2000-	Professor Emeritus and Senior Research Investigator, Imperial College London
1997-1999	Head, Department of Electrical & Electronic Engineering, Imperial College London
1984-2000	Professor of Information Engineering, Department of Electrical & Electronic Engineering, Imperial College London
1985-1990	Founder Director and Chairman, Interactive Solutions Ltd, London
1968-1984	Reader, Department of Electrical Engineering, Imperial College
1986	Visiting Professor, Nanjing Institute of Technology, China
1969	Visiting Professor, University of Ljubljana, Yugoslavia
1962-1968	Lecturer, Department of Electrical Engineering, Imperial College
1961-1962	Lecturer (part-time) University of Rochester, New York, USA
1959-1962	Senior Research Staff Member, General Dynamics/Electronics, Rochester, New York, USA
1958-1959	Research Assistant, Imperial College London

1950-1951 Youth-in-Training, Hull Corporation Telephones, Hull, England

Qualifications, degrees

1954	BSc (Engineering)	University of London
1955	DIC	Diploma of Imperial College
1959	PhD (Engineering)	University of London
1983	DSc (Engineering)	University of London (Higher Doctorate)
1997	DrRCA	Royal College of Art (Higher Doctorate)

Honours, distinctions

1976	FIEEE	(Fellowship of the IEEE)
1989	FCGI	(Fellowship of the City & Guilds of London Institute)
1990	FREng	(Fellowship of the Royal Academy of Engineering)
1995	Officier dans l'Ordre du Palme Academique (Conferred by the President of France)	
1999	Golden Jubilee Award, IEEE Circuits & Systems Society	

Editorships

1975-1982	Editor, IEE Proceedings Part G (Electronic Circuits & Systems): new journal in 1975
1973-1975	Associate Editor, IEEE Transactions on Circuits and Systems
1980-1983	Founding Editor, books on the CAD of Electronic Circuits, Elsevier
2001-	Associate Editor, Information Visualization (new journal in 2002)

Statements

(required under sections 2.7 and 2.8 of the “Regulations for the Award of the Doctor of Science (DSc) Degree”

Conjoint work (relevant to section 2.7 of the regulations)

Following each reference is a brief statement regarding the author's contribution to conjoint work.

Publications considered by the author to be particularly significant (relevant to section 2.8 of the regulations)

- (1) Citation counts (indicated by red numbers within references) provide some indication of the impact of each publication.
- (2) Within the four sections of the statement to be found on the following pages, the publications identified below are regarded as significant:

Information Visualization

Reference [1] provides, with a strong pedagogical focus, an ordered presentation of many of the outcomes of the research addressed by the remaining 29 publications, and places their content in context.

The Human Visual System

The publications [2] to [14] in this section represent a coherent and sustained sequence of pioneering inventions and studies over about twenty years, with no single publication singled out for special attention. It is the collection that is considered particularly significant. If a single publication has to be identified it would be the research monograph [12] that integrates the research and places it into context.

Interaction

Publication [19] is considered to be particularly significant because it addresses, in some depth and with some success, the challenging problem of providing design guidance to an interaction designer having little or no knowledge of the cognitive concepts underlying the potential value of an interactive visual artifact. Crucially, it contains supportive experimental evidence.

Dynamic Exploration

Publications [25] and [26] describing two pioneering interactive exploration tools (The Attribute Explorer and the Prosecution Matrix) are considered to be significant in view of the considerable potential they offer for a user to engage in exploration in order to gain insight into multiparameter relationships.

Interactive Visual Artefacts

1 Information Visualization

1.1 What are Interactive Visual Artefacts? And why do we need them?

The artefacts in question are, fundamentally, things (usually digital) with which human beings interact, usually in a two-way process. A Satnav (Figure 1.1), for example, presents information to a driver, whereupon the driver may touch the screen appropriately and, as a consequence, be presented with new visual information. Another example (Figure 1.2) is an interactive visual display used by forensic investigators to detect the presence of fraud within a bank's million or more daily transactions. By viewing suitable visual representations of those transactions an investigator can navigate interactively through a mass of data and seek patterns that will provide insight.

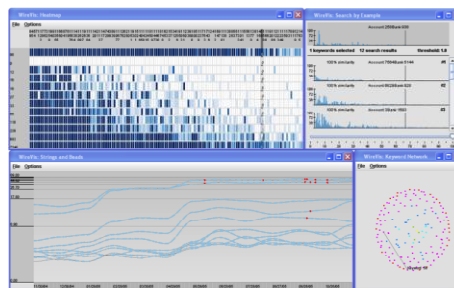


Figure 1.1 The visual display of a satnav permitting interaction by the driver. Figure 1.2 The WireVis interactive visualization system that supports investigations into bank fraud.

1.2 Information Visualization

A framework supporting organized thought about interactive visual artifacts is the so-called Reference Model of Information Visualization (Figure 1.3).

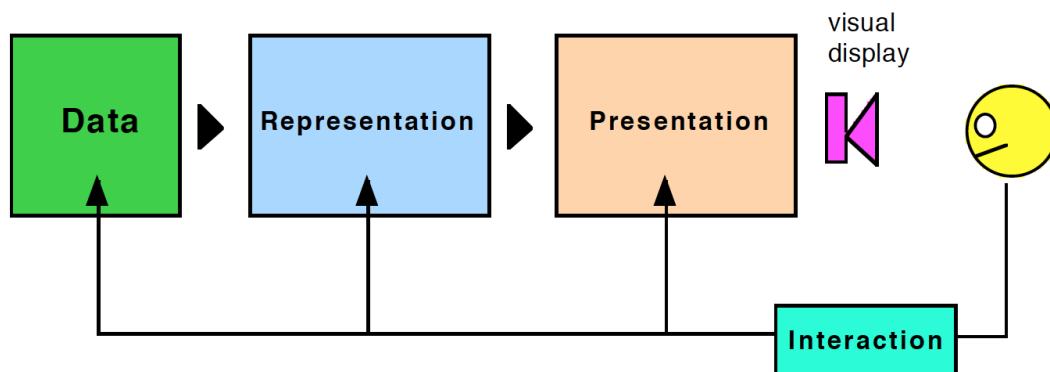


Figure 1.3 The Information Visualization Reference Model

The definition of visualization is:

Visualization: the formation of a mental model of something

which is precisely that activity for which interactive visual artefacts are created. On the left of Figure 1.3 we have data (often vast and numerical) into which insight is desired by the human user shown on the right. To support that user's acquisition of insight, interactively selected parts of the **data** are **represented** visually (e.g., encoded by colour or shape) and then **presented** to (i.e., laid out for) the user who, as insight is gained, may **interactively** reselect appropriate data, its representation and its presentation in order to further enhance that insight.

Information Visualization is a huge field with an immensely wide range of applications and is the subject of extensive research activity world-wide. It is one to which the candidate has contributed in many ways, both by research (see below) and teaching (Spence 2007, 2011, 2014 [1] **1936**).

The research described in this thesis has focused upon three broad subdisciplines of the field of information visualization (Figure 1.4). One concerns a particularly valuable feature of the **human visual system** called pre-attentive processing and the applications that exploit it. The second specifically addresses the topic of **interaction**. The third concerns engineering models relevant especially to **exploratory** interactive design. The candidate's research in those three broad areas are the subject of the three sections that follow though there is, unsurprisingly, some degree of commonality between them.

Section 2	The Human Visual System
Section 3	Interaction
Section 4	Dynamic Exploration

Figure 1.4 The three areas of research within the context of information visualization

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Sole authorship

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2. The Human Visual System

The success of any attempt to gain insight into data is heavily influenced – and sometimes limited by – certain features of the human visual system. One potentially beneficial feature is known as **pre-attentive processing**, (Healey et al, 1996) and underlies much of the candidate's research concerned with the human visual system.

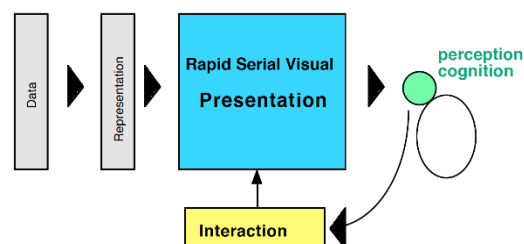
The best introduction to pre-attentive processing can be gained by considering the familiar action of riffling the pages of a book to locate an image of interest (Figure 2.1). Even at a page 'flip' rate of 10 per second, a Mondrian painting will almost certainly be successfully located. This approach to image search also exists in the digital world, as exemplified by the image 'flipping' facility of an iPad app. Unsurprisingly the descriptor **Rapid Serial Visual Presentation** (RSVP) has been applied to this activity.



Figure 2.1 Riffling the pages of an art book to locate a known painting

A complementary determinant of human visual behavior is eye gaze. Almost every image search involves rapid muscular actions that control where a person's gaze is focused, and can significantly affect the success of any search.

Our focus on RSVP can be placed within context of the Information Visualization Reference Model as shown in Figure 2.2).



the

Figure 2.2 Rapid Serial Visual Presentation identified within the context of the Information Visualization Reference Model of Figure 1.3

2.1 Rapid Serial Visual Presentation (RSVP)

What is so special about RSVP? Why does it warrant investigation and why has it led to so many applications? There are three reasons. First, it is useful, as we shall soon see. Second, each image need only be seen for 100 milliseconds or even less to be identifiable (Potter & Levy, 1969). And third, little or no cognitive effort is involved (Potter, 1999). Something that is *useful, fast* and requires little or *no cognitive effort* obviously warrants attention!

As indicated above, the perceptual phenomenon underlying RSVP is a feature of the human visual system called **pre-attentive processing** (Healey et al, 1996), so called because, with an image visible for only 100 milliseconds, there is no time to 'pay attention' to any detail of an image.

Whereas fundamental studies of RSVP were undertaken long ago by cognitive psychologists (e.g., Potter & Levy, 1969), the technology required to support RSVP, and

especially to facilitate its useful application, emerged much later, with significant applications only starting to appear in the late 1990s.

Moving RSVP

The search for one or more images of interest within a collection of images is one of the principal applications of RSVP. However, it was quickly realized that the 'classic' (often called 'slide-show') RSVP – in which each image is visible only for around 100ms (as with the riffled book pages) – could be unduly restrictive. Why? Simply because, following the disappearance of an image after 100 ms, there is no way for a user to confirm that the noted image really was the one that was sought.



Figure 2.3 The Carousel mode of RSVP. When interaction occurs, a stream of images emerges from one side of a folder, performs a roughly circular trajectory and moves back into the folder.

It was clear that some way of retaining each image on a display for a short time (e.g., one or two seconds) would support confirmation. In other words, the 'S' in RSVP might usefully be complemented by a parallel (P) – or simultaneous – presentation of images. A very simple example (Figure 2.3) was termed 'carousel mode RSVP': here, each image first emerges from one side of a folder and performs a roughly circular trajectory before entering the other side of the folder (Spence & de Bruijn, 2002, [5] **21**).

Initial exploration

The research of the candidate was well under way in the late 1990s, and focused largely but not exclusively on the 'space-time trade-off' offered by RSVP. That trade-off holds special significance for small displays – and especially mobiles and tablets – where display area is small but where images can nevertheless usefully appear in sequence – that is, *distributed temporally rather than spatially*. Studies of RSVP by de Bruijn and Spence (2000, [3] **119**) pointed to the fact that, in tasks such as image browsing and search, a user's visual system is a very significant limiting factor. Those studies identified and informed relevant research.

The views expressed in that paper were further elaborated by Spence (2002, [2] **90**), who surveyed a range of RSVP modes. Reference was made to existing experimental studies and especially to the relevance of RSVP to small displays. A major part of the paper identified issues requiring further research, including (1) the appropriate mapping of an RSVP mode to a specific task; (2) the relative benefits of human and automatic control of image presentation; (3) the potential that RSVP offers for the navigation of discrete information spaces (e.g., the Web); (4) the provision of landmarks; (5) the influence of eye-gaze; and (6) relevant cognitive mechanisms. Many of the papers referred to below address one or more of these issues.

Potential and problems of moving images

A major problem for a designer wishing to exploit the potential of RSVP is that there are many ways of presenting a collection of images as a sequence of moving images. Indeed it is easy to invent a 'mode' that retains each image for a second or two, so invention itself presents no problem. But there is no immediate way of knowing how effective or acceptable a particular mode would be. For early innovators, there was a realization that a moving image raises the likelihood of a complex sequence of eye-gaze movements (Figure 2.4), leading to many questions: where does the user tend to look?; their gaze always follow the moving images?; does the phenomenon of saccadic blindness (Erdmann & Dodge, 1898) favour some presentation modes over others? These and fundamental questions triggered many lines of research, all of which are addressed in the works that follow.

In an exploratory experimental study, de Bruijn and Spence (2002, [7] **17**) selected and implemented four very different but representative RSVP modes that reflect available design decisions. For each RSVP mode subjects were asked to respond to the appearance, in a presented image collection, of a pre-viewed target image. The eye movements of the participants were recorded. At the same time the investigators proposed a novel graphical characterization of RSVP modes. The value of eye-tracking to an investigation – and later design – of RSVP modes was firmly established by interpretations of the experimental results, particularly those relating image trajectories to eye-gaze behavior.

Static or Moving modes?

The initial exploratory studies described above prompted a more intensive and formal experimental study of gaze behaviour and user acceptance. Thus, Spence et al (2004, [8] **16**) selected and implemented three RSVP modes: 'slide-show', a 'static mode' and a 'mixed mode', all employing a fixed total presentation time and display area in order to reflect the fixed resources available to an interaction designer and permit a comparison of modes. Subjects were required to indicate the presence or absence of a pre-viewed target image within a collection. The outcome identified error profiles and subject preferences, and showed how eye gaze dispersion was affected by the RSVP mode. Statistically significant relations were discovered concerning the pace of image appearance and error levels.

Following on from the above work, Cooper et al (2006, [9] **28**) carried out carefully designed experiments using a number of participants and established for the chosen RSVP modes that (1) static modes are more successful with regard to identification success than moving modes; (b) static modes are far more preferred than moving ones; (c) target identification success generally increases with increase in presentation time per image; (d) for mixed and tile modes, identification success is relatively insensitive to

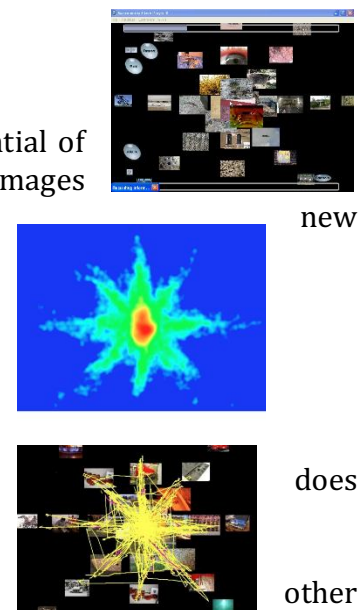


Figure 2.4 (top) Volcano RSVP in which images emerge at the centre, then move away along 8 trajectories (middle) eye-gaze ('fixation') density

image presentation time; and (e) success rate decreases with increase in task complexity except, notably, for slide-show and mixed modes. Evidence from eye-gaze records suggested that the eye-gaze strategy adopted by a subject exerts a very strong influence on both identification success and mode preference. Tentative conclusions were drawn about guidance that can be offered to an interaction designer.

A later experimental investigation (Brinded et al, 2011 [10] 7) investigated the flexibility and image identification success associated with overlapping images that may be used to provide perspective cues and suggest movement of images in '3D space'. Results identified a statistically significant effect of both overlap and image speed on the percentage of correctly identified images, and led to suggestions concerning interaction design for RSVP.

Eventually, focus on the implication of eye-gaze behaviour was strongly justified by the empirical experimental results of Corsato et al (2008) which suggested a strong relation between total eye-gaze travel, the success of target identification and the fatigue experienced by users.

Applications of RSVP

Concurrently with experimental investigations, and encouraged by the early exploitation of RSVP (e.g., by Wittenburg et al, 2003) many applications of RSVP were proposed and experimentally evaluated and, in turn, often found to point towards worthwhile experimental studies.

Mobile access to news

A detailed study by de Bruijn et al (2002 [6] 90) of the space-time trade-off made possible by RSVP led to a novel technique for presenting, to a user, a sequence of images (perhaps the image+text headers of items on a news website) (Figure 2.5). An RSVP browser was compared with a typical (non-RSVP) browser (a simulated Nokia 6210 on a regular display screen) in an experiment involving 30 participants randomly assigned to one of the two browsers. No participant had any prior experience of the browser they were required to use.



Figure 2.5 Appearance of the RSVP browser

The tasks required of the participants involved answering 8 questions. The experiment was specifically designed so that, while answering question 1 as well as 7 and 8, no help or instructions were provided by the experimenter. Browsing efficiency was measured by two variables (1) the time needed to find the answers, and (2) the number of extra steps taken to reach the answers relative to the minimum required.

Unsurprisingly, participants using the RSVP browser for the first time, and attempting to answer question 1 without assistance, took significantly longer to answer that question and used many more than the minimum number of steps. However, there was *essentially no difference in performance* – either time or steps needed to answer questions 7 and 8 – between the two browsers. The principal conclusion was that, once a user has discovered the RSVP function, they are able to browse the web just as efficiently as with a conventional browser, hopefully addressing any skepticism regarding the use of RSVP.

Serendipity

One – often unappreciated - source of the images associated with RSVP is the stream of retinal images arising from normal - and often apparently casual - gaze behaviour. The image on a person's retina typically changes about four times a second, often not with any articulated target in mind. Nevertheless, those images are processed and compared with *latent* goals, of which the normal human being has a huge number. An image associated with a latent goal (e.g., a picture of a chess piece for a user interested in chess) will almost certainly trigger conscious awareness of that image, an awareness that might well be followed up by some action on the part of the user. Such a **serendipitous** action forms the basis of opportunistic browsing, defined as:

Opportunistic browsing: the continuous but largely unconscious monitoring and filtering of information with the potential to trigger more purposeful behaviour.

Serendipity is often beneficial, and interfaces can be designed to exploit this fact. de Bruijn & Spence (2001 [4] 40) placed such opportunistic browsing in the context of Potter's (1999) model called Conceptual Short Term Memory – CSTM - that is relevant to such a process and which Potter suggests involves no conscious cognitive effort. Potter's model is shown in Figure 2.6. Briefly, a perceived image is held in sensory storage for a very short time and then categorized (e.g., as 'a wiggly line' or 'a cat in front of a house') by reference to knowledge stored in Long Term Memory (LTM). Its meaning or relevance to a latent goal is then established. If there is no relevance the image is forgotten: otherwise the user becomes consciously aware of relevance and the image is remembered. Until that occurs, the user is not consciously aware of the CSTM process.

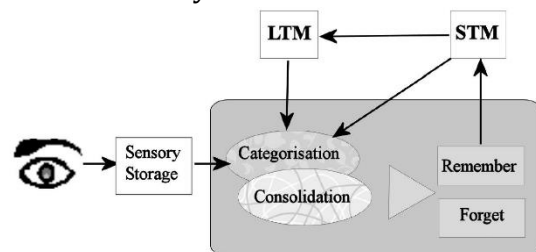


Figure 2.6 The Conceptual short-term memory (CSTM) model proposed by Potter (1999)

Opportunistic browsing can also be characterized as **ubiquitous** because it is a process of information filtering that occurs all the time and everywhere (e.g., while talking to friends or driving to work), and is consistent with the dictionary definition "being or seeming to be everywhere at the same time". The filtering of information is accounted for by the CSTM model since it takes account of immediately (i.e., within ~100ms) forgotten images.

It was identified that one of the most exciting opportunities created by ubiquitous computing is the possibility of enhancing serendipitous information capture by increasing the amount of information that is presented to a user. Existing techniques include, for example, familiar scrolling news bars (e.g., Times Square). One example arising from research by de Bruijn and Spence as well as others was a coffee table (Figure 2.7) in which small, slowly moving and largely unobtrusive icons representing local cultural activities moved around the periphery of a coffee table and could be touched to indicate interest, whereupon more detail appears: that detail can immediately be ignored or easily moved, with a simple stroke, to a token associated with a user's computer (Stathis et al, 2006 [14] 3). The intention was that the process did not cause socially undesirable disruption of ongoing activities such as conversation. The research context anticipated later extensive interest in ambient intelligence.



Figure 2.7 A coffee table designed to support serendipity within an urban (e.g., village) context. Small icons related to local events move unobtrusively around the periphery of the table and support interactive viewing without disruption of ongoing activities.

2.2 Design guidance

The above research (by Spence et al, 2004; Cooper et al, 2006; Brinded et al, 2011 and many others) established – and in some cases quantified - the importance of certain features of RSVP: (1) the rate (pace) at which images appear, (2) the speed at which images move after their appearance, (3) image size, (4) image overlap, and (5) eye-gaze behaviour. Over the next five years these issues were investigated and the outcomes brought together in a design-oriented paper (Witkowski & Spence, 2012 [11] 5) targeted at interaction designers considering the relevance of RSVP to their design commission. A companion research monograph (Spence & Witkowski, 2013 [12] 17) contains novel results in the following areas:

- A new notation for RSVP modes
- Gaze representation
- Limiting speeds of image movement

and offered answers to 5 major questions:

- What is the most effective visual style (mode) for RSVP?
- How quickly can a collection of images be viewed?
- How large should the images be?
- Should the presentation rate be fixed or under user control?
- How many images should simultaneously be visible on a display?

2.3 An unexpected discovery

Around 2008 the candidate made a suggestion that, at the time, may well have appeared ridiculous. The context was Wilderness Search and Rescue in which a drone with a downward pointing video camera flies over a region where a lost human being might be located. The interesting question is “What is the best way to present the output of that camera to an investigator (‘spotter’)?”

One approach is to allow the investigator to visually inspect, say for 3.9 seconds, a static view of part of the overflowed terrain Figure 2.8 (top). However, bearing in mind Potter et al’s experiment identifying a user’s ability to detect a target image within a collection presented as fast as 10 per second, Spence suggested that it would be interesting to explore an alternative (Figure 2.8 bottom)) approach to search and rescue in which the investigator sees, within the same 3.9 seconds, a *sequence* of 36 small segments together covering the same terrain area, necessarily each presented for 108 milliseconds if the investigator is to ‘keep up’ with the drone.



Figure 2.8 (top) A search and rescue ‘spotter’ is presented with a sequence of ground images (see left box) every 3.9 seconds. Alternatively (bottom), in the same period, the spotter sees a fast sequence of smaller segments (see lower left box), each for 108 milliseconds. The right column shows part of the overflowed territory and the portion selected for viewing.

The value of such an exploration could have been questioned: after all, whereas Potter’s experiments involved a collection of very distinctive and varied images (e.g., briefcase, ship, flower, face etc) one small terrain image was much like all the others. It was therefore astonishing to find that the success of target identification was statistically the same in the two cases (Mardell et al, 2012 [13] 4).

There are two outcomes of note from this study. One is evidence that provides carefully assembled experimental data requiring explanation on the basis of models of human visual behavior: that is a task appropriate to neurophysiologists. The other suggests there *may* be a possible alternative to more conventional approaches to search and rescue. Could crowd-sourcing using tablets be a promising avenue of investigation? Time will tell.

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Conjoint work

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Initiation, conduct and direction: Spence with de Bruijn, with student help.

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Initiation, conduct and direction: Spence with de Bruijn, with student help

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Initiation, conduct and direction: Equal contributions by Spence and Witkowski.

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Initiation, conduct and direction: equal contributions by Spence and Witkowski.

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based on image segmentation, ACM, Proceedings of Workshop on Advanced Visual Interfaces, pp.697-700 (4)
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One-quarter research contribution by Spence.

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3. Interaction

The essential simplicity and ubiquity of interaction – a brief hand gesture or a shift of gaze, for example – is in stark contrast to the vast range of tasks that interaction can support. No wonder that we are still waiting for the “Science of Interaction” advocated by the monograph by Thomas & Cook (2005).

It would be presumptuous to claim that what is described in this section is in any way a science of interaction. Rather, it describes three novel and hopefully useful small pieces of a jigsaw that might - or might not - eventually be recognized as such a science.

- The first item addresses the aim of allowing interaction designers to make direct use of cognitive theories without having to develop an in-depth knowledge of human cognition. It explains the new concept of **Design Actions**.
- The second item describes a (then) quite novel form of interaction, exploiting **eye gaze**. Among many applications, the technique is of potential value to tetraplegics wishing to collaborate in games over the internet.
- The third item addresses an activity for which interaction is fundamental – that of **navigating** a discrete information space such as the internet. Again, the ‘customer’ for the outcome of this research is the interaction designer.

3.1 Design Actions

To illustrate the concept of design actions we refer to one of the interactive visual artefacts described in the previous section: the hand-held device (Figure 3.1) designed to support opportunistic browsing, one example of which involves a user viewing a rapid presentation of images each, with brief text, suggesting the content of a news story. That presentation supports so-called Opportunistic Browsing (OB), the underlying attitude of which is ‘let’s see what’s there’.

While the idea behind such an artefact may be easy to appreciate, its design is far from straightforward, for one principal reason: a major determinant of the success of OB is a cognitive model that describes how design decisions influence the success of the designed artifact. Unfortunately, an interaction designer is unlikely to possess in-depth knowledge of such cognitive models.



Figure 3.1 A hand-held device designed to support opportunistic browsing

That challenge was addressed (de Bruijn & Spence, 2008 [18] **37**) by proposing the concept of **Design Actions**. Perhaps the best way to explain the concept is to consider the scenario in which an interaction designer is designing an interactive visual artifact to support opportunistic browsing. An example would be the hand-held device shown in Figure 3.1.

A cognitive concept directly relevant to the human behavior involved is Conceptual Short-term Memory, proposed by Potter (Figure 3.2, a repeat of Figure 2.6) and already summarized in Section 2.1. To repeat: a perceived image is briefly held in sensory storage and then categorized (e.g., as ‘a wiggly line’ or ‘a cat in front of a house’) by reference to knowledge stored in Long Term Memory (LTM). Its meaning or relevance in the context of opportunistic browsing is then established. If there is no relevance the image is forgotten: otherwise the user becomes consciously aware of relevance and the image is remembered. Until that occurs, the user is not consciously aware of the CSTM process. A challenge arises because very few interaction designers are aware of the CSTM model and its implications.

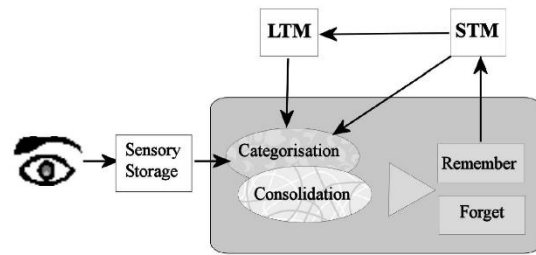


Figure 3.2 The Conceptual Short-term Memory model proposed by Potter (1999)

The development of the Design Action concept is illustrated in Figure 3.3. The cognitive model (CSTM) just discussed appears at the top left of the diagram under the label ‘Cognitive Theory A’ and is appropriately linked to the intended human behaviour that it influences and which the designer does understand. As illustrated in Figure 3.3 (bottom right) the two items together – the cognitive theory and desired human performance – lead to guidance for the designer: that guidance is called a Design Action. What Figure 3.3 also illustrates is the fact that human behaviour associated with an interactive visual artifact may be relevant to more than one cognitive theory: if that is the case, then related design actions will be present.

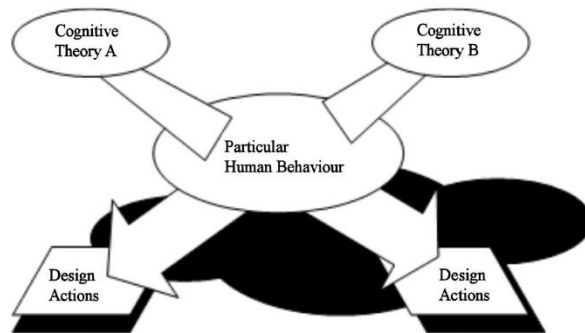


Figure 3.3 Illustration of the relation between cognitive theories relevant to a desired aspect of human behaviour and guidance (Design Actions) available to an interaction designer

Title	Design objective
Description	Clarification of title
Effect	“If you do this, that will happen”
Upside	The advantages of doing it
Downside	The disadvantages of doing it
Issues	Considerations
Theory	Reference to theoretical basis of Design Action

Figure 3.4 The format of a Design Action

What do Design Actions look like? Figure 3.4 identifies the general format of a Design Action and Figure 3.5 provides one example.

Application of the Design Action concept

To check the validity of the Design Action concept two investigations were undertaken. One was associated with the design of a mobile Web browser (see, for example, Figure 3.1) while the other considered design for involuntary browsing as might occur, for example, with the Philips Coffee Table (Figure 3.6) shown earlier in section 2 as Figure 2.6.

In each case two different cognitive models were involved. Also in each case at least two Design Actions were associated with the cognitive models. Thus, considerable detail was involved in the two design exercises which, for the sake of brevity, will only be summarized here.

ID	DA2
Title	Presentation for immediate action
Description	Presenting selectable information in images that can be inspected for at least 100ms allows a large number of items to be presented within an acceptably short time, provided that an immediate response can be initiated as soon as a relevant item is encountered.
Effect	This action gives reasonable certainty that the meaning of each fixated item can be established and that items that match a relevance threshold can trigger an immediate action supportive of a satisficing approach to browsing.
Upside	Many information items can be presented in a relatively short period of time either sequentially or concurrently (see DA1)
Downside	The lower limit of 100ms will, for a given application, establish an upper limit to the number of images that can be presented concurrently with the expectation that, during the normal - and often random and involuntary - eye gaze activity, a relevant one will be identified.
Issues	(1) unidirected/random eye-gaze activity is such that only a very short (e.g., 50 to 300ms) fixation on an information item may take place, further supporting the need for pictures of familiar objects or scenes. Conscious attention should not be necessary to recognize words or images within the information items. (2) The actions that are triggered in response to the interpretation of items needs to be simple so that they can be executed without delay or consideration. (3) Given the limits to people's reaction time, a mechanism needs to be provided that allows retreat after overshooting the target.
Theory	The ability to automatically and rapidly match an information need with a viewed image

Experiment 1 Mobile Web Browser

The browser was intended to support intentional browsing activities aimed at retrieving information from the Web. In the investigation, the prototype browser allowed users to browse daily news stories, and employed two levels of RSVP.

Figure 3.5 Example of a Design Action

As explained in Section 2, thirty participants were each asked to find answers to 8 questions: half used the experimental mobile phone and the other half employed Internet Explorer. When answering Question 1 the user was given no advice or instruction; for questions 2 to 7 they could ask any question and no advice was provided before an attempt was made on question 8. The evaluation of the mobile web browser was necessarily multi-faceted, but generally demonstrated the potential value of Design Actions.

Experiment 2 Coffee table supporting involuntary browsing

The coffee table shown in Figure 3.6 had been designed to support involuntary browsing (Stathis et al, 2002). It contains an LCD display; moving slowly around the curved periphery are small icons representing local social activities such as a chess tournament or a lost cat. If the gaze of one of the coffee drinkers alights upon one of the images of particular interest they may well become aware of the item, after which a number of actions can take place. No cognitive effort is involved (Ryall et al, 2004).



Figure 3.6 An interactive coffee table designed to support involuntary browsing

The second experiment was also based on an interactive table – not the one illustrated in Figure 3.6 but one that was functionally equivalent. Again, as with the mobile browser, more than one Design Action was involved, so the following discussion will be brief. The new Table was employed in an experiment to test some of the assumptions underlying its design based on the use of Design Actions. A crucial part of the experiment had to do with creating the experimental conditions under which involuntary browsing can be observed, a significant feature being the choice of a ‘priming’ task that precedes the main experiment without a participant being aware of the aim of that experiment.

As with the mobile browser, the application of Design Actions involved considerable detail and design decisions, and the observed results, both subjective and objective, were extensive in nature. While the overall evaluation was multi-faceted and challenging, it was concluded that, overall, Design Actions did beneficially influence the design of the coffee table.

Following the above investigations into the concept of Design Actions it would have been both premature and immature to conclude any form of superiority. That is for future follow-on studies – and, in particular, use - to gradually refine. What was pointed out was that other approaches to interaction design (e.g., Design Patterns (Borchers, 2001; Tidwell, 2006; Van Welie, 2002) offer broader granularity; reflect the subjective assessment of existing designs; are usually qualitative in their advice; and offer scope for multiple solutions. Design Actions, by contrast, have narrow granularity, are based rigorously upon experiment and theory and are usually quantitative in their advice. Time will tell.

3.2 Navigation

The past has seen many workshops and discussions devoted to the activity of navigating a discrete information space such as the Web, and the topic is still under active consideration. One challenge is posed by the fact that discrete information spaces can be immense, and cues to enable the user to decide upon individual transitions away from any location in those spaces are far from straightforward to design, partly in view of the scent (Pirolli, 2007) that must be perceived at any location. The relation to interaction is pervasive, since interaction is involved in each step taken in information space. The experience of ‘getting lost’ sums up many of the problems associated with navigation.

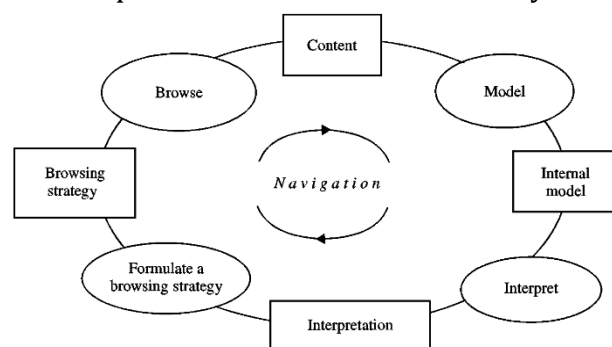


Figure 3.7 The proposed Navigation Framework

Dissatisfaction with the state of knowledge led to an attempt to establish a framework of navigation (Spence, 1999 [15] 168). In that publication navigation was defined as:

navigation: the creation and interpretation of an internal (mental) model

That definition intentionally assumes the associated interaction and consequent movement in discrete information space, and concentrates on the user's formation of a useful mental model.

The activity of navigation tends to be cyclic, as shown in Figure 3.7, involving four activities, each with its 'returned result': (1) browsing of represented data, resulting in an awareness of content; that browsing could be casual, or weighted to reflect interest; (2) the cognitive modeling of the perceived data; (3) interpretation of the model in order to (4) formulate an appropriate browsing strategy. The model of Figure 3.7 was inspired by the DEAP model familiar to statistical modellers (e.g., Su et al, 1996 [21] 18).

The design of external representations (e.g., visual representations) to support each of those four activities is a challenging task, especially in view of the range of possible intent on the part of the user, the rich nature of navigational activity and the extensive range of available interaction mechanisms.

The principal motivation of the study was not to carry out specific experiments but rather to provide a useful basis for organized thought about the design of externalizations (i.e., visual representations) to support the activity of navigation. A specific outcome of the study was a subsequent focus on the importance of 'sensitivity' as an extremely important concept in interaction design for navigation (Spence 2002 [16] 12; 2004 [17] 3)

3.3 Interaction by Gaze

A mode of interaction that has received relatively little attention is that associated with eye-gaze. In view of its novelty as well as its importance in certain scenarios (such as the control of internet games by tetraplegics (van Middlethorpe et al, 2015)) we took as a challenge the use of eye gaze in the zooming and panning of large images such as Google Earth.

Four ways in which gaze can be used to control zoom and pan were explored (Adams et al 2008 [19] 21. They are:

STZ: 'Stare to Zoom': Control of image position and resolution level determined solely by the user's gaze position on screen

HTZ: 'Head to Zoom' Gaze control: STZ augmented by head actions

DTZ: 'Dual-to-Zoom': Gaze control augmented by mouse actions

MTZ: 'Mouse-to-Zoom': Uses conventional mouse input as an experimental control



Figure 3.3 Eye gaze controls pan and zoom of Google Earth

Evaluations of all modes were undertaken by experiments involving 30 participants. Following a familiarity exercise with no time constraints each participant then undertook three activities (1) perform a straight line navigation from an image of the whole earth to a specific point on the earth's surface by continuous zooming and, if required, corrective panning and zooming actions (the task was repeated three times in order to detect any learning or improvement through practice), (2) search for as many London buses as possible within 90 seconds, and (3) complete a questionnaire concerning usability and acceptability.

Perhaps unsurprisingly, participants spent substantially less time to familiarize themselves with MTZ and DTZ. For the navigation task, HTZ was noticeably characterized by a longer target offset and mean time to complete, *but only on the first attempt*: thereafter there was *essentially little difference between the four modes*, suggesting that HTZ is simply less intuitive upon first encounter than the other modes. For the search task MTZ offers the highest level of control, followed by DTZ, then STZ, with HTZ proving the least effective. Regarding the subjective questionnaire, the principal result worthy of note was the greater degree of 'sickness' experienced with the HTZ mode.

Overall, the conclusion drawn was that both hands-free methods (STZ and HTZ) offer a viable image control and search method, notably for those users with severe motor disability but also for those who routinely monitor and search large image spaces and wish to use their hands for other tasks such as data entry.

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4. Dynamic Exploration

Many people have a strong interest in the effect that one feature of a system has upon another. For example, the effect of diet or exercise on obesity (Neufeld et al, 2008) or the consequence of an investment upon profit (Black & Scholes, 1973). So there is considerable interest in being able to vary a feature (we'll call it a **parameter**) and immediately see the effect on something we shall call **performance** (Figure 4.1).

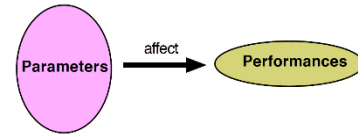


Figure 4.1 The performances of a system are determined by parameter values

To this end, and since 1970, the candidate has strongly advocated and demonstrated (Spence & Drew, 1971) the truly enormous potential for insight acquisition offered by a particular mode of interaction – that of **dynamic exploration**, often broadly referred to in a ‘what if?’ problem context.

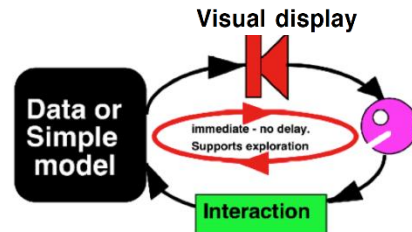


Figure 4.2 Conditions required for the continuous and dynamic manual exploration of the effect of a parameter on a performance

Basically, if a manual change of a variable parameter can be followed within less than a second (Goodman & Spence, 1978) by a representation of its effect on performance, a user can dynamically (i.e., smoothly and continuously) explore the effect of a parameter on a performance, thereby gaining considerable insight into their relationship.

The basic model of dynamic exploration is depicted in Figure 4.2. Its value depends upon the essentially immediate availability of data or the existence of a simple model capable of fast execution. In the context of the Information Visualization Reference Model (Figure 1.3) our focus here is summarized in Figure 4.3.

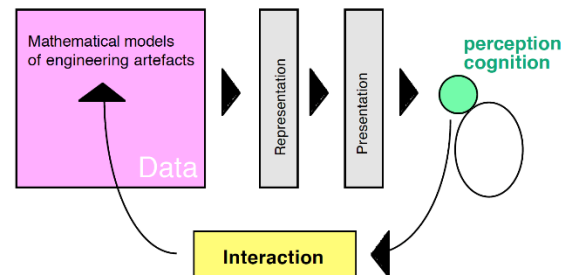


Figure 4.3 The Information Visualization Reference Model of Figure 1.3 redrawn to emphasize the essentials of Dynamic Exploration: interaction with data models to enhance the mental model of the user.

The obvious challenge to be met if so-called dynamic exploration is to be exploited is that of *finding simple models capable of fast execution*.

4.1 Model creation

Straightforward simulation is usually not the answer. For very simple systems the time elapsing between the change in a parameter and the calculation of the change in performance may be less than around the critical region of one second, but for realistic systems such as electronic circuits and electromagnetic devices this is not the case. Alternative approaches must be sought: we examine three.

Precalculation

One simple but often computationally expensive approach is **pre-calculation**. Here, a sufficient number of simulations to provide parameter/performance pairs is carried out

over a broad Region of Exploration such that manual exploration of these discrete data points can be interpreted by the human cognitive apparatus as being effectively continuous. To demonstrate the value of dynamic exploration and encourage its use this approach was demonstrated long ago (Spence, Apperley, 1977) in circumstances (simple electronic systems) where the designer may be prepared to wait for simulations to be carried out, knowing that essentially continuous exploration will then be possible. In certain circumstances that is acceptable.

Analytic

A second alternative approach is possible for certain classes of system (e.g., linear) if *a priori* knowledge is available of the identity of the parameter and the performance of interest. In this case, specialized algorithms may be developed that can be used to generate the simple model shown in Figure 4.2 (see, for example, Leung & Spence (1976) for linear electronic circuits).

Response Surface Models

However, for many systems, of which electronic circuits, structures and electromagnetic devices are examples, the computational cost associated with either of above approaches is so high that a more generally applicable approach is required. One such approach involves the use of Response Surface Models.

To provide the simple model of Figure 4.2 it possible to generate – though preferably parsimoniously – a number of parameter~performance combinations to which a continuous surface can be fitted. A simple example for two parameters and one performance is illustrated in Figure 4.4. That simply defined surface can then be sampled (Smith et al [30]) to generate, with minimal computational effort, the performance for combination of parameter values. That surface is called a **Response Surface Model** (Dyck et al, 1999, [28] 27). We show examples below.

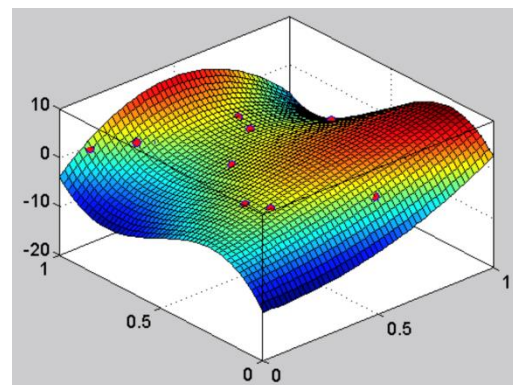


Figure 4.4 Illustrating the concept of a Response Surface Model. Plotted vertically is a single performance which is a function of two horizontal parameters. The small red dots represent computed values of performance, and the coloured continuous surface is the model that is fitted to those points and provides a relation between performance and the two parameters that is easily computed.

4.2 A modelling tool

The generation of response surface models typically involves either the delegation of their development to statisticians or for the circuit designer to develop sufficient statistical expertise to carry out the modeling task. Severe disadvantages are

associated with both these approaches, and it was for this reason that a modeling tool – the Model Maker - was developed specifically (Malik et al, 1998 [23], Smith et al, 2001 [29] **3**) for use by the ‘problem holder’ – the person who actually needs the response surface model in order to allow dynamic exploration of an otherwise familiar system.

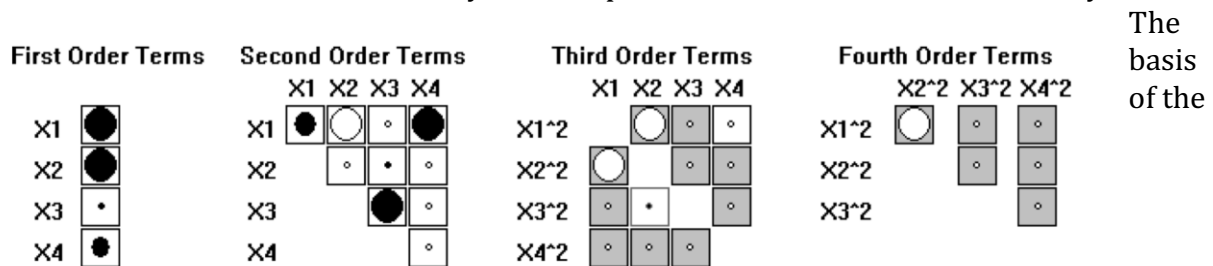


Figure 4.5 Outline of the interface of the modeling tool.

tool is

Each

single term in the polynomial response surface being fitted and is labeled accordingly. A black circle indicates a term already included in the model while a white circle identifies a term not yet included. In both cases the size of these circles indicates the actual or anticipated value of the term’s inclusion in the model. A white background indicates that a term can be added to or removed from the model; a grey background indicates that, for heuristic reasons, the term’s inclusion requires other terms to be included at the same time.

interactive modeling shown in Figure 4.5.

square represents a

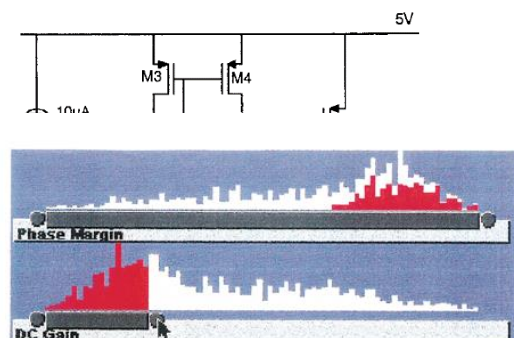
By employing the representation shown in Figure 4.5 and the associated interactive affordances, the Model Maker provides information about all possible changes ‘one step away’ to support an iterative exploration procedure aimed at the creation of a useful response surface model.

4.3 Application

Electronic circuit design

The Response Surface approach was illustrated (Spence, 1999 [20] **22**) in the context of the design of the integrated circuit amplifier shown in Figure 4.6. Briefly, the five parameters that had to be chosen by the designer were aspect ratio of five devices within the circuit. To permit the development of a response surface model their values were selected randomly within very wide ‘exploratory’ ranges to allow later exploration. One hundred and sixty simulations of the circuit were then carried out to enable a response surface to be fitted (see below).

Following each execution of the Response Surface Model – in other words, for each possible design - the five parameter values and their four corresponding performance values were then displayed in the form of histograms exploiting the concept of the Attribute Explorer (Spence & Tweedie, 1998 [26] **105**). The enormous potential offered by those



histograms was then realized by many exploratory actions performed by the human circuit designer.

To take one illustrative example (Figure 4.7), the designer selected all those potential designs having a low value of the performance 'DC Gain' (lower histogram), whereupon corresponding high values of 'phase margin' were highlighted, immediately drawing the designer's attention to a fundamental trade-off between those two performances, an insight of enormous value to the designer. Many other valuable outcomes of exploratory interaction are discussed in Spence (1999 [20]).

Structural design

A need arose within a well-known manufacturer of lamps for guidance regarding the design of structure supporting a filament (Figure 4.8): the aim of the design was to keep the internal stresses of the structure to a minimum, thereby reducing the risk of breakage.

For the structure of interest (Figure 4.8) the designer has to values for four dimensional parameters (denoted X1 to X4) order to 'minimise' the stresses (S1 to S4) at various points structure. The lamp designer had no prior understanding of the effect of the parameters upon the stresses.

The approach taken was to create a response surface model by fitting a response surface to 81 simulations corresponding to designs (i.e., choices of X1 to X4) distributed reasonably uniformly with a Region of Exploration considered by the designer to include realistic designs. This was achieved through the use of generalized linear regressions models (Su et al, 1996, [21] 18). As an example, the relation between the stress S4 and the designable parameters (X) was found to be:

$$S4 = 60.4 + 23X_1 - 3.8X_2 + 631.2X_3 - 26.4X_4 - 79.7X_1X_3 + 4.8X_2X_3 + 2.6X_1X_4 - 2.6X_1^2 - 278.2X_3^2 + 5.7X_1^2X_3$$

relation, of course, does not, as it stands, inform the lamp designer. However, that equation and the corresponding relations for the other stresses form the efficiently executable model required (Figure 4.2) to permit dynamic exploration. The model was used to generate corresponding values of X1 to X4 and S1 to S4 for 100 possible designs. The results were represented as interactive histograms as shown in Figure 4.9, allowing the lamp designer to place limits on all variables (as with the Attribute Explorer).

Figure 4.7 Dynamic manual selection of low values of the performance 'DC Gain' have been continuously brushed into the histogram of 'Phase margin' placing in evidence a trade-off between these two performances

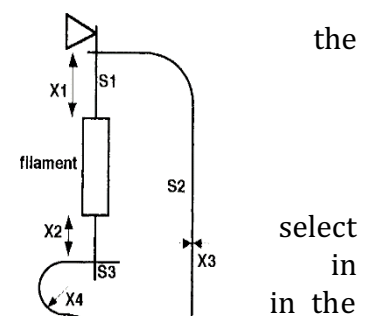


Figure 4.8 The internal structure of a filament lamp. The task of its designer is to choose values of X1 to X4 in order to minimize the stresses S1 to S4

This

The lamp designer began his exploration by selecting designs having a low value of S4 (see Figure 4.9), and immediately discovered a trade-off with S3, a correlation with S2 and an inverse correlation with one of the parameters. During the early, exploratory stages of design these are extremely valuable insights (Smith et al, 2001, [29] 3)

4.3 Enhancements for Dynamic Exploration

The value of gradient information

For many types of simulation, gradient information is simple and cheap to obtain enhance the process of generating a response surface model. Such an enhancement was investigated by Malik et al (1998, [24] 11; 1999, [27] 2) and applied to the design of an electromagnetic speaker: the use of the finite element method in the simulations allowed gradient information to be generated and exploited at little extra computational cost.

Optimization

A response surface model lends itself to the optimization of a system, as demonstrated by Rong et al (1997, [22] 53) in connection with the design and optimization of electromagnetic devices. Models were derived using a fractional factorial approach, allowing a genetic algorithm to solve the resulting constrained nonlinear optimization problem. A C-core actuator was used as an illustrative example.

The inverse problem

There is no doubt that it is immensely helpful for a designer to be able to explore the effect of parameters on performances (Figure 4.9, a repeat of Figure 4.1). But the overall and challenging task faced by a designer is the reverse effect (Figure 4.10). Usually, a designer has to achieve a prescribed set of performances by choosing values for many parameters. This extremely challenging task can, in fact, be supported by using a response surface model to generate what is called a Prosecution Matrix (Furnas & Buja, 1994; Tweedie & Spence, 1998

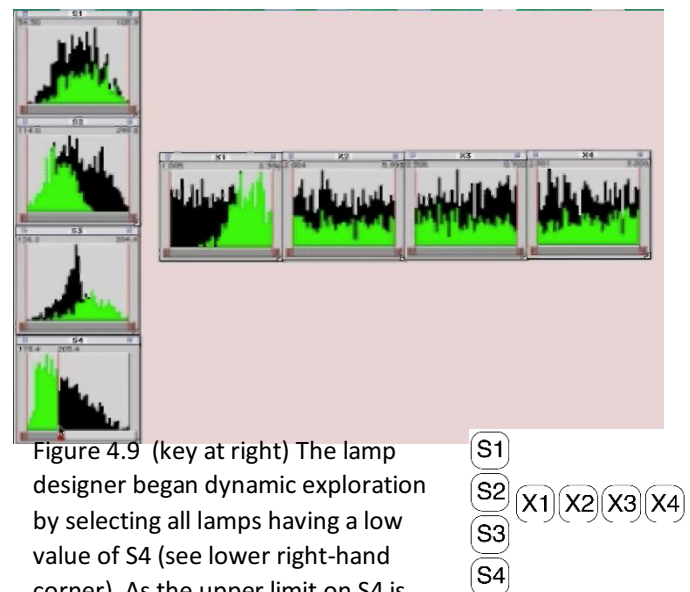


Figure 4.9 (key at right) The lamp designer began dynamic exploration by selecting all lamps having a low value of S4 (see lower right-hand corner). As the upper limit on S4 is gradually lowered, the colour-coding of all histograms is changed accordingly. This figure shows that low values of S4 correspond to high values of S3, low values of S2 and high values of the parameter X1 and can

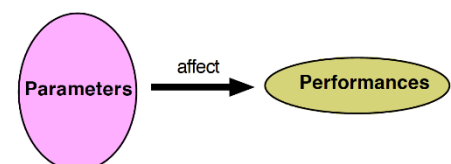


Figure 4.9 Parameter values determine performances

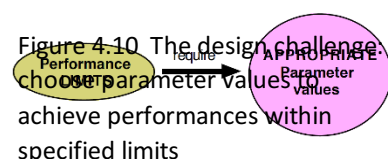


Figure 4.10 The design challenge: choose parameter values to achieve performances within specified limits

[25] **26**). For the lamp structure discussed above and shown again in Figure 4.11 the Prosection matrix is shown in Figure 4.12.

Each 'tile' of a Prosection Matrix (of which six are shown in Figure 4.12) corresponds to a pair of parameters. The content each tile is generated by taking a large number simulated designs and projecting them onto the tile, but encoding in colour the extent to which they satisfy each of the performance (i.e., stress) limits. If a design satisfies all limits it is encoded red; if it fails one limit it is encoded black; two limits attract dark grey encoding and three failed limits light grey encoding

Why is a Prosection Matrix valuable? There are three principal reasons. First, it shows a designer the location of the highest density of acceptable designs – the Region of Acceptability projected onto parameter space. In fact, a designer often has little idea where satisfactory designs are located in parameter space. Second, the designer can manually vary performance limits and see, immediately, the corresponding movement of the boundaries between different coloured regions. For example, it might be found that a particular performance limit has no effect whatsoever on the size of the Region of Acceptability: by contrast, a particularly demanding performance limit could be discovered. A third advantage of a Prosection Matrix has to do with the yellow rectangles in Figure 4.12: they represent tolerances on designable parameters, and can assist in design to achieve maximum manufacturing yield of a mass-produced product.

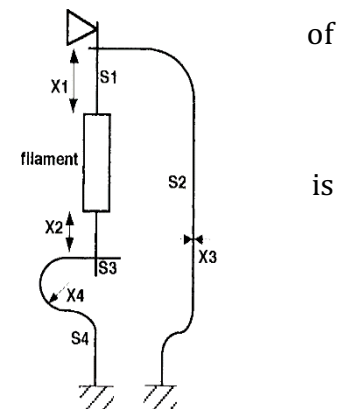


Figure 4.11 The lamp structure discussed earlier: X_1 to X_4 must be chosen to minimize S_1 to S_4

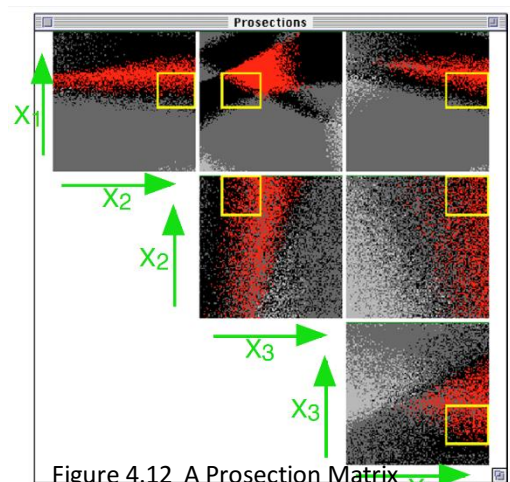


Figure 4.12 A Prosection Matrix associated with the design of the lamp structure shown in Figure 4.11

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